A METHODOLOGY FOR TECHNO-ECONOMIC COMPARISON OF PV INVERTER STRUCTURE TOPOLOGIES: A CASE STUDY ON PROPOSED 1 MWP SOLAR POWER DEVELOPMENT SCHEME IN SRI LANKA

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Degree of Master of Science

Department of Electrical Engineering

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Thesis/Dissertation submitted in partial fulfilment of the requirements for the degree
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DECLARATION

I declare that this is my own work and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other university or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Signature of the supervisor:

Dr. Asanka Rodrigo Date:

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ABSTRACT

Sri Lanka's recent energy policies are focused on promoting economically viable solar power generating schemes introducing novel market segments. It's envisioned to ensure nation's energy security while promoting utilization of indigenous energy generating resources. Recent 1 MWp solar power development scheme is one such novel market segment. PV inverters play a significant role in any PV plant performance. Lack of research on identifying the technically and economically most suited PV inverter architecture has caused high risk of failed project objectives. Following research presents a comprehensive framework for a techno-economic comparison of different PV inverter architectures which are central inverters, string inverters, micro inverters and power optimizer systems. 1 MWp capacity PV plant models are designed for analytical purposes of the research. Technical aspects such as energy yield, safety aspects, power output quality, reliability and performance monitoring are assessed using simulation tools (PVSyst, PSCAD and MATLAB), field data analysis, Cost Priority Number method and Markov reliability models. Economic impact is evaluated using Levelized Cost of Electricity calculations and project financial assessments followed by a sensitivity analysis. It's found that distributed power electronics in PV systems provide higher energy yield, reduced safety risk, higher reliability and lower system down-time due to failures compared to central and string inverters. String inverters and power optimizer systems are more economically feasible in 1 MWp scale. Finally, it's concluded that the presented methodology furnishes a proper techno-economic comparison for different PV inverter architectures.

Keywords: Inverter architectures, Solar power development in Sri Lanka, Photovoltaic, Central inverters, Micro inverters, String inverters, Power optimizers

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List of Abbreviations

Abbreviation	Description
AC	Alternating Current
BOS	Balance of System
CEB	Ceylon Electricity Board
DC	Direct Current
GOSL	Government of Sri Lanka
GW	Giga Watt
HV	High Voltage
LCOE	Levelized Cost of Electricity
LECO	Lanka Electricity Company
LV	Low Voltage
MPPT	Maximum Power Point Tracking
MV	Medium Voltage
MW	Mega Watt
OEM	Original Equipment Manufacturer
PV	Photovoltaic
RE	Renewable Energy
SLSEA	Sri Lanka Sustainable Energy Authority
STC	Standard Testing Conditions

CHAPTER 1

INTRODUCTION

1.1 Recent 1 MWp Solar Power Development Scheme in Sri Lanka

In order to ensure nation's energy security while promoting utilization of indigenous resources to energy generation, National Energy Policy of Sri Lanka considers development of economically viable Non-Conventional Renewable Energy (NCRE) sources as a key strategy to follow. As the authorized body established to generate, transmit, distribute and sell electrical energy in Sri Lanka, Ceylon Electricity Board (CEB), adopting to the National Energy Policy, has been extracting energy to generate electricity from NCRE sources. In their Long Term Generation Expansion Plan 2015-2034, CEB set their target to achieve 20% of electricity generation from NCRE plants by 2020 from the state of 11% by end of 2015. Since Sri Lanka has already harnessed most of its large hydro potential, it was decided to focus on promoting solar and wind power generation in the island [1].

Considering the solar power generation potential and its healthy climate conditions in Sri Lanka, the policy makers identified promoting of solar power generating technologies prominence to cater the growing need. This has been taken into consideration with decentralized solar power development from utility scale and as well as small scale roof top project development [2]. Figure 1-1: Solar PV Generation Capacity Development 2018-2037 [2] shows the planned decentralized solar power development as per the Long Term Generation Expansion Plan 2018-2037.

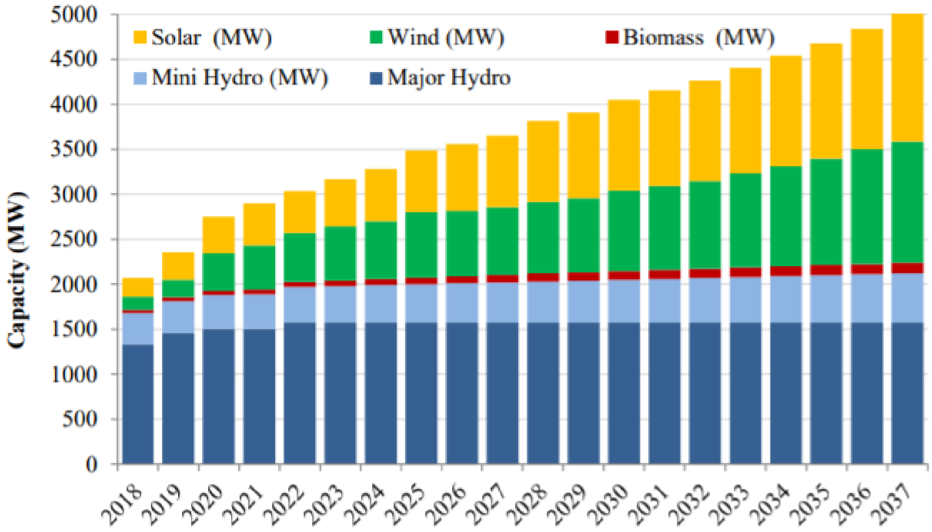


Figure 1-1: Solar PV Generation Capacity Development 2018-2037 [2]

To achieve such a significant solar PV generation capacity development, in 2016, Ministry of Power and Renewable Energy led by Government of Sri Lanka (GOSL) deployed a new solar power generation project titled 'Soorya Bala Sangramaya' (Battle for Solar Energy) with Sri Lanka Sustainable Energy Authority (SLSEA), Ceylon Electricity Board (CEB) and Lanka Electricity Company (Private) Limited (LECO) to promote solar power generation among the community. Project objectives are to achieve 200 MWp of solar PV generation capacity by 2020 and 1,000 MWp by 2025 [3]. This project created an exponential growth in the solar PV market in Sri Lanka motivating number of small solar power plants on the rooftops of households, religious places, hotels, commercial establishments and industries.

Furthermore, in order to accelerate the project objectives, in 2017, Government of Sri Lanka (GOSL) initiated the second phase to the project with opening up opportunities to develop 60 numbers of 1 MWp ground mounted solar PV projects at 20 selected grid substations [2]. Rapid growth of solar PV generation as well as the declination of market prices made the GOSL to select international competitive bidding process over existing feed-in-tariff for the evaluation and selection of successful bidders to grant the opportunity [1]. Proposed contract period is 20 years under Build, Own and Operate (BOO) basis. Following up the same approach, in 2018, GOSL opened up opportunities to develop another 90 number of 1 MWp ground mounted solar PV projects at 17 selected grid substations [4].

With this approach, a novel segment in Sri Lankan solar PV market as “1 MWp Ground Mounted Solar PV Plants” has been created where several investors and project developers in local as well as international backgrounds are actively engaged in.

1.2 Role of the PV Inverter in Solar PV Plant

Among the many components which composes a typical solar PV plant, solar PV modules, inverters, mounting system, transformers and grid connection interfaces act as key apparatuses. Solar radiation is converted into electricity through photovoltaic effect by the solar PV modules. Output dc electricity is then converted into ac electricity by the PV inverter. A step-up transformer is required to step-up the output voltage in order to transmit the energy to the national grid. PV mounting system permits the PV modules to be safely connected to the ground at a fixed tilt angle or on a tracking system which tracks the sun path. A grid connection interface or a grid substation contains grid interface switchgear for energy transmission, protection and measuring requirements of the PV plant electrical system [5].

Typical cost breakdown of the above main components which forms a typical PV plant can be categorized as in Figure 1-2. As per the figure, PV inverters are among the low cost components.

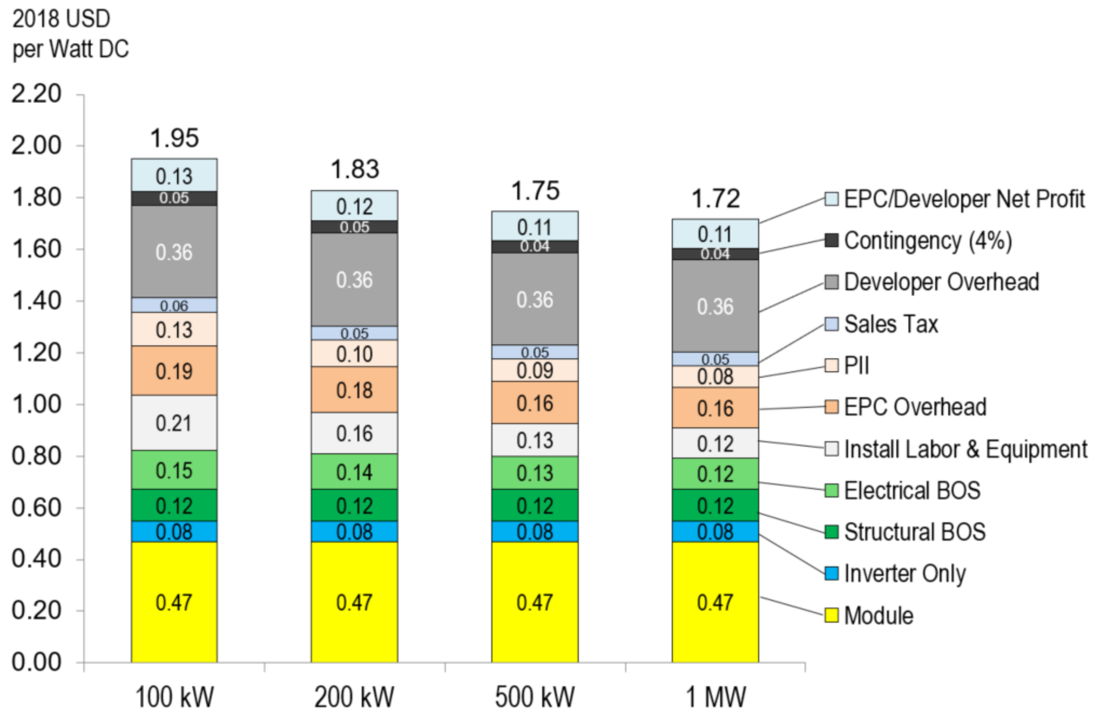


Figure 1-2: Q1 2018 U.S. Benchmark - Commercial PV System Cost (2018 USD/Wdc) [6]

Although the cost component of PV inverters is in the lower side, the functionality of a typical PV inverter is recognized as critical and important. Main function of a PV inverter is to convert dc electricity to ac electricity while making sure the power quality of the output complies with local grid regulatory requirements. PV inverters also optimizes the operating voltage throughout the PV module strings so that maximum energy is harvested from the PV modules. Apart from that, in-built electronics inside the PV inverter provides performance monitoring and data logging facilities of PV strings real time and historically. It is also equipped with essential protection and isolation mechanisms to safeguard from irregularities and complications in the national grid [5].

These functionalities of a PV inverter have been modified and upgraded with the evolution of the inverter. During the technology evolving process, PV inverters were transiting over several key design architectures or structure topologies such as centralized inverter topology, string or multi-string inverter topology and ac module topologies [7]. In contrast to the global market, advanced technologies with module level power electronics has been developed and commercialized to harness solar resource more efficiently. One such methodology is the use of Distributed Maximum Power Point Tracking (DMPPT) PV systems over conventional solar energy harnessing methods (i.e. central inverters and string inverters based PV systems). DMPPT PV systems offer advantages in safety, energy yield, lower power handling requirements, module-level maximum power point tracking and monitoring capability [8].

Each of these PV inverter architecture has its own inherent pros and cons which decide the PV plant upfront cost, overall energy generation & revenue, operations & maintenance costs and financial feasibilities of a solar PV plant based on its capacity, scale and other plant features.

1.3 Problem Statement

As it is detailed above, 1 MWp ground mounted solar PV projects are a novel market segment in Sri Lankan solar PV industry. Out of the available different PV inverter architectures, selection of best suited inverter architecture for this scale PV projects has become an intriguing matter among the interested project stakeholders due to this novelty.

It was recognised that lack of proper research work on identifying the technically and economically most suited inverter architecture for the aforesaid 1 MWp scale solar PV projects to be developed in Sri Lankan conditions has enabled the stakeholders to follow conventional methods in PV inverter selection. It has resulted in high risk of lower project IRR and high risk of unsatisfied project objectives of the stakeholders.

1.4 Objectives

In this thesis, it is aimed to provide a comprehensive framework for the 1 MWp scale solar PV ground mounted project stakeholders to analyse the pros and cons of utilizing different PV inverter architectures (structure topologies) available in their projects and to identify the technically and economically most viable PV inverter architecture in this scale.

It is envisioned to achieve following objectives in this thesis,

i. To design 1 MWp PV plant models using different inverter structure topologies and to optimize the design in terms of achieving lower upfront cost, higher energy yield and lower power losses.
ii. To evaluate technical features of each inverter architecture in 1 MWp scale and provide a comprehensive framework for a technical comparison between the topologies.
iii. To evaluate the economic impact of each inverter architecture in 1 MWp scale in terms of upfront cost, energy yield and running costs throughout its life time and provide a comprehensive economic comparison framework.

1.5 Thesis Outline

Following the successful achievement of objectives in section 1.4 above, the rest of the thesis is organized as follows,

Chapter 2 provides a comprehensive review on literature related to trends in global PV market, basics on PV plant components and importance of PV inverter selection. Furthermore, a classification of different PV inverter architectures is also highlighted.

Chapter 3 presents a brief roadmap of the proposed methodology which consists of three main parts.

Chapter 4 establishes the detailed methodology of the first part which develops 1 MWp scale PV plant models for the analytical purposes

Chapter 5 furnishes the detailed methodology of the second part which analyses technical features of different PV inverter structure topologies.

Chapter 6 presents the detailed methodology of the third part which analyses economic impact of utilizing different PV inverter structure topologies.

Chapter 7 delivers the results of the application of proposed methodology in the case study and discusses the impact and root causes for the results.

Chapter 8 presents the conclusions and future directions of the study.

1.6 Chapter Summary

In this chapter an introduction on the current 1 MWp solar power development scheme in Sri Lanka is briefed along with the importance of selection of PV inverter architecture in succeeding the scheme objectives. Problem statement is presented along with research work aim and objectives. Chapter organization in the thesis is outlined.

In the next chapter, literature related to the research work is reviewed.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a comprehensive review on the literature related to the subject area of solar PV basics and different PV inverter topologies.

2.1 Global PV Market and Its Future

During the last century, conventional electricity generation methods like coal, gas, nuclear and hydro were developed based on a centralized electricity network which requires electricity to be transmitted over miles. Due to stability and security issues threatened by chains of blackouts and electricity grid ruptures, distributed energy resources (solar, wind, biomass, biogas etc.) which are decentralized, modular and more flexible have been gaining the market attention for the past few decades. Reduced losses in the transmission, reduced fossil fuel consumption are considered as added benefits of distributed generation [9]. Solar energy has received a great interest among all above distributed alternative sources of energy due to several reasons [10]. Fast growing price competitiveness of solar energy is one of these reasons which made the industry to evolve in a short period of time [11].

In global perspective, Power Purchase Agreement (PPA) prices of solar energy has been rapidly falling over the last few years, making solar energy cheaper than wind after 2016 [11]. As indicated in Figure 2-1, at the end of 2018, cumulative global PV installations have reached 509 GWp, with an annual PV deployment of 102 GWp [12].

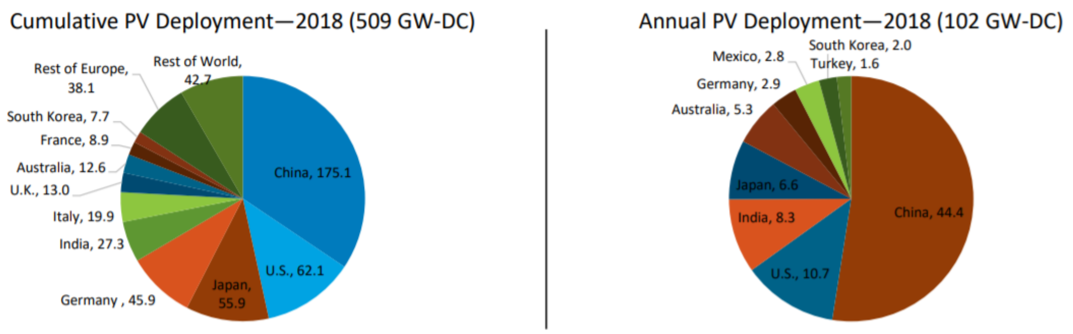


Figure 2-1: Global PV Installation Deployment [12]

Considering the future of global PV market, it is expected to continue the growth with added more projects from the emerging markets also which are to be supported by the further decreasing PV prices and further increasing market demands. Figure 2-2 shows the future projection of the industry. After 2018, it is predicted that the focus in the emerging markets shall also established on new electricity market designs, integration of storage technologies, improving distribution and transmission lines, to adapt more solar PV [11].

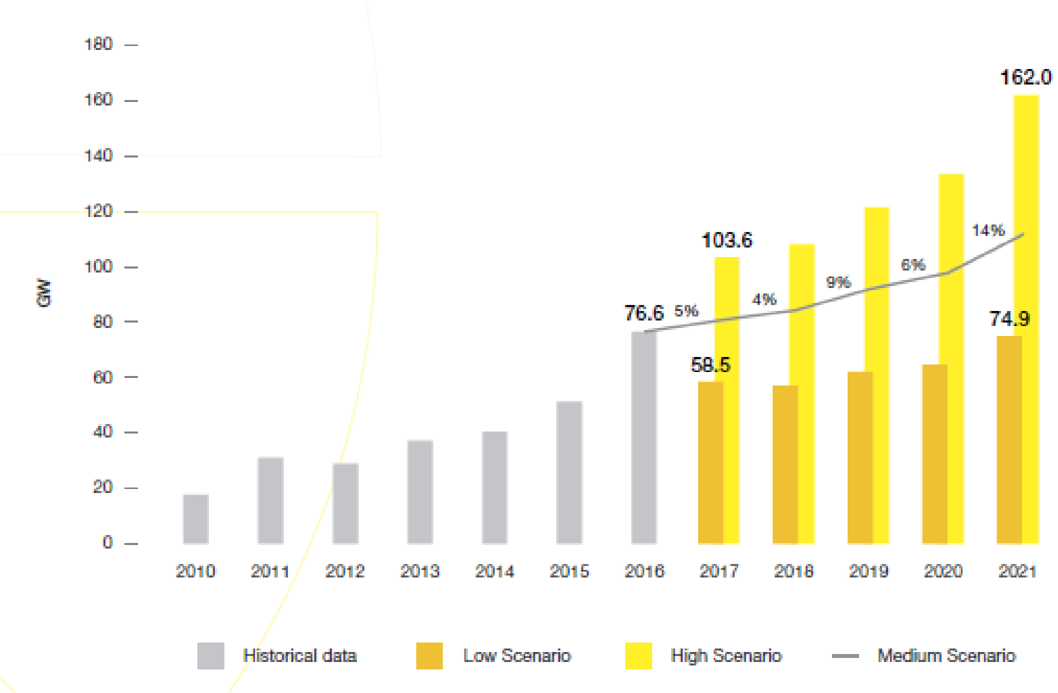


Figure 2-2: Future of Global PV Market [11]

2.2 Basics of Solar PV

2.2.1 Solar PV Cell, Array

Solar energy is a natural energy source available in abundance. Total solar energy available on earth surface is about 1.5 x 1018 kWh/year, which is 10,000 times of the annual global energy consumption. A solar cell is utilized to convert the photons in solar radiation in to direct current (dc) and voltage. A typical solar cell consists of, a semiconductor material to adsorb light and generate carrier charges, a junction to separate the charges and contacts of the cell to allow current flow to the external [13].

Main streams of manufacturing solar cells are flat plate technology and concentrated technology. Flat plate technology consists of crystalline technologies (mono and poly) and thin film technologies (amorphous silicon, cadmium telluride, copper indium selenide, copper indium (gallium) di-selenide) [5].

Addition to the PV modules bundled together with the above solar cell technologies, a PV inverter, a module mounting (or tracking) system, a step-up transformer and a grid connection interface shall be employed to construct a grid connected solar PV plant [5].

2.2.2 Role of a PV Inverter

A PV inverter acts as an interface between the PV module and the utility grid, converting dc power of the module in to ac power and injecting a sinusoidal current in to the grid [10]. Apart from the dc to ac conversion, PV inverter is responsible for maintaining the quality of the power output as required by different utility standards

[9]. In some PV architectures, the inverter performs few other functions to increase the efficiency and energy output from the PV plant. Some of those functions are optimizing the voltage across the strings, extracting the maximum energy from the PV modules and monitoring PV string performances. It also performs a significant role in providing necessary protection and isolation means during grid irregularities and faulty situations [5].

Internally, PV inverters utilize power switching devices such as thyristor or Insulated Gate Bipolar Transistor (IGBT) for the dc to ac conversion. In order to minimize the interferences and improve the quality, a filter shall be employed [5].

In order to control the dc to ac conversion and quality power output, PV inverters utilize two main control strategies as indicated follows [9, 10],

1. MPP controller – Main function is to extract the maximum energy yield from the PV module.
2. Inverter controller – Main functions are to control active and reactive power, maintain dc-link voltage, control quality of the power and perform grid synchronization.

These control strategies shall be employed by two cascaded current loop and external voltage loop [14].

Internationally accepted regulatory standards such as IEEE 1547.1-2005, VDE0126-1-1, EN50106, and IEC 61727 provide necessary requirements for PV inverters to be complied with [7]. Among these requirements, limits to the total harmonic distortion (THD), individual harmonics, dc current injections, operating ranges for voltage and frequency conditions, power factor, islanding detection, low voltage ride through capabilities, reactive and active power injection and synchronization requirements are specified mainly [7, 10].

2.2.3 Maximum Power Point Tracking

Maximum power point tracking (MPPT) is a technique used to extract maximum energy out of the PV modules. A MPP tracker finds the operating points where the maximum power can be extracted from the PV strings or modules [15].

This function is usually done in a dc-dc converter or dc-ac converter. Usually, the maximum power point of a PV module varies with the irradiance and temperature as shown in Figure 2-3. There are several algorithms utilized such as perturb and observe, incremental conductance, parasitic capacitance and constant voltage etc. [7, 10, 14].

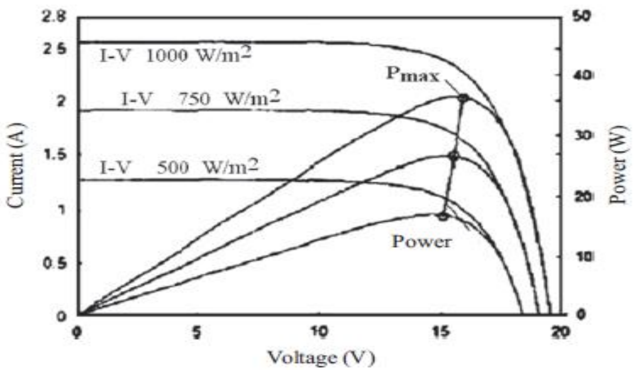


Figure 2-3: Maximum Power Variation with Irradiance Level

Pmax = Vmpp x Impp provides the maximum power generated by the PV module or strings where Vmpp and Impp are the maximum power generating voltage and current for a given irradiance and PV module temperature [14]. An overview of perturb and observe MPPT algorithm is shown in Figure 2-4.

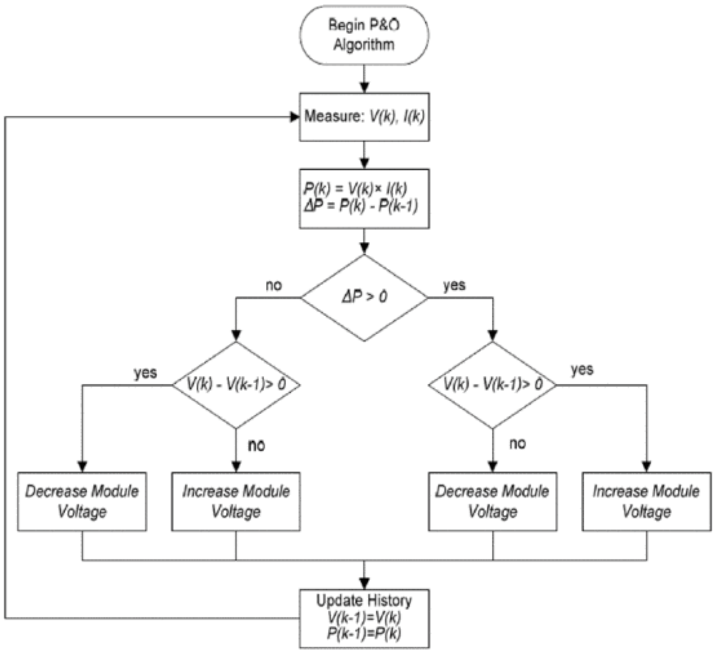


Figure 2-4: Overview of Perturb and Observe MPPT Algorithm [16]

2.2.4 DC-DC Converter

A dc-dc converter converts the direct current from one voltage level to a required voltage level. In PV systems, these power electronic devices perform a significant operation to detect the maximum power point according to the utilized MPPT algorithm and to amplify the voltage up to the required voltage level for the dc-ac convertor. Commonly used dc-dc converter topologies in PV systems can be identified as step-down (buck converters), step-up (boost converters), and combined unit of step-down and step-up (buck-boost and cuk converters) [14, 15].

2.3 Classification of PV Inverters

In this section, a detailed overview on classification of PV inverters is analysed based on the literature available.

2.3.1 Topologies Based on Number of Power Processing Stages

Reference [7] identifies three main categories of PV inverters based on the number of power processing stages, which are, single stage inverters, dual stage inverters and multi stage inverters. In single-stage inverter, maximum power point tracking, grid current control and voltage amplification (if applicable) are done at the dc-ac inverter. This can be identified as the basis for central inverter architecture. In dual-stage inverter, a dc–dc converter is performing maximum power point tracking and voltage amplification (if applicable) while the dc-ac inverter is controlling the grid current. This is the typical construction of a string inverter architecture. In multi-stage inverters, several dc-dc converters are connected to a dc link of a single dc-ac inverter. This forms the basis for multi-string inverter architecture [7].

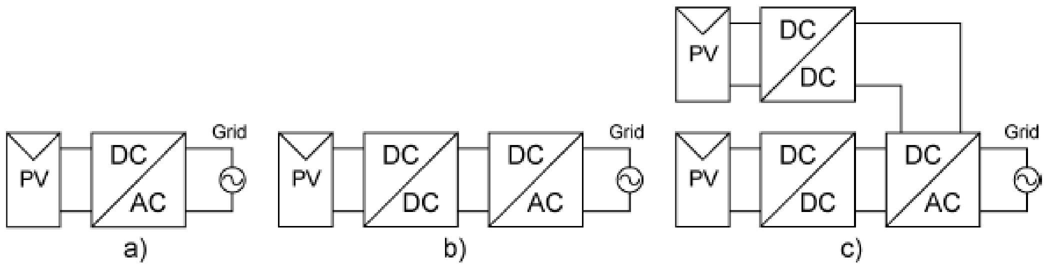


Figure 2-5: Classification of PV inverters based on number of power processing stages. (a) A single stage inverter, (b) A dual stage inverter, (c) A multi stage inverter [7].

2.3.2 Topologies Based on Location of Power Decoupling Capacitor

Reference [7] also identifies two main categories of PV inverters based on the location of the power decoupling capacitor, which are, PV inverters with the capacitor placed in parallel with the PV module (in single-stage inverters) and PV inverters with the capacitor placed either in parallel with the PV module or in the dc-link (in multi-stage inverters).

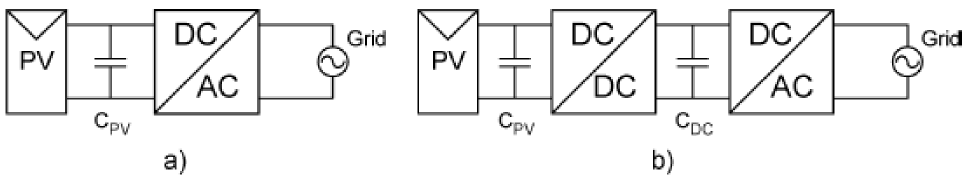


Figure 2-6: Different locations for power decoupling capacitors. (a) Capacitor placed in parallel with the PV module, (b) Capacitor placed either in parallel with the PV module or in the dc-link [7].

2.3.3 Grounded and Ungrounded PV Inverters

Based on the grounding of the current carrying conductors (CCC), PV inverters can be categorized in to two main classifications, which are, grounded PV inverters and ungrounded PV inverters. In grounded PV inverters, positive or negative dc conductor is connected to the equipment grounding conductor (EGC) through a ground fault detection and interrupter (GFDI) fuse, which is termed as "system grounding". Main purpose of this is to detect ground faults and provide protection from shock hazards. In ungrounded PV inverters, there is no connection between the current carrying conductors and equipment grounding conductor. Here, an alternative ground fault protection mechanism is provided by the PV inverters using residual current monitoring devices (RCD) and DC insulation resistance (Riso) measurements [17, 18]. Figure 2-7 shows a typical connection diagram of a grounded PV inverters.

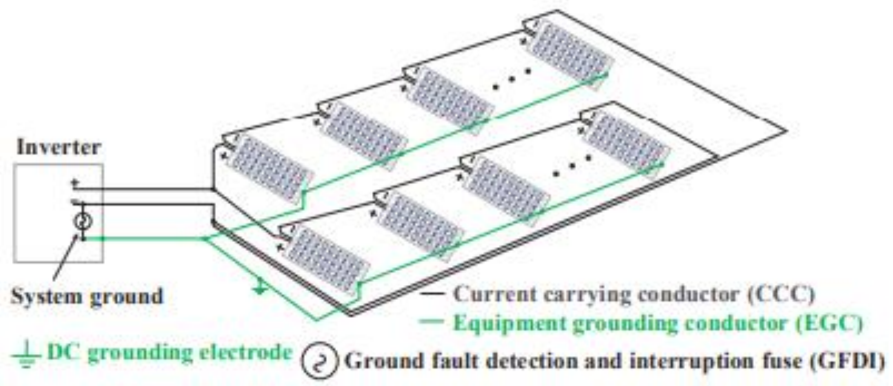


Figure 2-7: Typical Connection Diagram of Grounded PV Inverters [17]

2.3.4 Transformer and Transformer-less PV Inverters

Reference [7] also identifies four main categories of PV inverters based on the use of a transformer inside, which are, PV inverters with a line frequency transformer at the grid side, PV inverters with a high frequency transformer embedded in an high-frequency-link grid connected ac-ac inverter, PV inverters with a high frequency transformer embedded in an high-frequency-link PV module connected dc-dc converter and transformer-less PV inverters [7].

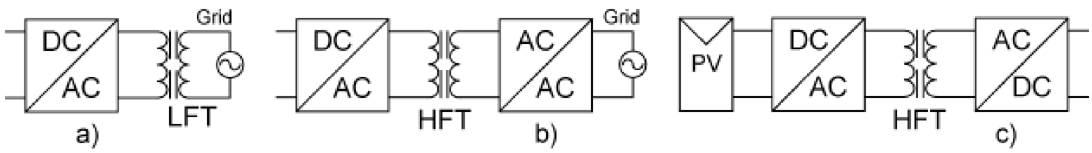


Figure 2-8: Transformer-included PV inverter categories (a) A PV inverter with a line frequency transformer, (b) A PV inverter with a high frequency transformer embedded in an high-frequency-link grid connected ac-ac inverter, (c) A PV inverter with a high frequency transformer embedded in an high-frequency-link PV-module-connected dc-dc converter [7].

Main objectives of using a transformer in PV inverters are stepping-up the dc voltage and providing galvanic isolation between dc and ac sides [5, 9]. In the modern PV market, most of the centralized inverter topologies utilize transformer inside [5]. Due to an electrically charged surface between the PV module and the grounded frame, a parasitic capacitance can be built-up depends on frame structure, cell surface and distance in between, weather conditions, humidity, dust or salt covering the PV panels. This parasitic capacitance creates leakages currents to flow and create undesirable hazards to the PV system. PV inverters with transformers provide necessary galvanic isolation as a solution while transformer-less PV inverters are designed and installed to minimize the effect of leakage currents [9].

PV inverter market is rapidly moving towards the transformer-less inverter topologies. Among the advantages of transformer-less PV inverters are, higher efficiency, reduced cost, reduced weight, and reduced size due to the removal of a bulky transformer. In this case, PV string or array voltages must be either higher than the ac voltage or a dc-dc converter needs to be employed. Main disadvantages of the topology are added cost for additional protection means and higher electromagnetic interferences [5, 9].

2.3.5 PV Inverter Structure Topologies

As the PV inverters evolves through the past decades, there are several structure topologies introduced to suit the dynamic requirements of the system designers [7, 14].

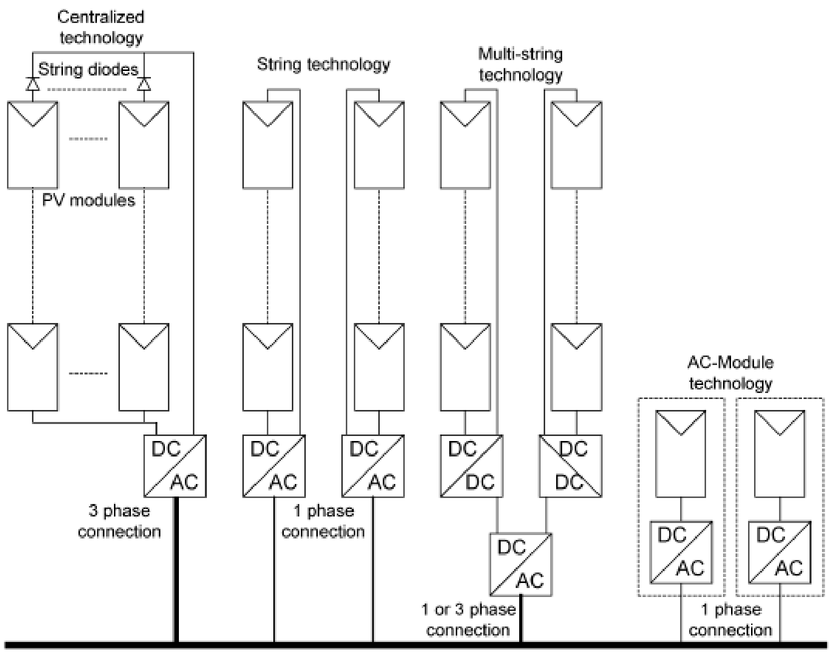


Figure 2-9: PV Inverter Structure Topologies [7]

2.3.5.1 Central Inverters

Central inverter topology is utilizing a central inverter which connects a large number of PV modules to the grid. In order to gain a sufficiently high voltage for the inverter input and avoid further amplification, these large number of modules are connected in series to establish PV strings. In order to reach high PV peak power levels of 250 kW or higher, these strings are connected in parallel, forming PV arrays. To provide the over-current protection means, these parallel connections are made through series diodes [10]. Each of these PV module parallel strings are connected to inverter inputs which has its own maximum power point tracking (MPPT) algorithm to extract the maximum power from the PV string [9].

This centralized inverter topology was developed few decades ago and has its own inherent limitations due to the design. Power losses due to cloud shading, partial shading (due to physical obstruction on PV module) and non-uniform soiling are significantly higher with central inverters due to the centralized MPPT. Further, it decreases the design flexibility. Malfunction of one parallel string can shut down the whole central inverter hence a significant portion of the whole power plant, providing a very low redundancy. Each of these parallel PV strings which are connected to the inverter require high DC voltage cables hence introduces significant DC cable losses to the PV plant. The grid-connected stage in the central inverter is usually line commutated by means of thyristors, resulting poor power delivered to the grid with large amount of current harmonics. Additionally, high DC voltage carried from the PV strings to the central inverter may have significant fire and safety hazards, leading to increased costs for cabling and, in turn, higher costs for installation and maintenance. In order to comply with recent industry standards for PV safety, the developers need to incorporate additional equipment to mitigate the risk hence occurs an additional cost to the initial investment [9, 10, and 19].

2.3.5.2 String Inverters

String inverter is a down-scaled version of the central inverter (with rated ac capacities below 100 kW). Single PV module string is connected to one string inverter. These strings are established to gain sufficiently high voltage for the inverter so that the further amplification can be minimized [10]. Normal dc operation voltages for single-phase grid connected string inverters are roughly 450 V – 510 V. Lesser number of PV modules can also be utilized along with an incorporation of a dc-dc converter or line-frequency transformer for voltage amplification [7]. The design may not require string diodes for over-current protection. Each PV string is connected to a separate maximum power point tracking (MPPT) algorithm in the inverter [10].

String inverters provide incremental improvement in the overall PV plant efficiency compared to conventional central inverter topology due to this one MPPT for each PV string design. Although, performance degradation of one PV module in the string have an unduly large impact on overall inverter output. But this approach reduces the impact of this performance degraded PV module to its PV string rather than to the entire PV array, which is the case with central inverters [19]. Therefore, string inverters decreases the impact of power losses due to cloud shading, partial shading (due to physical obstruction on PV module) and non-uniform soiling compared to central inverters [10].

Furthermore, a malfunction of one PV string affects the performance of the connected string inverter, which is a smaller portion of the whole PV plant, providing higher redundancy and enhanced system reliability compared to central inverters [10]. By eliminating the central inverter and its potential as a single point of failure, this approach improves system robustness [19]. Manufacturers and developers can gain the advantage of cost reductions due to mass production with string inverter topology. String inverters have evolved as a standard in PV system technology for grid connected PV plants [10]. However, string inverters still carries the drawbacks with the safety hazards and higher costs associated with DC voltage transmission [19].

2.3.5.3 Multi String Inverters

Multi string inverter is a further development of string inverter. Multi-string inverter allows several number of PV strings to be connected to their own individual maximum power point tracking (algorithms). This is achieved by interfacing the strings to a dc-dc converter. These dc-dc converters act as an interface to a common dc-ac inverter which forms the multi-level string inverter together [10].

Due to the individual MPPT algorithm, each string can be controlled individually, causing higher energy yield compared to central inverters. Additionally, these multi-level inverters provide a compact, cost-effective solution, which incorporates the benefits of both central and string inverter topologies. Furthermore, multiple strings consist of different PV module technologies and of different orientations (south, north, west and east) can be integrated to these multi-string inverters, providing design flexibility and higher efficiency gain to the PV designer [7, 10, and 14]. Further modular upgrades can be easily achieved since a new string with dc–dc converter can be plugged into the existing platform [7]. However, multi-string inverters also carries the drawbacks with the safety hazards and higher costs associated with DC voltage transmission [19].

2.3.5.4 AC Modules

Figure 2-9 illustrates the structure topology of ac modules which integrates the inverter and the PV module into one device. Even though with the multi-level string inverters, the problem of partial shading affects the performance of the string. In order to ensure a stable operation, most designers identified maximum power point tracking (MPPT) to be implemented at each and every module. As a solution it was tested to design systems that have inverters inside the PV modules. This type of design is also termed as Micro-Inverter (MI), Module Integrated Converters (MIC) or AC module [20].

Since there is one PV module, this topology eliminates the mismatch losses between PV modules. All the PV modules are connected to individual maximum power point tracking (MPPT) inputs so that the energy yield is not affected due to degraded PV modules. Modular structure of this topology enables easy further enlargements compared to other topologies. Most of the ac modules in the market provide “plug-and-play” support during installation and maintenance activities. The present solutions of ac modules use self-commutated dc–ac inverters, by means of IGBTs or MOSFETs, resulting high power quality in compliance with the standards. Price per watt is higher than the other inverter topologies due to the complex circuits inside [7, 14].

These ac modules or micro inverters are identified as a category of “Distributed Power Electronics in PV Systems” since it uses power electronic devices at distributed manner compared to centralized PV inverters. Recent developments in efficiency, reliability and cost of the power electronic devices have made these “Distributed Power Electronics in PV Systems” popular in the industry [20].

2.3.5.5 DC Conditioning Units (Power Optimizers/ Power Boosters) with String Inverters

Another novel category of “Distributed Power Electronics in PV Systems” is dc conditioning unit or power optimizer which also uses power electronics connected to each PV module to provide improvements to the PV system performance. These dc conditioning units contain dc-dc converters, which operate in connected with a string or multi-string inverter, which is still required for dc-ac conversion. Main function of these dc-dc converters is to track the maximum power point of the PV module connected to it and either increase (boost) or decrease (buck) the output voltage so that it matches with the string inverter’s optimum operating points. Internal design topology of these dc-dc converters are different from manufacturer to manufacturer, which are buck (decrease) converters, boost (increase) converters and buck-boost converters. Popular design of the dc conditioning unit is to enclose power electronics in a separate enclosure which can be hinged in the PV module frame or mounting structure. Recently, these power electronics are designed inside the PV module junction box itself by the PV module manufacturers making the “smart junction box” or “smart PV modules” [8]. Figure 2-10 shows the connection diagram of dc conditioning unit topology.

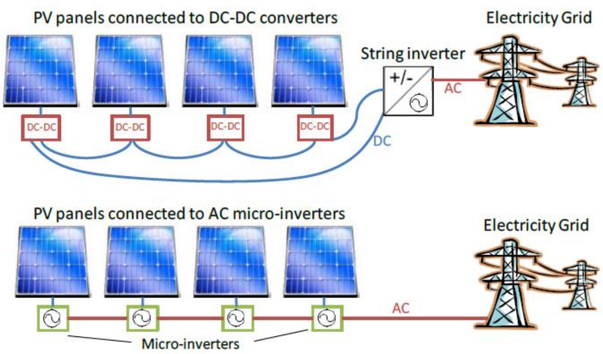


Figure 2-10: Schematics of dc conditioning units with string inverters (top) and micro inverters (bottom) topologies [8]

2.3.5.6 Pros and Cons in Distributed Power Electronics in PV Systems

Main advantage of using distributed power electronics in PV systems (micro inverters or dc-dc converters) is added energy yield in installation where partial shading and PV module mismatches are present. They also provide greater design flexibility for design engineers in system designing in complicated roofs, providing lower Levelized Cost of Electricity (LCOE) and lower Balance of System (BOS) cost. Due to the presence of power electronics at PV module, PV system performance monitoring facilities are offered by the manufacturers which are useful in remote diagnostics, remote performance monitoring and comparisons, and maintenance scheduling causing lower system downtime. Safety benefits of distributed power electronics in PV systems are due to delimiting capabilities of PV system operating voltage during shutdown only up to the PV module open circuit voltage. And also these power electronics are capable of identifying arc-faults in the PV systems and terminating. In contrast, central or string inverters introduce high risk of electrocution and arc-fault damage due to the presence of high dc voltages even during emergency shutdown [8].

Complications and additional considerations required during system designing can be a burden to the system designers. Further the added components increase the cost and the number of failure points in the whole PV plant [8].

2.4 Chapter Summary

This chapter reviews the literature available on the role of the PV inverter in a PV plant along with basics of solar PV. It classifies different PV inverter topologies based on several parameters. It also identifies different PV inverter structure topologies which are utilized in the research work.

The next chapter focuses on discussing the methodology of the research work.

CHAPTER 3

PROPOSED METHODOLOGY

Roadmap of the proposed methodology to achieve the research objectives in section 1.4 is sketched in this chapter. The methodology consists of three sections.

3.1 Part 1 – 1 MWp PV Plant Model Development

Different PV inverter architectures which are commonly used, are selected. Since the framework for evaluation is constructed as a case study for 1 MWp project development scheme, same capacity PV plant models are developed in this section utilizing selected PV inverter architectures. Developed models are optimized in terms of achieving lower upfront cost, higher energy yield and lower power losses. Detailed description of the methodology is provided in section CHAPTER 4.

3.2 Part 2 – Technical Comparison

A framework is composed to analyse technical aspects of the PV inverter structure topologies. Considered technical features are,

i. Energy yield output of the PV plants
ii. Safety aspects
iii. Power output quality
iv. System reliability
v. System monitoring, diagnostics & troubleshooting capabilities

PV plant models developed in part 1 are adopted in the evaluation. Detailed description of the methodology is provided in section CHAPTER 5.

3.3 Part 3 – Economic Comparison

A methodology to discuss economic impact of introducing different PV inverter structures to PV plants is presented. The impact is analysed by considering,

i. Upfront costs of the PV plants
ii. Lifetime revenue generated
iii. Levelized cost of electricity
iv. Sensitivity of the inputs to the models

PV plant models developed in part 1 are adopted in the evaluation. Detailed description of the methodology is provided in section CHAPTER 6.

The next chapter examines the part 1 of the methodology proposed.

CHAPTER 4

PROPOSED METHODOLOGY: PART I – 1 MWp PV PLANT MODEL DEVELOPMENT

Part one of the proposed methodology is based on developing PV plant models adhering to the solar power development scheme requirements and local standards & codes of practices. Four types of different PV inverter architectures are concentrated on these plant designs.

4.1 Technology Selection

In the process of PV plant model development, identifying a suitable technology for critical components in the plant is considered as the initial step. Critical components are recognized as PV module, PV inverter and mounting structure. In this section, key considerations followed through technology selection criteria, are detailed.

4.1.1 PV Module Technology

PV module technologies are classified mainly based on the raw materials and manufacturing process of the PV cells. Each of the above properties has unique impact to the cell performance, manufacturing method and cost of the PV modules. Among the commercially available PV module technologies, reference [5] identifies following technologies leading the industry, which are,

i. Crystalline silicon (c-Si)
   a. Mono-crystalline
   b. Multi-crystalline
ii. Thin-film
   a. Amorphous silicon (a-Si)
   b. Cadmium telluride (CdTe)
   c. Copper indium selenide (CIS)
   d. Copper indium (Gallium) di-selenide (CIGS/ CIS)
iii. Heterojunction with intrinsic thin-film layer (HIT)

Considering the higher market penetration in Sri Lankan solar PV industry, crystalline silicon (mono c-Si and multi c-Si) technologies are selected as the PV module technology for the PV plant model development in this research work.

Based on the selected PV module technology, a suitable PV module product is chosen, adhering to the following selection considerations, which are,

i. PV module degradation over time
ii. PV module efficiency

iii. Supplier identification based on proven track record and third party market researches
iv. Product warranty and performance warranty terms and conditions, whether it is in line with the market standards
v. Technology suitability for the environmental conditions (e.g., high temperatures, agricultural environment, salty environment etc.)
vi. Power tolerance is in line with the market standards
vii. Certification compliance
    a. IEC 61215:2016 - Terrestrial photovoltaic (PV) modules - Design qualification and type approval
    b. IEC 61730:2016 - Photovoltaic (PV) module safety qualification
    c. ISO 9001 – Quality management systems

4.1.2 PV Inverter Technology

Section 2.3 identifies several PV inverter structure topologies which is considered in PV inverter technology selection. Listed structure topologies are,

i. Central inverter structure topology
ii. String inverter/ multi-string structure topology
iii. Distributed power electronics in PV systems
    a. Micro inverter structure topology
    b. DC conditioning units (power optimizers/ power boosters) with string inverter structure topology

PV inverter technology is selected from above structure topologies in developing PV plant models for this research work. Adhering considerations in product selection are,

i. PV inverter capacity
ii. PV inverter efficiency
iii. Supplier identification based on proven track record and third party market researches
iv. Certification compliance
    a. IEEE 1547-2018 - Interconnection and interoperability of distributed energy resources with associated electric power systems interfaces
    b. UL 1741 - Standard for inverters, converters, controllers and interconnection system equipment for use with distributed energy resources
    c. ISO 9001 – Quality management systems
v. Compliance to “Grid connection requirement for solar power plants – addendum to the CEB guide for grid interconnection of embedded generators, December 2000”

4.1.3 Mounting Structure

A proper mounting structure needs to be employed where the PV modules are mounted to keep them oriented in the optimum direction and to provide structural support. Reference [5] identifies two main mounting structure methods which are used in the PV industry, which are,

i. Fixed tilted mounting structure
ii. Tracking systems (single axis and dual axis)

Considering lower capital cost, lower maintenance cost and suitability in local conditions, a fixed tilted mounting structure system is employed in this research work.

4.2 Design Considerations

PV plant model capacity is narrowed to 1 MWp since the case study is based on recent 1 MWp solar power development scheme in Sri Lanka. During designing stage, a focus is given to achieve an optimum balance between PV plant performance and cost. In this section, all the considerations followed through the design process are listed.

4.2.1 Site Selection

A suitable site is selected as the first step. Reference [4] identifies available grid substations for proposed 1 MWp solar power plant development scheme and its regulatory requirements to select a suitable land area. Additionally, following considerations are also examined, which are,

i. Selection of a site with high solar resource (A high average annual Global Tilted Irradiance)
ii. Availability of required land area based on the selected PV module technology and regulatory requirements
iii. Topography of the land which requires minimum land clearance
iv. Minimum impact to the environmental and social eco systems
v. Site accessibility
vi. Grid availability within minimum distance

4.2.2 Layout and Shading

General layout of the 1 MWp PV plant models is designed with the aim to achieve maximum revenue at a lowest possible cost. Considerations evaluated are,

i. Considerations towards minimizing ac and dc cable runs and associated electrical losses with component positioning
ii. Optimum tilt angle and azimuth angle for higher energy yield unique to the selected site
iii. Inter-row spacing determination between PV arrays to reduce shading effect

4.2.3 Electrical Design

Electrical design of the 1 MWp PV plant model is considered on a case-by-case basis with each PV inverter architecture. Expert judgement from the PV industry, Original Equipment Manufacturers' (OEM) recommendations, local and international standards, electric codes and guidelines are referred during the designing.

4.2.3.1 DC System

DC system consists of PV module arrays, dc cabling (including module, string & main cables, cable connectors and cable routing structures), junction boxes/ combiners, disconnection switches, protection devices and earthing [5]. Key design considerations are,

i. DC:AC ratio
ii. DC component sizing considering maximum output from PV modules
iii. DC components rating to allow thermal and voltage limits
iv. Multiplication factors for the calculations based on the site location
v. PV array component designing (maximum and minimum number of modules in a string, voltage optimization and number of strings) considering inverter voltage limits and OEM guidelines
vi. Cable selection and sizing considering cable voltage ratings, current carrying capacity, cable losses and voltage drop
vii. Protection device selection and sizing considering regulation requirements, maximum dc current, multiplication factors and cable characteristics

4.2.3.2 AC System

AC system consists of PV inverter, ac cabling (cables and cable routing structures), junction boxes/ combiners, protection devices, transformers and earthing [5]. Key design considerations are,

i. AC component sizing considering maximum output from PV inverter
ii. AC components are rated to allow thermal and voltage limits
iii. Multiplication factor for the calculations based on the site location
iv. Cable selection and sizing considering cable voltage ratings, current carrying capacity, cable losses and voltage drop
v. Protection device selection and sizing considering regulation requirements, maximum design current, multiplication factors and cable characteristics

4.2.4 Plant Monitoring

Plant monitoring facility is a critical component in a PV plant which eases the operation and maintenance activities during commercial operation [5]. Although there are several third party automatic data acquisition and monitoring technologies available in the market, plant monitoring facility in-built in commercial PV inverters is used for plant monitoring activities in the 1 MWp PV plant models developed here.

4.2.5 Standards and Guidelines

During the designing, following internationally and locally available standards and guidelines are referred, which are,

i. SLS 1522:2016 - Grid connected photovoltaic power systems – Requirements for system documentation, Installation, testing & commissioning.
ii. SLS 1542:2016 (EN 50618:2014) Electric cables for photovoltaic systems
iii. SLS 1543 Safety of power converters for use in photovoltaic power systems (IEC 62109:2010)
iv. SLS 1553 Photovoltaic (PV) module safety qualification – (IEC 61730:2016) Requirements for testing
v. SLS 1554 - Low-voltage switchgear and control gear (IEC 60947:2014) General rules
vi. Guidelines from international standards
    a. National Electric Code - Article 690 – Solar photovoltaic (PV) systems (United States standard)
    b. AS/NZS 5033:2014 - Installation and safety requirements for photovoltaic (PV) arrays (Australia standard)
vii. BS 7671 – Requirements for electrical installations
viii. IEC 62305 – Protection against lightning & overvoltage
ix. Guidelines, technical documents and manuals from product suppliers

4.3 System Configuration

Key output of the designing processes detailed in section 4.1, 4.2 and 4.3 is developed 1 MWp PV plant models using PV inverter structure topologies which are selected in section 4.1.2. These models can be labelled as,

i. **Model No.1 -** 1 MWp PV plant with central inverter topology
ii. **Model No.2 -** 1 MWp PV plant with string inverter topology
iii. **Model No.3 -** 1 MWp PV plant with micro inverter topology
iv. **Model No.4 -** 1 MWp PV plant with dc conditioning units (power optimizers/ boosters) and string inverter topology

Resulting system configurations of the PV plant models are presented in section 7.1.

4.4 Chapter Summary

In this chapter, methodology to develop 1 MWp PV plant models for techno economic comparison is conferred considering technology selection, site selection, layout designing, electrical system designing and plant sub system designing.

Next chapter discusses the part two of the proposed methodology which is to conduct technical comparison of PV inverter architectures.

CHAPTER 5

PROPOSED METHODOLOGY: PART II – TECHNICAL COMPARISON

In this section, it is aimed to provide a methodology to compare set of technical parameters throughout the lifetime of the PV plants with different PV inverter architectures. This shall be developed as a case study for the proposed 1 MWp PV plant development scheme in Sri Lanka.

5.1 Energy Yield Comparison

Energy yield is the main output of a solar PV plant which brings the revenue for the project over its lifetime. Calculating and predicting the energy yield throughout the period is considered as an important step in solar PV project feasibility, technology selection and funding allocations [5]. Many literatures suggest the impact of the selection of PV inverter structure topology on the energy yield of the PV plant [8]–[10]. Energy yield prediction involves sophisticated simulation of dynamic changes in environmental conditions over the life time of the PV plant. For the purpose, there are several PV plant modelling and simulation software tools utilized in the industry. Some of these software tools are PVSyst, PV*SOL, RETScreen, HOMER, INSEL, Archelios and Polysun [5].

A methodology to compare energy yield output throughout the lifetime of the PV plants with different PV inverter architectures is documented here. Section 5.1.1 indicates the simulation software used for energy yield prediction. Four number of scenarios are defined as in section 5.1.2 for the study. Simulations are carried out following the key steps described in section 5.1.3 to obtain the results.

5.1.1 Simulation Software: PVSyst

PVSyst software package (available at [21]) is selected for the simulation purposes. Reasons for selecting PVSyst can be listed as,

i. PVSyst is a powerful tool widely used in the PV industry for study purposes, designing, sizing and analysing activities.
ii. PVSyst contains a comprehensive database for meteorological data and manufacturer’s product data.
iii. Simplicity, flexibility and ability to accurately model large scale PV plants.
iv. PVSyst allows modelling by choosing the same geographical location of the PV plant and importing meteorological database from the database.

Figure 5-1 outlines the design steps to follow when simulating a PV plant design in PVSyst.

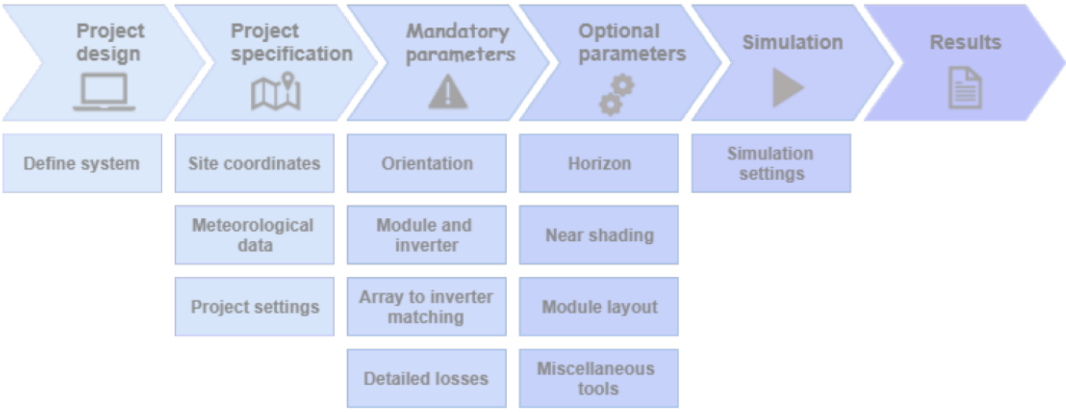


Figure 5-1: Project Design Steps in PVSyst [22]

5.1.2 Different Scenarios Initialization

Energy yield of a PV plant varies with several technical and environmental factors like irradiance, geographical location, PV module technology, PV inverter technology, near shading and far shading, degradation of plant components etc. [8]. In order to capture most of the above variations, there are four different modelling scenarios created in this research work, which are,

5.1.2.1 Scenario 1

Energy yield for the project life time with different PV inverter structure topologies is compared here. Four number of PVSyst simulation models are developed for the selected four PV inverter structure topologies in section 4.1.2. PV module technology and shaded condition are kept unchanged for the four models. Design parameters in scenario 1 are,

i. PV plant capacity – 1 MWp
ii. PV inverter structure topologies – Central, string, micro inverters and dc conditioning units
iii. Simulation time span – PV plant lifetime (Annually for 20 years as nominated in the case study [1, 4])
iv. PV module technology – Multi crystalline
v. Shaded condition – Unshaded

5.1.2.2 Scenario 2

Energy yield for the first year operation with different PV inverter structure topologies is compared here. Four number of PVSyst simulation models are developed for the selected four PV inverter structure topologies in section 4.1.2. PV module technology is changed while shaded condition is kept unchanged for the four models. Design parameters in scenario 2 are,

i. PV plant capacity – 1 MWp

ii. PV inverter structure topologies – Central, string, micro inverters and dc conditioning units
iii. Simulation time span – First year operation
iv. PV module technology – Multi crystalline and mono crystalline
v. Shaded condition – Unshaded

5.1.2.3 Scenario 3

Energy yield for the first year operation with different PV inverter structure topologies is compared here. Four number of PVSyst simulation models are developed for the selected four PV inverter structure topologies in section 4.1.2. Shaded condition is changed while PV module technology is kept unchanged for the four models. Design parameters in scenario 3 are,

i. PV plant capacity – 1 MWp
ii. PV inverter structure topologies – Central, string, micro inverters and dc conditioning units
iii. Simulation time span – First year operation
iv. PV module technology – Multi crystalline
v. Shaded condition – Shaded and unshaded

5.1.2.4 Scenario 4

Energy yield for the first year operation with different PV inverter structure topologies is compared here. Same parameters used in Scenario 2 is utilized, but with multiple PV inverter products from different inverter manufacturers in the market. Design parameters in scenario 4 are,

i. PV plant capacity – 1 MWp
ii. PV inverter structure topologies – Central, string, micro inverters and dc conditioning units
iii. Simulation time span – First year operation
iv. PV module technology – Multi crystalline and mono crystalline
v. Shaded condition – Unshaded
vi. Different PV inverter manufacturers in the market

These PV inverter manufacturers are identified considering the global PV market share as indicated by the third party independent market research institutes [23, 24]. Table 1 indicates the composition of the PV models developed in this scenario.

Table 1: Simulation Model Configuration of Scenario 4

Inverter Structure Topology	Inverter Manufacturer	Inverter Model No.	AC Capacity (kW)	DC-AC Ratio
Central Inverter Model	ABB	PVS800	875 kW	1.14
	Siemens	Sinacon PV1000	1000 kW	1

String Inverter Model	SMA	STP60	60 kW	1.11
	Sungrow	SG60KTL	60 kW	1.11
	Goodwe	GW60K-MT	60 kW	1.11
DCCU + String Inverter Model	SolarEdge	SE27.6k	27.6 kW	1.16
	Tigo	MMJ-ES50	60 kW	1.11
Micro Inverter Model	Enphase	S270	270 W	1.2
	Omnik	S270	270 W	1.2

5.1.3 Key Modelling Steps

First step of modelling in PVSyst is to initialize project specifications. A "Project" in PVSyst is the main object for which to construct different system configurations, which are called "Variants". When defining the project specifications, following steps are followed,

i. Project site is defined using site coordinates. These coordinates are used to calculate sun path throughout the year.
ii. Meteorological database is chosen from the available databases in PVSyst.
iii. Project settings are set as specific to the selected site location which are albedo, minimum operating temperatures, design conditions and other limitations.

Once the project file is specified, different system configurations are defined as "Variants" by changing input parameters. These parameters can be identified as follows,

i. Orientation, module tilt and azimuth angle
ii. PV module and inverter type, number of components, PV array and string configurations
iii. Detailed losses such as thermal loss factors, dc and ac ohmic wiring losses, PV module quality losses, Light Induced Degradation (LID), PV array mismatch losses, soiling losses, auxiliary losses, ageing losses and system unavailability factors
iv. Impact of the shading objects located far from the PV system can be modelled using "Far Horizon" parameter while impact from objects close to the PV system can be modelled by building a 3D model of the PV system and shading objects.

When modelling with four selected PV inverter architectures, following detailed loss factors in Table 2 are set as per the product manufacturer's guidelines. Reference [21], [25], and [26] details about selection of detailed factors based on the inverter structure topology.

Table 2: Selected Detailed Loss Factors for PVSyst Modelling

	Central Inverter Model	String Inverter Model	Micro Inverter Model	DCCU + String Inverter Model
DC circuit ohmic losses (@STC) [1]	3%	2%	-	2%
AC circuit ohmic losses (@STC) [2]	-	1%	2%	1%
Module quality loss	2.5% (Default value in PVSyst)			
LID	2%(Default value in PVSyst)			
Module mismatch loss[3]	2.5%	2.5%	-	-
Soiling loss	4%			
Tilt	8^0			
Azimuth	0^0 (South facing)			
PV module	325 Wp Multi Crystalline, 330 Wp Mono Crystalline			
GPS location	Mamaduwa, Vavuniya 8.77°, 80.53°			
Meteo database	Meteonorm v7.1			

[1] DC ohmic losses are not considered in micro inverter structure topology due to negligible dc cable length. Total ac and dc ohmic losses are kept at 3% complying with SLS 1522:2016 local standard.

[2] AC ohmic losses are not considered in central inverter structure topology due to considered scope of the research work up to step up transformer low voltage side and hence negligible ac cable length.

[3] Module mismatch losses are zero with micro inverters and DCCU + string inverter structure topologies due to module level MPPT [25, 26].

5.1.4 Uncertainty in Energy Yield Prediction

Uncertainty in energy yield simulation results can be varied due to several factors like in-built inaccuracy of modelling software, uncertainties aggregated at each modelling stage and input variables, uncertainty in meteorological database and inter annual variability. Total uncertainty in energy yield prediction using a simulation software can be varied in the ranges of 5-10% [21, 22]. Since the uncertainty affects all the simulation models developed using selected inverter structure topologies, it is not considered in developing the methodology for technical comparison in this section. Although, certain values are assumed and total uncertainty figure is introduced to the energy yield prediction in developed methodology for economic comparison in section CHAPTER 6.

5.2 Safety Aspects

In PV systems, safety aspects are considered important considering the hazardous events that can be resulted, as well as the potential economic losses to the revenue generation. These risks exist in PV systems in two aspects, as shock hazards causing risk of electrocution and as arc faults causing catastrophic fire events [27].

A detailed methodology is proposed here to compare the risks exists in PV systems with different inverter structure topologies. Shock hazards are evaluated in section 5.2.1 while arc fault hazards are considered in section 5.2.2.

5.2.1 Risk Assessment of Shock Hazards

Shock hazards in PV systems are directly associated with the magnitude of current flow and voltage level [28]. Reference [27] lists several types of fault conditions that can introduce shock hazards in PV systems. In order to evaluate shock hazards in the proposed methodology, PV plants with selected inverter structure topologies are modelled in PSCAD simulation software. Four types of selected fault conditions are fed to the PSCAD models. Magnitude of the fault current and voltage level at the fault location are received as results from the PSCAD models. A pre-defined hazard severity index is assigned to each PV inverter model considering the fault current and voltage to assess the overall risk index. Four types of selected faults which are fed in to the PSCAD model are as follows,

i. Fault 1 – Positive to negative short circuited scenario (DC side)
ii. Fault 2 – Earth fault scenario (DC side)
iii. Fault 3 – Line-line-earth short circuited scenario (AC side)
iv. Fault 4 – Earth fault scenario (AC side)

These faults are illustrated in Figure 5-2.

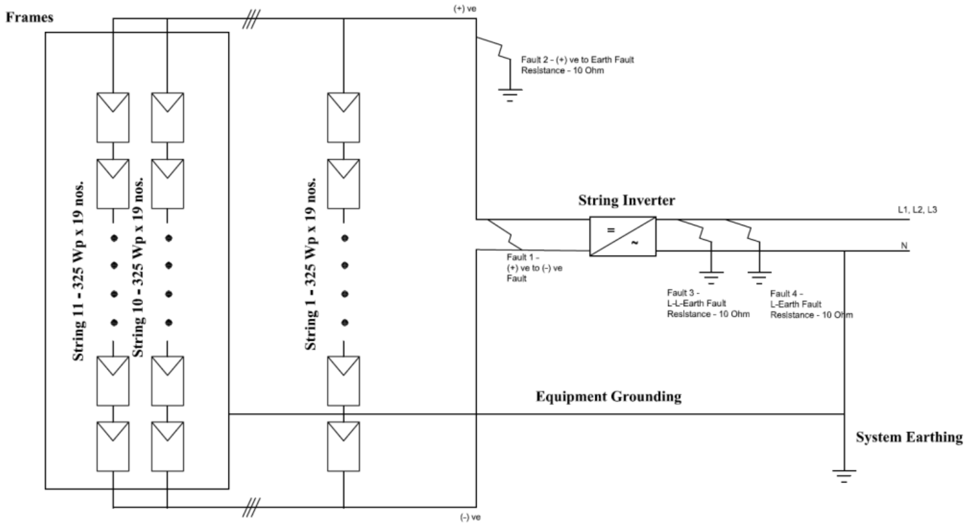


Figure 5-2: Four types of selected faults to be fed in to the PSCAD model

Many standards have been developed by international organizations to address the shock hazard risks introduced by PV systems. Adhering to these standards, PV systems are designed and deployed to provide a disconnection mean during an emergency, maintenance or system installation activities. These disconnection means shutdown the PV systems at different levels, at PV string level or at PV module level, minimizing the risk of electrocution. Level of disconnection mean is related to the type of PV inverter structure topology and available controlling mechanism. Central inverters or string inverters provide PV string level disconnection while distributed power electronic PV systems provide PV module level disconnection [28]. In this methodology, a hazard severity index is also provided for the available disconnection mean with PV inverters.

Pre-defined hazard severity indices used for evaluating shock hazards, are provided in the Table 3.

Table 3: Hazard Severity Index for Shock Hazard Risk Assessment

Hazard Severity Index	**Evaluation Criteria**
3	DC side positive to negative fault current > PV module I-sc
3	DC side earth fault current > PV module I-sc
3	PV system disconnection during hazardous situation is possible at PV string level
2	AC side line-line-earth fault current/ earth fault current > inverter maximum continuous output current
1	DC side positive to negative fault current < PV module I-sc
1	DC side earth fault current < PV module I-sc
1	DC side earth fault voltage rise across 10 Ohm impedance < 120 V-dc
1	PV system disconnection during hazardous situation is possible at PV module level
1	AC side line-line-earth fault current/ earth fault current < inverter maximum continuous output current

5.2.2 Risk Assessment of Arc Faults

Arc faults in PV systems can present as serial arcs or parallel arcs. Usually, arcs in the dc side installations are considered high risky since dc arcs can sustain for a period of time. In contrast, ac side installations are less likely to sustain arcs with its alternating current flow [28, 29]. Therefore, only the arc fault risks exist in the dc side of the PV systems with different inverter structures are assessed in this proposed methodology.

Risk of arc faults in PV systems are directly related to the operating voltage, operating current and geographical distribution of wiring [28]. Considering each of the above evaluation criteria, a pre-defined hazard severity index is assigned to the PV inverter model and overall risk index is calculated.

Pre-defined hazard severity indices used for evaluating arc fault hazards, are provided in the Table 4.

Table 4: Hazard Severity Index for Arc Fault Hazard Risk Assessment

Hazard Severity Index	**Evaluation Criteria**
3	Operating dc voltage > 120 V-dc
3	Operating dc current > PV module I-sc
3	DC cabling distribution is all-throughout the PV plan
2	DC cabling distribution is limited to PV array block
1	DC cabling distribution is limited to PV module
1	Operating dc voltage < 120 V-dc
1	Operating dc current < PV module I-sc

5.3 Power Quality Aspects

Power quality in a grid is considered as one of the important factors which affects the grid stability and reliability. With high penetration of distributed renewable energy generators, it is identified that the PV inverters would present power quality issues to the national grid. Moreover, as they are connected to the grid, these PV inverters need to comply with grid operators' grid codes and standards which outlines the requirements to meet power quality, detection of islanding operation, grounding, etc [30].

In this sub section, standardized recommendations for PV inverters when connected with utility distribution system are analysed referring to the international standards and local grid operators' requirements. Then, compliance to the identified requirements by different PV inverter structure topologies is assessed to recognize the ability to meet the standards. International standards and local grid operators' requirements are analysed referring to,

i. IEC 61727 Photovoltaic (PV) Systems - Characteristics of the Utility Interface
ii. IEEE 1547 Standard for Interconnecting Distributed Energy Resources with Electric Power Systems
iii. CEB Guide for Grid Interconnection of Embedded Generators

In order to assess the compliance of different PV inverter structures, PV inverters manufactured by different manufacturers identified in section 5.1.2.4 are utilized. Their original equipment manufacturer's literature and technical catalogues are referred during the process along with accredited third party compliance certifications.

5.4 System Reliability

Reliability is another key technical concern of PV systems and PV inverters which has dragged an increasing attention over the recent years [31]. It is identified in reference [32], that the reliability is the probability that an item (component, subsystem, or system) performs required functions for an intended period of time under given environmental and operational conditions. It is also can be defined as the probability that the item will function without a failure during the defined time period.

Although the reliability evaluation is vital, the complex nature of PV systems has caused lack of proper reliability quantification methodology which can take an entire PV system in to consideration [31]. Reference [32] identifies several reliability assessment methods of power electronic systems, indicated as,

i. **Component Level Reliability Models -** Several empirical-based models are widely employed to assess the power electronic systems reliability at the component level. Here, it is mainly focused on the failure rate models for components i.e. semiconductors, capacitors, switches etc. to analyse the reliability of components. Military handbook for reliability prediction (widely known as MIL-217) of power electronic equipment is considered as commonly used component level reliability assessment model.
ii. **System or Subsystem-Level Reliability Models -** System level reliability assessment models consider the functional interdependencies in the power electronic system and provide a framework to develop quantitative reliability assessment of systems or sub-systems. There are several methodologies developed based on system level reliability models which are identified as Markov Model, Part-Count Models, and Combinatorial Models.

In this research work, Markov Reliability Models are utilized as the framework in assessing the reliability of PV inverter systems with different structures. System reliability of a PV plant needs to be interlinked with energy yield prediction to provide proper assessment of the performance of the system. Many researches identify that Markov models provide unified tools to integrate system reliability in to energy yield prediction [33].

In this sub section, reliability of PV inverter systems with different structures are assessed using Markov models incorporating failure rates and repair strategies in different scenarios. Section 5.4.1 designates the Markov models developed for the purpose. Key modelling steps to compare energy yield prediction interlinked with the system reliability, are presented in section 5.4.2.

5.4.1 Markov Reliability Models

A simple Markov model is utilized to model the reliability of different PV inverter structures. For an example, state-transition diagram shown in Figure 5-3 drafts the characteristics of a PV system with 26 number of PV inverters. Each node in the diagram is a state in the process which is allotted to the number of PV inverters operating under normal operation. Transitions between two states are due to PV inverter failures and repairs. Related PV inverter failure rate is identified as λ and PV inverter repair rate is identified as μ.

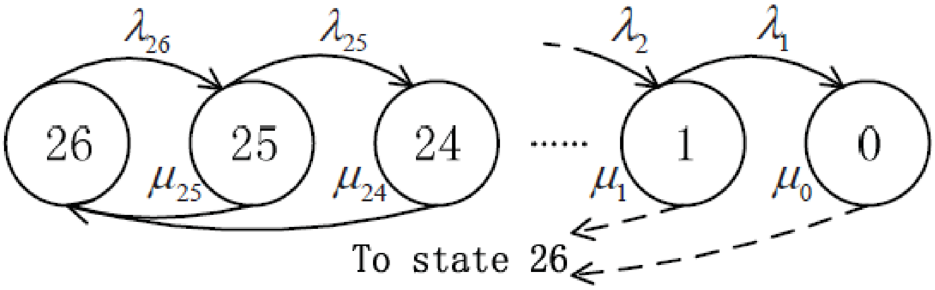


Figure 5-3: Sample Markov Model State-transition Diagram for 26 Number of PV Inverters

Considering the limited scope in this research work, following assumptions are made.

i. PV inverter failure rate (λ) is assumed as same to all the PV inverters in the model.

ii. At each state, faulty PV inverters are repaired simultaneously to restore the system to complete operation.

Therefore,

$$\begin{cases} \lambda_i = i\lambda_{inv} \\ \mu_i = \mu_{inv} \end{cases} \quad i \in [0, N] \tag{1}$$

In equation (1), λ_{inv} is defined as PV inverter failure rate, μ_{inv} is defined as PV inverter repair rate and N defined as number of PV inverters in the model.

Differential equations that characterize the probability of being in one state at a given time are called Chapman-Kolmogorov equations [33, 34]. Chapman-Kolmogorov equations for the models in this research work can be obtained as,

$$\dot{p}_i(t) = \begin{cases} -(\lambda_i + \mu_i)p_i(t) + \lambda_{i+1}\, p_{i+1}(t), & 0 \le i \le N-1 \\ -\lambda_i p_i(t) + \sum_{m=1}^{N-1} \mu_m p_m(t), & i = N \end{cases} \tag{2}$$

where i is the state of the Markov Model, λ_i is the failure rate, μ_i is the repair rate and $p_i(t)$ is the occupational probability of being in state i.

Steady-state occupational probabilities, denoted by p_i*, can be identified as a fraction of time where the PV plant operates with i number of PV inverters (or operates in the i^{th} state). Steady-state occupational probabilities can be obtained by setting the derivative of equation (2) to zero. A normalization equation shown in equation (3) is also taken into consideration.

$$\sum_{i=1}^{N} p_{\mathrm{i}}* = 1 \tag{3}$$

After obtaining the steady-state occupational probabilities to each state of the Markov model, the values are integrated into energy yield prediction using the equation (4).

$$E = \sum_{i=0}^{N} i.E_{\mathrm{INV,\ YEAR1}}.p_{\mathrm{i}}* \tag{4}$$

where E is the energy output of the PV plant integrated with system reliability and $E_{INV,\ YEAR1}$ is the energy output of a PV inverter without considering system reliability. Energy output is considered for the duration of the study period.

5.4.2 Different Scenario Initialization

In this research work, Markov models for 1 MWp central inverter, string inverter and micro inverter PV plant models are developed. Steady-state occupational probabilities are obtained using MATLAB for each PV plant model under three main scenarios. These scenarios are categorized as follows,

5.4.2.1 Scenario 1

In this scenario, PV inverter failure rates (λ) for central inverters, string inverters and micro inverters are considered based on their manufacturer's available product warranty periods. Repair rates (μ) are considered the same for all PV inverter models. Study period is considered as first year of PV plant operation. Energy output ($E_{INV,\ YEAR1}$) values for 1 MWp central inverter, string inverter and micro inverter PV plant models are taken from first year energy yield simulation results obtained in section 5.1.2.1.

5.4.2.2 Scenario 2

In this scenario, PV inverter failure rates (λ) and repair rates (μ) are considered the same for all PV inverter models. Study period is considered as first year of PV plant operation. Energy output ($E_{INV,\ YEAR1}$) values for 1 MWp central inverter, string inverter and micro inverter PV plant models are taken from energy yield simulation results obtained in section 5.1.2.1.

5.4.2.3 Scenario 3

In this scenario, a range of PV inverter failure rates (λ) and repair rates (μ) are considered for all PV inverter models. Study period is considered as first year of PV plant operation. Energy output ($E_{INV,\ YEAR1}$) values for 1 MWp central inverter, string inverter and micro inverter PV plant models are taken from energy yield simulation results obtained in section 5.1.2.1.

Energy outputs of the PV plant models after integrating system reliability, are compared in each scenario to evaluate the system reliability of different PV structure topologies.

5.5 System Monitoring, Diagnostics & Troubleshooting

Among the key functions performed by a typical PV inverter, system monitoring, diagnostics and troubleshooting functionality is considered vital to detect possible failures of the PV plant. This requires to measure both electrical (current, voltage) and environmental (temperature, irradiance) parameters of the PV plant in online and offline modes [35]. Although the system monitoring functionality is a powerful tool to understand the state of the PV plant, its operating levels of the sensors or electronic data acquisition components have caused inherent limitations based on the PV inverter structure topology [36].

Manufacturer’s literature of the selected four types of PV inverter architectures categorizes three different operating levels of the aforementioned sensors, which are,

i. PV inverter level performance monitoring (Available with central and string inverters)
ii. PV string level performance monitoring (Available with string inverters)
iii. PV module level performance monitoring (Available with distributed power electronic topologies)

Key applications of performance monitoring functionality in inverters can be listed as,

i. To monitor and assess the PV plant technical and financial performance
ii. To forecast the performance of the PV plant
iii. To store historic data and generate performance reports for evaluation
iv. For effective PV plant management with improved operation and maintenance strategy by,
    a. Indicating automatic alerts and diagnostics for identified failures/ non-conformances
    b. Reducing troubleshooting time and system downtime
    c. Guided predictions and root-cause fault analysis
    d. Optimizing the scheduling of routine maintenance activities
    e. Remote monitoring of the PV plant

In this subsection, a methodology to evaluate system monitoring, diagnostics and troubleshooting functionality of different PV inverter structures is presented using 1 MWp PV plant models developed in the research case study. First, a pre-identified set of common failures in typical PV plant is listed. Table 5 provides the common failures discussed in this research work.

Table 5: Identified Common Failures in a PV Plant [37]

Component	Failure Mode
PV Module	Hot spot
	Delamination

	Glass breakage
	Soiling losses
	Shading losses
	Snail track
	Cell cracks
	PID
	Failure of bypass diode and junction box
	Overheating junction box
	Broken module
	Corrosion in the junction box
	Theft or vandalism
PV Inverter	Inverter failure
DC Cabling	UV aging
	Theft of cables
	Damaged cables
	Damaged connectors
DC Combiner Boxes	Switch disconector/ breaker failure

Root causes of the listed failures are analyzed with related to the 1 MWp PV plant models to identify the possible causes and rectification method. A common Fault Detection Strategy (section 5.5.2) considering PV inverter performance monitoring level is developed and deployed to detect the identified failures. Financial impact of these failures are calculated and compared using Cost Priority Number method (section 5.5.1) which considers the cost of system downtime and cost of fixing the failure.

5.5.1 Cost Priority Number Method

Failure Mode and Effect Analysis (FMEA) has been using vividly in the semi-qualitative reliability evaluation industry to prioritize potential failure modes of a system and assess the impact of the failure mode to the performance. Typical approach of a FMEA is to prioritize the failure modes through their Risk Priority Number (RPN) which is calculated to each failure mode using its severity (S), occurrence (O) and detectability (D) [38]. For each failure mode, a pre-determined scale from 1 to 10 is assigned for severity, occurrence and detectability of the failure. Typical RPN is calculated by multiplying S, O and D.

In this research work, it is aimed to evaluate the impact of the different levels of performance monitoring functionality to the economic aspects. Therefore, a typical FMEA is considered inadequate for the purpose. Reference [37] discusses a novel approach of cost-based FMEA which is widely used in auto mobile and wind turbine markets. Corresponding to RPN in classical FMEA, a special coefficient called Cost Priority Number (CPN) is introduced in this approach and hence it is named as CPN method. It is found that this approach is more in-line with the purpose of this research work.

Key steps of calculating CPN for a failure mode as detailed in Reference [37] is as follows,

Calculation of average downtime caused by a specific failure ($t_{down,fail}$ – *h/failure*) is obtained using Equation (5).

$$t_{\text{down, fail}} = (t_{\text{td}} + t_{\text{td}}) \times PL \times M \tag{5}$$

where t_{td} is the time to detection, t_{tf} is the time to fix, PL is the power loss in % and M is the multiplier to take impact in higher component level into account.

Calculation of total downtime for n number of component failures (t_{down} – *h/year*) in a reference database is made using Equation 6.

$$t_{\text{down}} = t_{\text{down, fail}} \times n_{\text{fail,1year}} \tag{6}$$

where $n_{fail,1year}$ is the number of failed components from the specific failure in a reference database over 1 year.

Equation 7 is used to calculate total downtime normalized by the component ($t_{down,comp}$ – *h/year*)

$$t_{\text{down,comp}} = t_{\text{down}} \div n_{\text{comp}} \tag{7}$$

where n_{comp} is the number of total components in the reference database.

Occurrence of the failure in the system over a reference time period is calculated using the Equation 8. Reference time period is considered here as one year.

$$O = t_{\text{down,comp}} \div t_{\text{ref}} \tag{8}$$

where O is the percentage reduction of performance due to failure in the system averaged over one year of period and t_{ref} is the total number of hours per year.

Performance loss due to the failure in the system (L – *kWh*) is calculated using Equation 9.

$$L = O \times S \tag{9}$$

where S is the total system's performance without the failure.

Downtime cost due to the failure (C_{down} – *LKR*) is calculated using Equation 10.

$$C_{\text{down}} = L \times FIT \tag{10}$$

where *FIT* is the feed-in-tariff rate of the system.

Fixing cost of the failure (C_{fix} – *LKR*) is calculated using Equation 11.

$$C_{\text{fix}} = (C_{\text{det}} + C_{\text{rep}} + C_{\text{transp}}) \times n_{\text{fail}} \tag{11}$$

where C_{det} is the cost of detection, C_{rep} is the cost of repair, C_{transp} is the cost of transportation, n_{fail} is the number of component failures in the system averaged over 1 year.

Finally, Cost Priority Number (*CPN – LKR/annum*) for the specific failure mode is calculated as Equation 12.

$$CPN = C_{\text{down}} + C_{\text{fix}} \tag{12}$$

5.5.2 Fault Detection Strategy

A typical operation and maintenance strategy of a PV plant consists of activities such as monitoring and reporting, preventive and corrective maintenance, ground keeping, security, spare parts management, and health and safety [35]. Process to detect faults during the operation and maintenance is usually defined in the O&M strategy.

Fault detection means detailed in Table 6 as O&M strategy are followed to assess the fault detection with different performance monitoring levels. This is directly related to the system downtime of the plant.

Table 6: Detection Means Available in a Typical O&M Strategy ([5], [35], [39])

Fault Detection Mean		Frequency
i.	Visual plant inspection during preventive maintenance cycles	Monthly
ii.	Manual electrical inspections (string testing, I-V curve tracing, soil testing, component functional testing, continuity checks etc.) during preventive maintenance cycles	Quarterly
iii.	Aerial and component wise thermal imaging during preventive maintenance cycles	Quarterly
iv.	Data monitoring and analytics - Real time/ remote monitoring tied to data acquisition system (DAS) and supervisory control and data acquisition (SCADA)	Real Time

A PV plant with any PV inverter structure topology is facilitated with item number 1 – 3 to detect failures. However, data monitoring and analytics facility is enabled at different levels. Table 7 depicts different levels of monitoring available with PV inverter topology.

Table 7: Different Levels of Monitoring Available with PV Inverter Structure Topology

PV Inverter Structure Topology	Data Monitoring and Analytics Level Available
Central Inverters	PV inverter level
String Inverters	PV inverter level, PV string level

Micro Inverters	PV inverter level, PV string level, PV module level
DCCU + String Inverters	PV inverter level, PV string level, PV module level

With higher number of data monitoring levels, PV inverter structures are capable of detecting failures faster causing lower system downtime. For an example, a bypass diode failure of a PV module can be identified with I-V curve testing during manual electrical inspection or aerial thermal imaging which is scheduled quarterly as the developed strategy in Table 6. If the PV plant is employed with PV module level data monitoring and analytics, a bypass diode failure can be detected real time or within one day. This shall reduce the system downtime due to bypass diode failure.

5.6 Chapter Summary

Chapter 5 fulfils the part two of the proposed methodology to develop the framework which preforms the technical comparison of different PV inverter architectures. Technical parameters proposed to assess are, energy yield output of the plant, safety features available, power output quality, system reliability and system monitoring & diagnostic facilities available. The framework analyses all the listed parameters relating to the PV plant models developed in chapter 4.

Chapter 6 discusses the methodology to develop a framework to analyse economic impact with different PV inverter architectures.

CHAPTER 6

PROPOSED METHODOLOGY: PART III – ECONOMIC COMPARISON

Following the framework for technical aspects comparison, a methodology to compare economic aspects throughout the lifetime of the PV plants with different PV inverter structure topologies, is constructed here. This is developed as a case study for the proposed 1 MWp PV plant development in Sri Lanka.

A thorough realization of the relative cost-effectiveness and economic feasibility of different PV inverter structure topologies always need to be associated with a technical review for the comparison to be successful. Therefore, a comparison is made on PV plant upfront cost (described in section 6.1) and Levelized Cost of Electricity (LCOE) of the generated output (described in section 6.2). A certain sensitivity analysis is also made on the models to accommodate uncertainties in the input parameters used for the calculations (described in section 6.3).

For the development of the methodology in this research work, 1 MWp PV plant models established in section CHAPTER 4 are utilized here as well.

6.1 PV Plant Upfront Cost

First step to calculate the LCOE is to obtain the upfront cost of the PV plant model which can be subdivided into PV inverter upfront cost and balance of system (BOS) cost. Bills of materials for each 1 MWp PV plant model are developed. Cost estimates for each PV plant model are received based on OEM literature and manufacturer's/ supplier's quotations.

6.1.1 PV Inverter Upfront Cost

Different PV inverter structure topologies inherently carry variations in the upfront cost. The cost of the PV inverters also varies from manufacturer to manufacturer. Reference [6] indicates a cost benchmark for the market available PV inverters based on different structure topologies, which has been used as an input in calculating the PV inverter upfront cost of a 1 MWp PV plant model. The benchmark values are based on Q1 2018 US market prices. (These input values can be varied as per the stakeholder requirements which changes the final output accordingly. Since the focus is on developing the framework for economic comparison, the impact of the final values is tolerable in achieving the research objectives.)

Manufacturer's limited product warranty for each PV inverter varies with the structure topology due to inherent technical limitations. For an example, many micro inverter manufacturers utilize film capacitors in the internal circuitry which has a higher Mean Time Between Failures (MTBF) compared to electrolyte capacitors used in most of the string or central PV inverters [40]. This has forced the PV inverter manufacturers to limit the product warranty period based on the structure topology of the inverter. Many PV inverter manufacturers provide an extended product warranty period associated with an additional fee. Therefore, a comprehensive comparison can only be made on the PV inverter upfront cost by integrating the manufacturer's product warranty to the cost as well. This has been achieved by referring to OEM literature and price quotations received for the 1 MWp PV plant models developed.

6.1.2 Balance of System Cost

Based on the PV inverter structure topology, bill of materials of PV plant balance of the system also varies. For an example, dc cables are majorly utilized in the 1 MWp central inverter model in order to acquire the scope of work of PV array to the main LV panel of the PV plant. For the same scope of work, ac cables are utilized in the 1 MWp micro inverter model which causes a change in the bill of materials. A comparison of PV plant upfront cost also needs to be aligned with a proper comparison on cost of the balance of system.

6.2 Levelized Cost of Electricity (LCOE)

LCOE methodology is one of the methodologies used in energy sector to benchmark and compare the cost-effectiveness in different energy generating methods [41]. It calculates the lifetime generated energy and costs to estimate a price per unit energy generated. LCOE methodology is used in this research work to analyse the cost-benefit of different PV inverter structure topologies. Reference [41] suggests Equation 13 for the calculation of LCOE which is applied in each 1 MWp PV plant model.

$$LCOE = \frac{\textit{Sum of costs over lifetime}}{\textit{Sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{13}$$

where I_t is the investment expenditure in year t, M_t is the operation and maintenance expenditure in year t, E_t is the electricity generated in year t, r is the discount rate and n is the expected lifetime of the PV plant.

Total PV plant upfront cost which is calculated as per section 6.1 methodology, is used as the investment expenditure. Electricity generated is calculated using the PVSyst simulation results obtained as per section 5.1.2.1 methodology. A provision needs to be allocated for the uncertainty of solar PV energy yield prediction [5]. Certain assumptions are made on incorporating the uncertainties in inter annual variability of solar resource, energy simulation modelling software, and solar resource data in to LCOE calculations.

Calculated LCOE is used for the comparison of cost-benefit of selection of different PV inverter structures in this research. Based on assumptions on the financial strategy of the PV plant models, a detailed analysis is also made on project IRR and equity IRR along with LCOE. Results are provided in section 7.7.3.

6.3 Sensitivity Analysis

Sensitivity analysis is the study of how the uncertainty in a financial model output can be allocated to different sources of uncertainty in its inputs [41]. Several inputs used in the financial model developed to calculate LCOE of the 1 MWp PV plants are varied in sensitivity analysis with the motive to observe the variations in the results. Following scenarios has been altered in the study,

i. Scenario 1 – An escalation of PV plant total upfront cost by 10%.
ii. Scenario 2 – A plant failure or grid unavailability for 6 months of time period in the first year of operation
iii. Scenario 3 – An escalation of loan interest rate up to 18%.

Project developers are allowed to create individual scenarios for the sensitivity analysis based on their risk appetite, industry focus and investment requirements. Calculated LCOE results are provided in section 7.7.4 for each PV plant model.

6.4 Chapter Summary

Part three of proposed methodology to develop the framework which analyses the economic impact of different PV inverter architectures, is presented in this chapter. Cost estimates are prepared for the PV plant models developed in chapter 4 considering the bills of materials. Energy output of the PV plants are obtained using energy yield prediction results. Levelized Cost of Electricity (LCOE) of the energy generated by each PV plant model is compared to understand the economic impact followed by a sensitivity analysis varying several inputs. In addition, an approach to calculate project feasibility indices such as project IRR and equity IRR are also presented.

With this chapter, the methodology of this research work is fully depicted. It is applied in the case study of this research and the results are analysed in the next chapter.

CHAPTER 7

RESULTS AND ANALYSIS

7.1 System Configuration: 1 MWp PV Plant Models

Based on the methodology in section CHAPTER 4, 1 MWp capacity PV plant models from each PV inverter architecture is developed and the results are presented here. System configuration of the models classified in to two sections as,

i. Basic system configuration – Configuration of basic parameters of the model such as site location, plant capacity, number of PV inverters and PV modules, details on string configuration and inverter configuration etc.
ii. Detailed system configuration – Presentation of detailed parameters of the models such as single line diagrams, layout diagrams, bills of materials etc.

7.1.1 Basic System Configuration

7.1.1.1 Site Location

Site details selected for the PV plant models are described as follows,

i. Location – Mamaduwa, Vavuniya
ii. Grid substation – Vavuniya
iii. GPS coordinates – 8.77°, 80.53°
iv. Land area – 105m x 125m

Figure 7-1: Selected site location for 1 MWp PV plant models

7.1.1.2 Model No.1 - 1 MWp PV Plant with Central Inverter Topology

Basic system configuration of the model is as follows,

i. PV plant capacity – 1 MWp
ii. PV module configuration – Multi crystalline 325 Wp x 3,078 nos.
iii. PV inverter configuration – Central inverter 875 kW x 01 nos.
iv. DC-AC ratio – 1.16
v. PV string configuration – 19 modules per string x 2 nos., 20 modules per string x 152 nos.
vi. Total number of strings – 154 nos.

7.1.1.3 Model No.2 - 1 MWp PV Plant with String Inverter Topology

Basic system configuration of the model is as follows,

i. PV plant capacity – 1 MWp
ii. PV module configuration – Multi crystalline 325 Wp x 3,078 nos.
iii. PV inverter configuration – String inverter 60 kW x 15 nos.
iv. DC-AC ratio – 1.11
v. PV string configuration – 19 modules per string x 162 nos.
vi. PV inverter configuration – 11 strings per inverter x 13 nos., 10 string per inverter x 1 nos., 9 strings per inverter x 1 nos.
vii. Total number of strings – 162 nos.

7.1.1.4 Model No.3 - 1 MWp PV Plant with Micro Inverter Topology

Basic system configuration of the model is as follows,

i. PV plant capacity – 1 MWp
ii. PV module configuration – Multi crystalline 325 Wp x 3,078 nos.
iii. PV inverter configuration – Micro inverter 270 W x 3,078 nos.
iv. DC-AC ratio – 1.20
v. AC branch circuit configuration – 18 micro inverters x 2 (centre-fed) and 9 micro inverters x 2 (centre-fed)
vi. Total number of ac branch circuits – 87 nos.

7.1.1.5 Model No.1 - 1 MWp PV Plant with DC Conditioning Unit and String Inverter Topology

i. PV plant capacity – 1 MWp
ii. PV module configuration – Multi crystalline 325 Wp x 3,078 nos.
iii. PV inverter configuration – String inverter 27.6 kW x 31 nos.
iv. DC-AC ratio – 1.16
v. DC conditioning units – 700 W x 1,539 nos. (2-1 configuration)
vi. PV string configuration – 34, 34, 32 modules per string configuration and 34, 32, 32 modules per string configuration
vii. Total number of strings – 93 nos.

7.1.2 Detailed System Configuration

Detailed system configuration of the 1 MWp PV plant models is provided in *"Annexure A – Design Diagrams: 1 MWp PV Plant Models"*. In this annexure, layout diagrams of each PV plant model, electrical drawings, detailed specification on PV plant components and their placements are described vividly.

7.2 Energy Yield Comparison

Detailed methodology in section 5.1 for energy yield comparison of different PV inverter structures is applied to the 1 MWp PV plant models developed and results are analysed in this section.

7.2.1 Scenario 1: Results and Analysis

In scenario 1 (section 5.1.2.1), energy yield output of 1 MWp PV plant models are obtained from using PVSyst simulation software and the results are provided in Table 8.

Table 8: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 1

	Central Inverter Model	String Inverter Model	Micro Inverter Model	DCCU + String Inverter Model

Year 1 (MWh)	1414	1418	1420	1428
Year 2 (MWh)	1409	1413	1411	1423
Year 3 (MWh)	1403	1407	1405	1417
Year 4 (MWh)	1397	1401	1400	1411
Year 5 (MWh)	1390	1394	1394	1406
Year 6 (MWh)	1382	1386	1388	1400
Year 7 (MWh)	1374	1378	1383	1394
Year 8 (MWh)	1365	1369	1377	1389
Year 9 (MWh)	1356	1360	1371	1383
Year 10 (MWh)	1347	1351	1366	1378
Year 11 (MWh)	1338	1342	1360	1372
Year 12 (MWh)	1329	1333	1354	1366
Year 13 (MWh)	1320	1324	1349	1361
Year 14 (MWh)	1312	1316	1343	1355
Year 15 (MWh)	1303	1307	1349	1337
Year 16 (MWh)	1295	1300	1344	1332
Year 17 (MWh)	1288	1293	1338	1326
Year 18 (MWh)	1281	1286	1333	1320
Year 19 (MWh)	1274	1279	1327	1315
Year 20 (MWh)	1264	1270	1321	1309
Lifetime Generation (MWh)	**26,841**	**26,927**	**27,495**	**27,260**

Data in Table 8 is illustrated in Figure 7-2 for data representation and further analysing purposes.

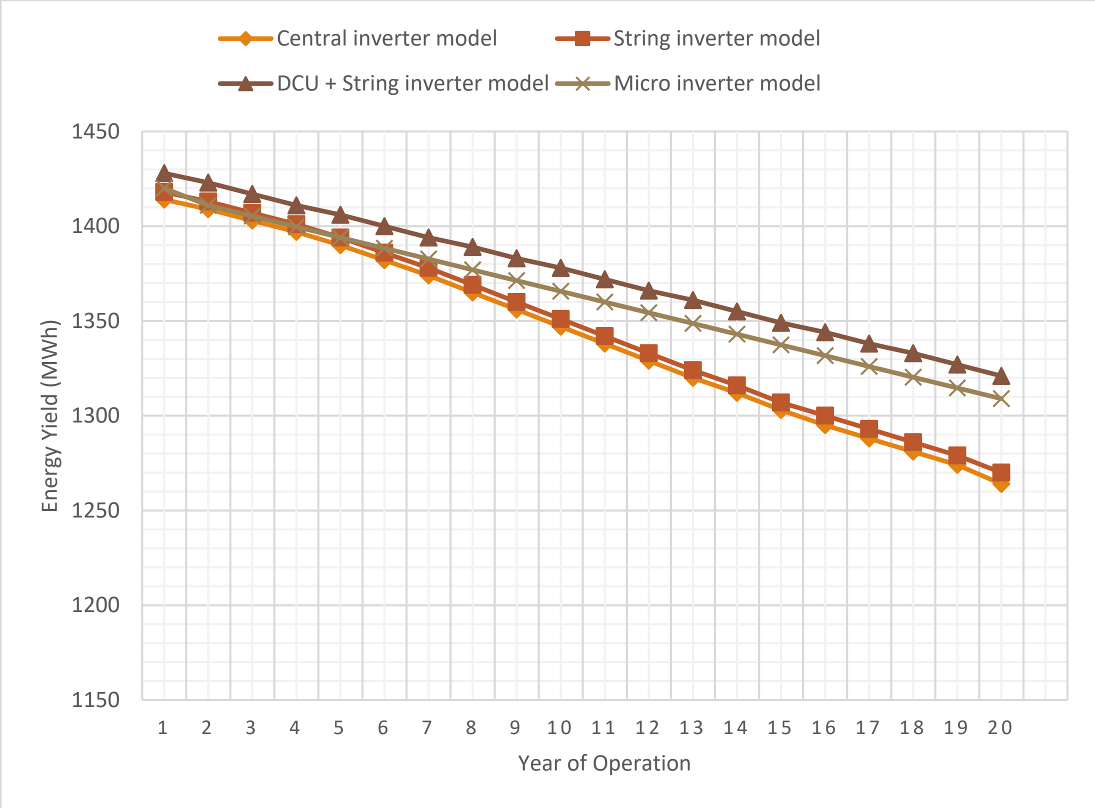


Figure 7-2: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 1

In this graph, three key cases are identified as case 1, 2 and 3.

i. Case 1 – Higher energy yield with DCCU + string inverter model compared to central inverter model (or string inverter model)

ii. Case 2 - Higher energy yield with DCCU + string inverter model compared to micro inverter model

iii. Case 3 – Incremental energy yield difference between DCCU + string or micro inverter models and central or string inverter models over the years of operation

Analysis of these three cases are performed comparing the "Energy Loss Diagrams" provided in each PVSyst simulation report. These diagrams are used to provide quick insight into a PV system design, by categorising main sources of energy losses [21].

As shown by Figure 7-3, higher energy yield with DCCU + string inverter model compared to central inverter model or string inverter model in case 1 is mainly due to the PV module mismatch losses. In DCCU + string inverter structure and micro inverter structure topologies, MPP is tracked in PV module level causing zero loss due to PV module mismatches. As shown in Figure 7-4, module mismatch loss factor of these inverter structure topologies are set to zero as default values when defining the PVSyst models.

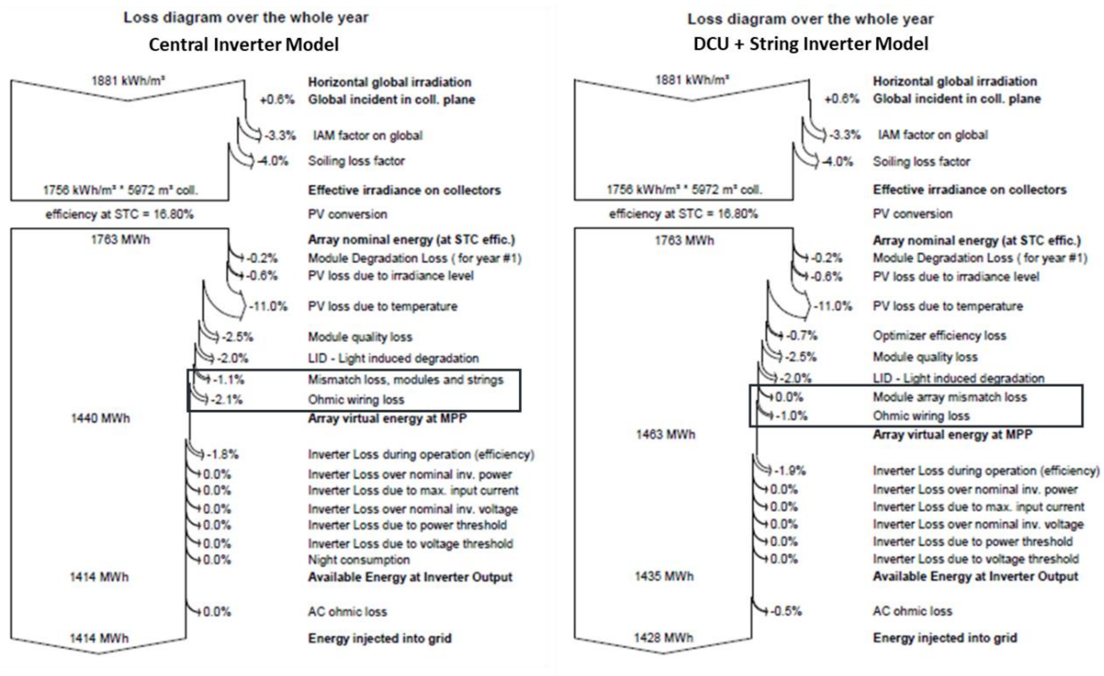


Figure 7-3: Analysis of Loss Diagrams in PVSyst Simulation Reports – Central Inverter Model Vs DCCU + String Inverter Model

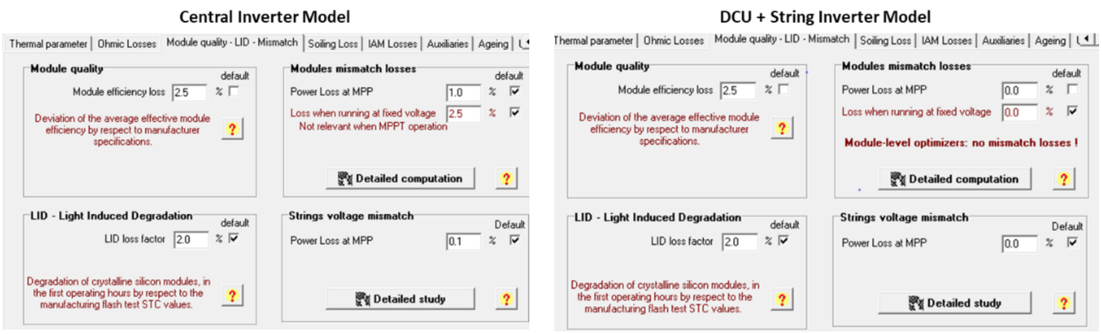


Figure 7-4: Default Detailed Losses Input Parameters – Central Inverter Model Vs DCCU + String Inverter Model

As shown by Figure 7-5, higher energy yield with DCCU + string inverter model compared to micro inverter model or string inverter model in case 2 is mainly due to the higher PV inverter efficiency loss in micro inverters. Although both DCCU + string inverter structure and micro inverter structure topologies are not affected by PV module mismatch losses due to module level MPPT, micro inverter model contains a full functioning PV inverter at each PV module causing higher PV inverter efficiency loss. In contrast, DCCU + string inverter model contains only a dc conditioning unit (optimizer) at each PV module causing lesser PV inverter efficiency loss.

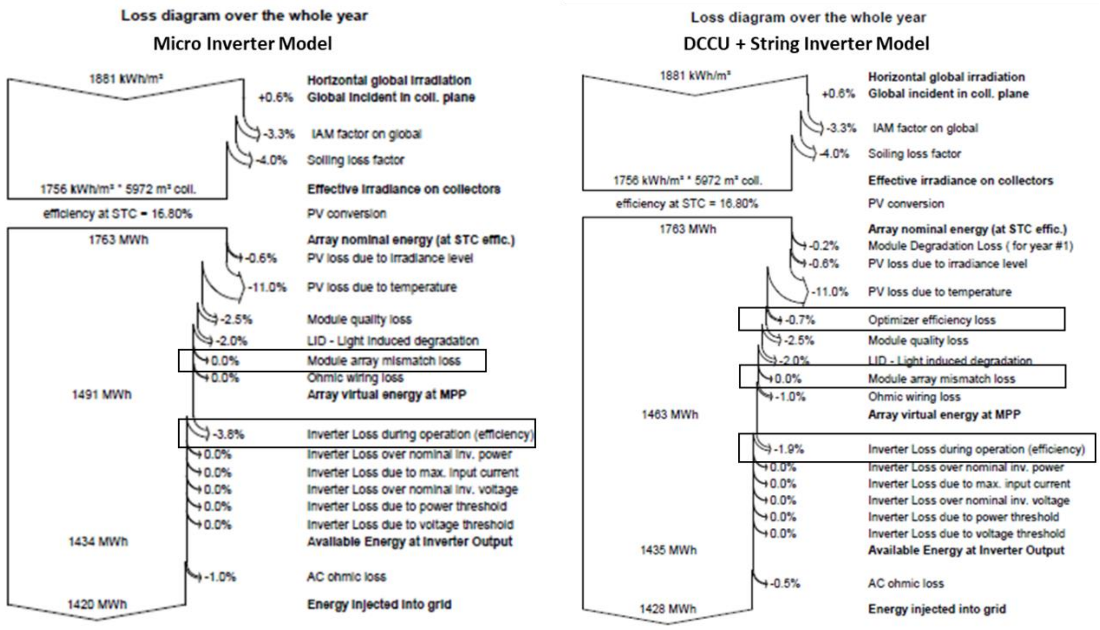


Figure 7-5: Analysis of Loss Diagrams in PVSyst Simulation Reports – Micro Inverter Model Vs DCCU + String Inverter Model

Case 3 identifies an incremental energy loss with central and string inverter models with ageing of the PV system. Figure 7-6 shows a comparison between 1st year of operation and 20th year of operation loss diagrams of central inverter model simulation. It is highlighted that the initial PV module mismatch loss has incremented with ageing of the PV system (or PV module). In contrast, Figure 7-7 shows the same comparison with DCCU + string inverter model where the module mismatch loss is zero. Therefore, it can be determined that the module ageing has not affected the increment of initial PV module mismatch loss with module level MPPT. PVSyst allows to incorporate cumulative degradation of a PV module over time into energy yield calculation. This is achieved by defining a "Mismatch Degradation Factor" which computes cumulated mismatch loss using a Monte Carlo model for the specified year [21]. As shown in Figure 7-8Figure 7-4, module mismatch degradation factor of DCCU + string inverter model is set to zero as default values when defining the PVSyst models.

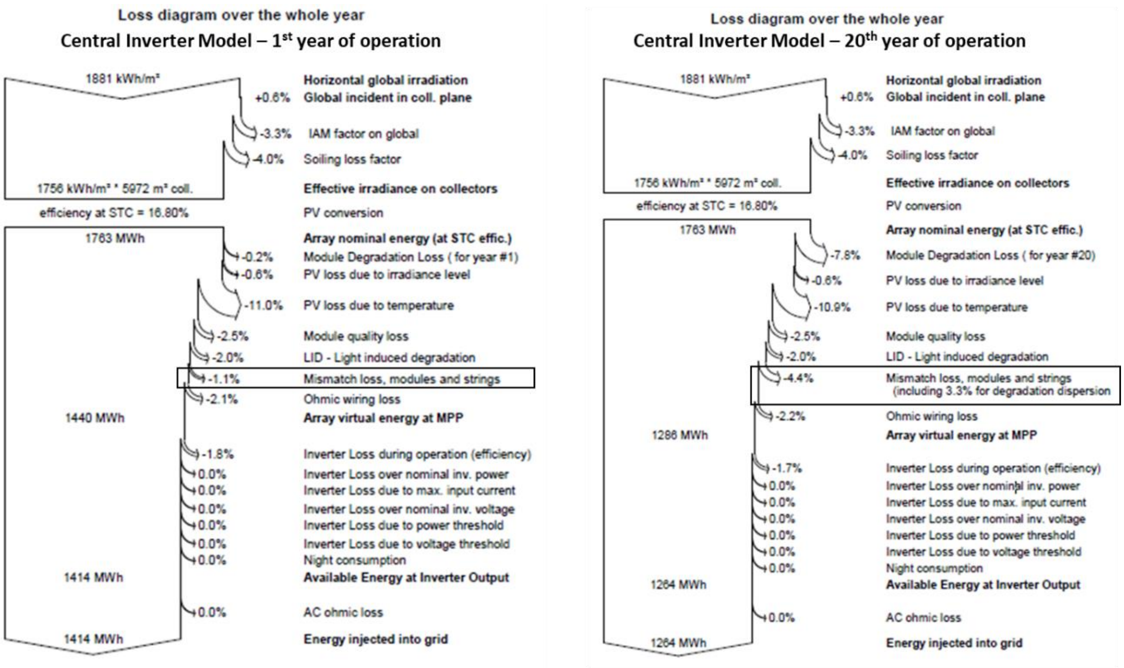


Figure 7-6: Analysis of Loss Diagrams in PVSyst Simulation Reports – Central Inverter Model 1st Year of Operation Vs 20th Year of Operation

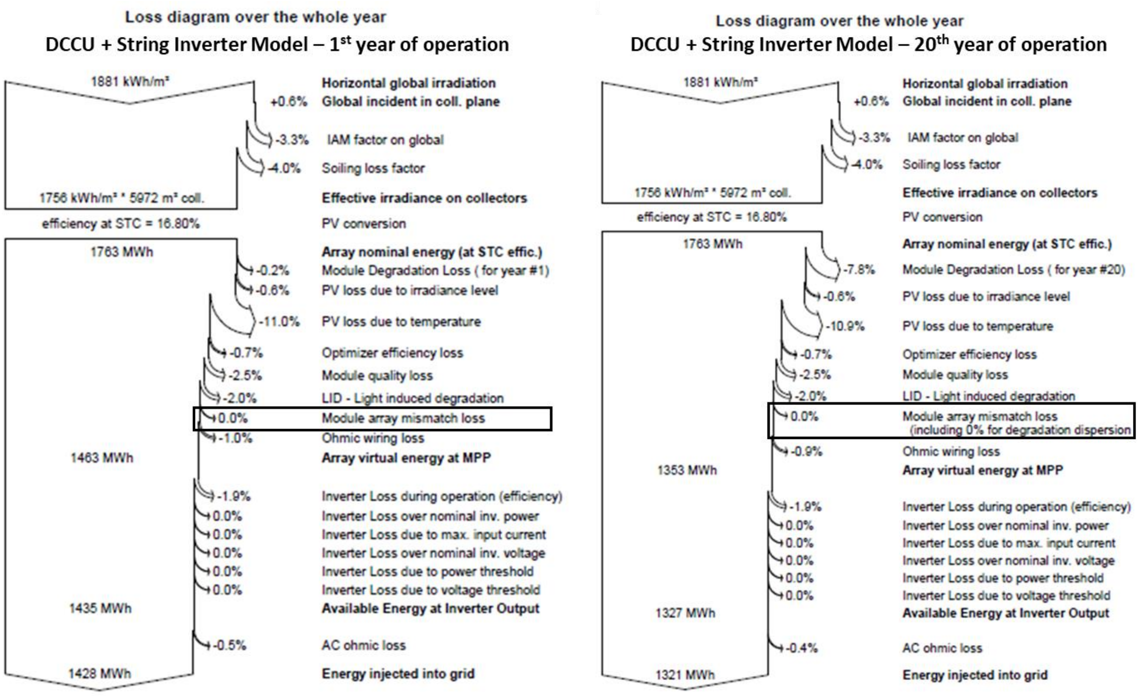


Figure 7-7: Analysis of Loss Diagrams in PVSyst Simulation Reports – DCCU + String Inverter Model 1st Year of Operation Vs 20th Year of Operation

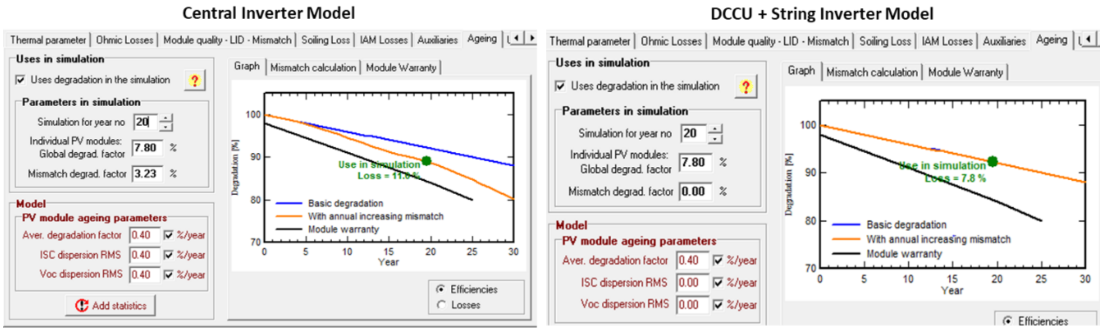


Figure 7-8: Default Module Mismatch Degradation Loss Factor – Central Inverter Model Vs DCU + String Inverter Model

7.2.2 Scenario 2: Results and Analysis

In scenario 2 (section 5.1.2.2), first year energy generation of 1 MWp PV plant models with different PV module technologies are obtained using PVSyst simulation software and the results are provided in Table 9.

Table 9: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 2

	Central Inverter Model	String Inverter Model	Micro Inverter Model	DCCU + String Inverter Model
Year 1 Generation with Mono Crystalline PV Modules (MWh)	1415	1420	1421	1428
Year 1 Generation with Multi Crystalline PV Modules (MWh)	1414	1418	1420	1428

Data in Table 9 are illustrated in Figure 7-9 for data representation and further analysing purposes.

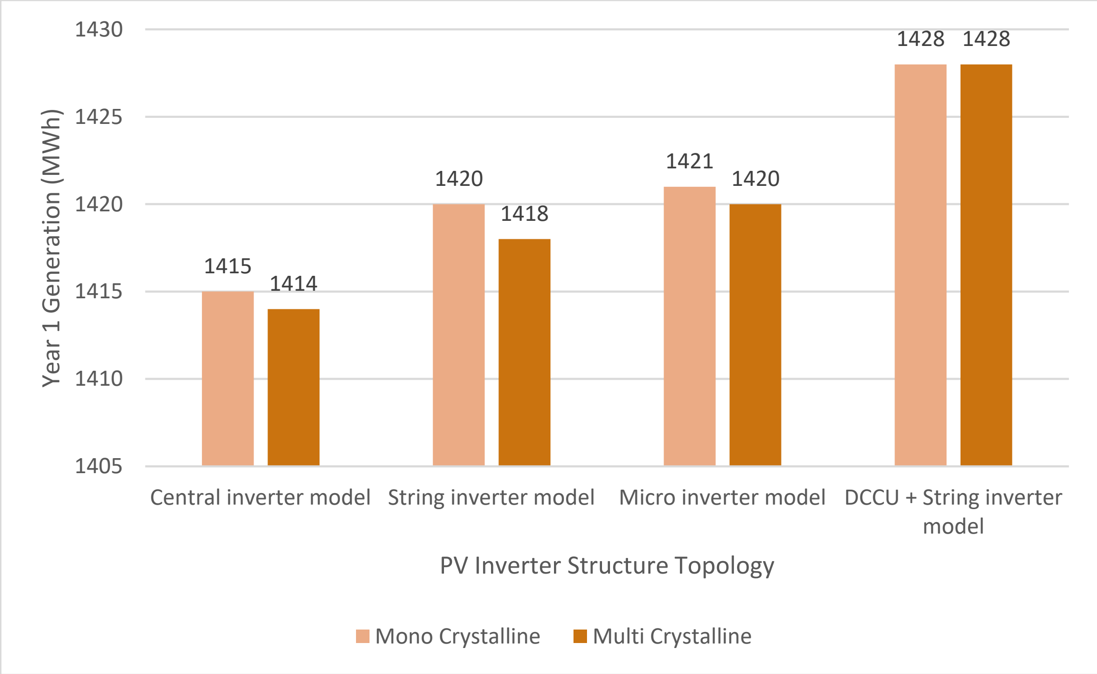


Figure 7-9: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 2

It is shown that the PV module technology affects the first year energy generation of different PV inverter structure topologies. Mono crystalline PV modules tend to have higher yield compared to multi crystalline PV modules. Although, it has not affected the higher first year energy yield generated by distributed power electronics based PV inverter topologies, following the same pattern as scenario 1. Figure 7-10 shows the loss diagrams of central inverter model PVSyst simulation with multi and mono crystalline PV modules. It is shown that the higher yield with mono crystalline PV modules is mainly due to higher conversion efficiency at standard testing conditions (STC) and lower PV efficiency losses due to irradiance level and temperature.

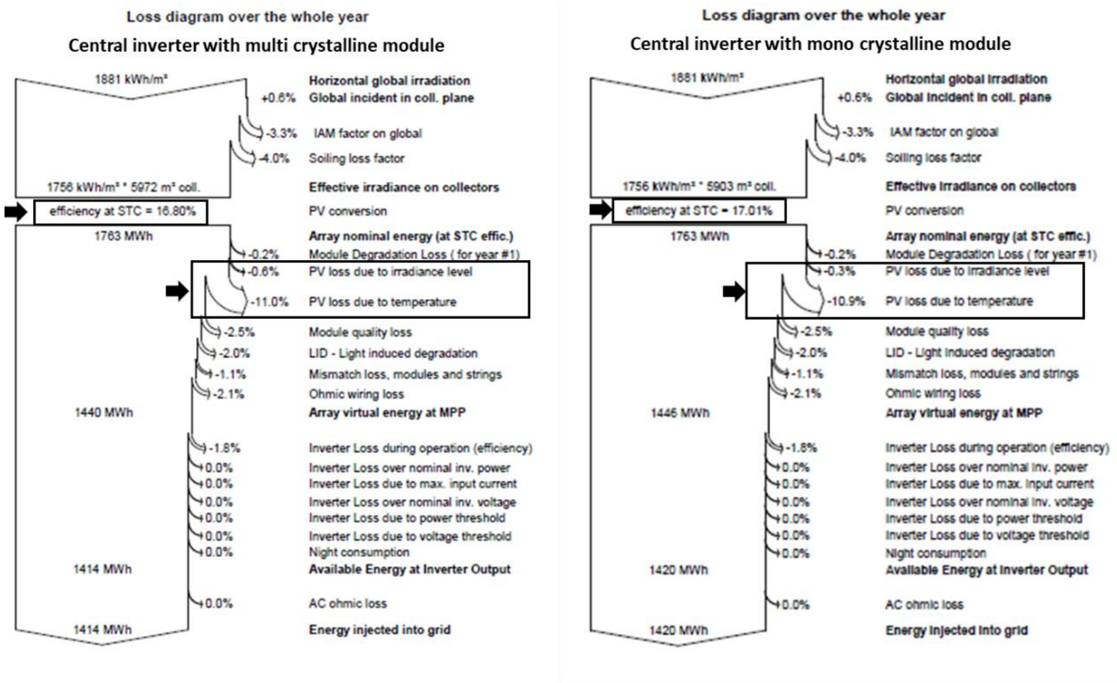


Figure 7-10: Analysis of Loss Diagrams in PVSyst Simulation Reports – Central Inverter Model with Different PV Module Technologies

7.2.3 Scenario 3: Results and Analysis

In scenario 3 (section 5.1.2.3), first year energy generation of 1 MWp PV plant models in shaded and unshaded conditions are obtained using PVSyst simulation software. Modelled shading condition in PVSyst is illustrated in Figure 7-11.

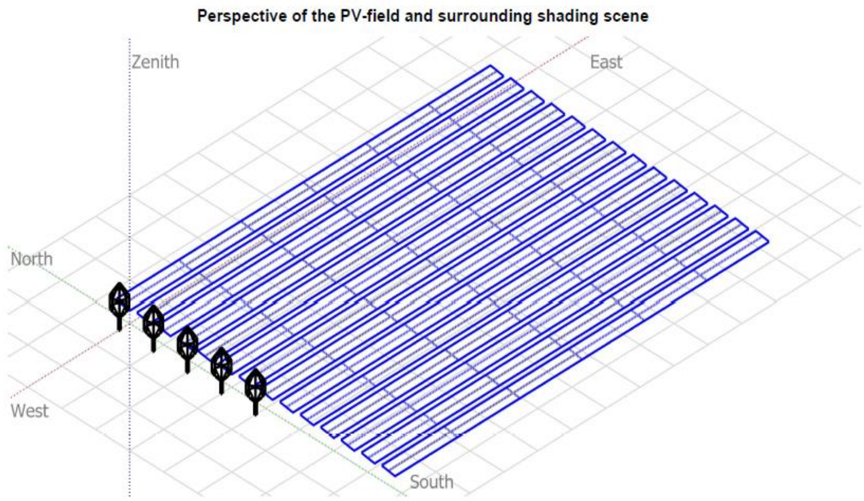


Figure 7-11: Illustration of Modelled Shading Condition in PVSyst 1 MWp PV Plant Models

Table 10: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 3

	Central Inverter Model	String Inverter Model	Micro Inverter Model	DCCU + String Inverter Model
Year 1 Generation in Unshaded Conditions (MWh)	1414	1418	1420	1428
Year 1 Generation in Shaded Conditions (MWh)	1402	1407	1416	1419
Effect of Shading	-0.8%	-0.8%	-0.3%	-0.6%

Data in Table 10 are illustrated in Figure 7-12 for data representation and further analysing purposes.

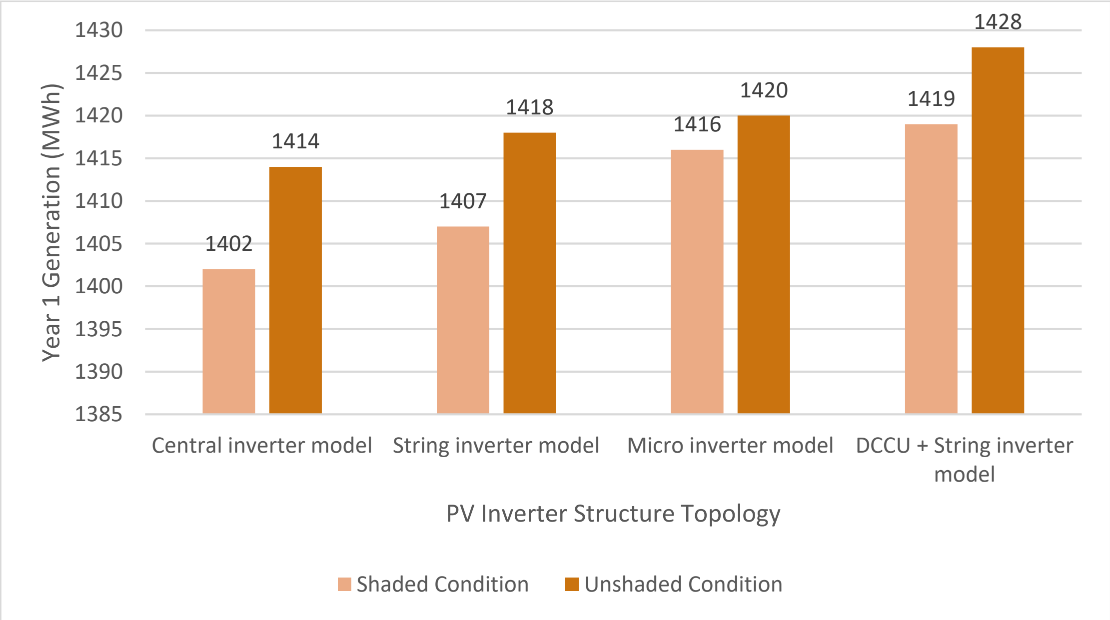


Figure 7-12: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 3

As shown above, the effect of shaded condition to the energy yield is higher in central and string inverter topologies while it is minimum with distributed power electronic based PV inverter topologies. Effect of partial shading limits the series current in a PV array leading for a lower energy output. This phenomena can be modelled in PVSyst with calculating a loss factor names as “Electrical loss according to module strings” [21]. In Figure 7-13, it shows that the irradiance loss due to modelled shading condition is the same for both PV inverter models, while electric loss according to module strings is higher with central inverter model than DCCU + string inverter model. This implies the ability to track MPP in PV module level has a positive impact in the case of partial shading incidents, compared to string level MPPT.

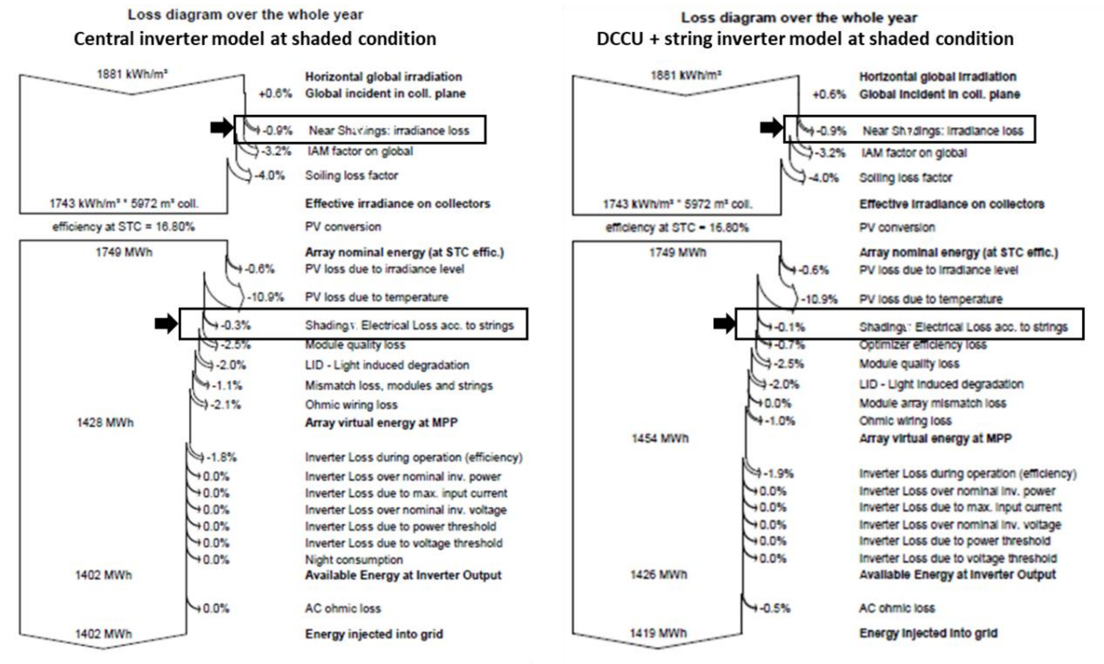


Figure 7-13: Analysis of Loss Diagrams in PVSyst Simulation Reports – Central Inverter Model Vs DCCU + String Inverter Model in Shaded Conditions

7.2.4 Scenario 4: Results and Analysis

In scenario 4 (section 5.1.2.4), first year energy generation of 1 MWp PV plant models comprised of PV inverters from various inverter manufacturers are compared using PVSyst simulation software. Results of the simulations are shown in Table 11.

Table 11: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 4

Inverter Structure Topology	Inverter Manufacturer	Inverter Model No.	AC Capacity (kW)	DC-AC Ratio	Year 1 Generation (MWh)
Central Inverter Model	ABB	PVS800	875 kW	1.14	1414
	Siemens	Sinacon PV1000	1000 kW	1	1415
String Inverter Model	SMA	STP60	60 kW	1.11	1418
	Sungrow	SG60KTL	60 kW	1.11	1417
	Goodwe	GW60K-MT	60 kW	1.11	1413
DCCU + String Inverter Model	SolarEdge	SE27.6k	27.6 kW	1.16	1428
	Tigo	MMJ-ES50	60 kW	1.11	1429
Micro Inverter Model	Enphase	S270	270 W	1.2	1420
	Omnik	S270	270 W	1.2	1416

Data in Table 11 are illustrated in Figure 7-14 for data representation and further analysing purposes.

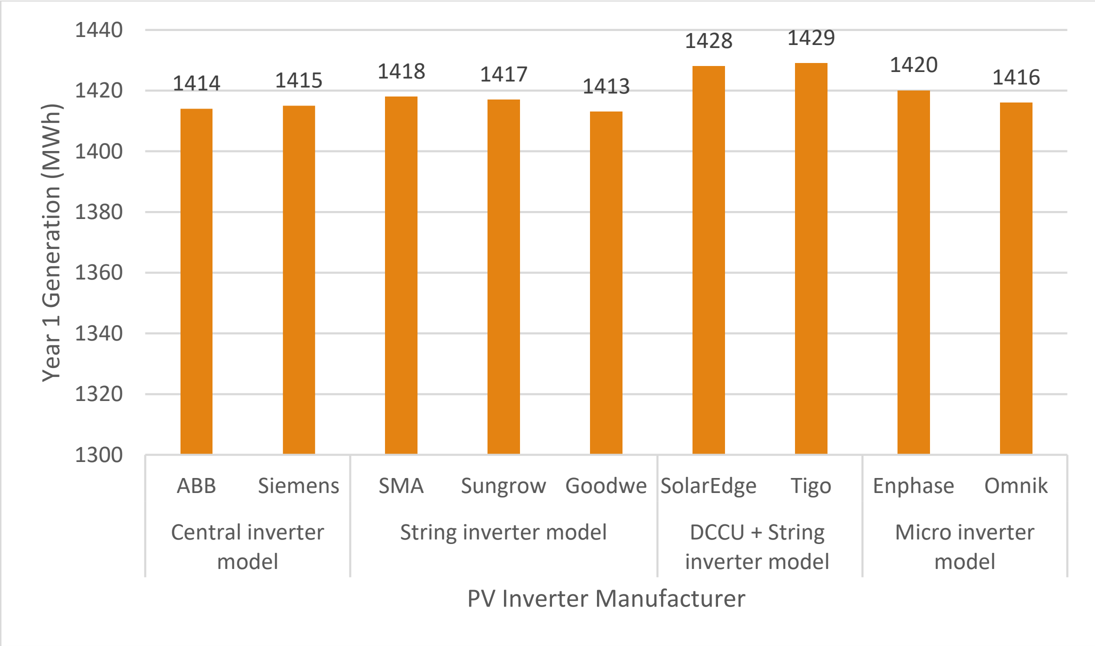


Figure 7-14: PVSyst Simulation Results of 1 MWp PV Plant Models for Scenario 4

As shown above, first year of energy generation by various PV inverter manufacturers of central and string inverter structure topologies fall within the same range without a significant deviation. Micro inverter models generate slightly higher energy output within first year. But, dc conditioning units from selected manufacturers leads the energy generation significantly. In overall, it can be seen that the energy output of different PV inverter topologies is hardly effected by the PV inverter manufacturer.

7.3 Safety Aspects: Results and Analysis

As detailed in section 5.2.1, PV systems with selected inverter structure topologies are modelled in PSCAD to evaluate safety aspects. 1 MWp PV plant models developed in section CHAPTER 4 are utilized to configure the models. Figure 7-15 indicates a PSCAD model developed for 1 MWp central inverter model to simulate an earth fault scenario and the resulted fault current & voltage levels.

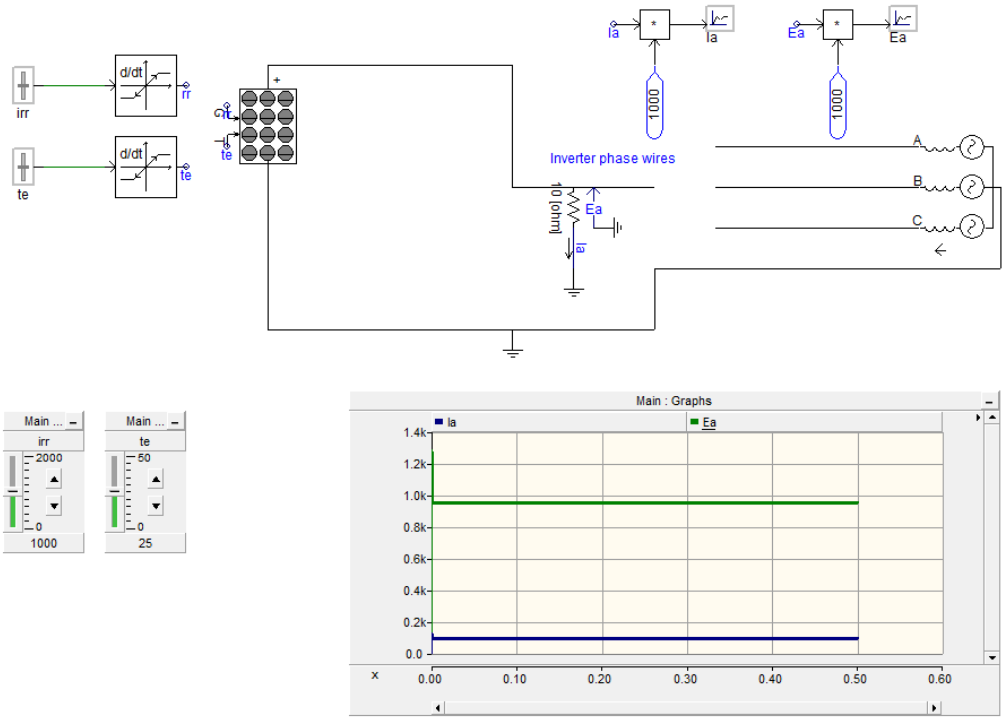


Figure 7-15: PSCAD model developed for 1 MWp central inverter model to simulate an earth fault scenario

Results of the PSCAD models are shown in Table 12. In the same table, weighted risk index of the PV plant model is also calculated, after assigning a pre-defined hazard severity index as in section 5.2.1.

Table 12: PSCAD Simulation Results of Shock Hazard Risk Assessment

Inverter Topology	**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
Fault 1 – Positive to negative short circuited scenario (DC side)	Ia = 1415 A	Ia = 101 A	Ia = 9.18 A	Ia = 45 A
Fault 2 – Earth fault scenario (DC side)	If = 124 A-DC, Ef = 1245 V-DC	If = 88 A-DC, Ef = 882 V-DC	If = 5.35 A-DC, Ef = 53.57 V-DC	If = 45 A-DC, Ef = 450 V-DC
Fault 3 – Line-line-earth short circuited scenario (AC side)	Ib = 892 A	Ib = 806 A	Ib = 722 A	Ib = 765 A
Fault 4 – Earth fault scenario (AC side)	Ic = 1213 A	Ic = 1095 A	Ic = 981 A	Ic = 1040 A
Available disconnection mean	PV string level	PV string level	PV module level	PV module level
Weighted Risk Index	108	108	4	36

Proposed evaluation criteria to assess arc fault risk in PV systems is performed for the 1 MWp PV plant models with different PV inverter structures. These evaluation values are listed in Table 13. In the same table, weighted risk index of the PV plant model is also calculated, after assigning a pre-defined hazard severity index as in section 5.2.2.

Table 13: Results of Arc Fault Risk Assessment

Inverter Topology	**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
Operating DC Voltage	1100 V	1000 V	<60 V	750 V
Operating DC Current	1710 A	110 A	< 15 A	< 40 A

Geographical Distribution of DC Wiring	Whole PV plant	PV array block level	PV module level	PV array block level
Weighted Risk Index	27	6	1	18

Overall risk index is calculated using weighted risk indices obtained in the previous sections and final result is provided in Table 14.

Table 14: Overall Risk Index of Safety Aspects Evaluation

Inverter Topology	**Weighted Risk Index for Shock Hazards**	**Weighted Risk Index for Arc Fault Hazards**	**Overall Risk Index**
Central Inverter Model	108	27	135
String Inverter Model	108	6	114
Micro Inverter Model	4	1	5
DCCU + String Inverter Model	36	18	54

When analysing the overall risk indices, it should be noted that higher the index, greater the risk. It is shown that micro inverters introduce the lowest safety risk. Micro inverters are connected to each and every PV module avoiding high dc string voltages. DC cable lengths are also negligible compared to other inverter structures which eliminates arc fault risk. Due to the distributed power electronic devices, micro inverter PV systems can be turned-off from PV module level, minimizing the risk of electrocution for installers or maintenance workers. Although the dc conditioning units provide module level shutdown ability, its high dc voltage present during operation cause higher risk with shock hazards than micro inverters. Central inverter and string inverter models carries similar amount of risk while the risk is greatest with central inverter models due to higher geographical distribution of dc wiring in a PV plant.

7.4 Power Quality Aspects: Results and Analysis

As specified in section 0, following requirements are identified after analysing the listed international and local standards and it is found that all the PV inverters identified in section 5.1.2.4 are complying with it.

Table 15: Result Analysis on Power Quality Standard Requirements

Grid Compliance	IEC 61727	IEEE 1547	CEB Requirement	Compliance by Inverter Structure Topology
Harmonic currents (Order – h) Limits	(3-9) 4.0% (11-15) 2.0% (17-21) 1.5% (23-33) 0.6%	(2-10) 4.0% (11-16) 2.0% (17-22) 1.5% (23-34) 0.6% (>34) 0.3%	(<11) 4.0% (11-16) 2.0% (17-22) 1.5% (23-34) 0.6% (35-50) 0.3%	All PV inverter models identified in section 5.1.2.4 (Central inverters, string inverters, micro inverters and DCCU + string inverters) comply with the requirements
Maximum current THD	5.0%	5.0%	5.0%	
Power factor at 50% of rated power	0.9	0.9	0.9	
DC current injection	Less than 1.0% of rated output current	Less than 0.5% of rated output current	Less than 0.5% of rated output current	
Voltage range for normal operation	85% - 110% (196V – 253V)	88% - 110% (97V – 121V)	230V ±10%	
Frequency range for normal operation	50 ±1 Hz	59.3 Hz to 60.5 Hz	47 Hz to 52 Hz	
Flicker			Flicker emission should comply with IEC 61000-4-15 and IEC 61000-3-7	

Harmonic distortions are considered as one of the major power quality issues. Identified standards have defined maximum limits for harmonic current injections by the PV inverters. These injected voltage and current harmonics will result in power harmonics which will introduce instability and unreliability to the grid due to the overheating in capacitor banks and transformers [42]. All PV inverters identified in section 5.1.2.4 from different inverter structures provides necessary certifications to prove compliance.

Maximum allowable dc current injection from PV inverters, which leads to avoid saturation of distribution transformers in the grid, are also defined in the assessed standards. Other main power quality issues which are analysed are voltage flicker, voltage operating range and frequency operating ranges [30].

It is identified from these standards that if grid voltage or frequency falls outside the said ranges, PV inverters need to be turned off. However, as per IEEE 1547, PV inverters should be able to “ride through” minor voltage or frequency disturbances, helping the grid to self-heal from such disturbances. These riding through capabilities are categorized as under/over frequency ride-through and under/over voltage ride-through [43]. IEEE 1547 outlines the following PV inverter’s response to abnormal voltages listed in Table 16.

Table 16: IEEE 1547A-2014 Interconnection System Responses to Abnormal Voltages [30]

Default settings		**Maximum settings – Clearing time: Adjustable up to and including (s)**
Voltage range (% of base voltage)	**Clearing time (s)**	
V < 45	0.16	0.16
45 < V < 60	1	11
60 < V < 88	2	21
110 < V < 120	1	13
V > 120	0.16	0.16

It is revealed in the OEM literature that the identified PV inverters from different structure topologies are capable of supporting the ride through functions with inverters’ software and operation protocol updates.

7.5 System Reliability

As detailed in section 5.4, system reliability of different PV inverter architectures is assessed using Markov Models under three scenarios and the results are analysed in this section.

7.5.1 Scenario 1: Results and Analysis

In scenario 1, different PV inverter failure rates (λ) for 1 MWp PV plant models are considered while repair rates (μ) are unchanged. Table 17 details about the input parameters for the developed Markov model.

Table 17: Input Parameters for 1 MWp PV Plant Models in Reliability Assessment Scenario 1

1 MWp PV Plant Model	Central Inverter Model	String Inverter Model	Micro Inverter Model
Energy Output in Year 1 (MWh)	1,414	1,418	1,420
Per Inverter Energy Output in Year 1 (MWh)[1]	1,414.00	94.53	0.46
Number of Inverters (N)	1	15	3078
Failure Rate (λ)[2] Yr^{-1}	1/5	1/8	1/25
Repair Rate (μ)[3] Yr^{-1}	365/30	365/30	365/30

[1] Per inverter energy output is calculated from energy yield simulation results obtained in section 5.1.2.1.

[2] Failure rates for different PV plant models are assumed based on the typical warranty periods provided by manufacturers for each PV inverter structure topology.

[3] Repair rate is assumed as 30 days.

Differential equations which characterize the developed Markov models are solved in MATLAB as shown in Figure 7-16.

```
function [Energy] = CustomMarkov(E_per_inv, N, lamda, u)

% E_per_inv = 0.46;
%
% N = 3078;
% lamda = 1/25;
% u = 365/30;


p_N = 0;
p_i = []; % will have N+1 elements, since it goes from 0 -> N
pi = 1;

for i = N:-1:0
    if i == N
        p_N = u / (lamda*N + u);
        p_i = [p_i p_N];
        pi =p_N; %
    else
        pi = ( (i+1)*lamda / (i*lamda + u) ) * pi;
        p_i = [p_i pi];
    end
end

% for i = 1:length(p_i)
%     fprintf('p_%d = %e \n',length(p_i)-i,p_i(i));
% end

Energy = 0;
p_i = fliplr(p_i);

for i = 1:N
    Energy = Energy + (i * p_i(i+1) * E_per_inv);
%     p_i(i+1)
end

% fprintf('\n\nEnergy = %e MWh \n',Energy);

end
```

Figure 7-16: Solving Differential Equations in Developed Markov Models

Energy output results of the 1 MWp PV plant models after integrating system reliability are shown in Table 18.

Table 18: Reliability Assessment Results - Scenario 1

1 MWp PV Plant Model	**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**
Energy Output in Year 1 (MWh)	1414	1418	1420
Energy Output in Year 1 (MWh) Integrating System Reliability	1391.1	1403.5	1415.2
Deviation (MWh)	22.9	14.5	4.8

Data in Table 18 is illustrated in Figure 7-17 for data representation and further analysing purposes.

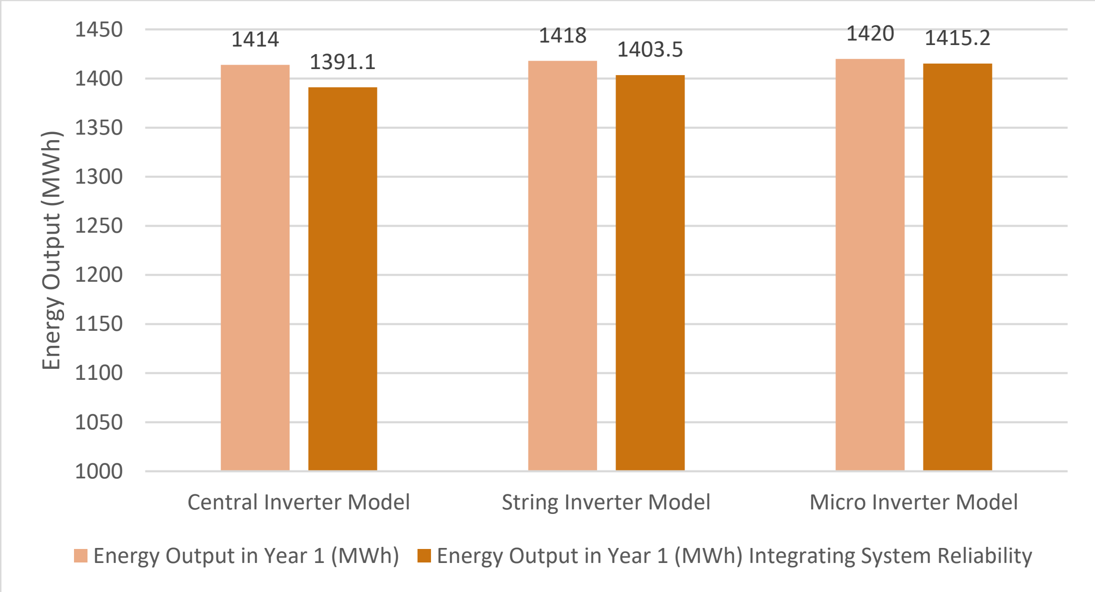


Figure 7-17: Reliability Assessment Results - Scenario 1

System reliability of central inverter model is the lowest in the cluster while micro inverter model shows the highest system reliability. Results in this scenario are affected by two main input parameters, i.e. number of inverters in the model and PV inverter failure rates. Central inverter model includes lowest number of inverters and highest failure rate in this scenario while micro inverter model includes highest number of inverters and lowest failure rate.

7.5.2 Scenario 2: Results and Analysis

In scenario 2, PV inverter failure rates (λ) and repair rates (μ) are unchanged for 1 MWp PV plant models. Table 19 details about the input parameters for the developed Markov model.

Table 19: Input Parameters for 1 MWp PV Plant Models in Reliability Assessment Scenario 2

1 MWp PV Plant Model	Central Inverter Model	String Inverter Model	Micro Inverter Model
Energy Output in Year 1 (MWh)	1,414	1,418	1,420
Per Inverter Energy Output in Year 1 (MWh)[1]	1,414.00	94.53	0.46
Number of Inverters (N)	1	15	3078
Failure Rate (λ)[2] Yr^{-1}	1/5	1/5	1/5
Repair Rate (μ)[3] Yr^{-1}	365/30	365/30	365/30

[1] Per inverter energy output is calculated from energy yield simulation results obtained in section 5.1.2.1.

[2] Failure rates for different PV plant models are assumed as once in every 5 years.

[3] Repair rate is assumed as 30 days.

Energy output results of the 1 MWp PV plant models after integrating system reliability are shown in Table 20.

Table 20: Reliability Assessment Results - Scenario 2

1 MWp PV Plant Model	**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**
Energy Output in Year 1 (MWh)	1,414	1,418	1,420
Energy Output in Year 1 (MWh) Integrating System Reliability	1,412.5	1,416.4	1,418.3
Deviation (MWh)	1.5	1.6	1.7
Deviation (%)	0.11%	0.11%	0.12%

Data in Table 20 is illustrated in Figure 7-18 for data representation and further analysing purposes.

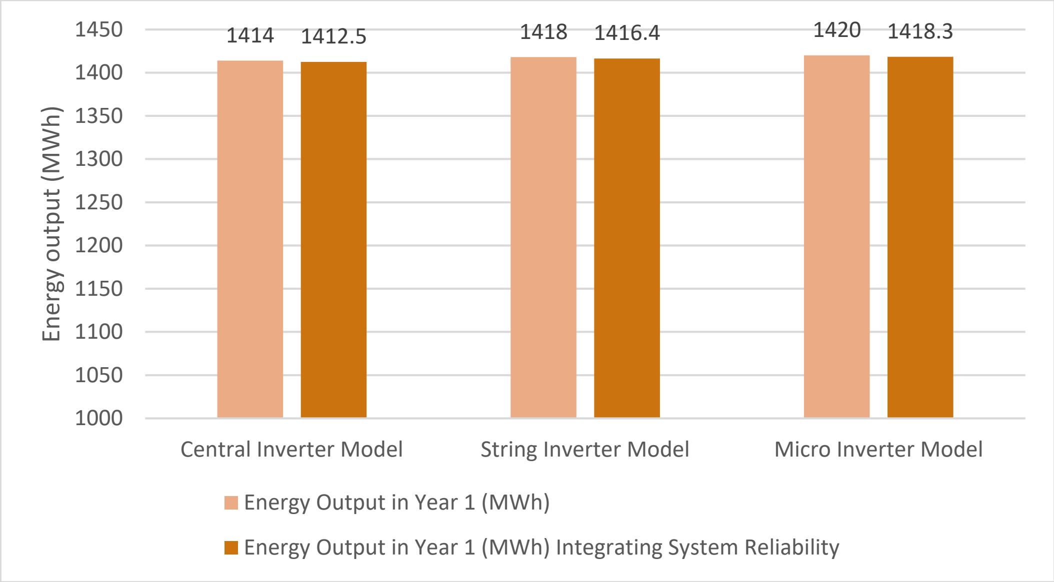


Figure 7-18: Reliability Assessment Results - Scenario 2

Energy output difference before and after integrating system reliability can be identified as the same for all PV plant models. It concludes that the system reliability of PV inverters is mainly affected by the PV inverter failure rates.

7.5.3 Scenario 3: Results and Analysis

In scenario 3, a range of values are assigned for PV inverter failure rates (λ) and repair rates (μ) to develop a methodology to assess the system reliability in different PV plant models. Table 21 details about the input parameters for the developed Markov model.

Table 21: Input Parameters for 1 MWp PV Plant Models in Reliability Assessment Scenario 3

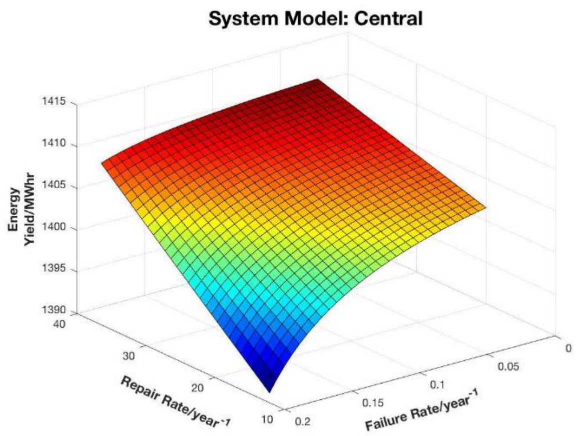
1 MWp PV Plant Model	Central Inverter Model	String Inverter Model	Micro Inverter Model
Energy Output in Year 1 (MWh)	1,414	1,418	1,420
Per Inverter Energy Output in Year 1 (MWh)[1]	1,414.00	94.53	0.46
Number of Inverters (N)	1	15	3078
Failure Rate (λ)[2] Yr^{-1}	1/5 – 1/25		
Repair Rate (μ)[3] Yr^{-1}	365/10 – 365/30		

[1] Per inverter energy output is calculated from energy yield simulation results obtained in section 5.1.2.1.

[2] Failure rate value ranges for different PV plant models are assumed as once in every 5 - 25 years.

[3] Repair rate value range is assumed as 10 - 30 days.

Energy output results of the 1 MWp PV plant models after integrating system reliability are calculated using MATLAB and shown in Figure 7-19.



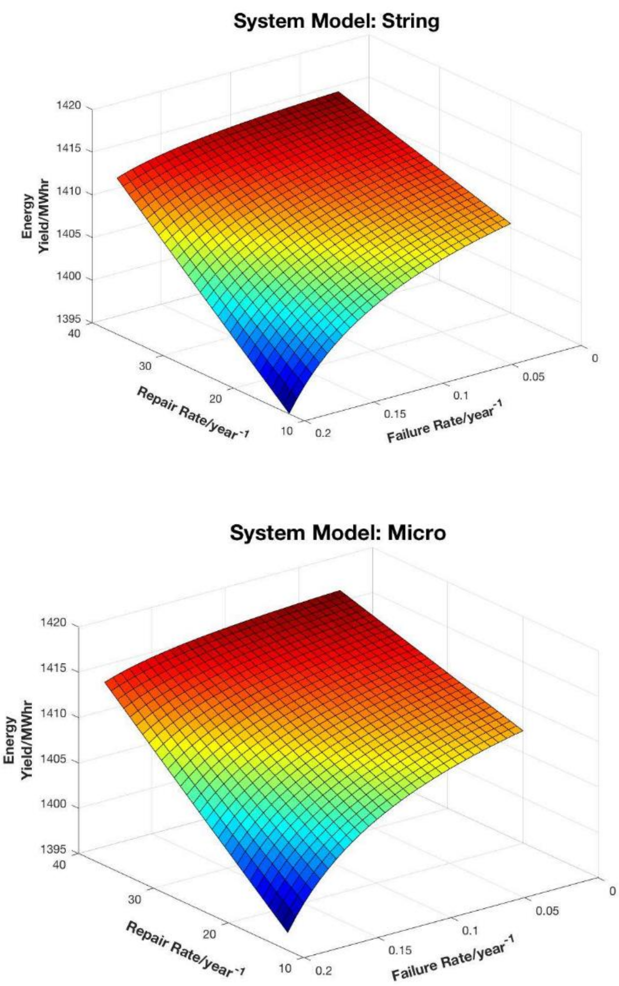


Figure 7-19: Reliability Assessment Results - Scenario 3

Inverter failure rates are highly depending on the manufacturers methodologies, raw materials and quality standards and varies from manufacturer to manufacturer. In this scenario, the impact of system reliability to the energy output is assessed considering a range of failure rates which provides a proper methodology to achieve the purpose of this research work.

7.6 System Monitoring, Diagnostics & Troubleshooting: Results and Analysis

Methodology discussed in 5.5 is applied in the 1 MWp PV plant models to evaluate system monitoring, diagnostics and troubleshooting functionality of PV inverters and results are analysed in this section.

Identified set of common failures, possible causes and rectification methods are discussed in Table 22.

Table 22: Root Causes and Rectification Methods of Common Failures [37]

Component	Failure Mode	Description	Rectification
PV Module	Hot spot	Burned marks caused by overheating cells. Can be identified by thermal inspections.	Module replacement
	Delamination	Insufficient lamination in manufacturing can cause separation of cells from tedlar. Can be detected by visual inspection.	Module replacement
	Glass breakage	Thermal shocks during operation, mishandling during maintenance can break the glass. Can be identified by visual inspection.	Module replacement
	Soiling losses	Sand particles, bird's droppings deposited on top can cause irradiance losses.	Module cleaning during preventive maintenance cycle
	Shading losses	Irradiance losses due to physical obstructions like growing vegetation etc.	Vegetation management during preventive maintenance cycle
	Snail track	Discoloration effect mainly caused by micro cracks in solar cells	Module replacement
	Cell cracks	Caused by mechanical or thermal loads	Module replacement
	PID	PID occurs when module voltage and leakage current drive ion mobility within the semiconductor material and other elements of the module (e.g. glass, mount and frame). This causes the	Module replacement

		module's power output capacity to degrade.	
	Failure of bypass diode and junction box	Due to heating of cells or manufacturing defects	Module replacement
	Overheating junction box	Increase the risk of fire and energy loss.	Module replacement
	Broken module	Caused by extreme weather conditions or environmental effects	Module replacement
	Corrosion in the junction box	Caused by the atmospheric content	Module replacement
	Theft or vandalism	Caused by lack of security	Module replacement
PV Inverter	Inverter failure	Can be caused due to wrong configuration, manufacturing defect or malfunction	Inverter replacement
DC Cabling	UV aging	Due to exposure to UV radiation.	Cable replacement
	Theft of cables	Caused by lack of security	Cable replacement
	Damaged cables		Cable replacement
	Damaged connectors		Connector replacement
DC Combiner Boxes	Switch disconector/ breaker failure		Breaker replacement

Fault detection strategy defined in section 5.5.2 is employed in each PV plant model to detect the above common set of failures. Cost Priority Number method discussed in section 5.5.1 is followed to calculate system downtime cost and failure fixing cost.

During the calculations, following assumptions are made for all PV plant models, which are,

i. Labour costs are assumed as 1000 LKR/Man Day (8 hours per day).
ii. Cost of detection - Monitoring and data acquisition system cost is included in the initial project cost.
iii. Cost of transportation – Spare part stock is managed on-site and the cost is included in the initial project cost. Therefore, the transportation cost is neglected assuming all the spare parts and labour are available on-site.
iv. Reference database for component failure rate calculation as specified in Cost Priority Number method in section 5.5.1 is selected from Reference [37] - Solar Bankability Project 2015 – Reference database from EURAC and TÜV

Rheinland, Private Research Institutes in Europe. This database is equipped with items listed in Table 23.

Table 23: Reference Database for Component Failure Rate Calculation [37]

Total number of PV plants in the database	772
Total database capacity	441.676 MWp
Average number of years of data available	2.7 Years
Components Included	**Number of Components**
PV modules	2,058,721
PV inverters	11,967
Mounting structures	43,916
Connection & distribution boxes	25,305
Cabling	246,084
Transformer stations	759

Economic impact of the PV inverter's system monitoring, diagnostics and troubleshooting functionality is assessed comparing the CPN value of PV plant models for the identified common failures.

Table 24 provides summary overview of the total CPN value calculation. Detailed CPN value calculation is included in *"Annexure B - CPN Calculation for 1 MWp PV Plant Models"*.

Table 24: Summary Results of Total CPN Value Calculations

Component	**Failure Mode**	**CPN Value for Central Inverter Model (LKR/anum)**	**CPN Value for String Inverter Model (LKR/anum)**	**CPN Value for Micro Inverter Model (LKR/anum)**	**CPN Value for DCCU + String Inverter Model (LKR/anum)**
PV Module	**Hot spot**	65,163.00	65,180.53	65,189.29	65,224.35
	Delamination	72,350.46	72,354.06	72,355.86	72,363.06
	Glass breakage	229,025.11	229,123.46	229,172.64	229,369.35
	Soiling losses	192,652.88	193,197.86	59,059.37	59,392.10
	Shading losses	394,435.85	395,194.56	135,016.06	135,065.54
	Snail track	130,654.70	130,661.20	130,664.45	130,677.44
	Cell cracks	4,294.33	4,294.93	4,084.70	4,084.73
	PID	227,176.52	227,397.87	175,698.50	175,849.31
	Failure of bypass diode and junction box	79,118.02	79,259.97	30,048.24	30,054.48
	Overheating junction box	32,867.88	32,876.72	32,881.14	32,898.83
	Broken module	27,449.82	27,457.86	27,461.88	27,477.96
	Corrosion in the junction box	1,596.26	1,596.34	1,596.38	1,596.54

	Theft or vandalism	2,129.77	2,130.39	2,130.71	2,131.95
PV Inverter	**Inverter failure**	158,533.97	76,513.93	33,873.37	55,964.59
DC Cabling	**UV aging**	36,640.05	35,303.10	-	5,402.90
	Theft of cables	58.12	55.07	-	20,225.72
	Damaged cables	113,508.21	109,265.04	-	30.20
	Damaged connectors	67,215.11	64,702.47	-	62,453.56
DC Combiner Boxes	**Switch disconector/ breaker failure**	355.83	367.60	-	36,982.55
Total CPN Value (LKR/anum)		**1,835,225.90**	**1,746,932.96**	**999,232.59**	**1,147,245.16**

It is revealed that the CPN value for identified common failures is the highest with central inverters while the lowest with micro inverters. PV module level performance monitoring functionality available with distributed power electronics in PV systems improves the detection time of a failure. This has reduced the system downtime due to the failure and the impact to the economic aspects of the PV plant.

7.7 Economic Comparison

Section CHAPTER 6 outlines the proposed methodology to follow during evaluating economic aspects related to different PV inverter structure topologies. The methodology has been applied in the developed 1 MWp PV models in section CHAPTER 4. A review on the results is provided here.

7.7.1 Inverter Upfront Cost: Results and Analysis

Table 25 indicates the results of the comparison made on PV inverter upfront costs.

Proposed Power Purchase Agreement (PPA) by CEB for the 1 MWp PV plants indicates the project duration as 20 years [1, 4]. In order to evaluate the upfront cost in the common grounds, following steps are taken,

i. Adding warranty extension fee up to 20 years to the upfront cost
ii. Adding cost of PV inverter to the upfront cost assuming PV inverter replacement is required after standard product warranty period expiration.

Table 25: PV Inverter Upfront Cost Comparison Results

1 MWp PV Plant Model	Central Inverter Model	String Inverter Model	Micro Inverter Model	DCCU + String Inverter Model
Factory Gate Price ($/W-AC)[1]	0.06	0.08	0.32	0.16
AC Capacity of the Model (W)	875,000	900,000	831,060	855,600
Inverter Price (USD)	52,500	72,000	265,939.2	136,896
Inverter Price (LKR)[2]	8,925,000	12,240,000	45,209,664	23,272,320
Standard Warranty Period[3]	5 years	5 Years	20 Years	12 Years
Warranty Extension Fee up to 20 Years (LKR) [4]	17,850,000	8,568,000	0	2,371,500
Upfront Cost after adding Warranty Extension Fee (LKR)	26,775,000	20,808,000	45,209,664	25,643,820

[1] Factory Gate Prices (First Buyer Price) is taken from Reference [6]: U.S. Solar Photovoltaic System Cost Benchmark Q1 2018.

[2] USD to LKR conversion rate is considered as 170 LKR/USD.

[3] Standard Warranty Period for each PV inverter structure is taken referring to manufacturer's literature. (Referred documents are provided in "*Annexure C – Manufacturer's Product Warranty Documentation"*).

[4] 3,300 USD per each string PV inverter and 450 USD per each DCCU + string PV inverter are considered. Micro inverters are usually provided with 20 years' standard product warranty hence an additional extension fee is not required. Central inverters do not provide the facility for warranty extensions. Therefore, the cost of upfront cost is considered assuming PV inverter replacement is required after standard product warranty period expiration.

Upfront costs are higher with micro inverters and DCCU systems due to the additional electronic component at each PV module, compared to central and string inverters. Reason for micro inverter costs to be the highest can be suggested due to the replacement of a complete PV inverter at each PV module while in DCCU systems merely a dc-dc converter operates at each PV module. Central inverters introduce the lowest upfront cost due to the lowest number of PV inverters operating in a PV plant. Although, the standard manufacturer's product warranty periods with micro inverters last for 20 years due to the inclusion of more reliable power electronic components as explained in section 6.1.1.

The proposed methodology results in providing common ground to compare upfront costs of the PV inverters. The final results of the upfront costs can be varied with the change of input parameters as per project stakeholders' requirement. Since the focus is on the framework, the impact of that kind of a change has tolerable influence towards achieving research objectives here.

7.7.2 Balance of System Cost: Results and Analysis

Costs which are variable with the PV inverter structure topology are characterized under this sector. Bills of materials of the variables costs in 1 MWp PV plant models are provided in *"Annexure D - Variable Cost Breakdown for 1 MWp PV Plant Models"*. A summary of the annexure is provided in Table 26.

Table 26: Summary of Variable Balance of System Costs of 1 MWp PV Plant Models

Item Category	**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
Communication Components Cost (LKR)	Included	278,892	1,170,000	221,760

LV Electrical Switchgear Cost (LKR)	4,389,840	1,739,210	2,127,980	1,791,867
DC Cabling Cost (LKR)[1]	10,406,460	7,438,314	-	3,468,472
AC Cabling Cost (LKR)[2]	-	1,272,454	6,227,042	1,362,554
Total Variable BoS Cost (LKR)	**14,796,300**	**10,728,870**	**9,525,022**	**6,844,653**

[1] DC cabling cost is considered negligible in micro inverter model since PV modules are directly connected to micro inverters without using additional dc cables.

[2] Considered scope in this costing is from PV array up to the LV combiner panel at the plant step up transformer. Therefore, ac cabling cost is not considered in central inverter model.

Data in Table 26 is illustrated in Figure 7-20 for data representation and further analysing purposes.

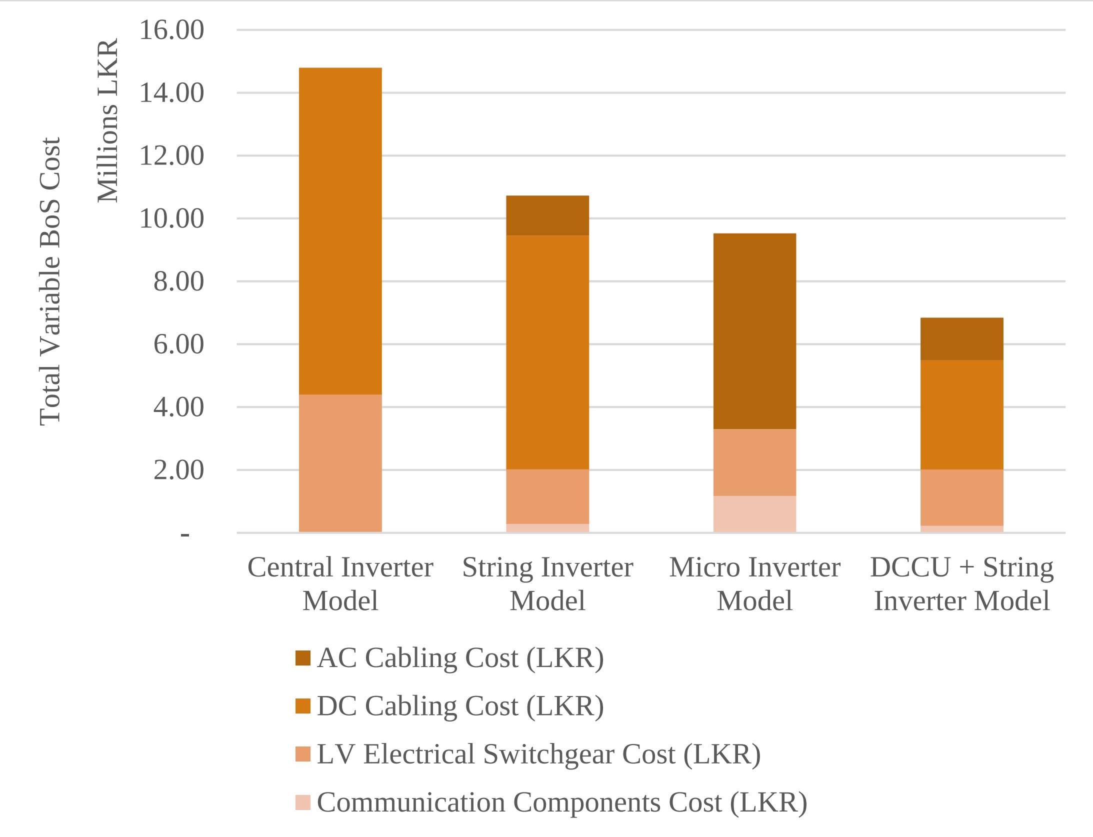


Figure 7-20: Summary of Variable Balance of System Costs of 1 MWp PV Plant Models

Costs which are fixed with the PV inverter structure topology are characterized under this sector. Bills of materials of the fixed costs in 1 MWp PV plant models are provided in *"Annexure E - Fixed Cost Breakdown for 1 MWp PV Plant Models"*. A summary of the annexure is provided in Table 27.

Table 27: Summary of Fixed Balance of System Costs of 1 MWp PV Plant Models

Item Category	Quantity	Unit	Unit Cost (LKR)	Total Cost (LKR)
PV Module and Mounting Structure	1	Item	1,170,000.00	65,692,090.00
MV Equipment and Cabling	1	Item	2,127,980.00	12,161,012.00
Logistics	1	Item	-	910,000.00
Labor	1	Item	6,227,042.00	2,579,000.00
Civil Works	1	Item	9,525,022.00	3,720,000.00
Project Management				2,400,000.00
Auxiliary Systems	1	Item		7,873,000.00
Total Fixed BoS Cost (LKR)				**95,335,102.00**

Total upfront cost of the 1 MWp PV plant models is calculated adding PV inverter upfront cost, variable BoS cost and fixed BoS and the results are detailed in *"Annexure F - Total Upfront Cost of 1 MWp PV Plant Models"*.

7.7.3 LCOE: Results and Analysis

Methodology discussed in 6.2 is applied for the 1 MWp PV plant models and the results are analysed in this section. Following assumptions are made for the calculation of LCOE, project IRR and equity IRR.

i. Debt: Equity ratio – 3:1
ii. Loan period – 5 years
iii. Loan interest rate – 14% per annum
iv. Tariff paid as per the PPA – 18.27 LKR/kWh
v. 100% depreciation is considered for the PV plant over 20 years with unit rate
vi. O&M cost is considered 1% from total project upfront cost with 6% annual escalation
vii. 1 USD = 170 LKR
viii. Tax rate is considered as 28% from taxable income
ix. Discount rate is considered as 10%
x. Electricity generated by the PV plant models:
    a. PVSyst simulation model results obtained in section 5.1.2.1 is considered for life time plant energy generation
    b. Provisions for uncertainty are assumed as per reference [5]
        i. Inter annual variability of solar resource – ±2.2%

ii. Energy simulation modelling software uncertainty – ±2%
iii. Solar resource data uncertainty – ±5%
iv. Total uncertainty – ±5.8%
v. Energy generation value with – 5.8% uncertainty is considered as "Worst Case Scenario", with no uncertainty is considered as "Average Case Scenario" and with + 5.8% uncertainty is considered as "Best Case Scenario".

LCOE, project IRR and equity IRR for each 1 MWp PV plant model is detailed in *"Annexure G – Cash Flow Analysis of 1 MWp PV Plant Models"*. The results are summarized here. Table 28 provides a comparison of LCOE of 1 MWp PV plant models.

Table 28: LCOE Comparison

PV Plant Model		**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
Worst Case	**LCOE (LKR/kWh)**	18.23	17.23	19.35	17.14
Average Case	**LCOE (LKR/kWh)**	17.47	16.53	18.52	16.44
Best Case	**LCOE (LKR/kWh)**	16.79	15.9	17.79	15.82

Table 29 provides a comparison of project IRR of 1 MWp PV plant models.

Table 29: Project IRR Comparison

PV Plant Model		**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
Worst Case	**LCOE (LKR/kWh)**	14.92%	16.12%	13.73%	16.21%
Average Case	**LCOE (LKR/kWh)**	15.82%	17.09%	14.57%	17.17%
Best Case	**LCOE (LKR/kWh)**	16.72%	18.04%	15.41%	18.12%

Table 30 provides a comparison of equity IRR of 1 MWp PV plant models.

Table 30: Equity IRR Comparison

PV Plant Model		**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String**

					Inverter Model
Worst Case	**LCOE (LKR/kWh)**	15.34%	17.16%	13.61%	17.28%
Average Case	**LCOE (LKR/kWh)**	16.70%	18.67%	14.83%	18.79%
Best Case	**LCOE (LKR/kWh)**	18.09%	20.22%	16.06%	20.34%

Results of the LCOE in Table 28 are illustrated in Figure 7-21 for analysing purposes.

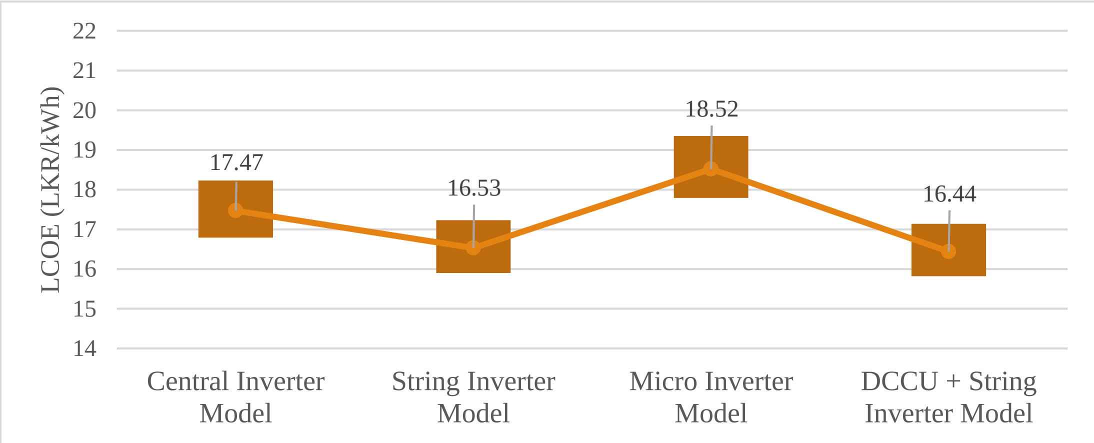


Figure 7-21: Results LCOE Comparison

It is detailed that the employment of string inverters and dc conditioning units + string inverter PV systems in 1 MWp scale PV plant development scheme provide the best LCOE. Lower upfront costs with string inverters and added energy yield, lower balance of system costs and lower warranty extension fee with dc conditioning unit PV systems (DCCU + string) can be considered as the main driving factors in achieving best LCOE. Although PV inverter cost is the lowest with central inverters, higher warranty extension fees, higher balance of system costs and lower energy yield has caused the central inverter PV plant model to own a higher LCOE. Although an added energy yield is harvested with micro inverter systems due to distributed power electronics, higher upfront cost has caused micro inverters to introduce the highest LCOE among the considerations. Project IRR and equity IRR values of different PV plant models also follow the same pattern as the LCOE.

7.7.4 Sensitivity Analysis

A sensitivity analysis is done as described in 6.3 and the results are detailed in this section. In scenario 1, total PV plant upfront cost is escalated by 10% and the results are detailed in Table 31.

Table 31: Results of the Sensitivity Analysis with 10% Upfront Cost Escalation

PV Plant Model		**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
LCOE (LKR/kWh)	**Worst Case**	19.54	18.45	20.77	18.34
	Average Case	18.70	17.67	19.86	17.57
	Best Case	17.96	16.98	19.05	16.89

Results of the LCOE in Table 31 are illustrated in Figure 7-22 for analysing purposes.

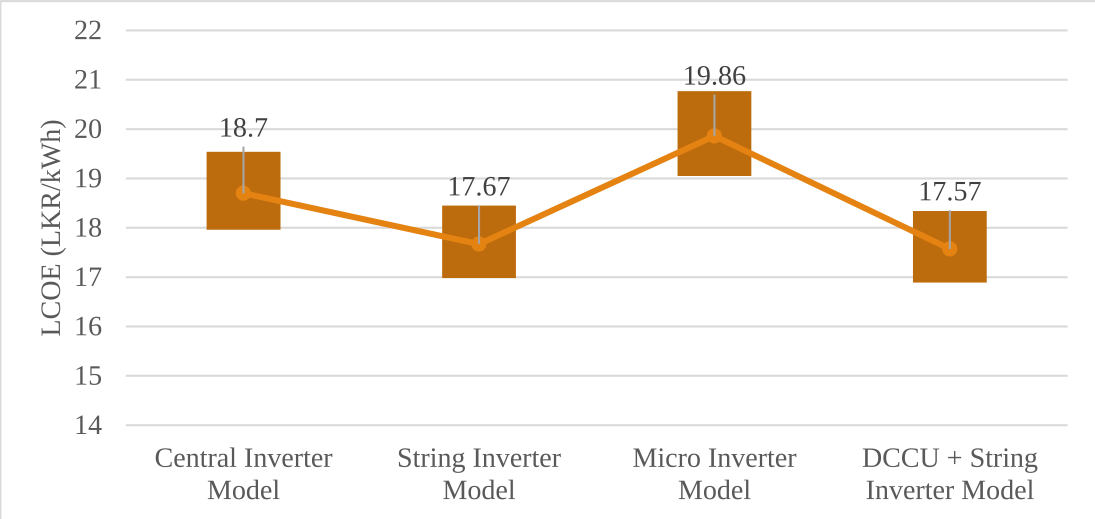


Figure 7-22: Results LCOE Comparison with 10% Upfront Cost Escalation

Escalation of PV plant upfront cost by 10% has increased the LCOE of all four PV plant models compared to the base case. Although, the same pattern is observed in the results which concludes that the factors affected string inverter model and DCCU PV system model to provide the best LCOE are not influenced with the cost escalation.

In scenario 2, A plant failure or grid unavailability for 6 months of time period in the first year of operation is introduced and the results are detailed in Table 32.

Table 32: Results of the Sensitivity Analysis with 6 Months Grid Unavailability

PV Plant Model		**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
LCOE (LKR/kWh)	**Worst Case**	19.00	17.94	20.18	17.84
	Average Case	18.19	17.20	19.30	17.10
	Best Case	17.47	16.53	18.52	16.44

Results of the LCOE in Table 32 are illustrated in Figure 7-23 for analysing purposes.

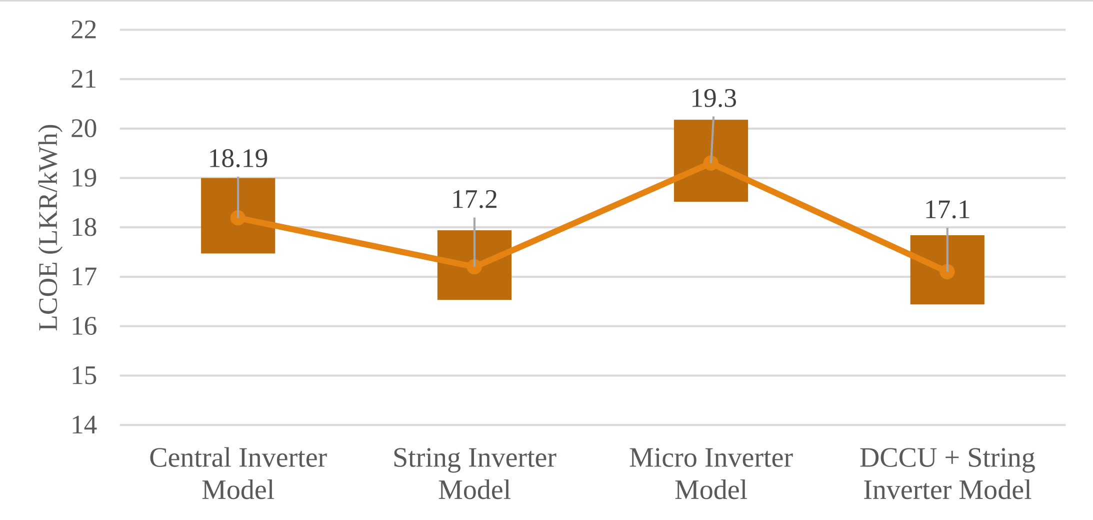


Figure 7-23: Results LCOE Comparison with 6 Months Grid Unavailability

Grid unavailability for 6 months in the first year of operation has reduced the revenue in all four PV plant models in the same pattern. This has increased the individual LCOE value but has not affected the base case LCOE distribution pattern among the PV plant models.

In scenario 3, an escalation of loan interest rate up to 18% is considered and the results are detailed in Table 33.

Table 33: Results of the Sensitivity Analysis with Loan Interest Rate Escalation up to 18%

PV Plant Model		**Central Inverter Model**	**String Inverter Model**	**Micro Inverter Model**	**DCCU + String Inverter Model**
LCOE (LKR/kWh)	**Worst Case**	18.89	17.84	20.06	17.74
	Average Case	18.08	17.10	19.19	17.00
	Best Case	17.37	16.44	18.42	16.35

Results of the LCOE in Table 33 are illustrated in Figure 7-24 for analysing purposes.

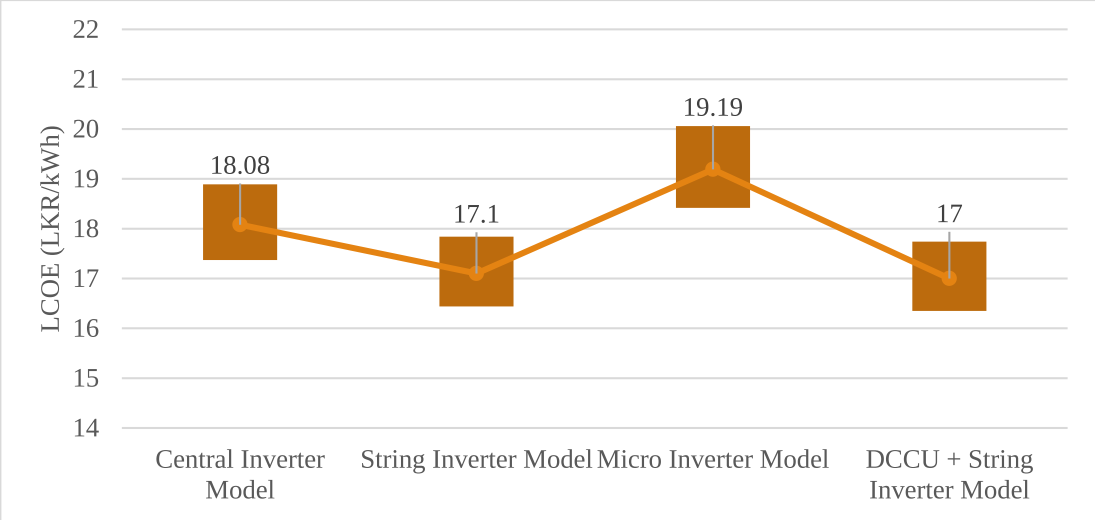


Figure 7-24: Results LCOE Comparison with Loan Interest Rate Escalation up to 18%

It is concluded that the increment in loan interests rate has also affected the LCOE in each PV plant model in the same pattern.

7.8 Chapter Summary

In this chapter, the methodology for techno-economic comparison is applied in the case study of recent 1 MWp solar power development scheme in Sri Lanka and the results are studied for analytical purposes. Based on the technical and economic final outcome, the research work is concluded in the next chapter along with suggestions for future improvements.

CHAPTER 8

CONCLUSION AND FUTURE DIRECTION

8.1 Conclusion

As detailed in previous sections, key objective of the research is to provide a framework for the techno-economic comparison of different PV inverter architectures. Since the case study is based on recently proposed 1 MWp solar power development scheme in Sri Lanka, same capacity PV plant models are developed using different PV inverter structures to analyze the impact to the technical and economic aspects of the project. Four types of inverter architectures, i.e. central inverters, string inverters, micro inverters and dc conditioning units with string inverters, are considered.

Methodology for the technical comparison is facilitated with assessing energy yield output of the PV plants, safety aspect, power output quality, system reliability and system monitoring, diagnostics & troubleshooting capabilities.

Distributed power electronics in PV systems tracks the MPP at each PV modules which eliminates mismatch losses, shading losses, and losses due to PV module degradation with aging. As a result, a higher energy yield is generated compared to central and string inverter architectures. Among the distributed power electronic systems, inverter efficiency losses are higher with micro inverters due to addition of components at each PV module which causes lower energy yield compared to dc conditioning unit systems. Framework developed for energy yield comparison is capable of absorbing different inverter manufacturers, PV module technology variations and introduction of shading effect.

Safety aspects comparison is differentiated in to safety from shock hazards and safety from arc fault risks. Micro inverters introduce the lowest safety risk due to the presence of lower dc string voltages, minimum dc cable distribution and availability of PV module level disconnection means. Although the dc conditioning units also provide PV module level shutdown ability, its high dc voltage present during operation causes higher risk with shock hazards. Safety risk is higher with central and string inverters due to high dc voltages and PV string level disconnection means and the greatest with central inverters due to higher geographical distribution of dc wiring in a PV plant.

Meeting power output quality and compliance to local/ international requirements is made common for all PV inverter architectures by the industry leading manufacturers. It is found independent from the inverter technology.

Reliability of PV plants varies with number of PV inverters used and component failure rates. For a given number of PV inverters, the framework has introduced a novel approach to interlink system reliability with energy yield prediction. The approach is applied in the case study and a range of results are obtained where the project stakeholders can refer based on their requirement.

A cost prioritized methodology is introduced to compare the system monitoring, diagnostics and troubleshooting functionality of PV inverters which is also applied in the case study. Availability of additional performance monitoring levels up to PV module escalates the probability of failure detection causing lower system downtime due to the failure. The methodology evaluates this impact to the project financials for different PV inverter architectures.

Economic impact due to selection of different PV inverter architectures in PV plant designs is quantified by the proposed methodology, comparing upfront costs of the PV plant, lifetime revenue generated and Levelized Cost of Electricity (LCOE) of the energy output. Several cost benchmarks prevail in the PV industry are utilized in the work. Resulting fixtures and numbers are expected for deviations based on the used input parameters other than the cost benchmarks. However, the objective of this research work is develop the framework for the assessment. Therefore, freedom of selection of input parameters for the economic comparison model is given to the project stakeholders since the impact of such variations are not in the research objectives.

The framework suggests the importance of comparing PV inverter upfront costs standing on a common ground which also incorporates manufacturer’s product warranty periods. It also implies that the PV plant balance of system cost is influenced by the PV inverter architecture. An accurate upfront cost estimate of PV plants with different PV inverter topologies can only be made taking PV inverter cost, supplier warranty period and balance of system costs in to account. After examination of PV plant upfront cost, the framework also suggests calculation of Levelized Cost of Electricity (LCOE) value for a better understanding of the best suited solution. The methodology reflects the upfront investment, energy generation and operating costs. Application of the methodology in the case study concluded that the string inverters and dc conditioning unit PV systems harvest more attractive feasibility than central and micro inverters in 1 MWp scale. A sensitivity analysis followed up by the financial consideration is also proposed for the project stakeholders to absorb the uncertainties in the model.

Considering the above, it is established to say that the developed methodology in this research work is furnished with providing a comprehensive techno-economic comparison for different PV inverter architectures.

8.2 Future Direction

Constraints in time and other resources have limited the scope of this research work to conclude at section 8.1 with a successful outcome. However, following advancements are proposed for the continuation of the future work related to this topic.

Comparison of the different PV inverter architectures is mainly done as a case study for the 1 MWp scale PV plants. The outcome is possible to vary in residential level lower project capacities and utility scale higher project capacities. Therefore, it is recommended to research on add-ons for tailoring purposed of the existing framework.

During the energy yield prediction, life time energy yield is considered only for the inverter manufacturers who have the largest market share. It is suggested to incorporate other PV manufacturer’s products and technologies since the manufacturing quality processes have a significant influence. Interlinking of system reliability into energy yield prediction which is proposed in section 5.4, is advised to be considered in life time energy yield calculations in future.

Accuracy of the energy yield prediction needs to be enhanced with better-quality weather data and improved uncertainties. Uncertainty in energy yield simulation results can be varied due to several factors like in-built inaccuracy of modelling software, uncertainties aggregated at each modelling stage and input variables, uncertainty in meteorological database and inter annual variability. Although a fixed value is considered in this research work, a significant improvement is suggested for all the potential uncertainties listed above.

In the PV plant development, only the crystalline silicon PV module technologies are considered. There has been a significant improvement in other PV module technologies as well which needs to be incorporated.

Unavailability of field data in safety aspects analysis, component failure rate calculations, system monitoring & diagnostics comparison is another limitation which is experienced. Many project developers, manufacturers and installers are reluctant to provide product-related data due to market competition. However, a methodology to develop a quality database with field data in local conditions is capable of improving the accuracy of the outcome.

During the calculations of economic impact, component prices are taken referring to industry benchmarks and supplier quotations. These prices are highly dynamic and changes over time. Therefore, revisions are suggested to conduct for the developed framework here on regular basis.

CHAPTER 9

REFERENCES

[1] Ceylon Electricity Board, *Request for proposals for the establishments of sixty solar PV power plants on build, own and operate basis under "Soorya Bala Sangramaya – Phase II,"* vol. I. 2017.

[2] Ceylon Electricity Board, "Long Term Generation Expansion Plan 2018-2037," pp. 5/16-5/20.

[3] Sri Lanka Sustainable Energy Authority, "Soorya Bala Sangramaya." [Online]. Available: http://www.energy.gov.lk/index.php/en/soorya-bala-sangramaya.

[4] Ceylon Electricity Board, *Request for proposals for the establishments of ninety solar PV power plants on build, own and operate basis under "Soorya Bala Sangramaya – Phase II,"* vol. I. 2018.

[5] International Finance Corporation, *Utility-Scale Solar Photovoltaic Power Plants*. 2015.

[6] R. Fu, D. Feldman, and R. Margolis, "U. S. Solar Photovoltaic System Cost Benchmark : Q1 2018," *Natl. Renew. Energy Lab.*, p. 26.

[7] P. Dewangan, P. K. Dewangan, and U. T. Nagdeve, "A Review of Single-Phase Grid-Connected Inverters for Photovoltaic generation system," *Int. J. Res.*, vol. 1, no. 9, pp. 521–525, 2014.

[8] C. Deline, B. Marion, J. Granata, and S. Gonzalez, "A Performance and Economic Analysis of Distributed Power Electronics in Photovoltaic Systems."

[9] M. Islam, S. Mekhilef, and M. Hasan, "Single phase transformerless inverter topologies for grid-tied photovoltaic system: A review," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 69–86, 2015.

[10] L. Hassaine, E. Olias, J. Quintero, and V. Salas, "Overview of power inverter topologies and control structures for grid connected photovoltaic systems," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 796–807, 2014.

[11] Africa-EU Renewable Energy Cooperation Programme (RECP), "Global Market Outlook - For Solar Power/2017-2021," 2017.

[12] R. Margolis, D. Feldman, and D. Boff, "Q4 2017/Q1 2018 Solar Industry Update - NREL," 2018.

[13] P. Jayakumar, "Solar Energy Resource Assessment Handbook," *Asian Pacific Cent. Transf. Technol. United Nations – Econ. Soc. Comm. Asia Pacific*, no. September, pp. 1–117, 2009.

[14] O. P. Mahela and A. G. Shaik, "Comprehensive overview of grid interfaced solar photovoltaic systems," *Renew. Sustain. Energy Rev.*, vol. 68, no. July 2015, pp. 316–332, 2017.

[15] A. S. K. Chowdhury and M. A. Razzak, “Single phase grid-connected photovoltaic inverter for residential application with maximum power point tracking,” *2013 Int. Conf. Informatics, Electron. Vision, ICIEV 2013*, no. c, pp. 0–5, 2013.

[16] J. J. Nedumgatt, K. B. Jayakrishnan, S. Umashankar, and D. Vijayakumar, “Perturb and Observe MPPT Algorithm for Solar PV Systems-Modeling and Simulation,” vol. 19, no. 1.

[17] S. Roy, M. K. Alam, F. Khan, J. Johnson, and J. Flicker, “An Irradiance-Independent, Robust Ground-Fault Detection Scheme for PV Arrays Based on Spread Spectrum Time-Domain Reflectometry (SSTDR),” *IEEE Trans. Power Electron.*, vol. 33, no. 8, pp. 7046–7057, 2018.

[18] J. C. Wiles, “Photovoltaic System Grounding Prepared by Solar America Board for Codes and Standards,” 2012.

[19] M. Bouzguenda, A. Gastli, A. H. Al Badi, and T. Salmi, “Solar photovoltaic inverter requirements for smart grid applications,” *2011 IEEE PES Conf. Innov. Smart Grid Technol. - Middle East, ISGT Middle East 2011*, vol. 2010, pp. 1–5, 2011.

[20] H. A. Sher and K. E. Addoweesh, “Energy for Sustainable Development Micro-inverters — Promising solutions in solar photovoltaics,” *Energy Sustain. Dev.*, vol. 16, no. 4, pp. 389–400, 2012.

[21] “PVSyst PV Simulation Software Package.” [Online]. Available: https://www.pvsyst.com/.

[22] M. Klever, “Design and simulation of a grid-connected PV system in South Africa: technical, commercial and economical aspects,” Norwegian University of Life Sciences, 2018.

[23] “IHS Markit.” [Online]. Available: https://ihsmarkit.com/index.html.

[24] “Bloomberg New Energy Finance.” [Online]. Available: https://about.bnef.com/.

[25] E. Energy, “Guide to Modeling Enphase Microinverter Systems with PVsyst v6,” vol. 6, no. September 2015, pp. 1–7.

[26] V. History, “Application Note-How to Simulate a SolarEdge System in PVsyst Version History,” no. November, pp. 1–13, 2017.

[27] M. K. Alam, F. Khan, J. Johnson, and J. Flicker, “A Comprehensive Review of Catastrophic Faults in Mitigation Techniques,” *IEEE J. Photovoltaics*, vol. 5, no. 3, pp. 982–997, 2015.

[28] S. Harb, M. Kedia, H. Zhang, and R. S. Balog, “Microinverter and string inverter grid-connected photovoltaic system - A comprehensive study,” *Conf. Rec. IEEE Photovolt. Spec. Conf.*, pp. 2885–2890, 2013.

[29] J. Johnson *et al.*, “Differentiating series and parallel photovoltaic arc-faults,”

Conf. Rec. IEEE Photovolt. Spec. Conf., pp. 720–726, 2012.

[30] X. Liang, "Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources," *IEEE Trans. Ind. Appl.*, vol. 53, no. 2, pp. 855–866, 2017.

[31] P. Zhang, W. Li, S. Li, Y. Wang, and W. Xiao, "Reliability assessment of photovoltaic power systems: Review of current status and future perspectives," *Appl. Energy*, vol. 104, pp. 822–833, 2013.

[32] Y. Song, B. Wang, and S. Member, "Survey on Reliability of Power Electronic Systems," vol. 28, no. 1, pp. 591–604, 2013.

[33] S. V. Dhople, A. Davoudi, P. L. Chapman, and A. D. Domínguez-García, "Integrating photovoltaic inverter reliability into energy yield estimation with Markov models," *2010 IEEE 12th Work. Control Model. Power Electron. COMPEL 2010*, 2010.

[34] Y. Wang, X. Zhu, and Y. Wang, "Large-scale photovoltaic power station reliability model and energy-yield sensitivity analysis," *2015 18th Int. Conf. Electr. Mach. Syst. ICEMS 2015*, pp. 1655–1659, 2016.

[35] S. P. Alliance SuNLaMP O and M. Working Group, "Best Practices in Photovoltaic System Operations and Maintenance 2nd Edition NREL/Sandia/Sunspec Alliance SuNLaMP PV O&M Working Group," no. December, 2016.

[36] L. Cristaldi, M. Faifer, M. Lazzaroni, M. M. A. F. Khalil, M. Catelani, and L. Ciani, "Diagnostic architecture: A procedure based on the analysis of the failure causes applied to photovoltaic plants," *Meas. J. Int. Meas. Confed.*, vol. 67, pp. 99–107, 2015.

[37] D. Moser *et al.*, "Technical risks in PV projects," *Sol. Bankability Proj.*, vol. 1, pp. 1–109, 2016.

[38] A. Colli, "Failure mode and effect analysis for photovoltaic systems," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 804–809, 2015.

[39] EPRI, "Budgeting for Solar Pv Plant Operations & Maintenance : Practices," no. December, 2015.

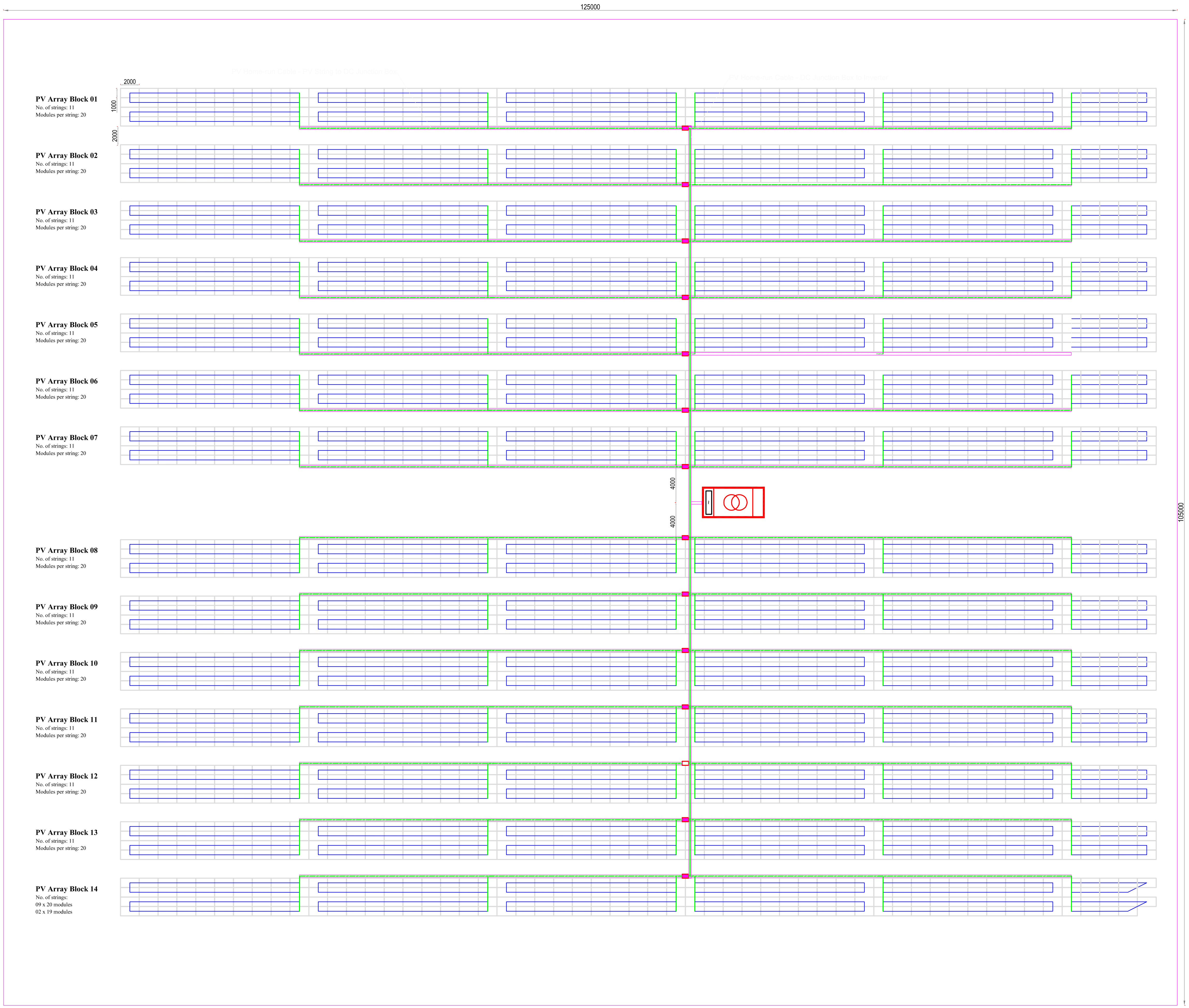
[40] S. J. Castillo, R. S. Balog, and P. Enjeti, "Predicting Capacitor Reliability in a Module-Integrated Photovoltaic Inverter Using Stress Factors from an Environmental Usage Model," 2009.

[41] J. M. Pearce, "A Review of Solar Photovoltaic Levelized Cost of Electricity K. Branker, M. J. M. Pathak, J. M. Pearce," vol. 4482, pp. 4470–4482, 2011.

[42] S. V. S. Kumary, V. A. A. M. T. Oo, G. M. Shafiullah, and A. Stojcevski, "Modelling and power quality analysis of a grid-connected solar PV system," *2014 Australas. Univ. Power Eng. Conf. AUPEC 2014 - Proc.*, no. October, pp. 5–10, 2014.

[43] National Renewable Energy Laboratory, “Advanced Inverter Functions To Support High Levels of Distributed Solar Policy and Regulatory the Need for Advanced,” *NREL Tech. Rep. NREL/TP-5200-57991*, pp. 1–8, 2014.

Annexure A - Design Diagrams: 1 MWp PV Plant Models



PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT, VAVUNIYA

PROJECT DATA	
Number of inveters	1
Type of inverter/power	ABB PVS 800-57-0875 / 875 kW
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) /325Wp
Modules per string	19 x 2 nos., 20 x 152 nos.
DC/AC ratio	1.16
Total number of strings	154
Plant system rating	1MW

TYPE	DESCRIPTION
	PV Module
	PV Module to Module Connection
	PV Home-run Cable
	DC Cable Tray
	DC Junction Box
	Central Inverter + Main LV Panel + Step-up Transformer

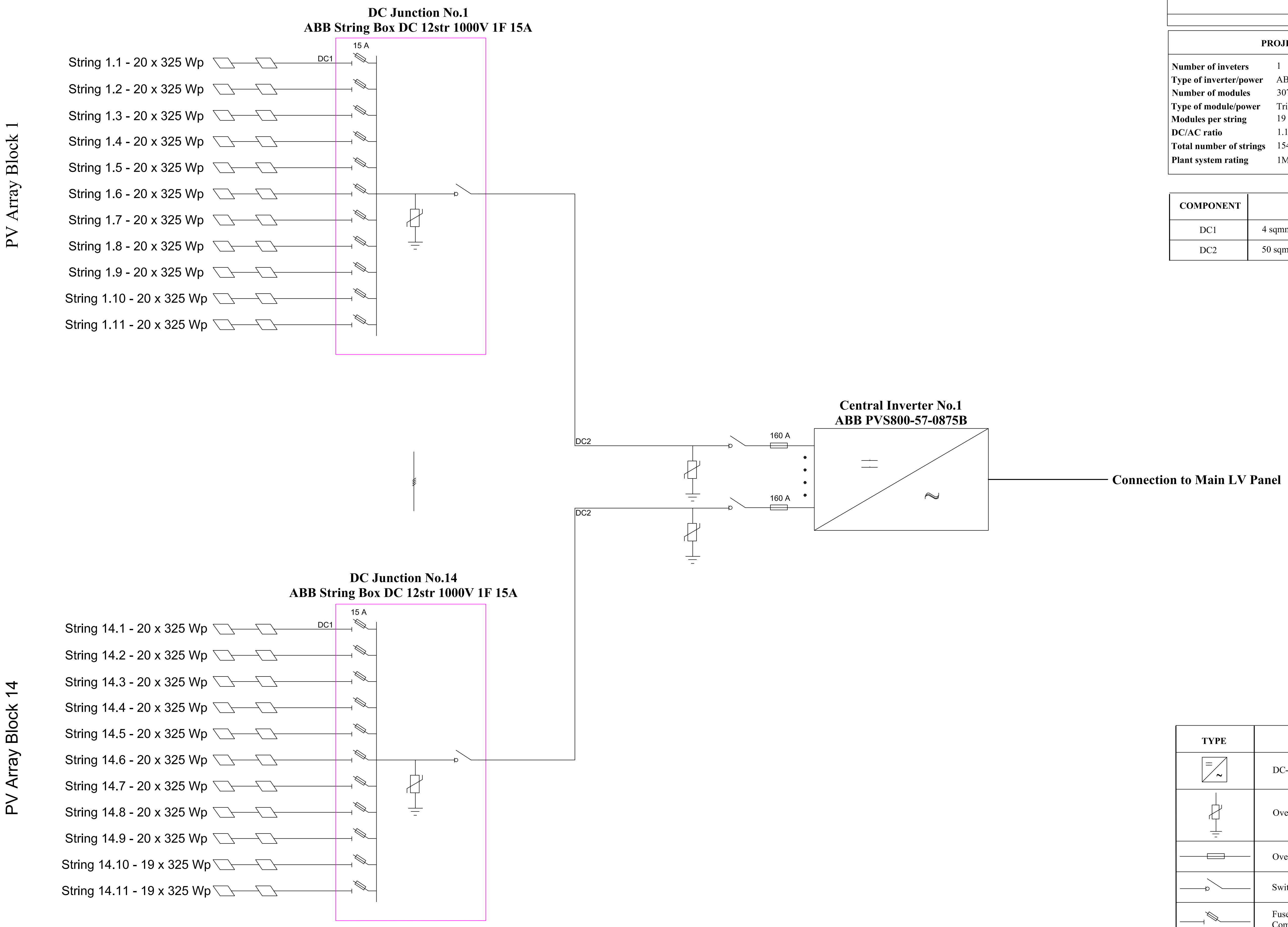
CABLE	DESCRIPTION
From PV string to JB	4 sqmm, 1 core, 1000 V-DC
From JB to Inverter	50 sqmm, 1 core, 1000 V-DC

PRELIMINARY DESIGN

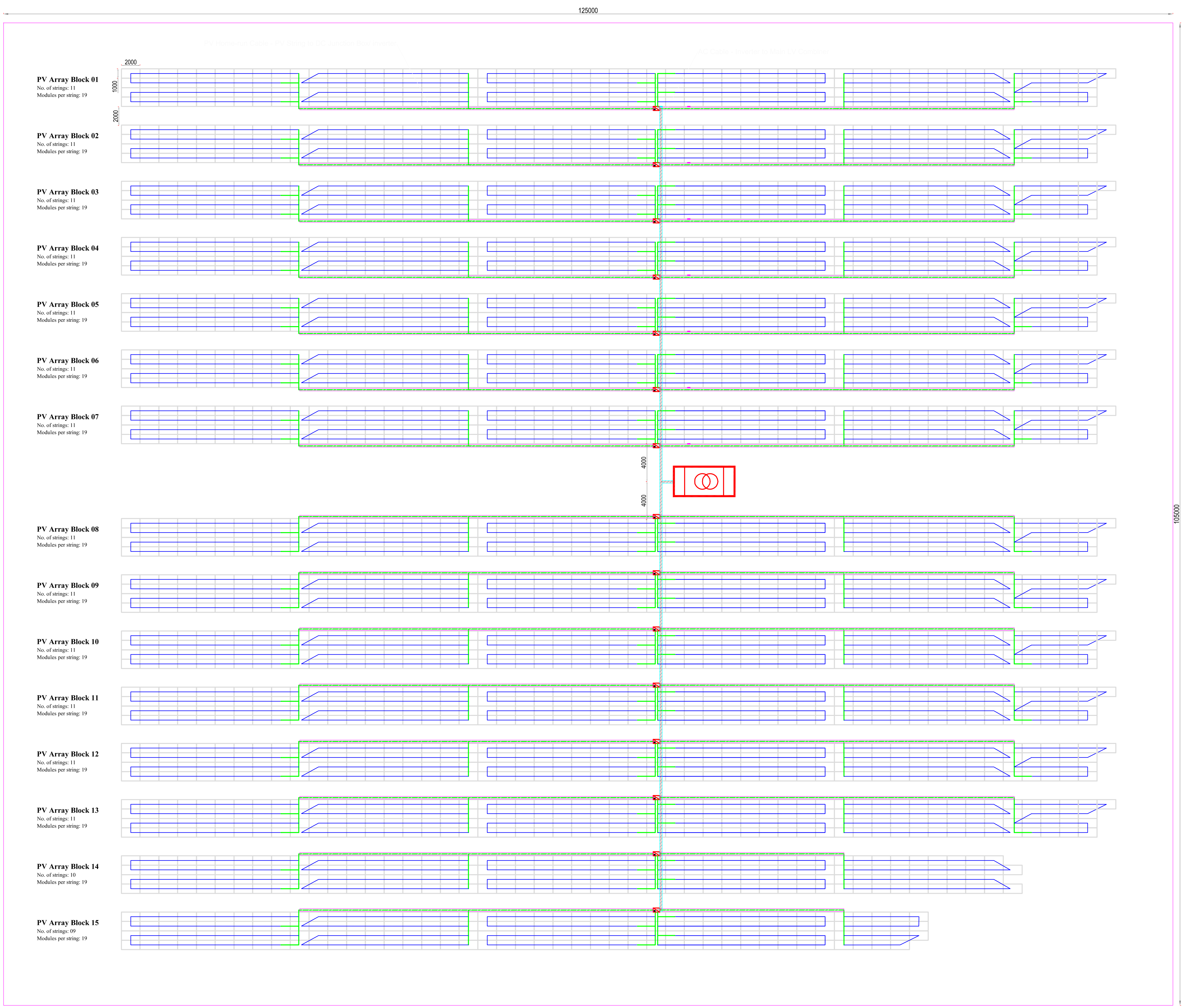
1 MW SOLAR PV PROJECT - VAVUNIYA

PROJECT DATA	
Number of inveters	1
Type of inverter/power	ABB PVS 800-57-0875 / 875 kW
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) / 325Wp
Modules per string	19 x 2 nos., 20 x 152 nos.
DC/AC ratio	1.16
Total number of strings	154
Plant system rating	1MW

COMPONENT	SPECIFICATION
DC1	4 sqmm, 1c, 1000 V-DC
DC2	50 sqmm, 1c, 1000 V-DC



TYPE	DESCRIPTION
	DC-AC Inverter
	Overvoltage Protection - SPD
	Over-current Protection - Fuse
	Switch Disconnector
	Fuse + Switch Disconnector Combination
	PV Module



PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT, VAVUNIYA

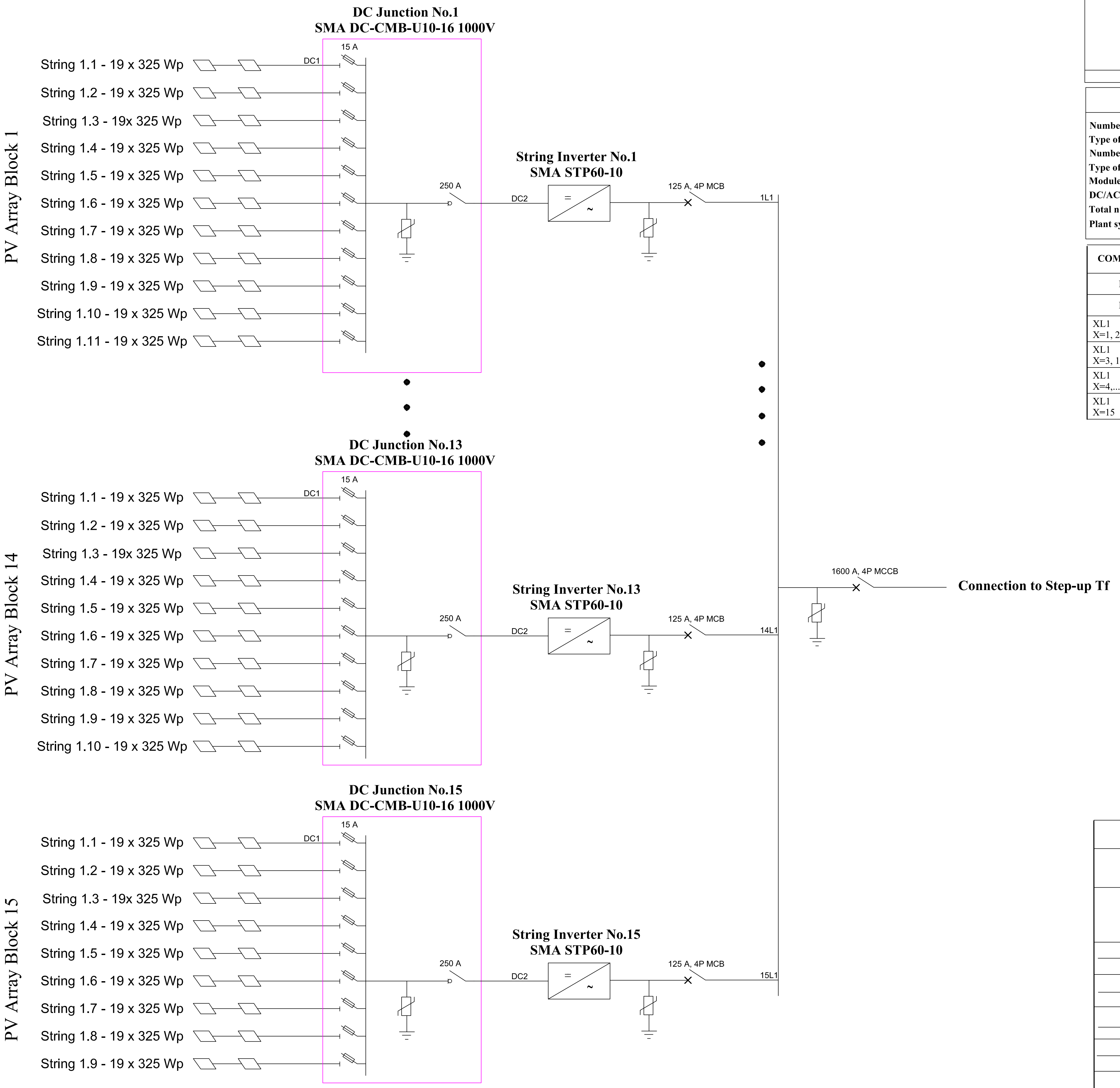
PROJECT DATA	
Number of inveters	15
Type of inverter/power	SMA Sunny Boy STP-60-10 / 60 kW
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) /325Wp
Modules per string	19 x 162 nos.
DC/AC ratio	1.11
Total number of strings	162
Plant system rating	1MW

TYPE	DESCRIPTION
	PV Module
	PV Module to Module Connection
	PV Home-run Cable
	AC Cable
	DC Cable Tray
	AC Cable Tray
	String Inverter
	Main LV Combiner Panel + Step-up Transformer

CABLE	DESCRIPTION
From PV string to Inv	4 sqmm, 1 core, 1000 V-DC
From Inv 1, 2, 13, 14 to Main LV C.	50 sqmm, 4 core, Cu/XLPE/PVC/Steel
From Inv 3, 12 to Main LV C.	35 sqmm, 4 core, Cu/XLPE/PVC/Steel
From Inv 4, 5, 6, 7, 8, 9, 10, 11 to Main LV C.	25 sqmm, 4 core, Cu/XLPE/PVC/Steel
From Inv 15 to Main LV C.	70 sqmm, 4 core, Cu/XLPE/PVC/Steel

PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT - VAVUNIYA



PROJECT DATA

Number of inveters	15
Type of inverter/power	SMA STP-60-10 / 60 kW
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) / 325Wp
Modules per string	19 x 162 nos.
DC/AC ratio	1.11
Total number of strings	162
Plant system rating	1MW

COMPONENT	SPECIFICATION
DC1	4 sqmm, 1c, 1000 V-DC
DC2	6 sqmm, 1c, 1000 V-DC
XL1 X=1, 2, 13, 14	50 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL1 X=3, 12	35 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL1 X=4,......., 11	25 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL1 X=15	70 sqmm, 4c, Cu/ XLPE/ PVC/ Steel

TYPE	DESCRIPTION
	DC-AC Inverter
	Overvoltage Protection - SPD
	Over-current Protection - Fuse
	Switch Disconnector
	Fuse + Switch Disconnector Combination
	PV Module
	Over-current Protection - Circuit Breaker

PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT, VAVUNIYA

PROJECT DATA	
Number of inveters	3078
Type of inverter/power	Enphase S270 / 270 W
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) /325Wp
Modules per branch	18 nos. x 02; 09 nos. x 02; (Center-fed)
DC/AC ratio	1.2
Total branch circuits	87
Plant system rating	1MW

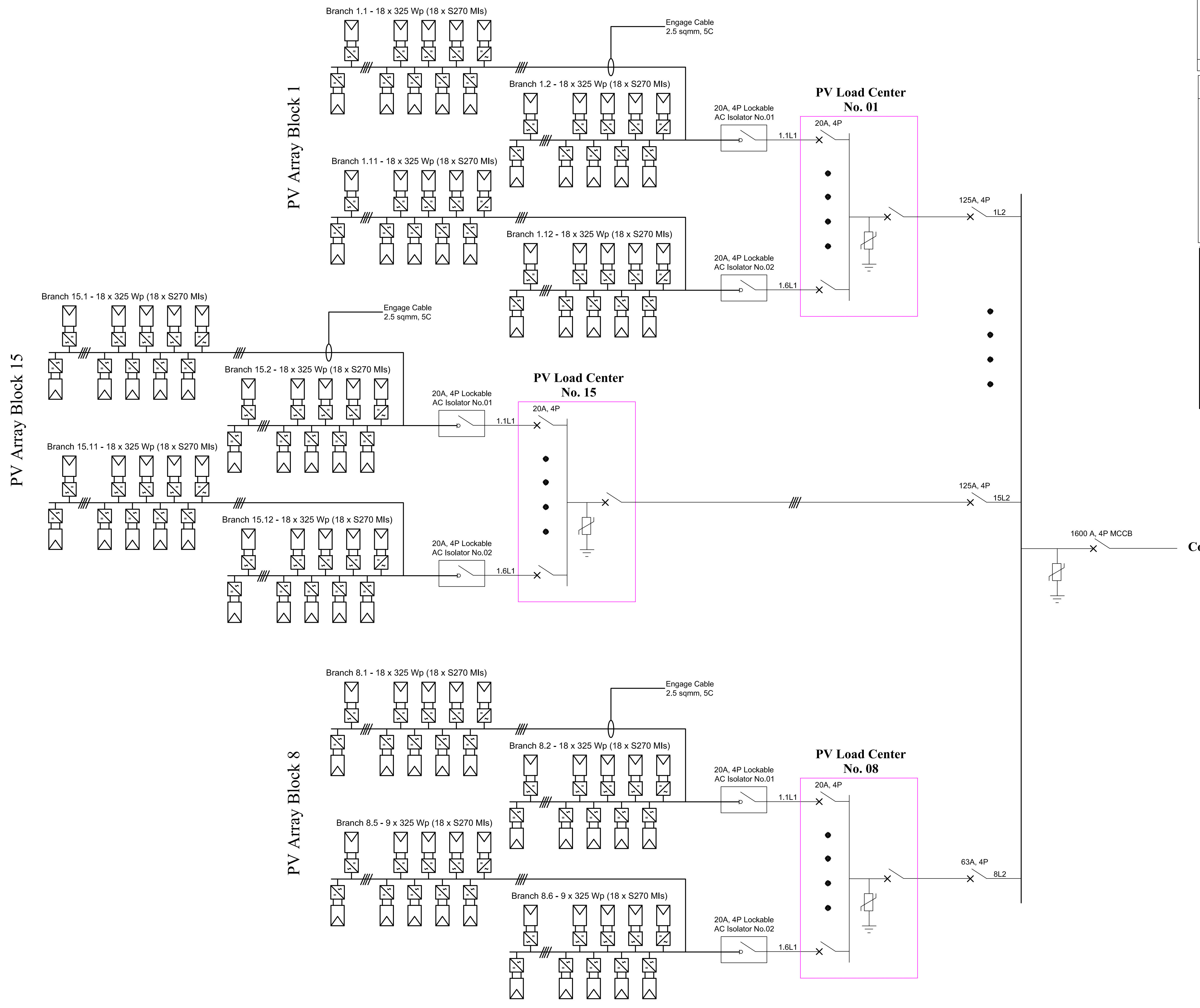
TYPE	DESCRIPTION
	PV Module + Micro Inverter
	Engage Cable (AC Bus)
	AC Home-run Cable
	AC Cable Tray - AC JB to PVL Center
	AC Cable Tray - PVL Center to Main C.
	PV Load Center
	AC Junction Box
	Main LV Panel + Step-up Transformer

CABLE	DESCRIPTION
Engage cable	2.5 sqmm, 5C
From AC JB to PV Load Center	10 sqmm, 4C, Cu/XLPE/PVC 2.5 sqmm, 4C, Cu/XLPE/PVC
From PVLC 7, 9 to Main LV Panel	16 sqmm, 4C, Cu/XLPE/PVC/ Steel
From PVLC 6, 8, 10 to Main LV Panel	25 sqmm, 4C, Cu/XLPE/PVC/ Steel
From PVLC 5, 11 to Main LV Panel	35 sqmm, 4C, Cu/XLPE/PVC/ Steel
From PVLC 4, 12 to Main LV Panel	50 sqmm, 4C, Cu/XLPE/PVC/ Steel
From PVLC 1, 2, 3, 13, 14, 15 to Main LV Panel	70 sqmm, 4C, Cu/XLPE/PVC/ Steel

PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT - VAVUNIYA

CORDINATES 80°36 30.775 E 7 34 19.834 N



PROJECT DATA

Number of inveters	3078
Type of inverter/power	Enphase S270 / 270 W
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) /325Wp
Modules per branch	18 nos. x 02; 09 nos. x 02; (Center-fed)
DC/AC ratio	1.2
Total branch circuits	87
Plant system rating	1MW

COMPONENT	SPECIFICATION
X.YL1 Y=1.1, 1.2	10 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
X.YL1 Y=1.3-1.6	2.5 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL2 X=1, 2, 13, 14	50 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL2 X=3, 12	35 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL2 X=4,......., 11	25 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL2 X=15	70 sqmm, 4c, Cu/ XLPE/ PVC/ Steel

TYPE	DESCRIPTION
	DC-AC Inverter
	DC Conditioning Unit (DC-CU)
	Overvoltage Protection - SPD
	Over-current Protection - Fuse
	Switch Disconnector
	Fuse + Switch Disconnector Combination
	PV Module
	Over-current Protection - Circuit Breaker

PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT, VAVUNIYA

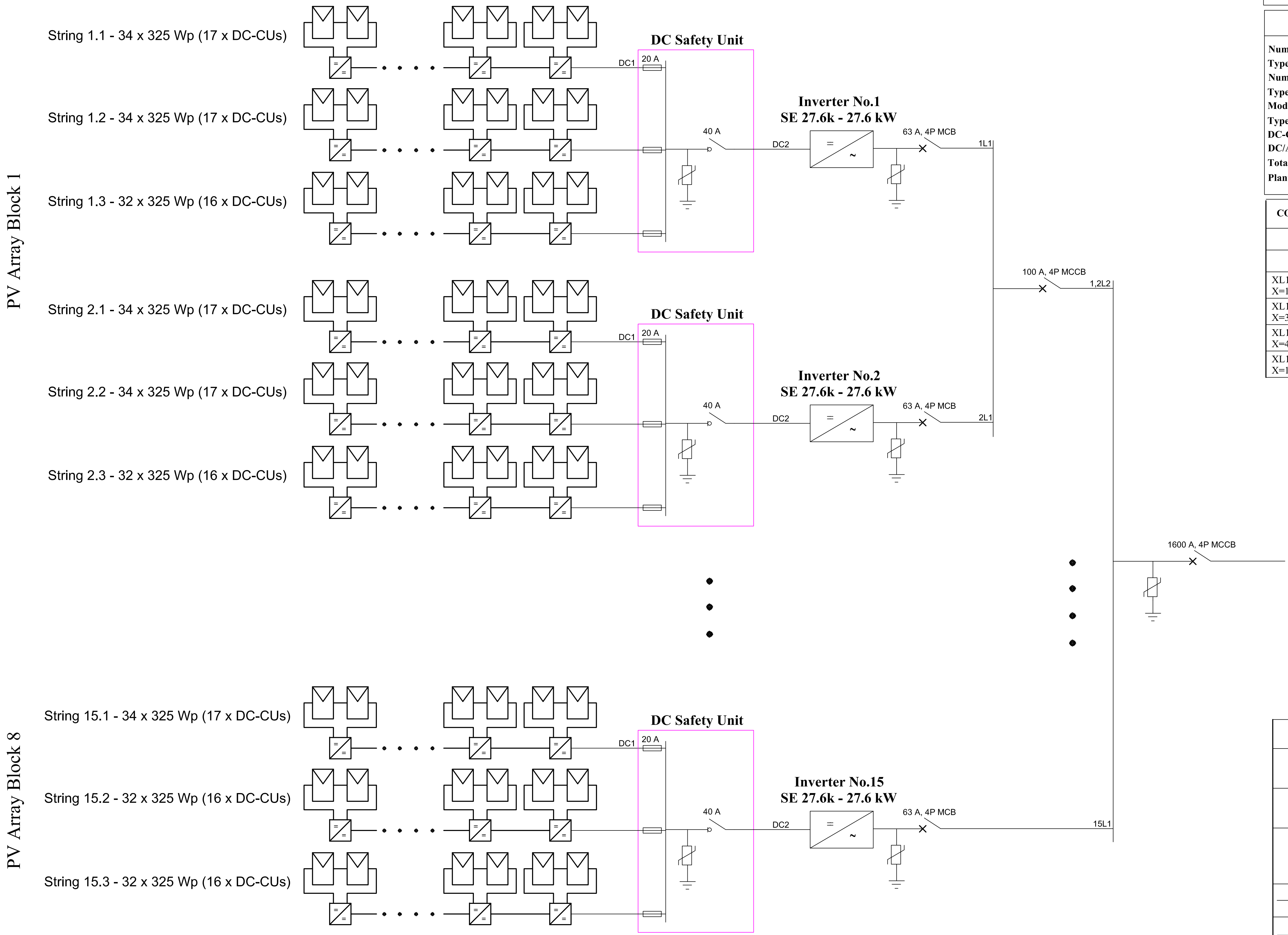
PROJECT DATA	
Number of inveters	31
Type of inverter/power	SolarEdge SE27.6k / 27.6 kW
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) /325Wp
Modules per string	34, 34, 32; 34, 32, 32
Type of DC-CU	SolarEdge P700 /700Wp
DC-CUs per string	17, 17, 16; 17, 16, 16
DC/AC ratio	1.16
Total number of strings	93
Plant system rating	1MW

TYPE	DESCRIPTION
	PV Module
	PV Module to Module Connection
	PV Home-run Cable
	AC Cable
	DC Cable Tray
	AC Cable Tray
	String Inverter
	Main LV Combiner Panel + Step-up Transformer

CABLE	DESCRIPTION
From PV string to Inv	4 sqmm, 1 core, 1000 V-DC
From Block 1, 2, 14, 15 to Main LV C.	50 sqmm, 4 core, Cu/XLPE/PVC/Steel
From Block 3, 8, 13 to Main LV C.	35 sqmm, 4 core, Cu/XLPE/PVC/Steel
From Block 4, 5, 6, 7, 9, 10, 11, 12 to Main LV C.	25 sqmm, 4 core, Cu/XLPE/PVC/Steel
From Block 16 to Main LV C.	70 sqmm, 4 core, Cu/XLPE/PVC/Steel

PRELIMINARY DESIGN

1 MW SOLAR PV PROJECT - VAVUNIYA



PROJECT DATA

Number of inveters	31
Type of inverter/power	SolarEdge SE27.6k / 27.6 kW
Number of modules	3078
Type of module/power	Trina Solar TSM-325DD14A(II) / 325Wp
Modules per string	34,34,32; 34,32,32
Type of DC-CU	SolarEdge P700 / 700Wp
DC-CUs per string	17,17,16; 17,16,16
DC/AC ratio	1.16
Total number of strings	93
Plant system rating	1MW

COMPONENT	SPECIFICATION
DC1	4 sqmm, 1c, 1000 V-DC
DC2	6 sqmm, 1c, 1000 V-DC
XL1 X=1, 2, 14, 15	50 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL1 X=3, 8, 13	35 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL1 X=4,........, 12	25 sqmm, 4c, Cu/ XLPE/ PVC/ Steel
XL1 X=16	70 sqmm, 4c, Cu/ XLPE/ PVC/ Steel

TYPE	DESCRIPTION
	DC-AC Inverter
	DC Conditioning Unit (DC-CU)
	Overvoltage Protection - SPD
	Over-current Protection - Fuse
	Switch Disconnector
	Fuse + Switch Disconnector Combination
	PV Module
	Over-current Protection - Circuit Breaker

Annexure B – CPN Calculation for 1 MWp PV Plant Models

Annexure B: CPN Calculation for 1 MWp PV Plant Models

A. 1 MWp Central Inverter Model

Component	Failure Mode	Detection Mean	Time to detect (h)	Cost of detect(LKR)	Time to repair/ substitute (h)	Labor Requirement to fix (Man Days)	Cost of labor to fix (LKR)	Cost of transport	Performance Loss (1 = Total loss)	Multiplier	Number of failures (In reference database)	Number of total components (In reference database)	Component Failure Rate (In reference database)	Sample Time Frame (In reference database)	Number of components in 1 MW model	Occurance	Specific yield per component (kWh/anum)	Cost of downtime (LKR/anum)	Cost of fixing (LKR/anum)	CPN Value (LKR/anum)
A Module	Hot spot	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	13311	2058721	0.006465665	2.7	3078	0.734228219	459.3892138	6,196.14	58,966.86	65,163.00
	Delamination	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	16045	2058721	0.007793674	2.7	3078	0.150747603	459.3892138	1,272.16	71,078.31	72,350.46
	Glass breakage	Monthly visual inspection	720	0	24	8	8000	0	0.1	20	43851	2058721	0.021300118	2.7	3078	4.119933407	459.3892138	34,768.04	194,257.08	229,025.11
	Soiling losses	Quarterly manual electrical inspection	2160	0	120	0	0	0	0.05	20	158578	2058721	0.077027436	2.7	3078	22.82892948	459.3892138	192,652.88	-	192,652.88
	Shading losses	Quarterly manual electrical inspection	2160	0	48	2	2000	0	0.1	20	113982	2058721	0.055365443	2.7	3078	31.78140563	459.3892138	268,202.64	126,233.21	394,435.85
	Snail track	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	28975	2058721	0.014074272	2.7	3078	0.272228844	459.3892138	2,297.33	128,357.36	130,654.70
	Cell cracks	Quarterly manual electrical inspection	2160	0	24	8	8000	0	0.01	20	921	2058721	0.000447365	2.7	3078	0.025400954	459.3892138	214.36	4,079.97	4,294.33
	PID	Quarterly manual electrical inspection	2160	0	24	8	8000	0	0.1	20	33619	2058721	0.016330042	2.7	3078	9.272037603	459.3892138	78,246.54	148,929.98	227,176.52
	Failure of bypass diode and junction box	Quarterly manual electrical inspection	2160	0	24	8	8000	0	0.33	20	6533	2058721	0.003173329	2.7	3078	5.945891653	459.3892138	50,177.26	28,940.76	79,118.02
	Overheating junction box	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	6714	2058721	0.003261248	2.7	3078	0.370340941	459.3892138	3,125.30	29,742.58	32,867.88
	Broken module	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	5555	2058721	0.002698277	2.7	3078	0.336715462	459.3892138	2,841.54	24,608.29	27,449.82
	Corrosion in the junction box	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	354	2058721	0.000171951	2.7	3078	0.003325937	459.3892138	28.07	1,568.20	1,596.26
	Theft or vandalism	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	431	2058721	0.000209353	2.7	3078	0.026124998	459.3892138	220.47	1,909.30	2,129.77
B Inverter	Inverter failure	Real time data monitoring (Inverter analytics)	24	0	168	224	224000	0	1	1	-	-	0.2	1	1	0.004378563	1414000	113,733.97	44,800.00	158,533.97
C DC Cabling	UV aging	Quarterly manual electrical inspection	2160	0	24	24	24000	0	0.01	1	2967	246084	0.012056859	2.7	336	0.003736481	9181.818182	630.23	36,009.82	36,640.05
	Theft of cables	Monthly visual inspection	720	0	24	24	24000	0	1	1	3	246084	1.2191E-05	2.7	336	0.000128702	9181.818182	21.71	36.41	58.12
	Damaged cables	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	9006	246084	0.036597259	2.7	336	0.024926754	9181.818182	4,204.40	109,303.81	113,508.21
	Damaged connectors	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	5333	246084	0.021671462	2.7	336	0.014760646	9181.818182	2,489.68	64,725.43	67,215.11
D DC Combiner Boxes	Switch disconector/ breaker failure	Real time data monitoring (Inverter analytics)	24	0	24	8	8000	0	1	1			0.0014	1	14	0.000107275	101000	199.03	156.80	355.83
															Total CPN Value (LKR/ Annum)					1,835,225.90

B. 1 MWp String Inverter Model

Component	Failure Mode	Detection Mean	Time to detect (h)	Cost of detect(LKR)	Time to repair/ substitute (h)	Labor Requirement to fix (Man Days)	Cost of labor to fix (LKR)	Cost of transport	Performance Loss (1 = Total loss)	Multiplier	Number of failures (In reference database)	Number of total components (In reference database)	Component Failure Rate (In reference database)	Sample Time Frame (In reference database)	Number of components in 1 MW model	Occurance	Specific yield per component (kWh/anum)	Cost of downtime (LKR/anum)	Cost of fixing (LKR/anum)	CPN Value (LKR/anum)
A Module	Hot spot	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	13311	2058721	0.006465665	2.7	3078	0.734228219	460.6887589	6,213.67	58,966.86	65180.52853
	Delamination	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	16045	2058721	0.007793674	2.7	3078	0.150747603	460.6887589	1,275.75	71,078.31	72354.06015
	Glass breakage	Monthly visual inspection	720	0	24	8	8000	0	0.1	20	43851	2058721	0.021300118	2.7	3078	4.119933407	460.6887589	34,866.39	194,257.08	229123.4639
	Soiling losses	Quarterly manual electrical inspection	2160	0	120	0	0	0	0.05	20	158578	2058721	0.077027436	2.7	3078	22.82892948	460.6887589	193,197.86	-	193197.863
	Shading losses	Quarterly manual electrical inspection	2160	0	48	2	2000	0	0.1	20	113982	2058721	0.055365443	2.7	3078	31.78140563	460.6887589	268,961.35	126,233.21	395194.5579
	Snail track	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	28975	2058721	0.014074272	2.7	3078	0.272228844	460.6887589	2,303.83	128,357.36	130661.1962
	Cell cracks	Quarterly manual electrical inspection	2160	0	24	8	8000	0	0.01	20	921	2058721	0.000447365	2.7	3078	0.025400954	460.6887589	214.96	4,079.97	4294.934564
	PID	Quarterly manual electrical inspection	2160	0	24	8	8000	0	0.1	20	33619	2058721	0.016330042	2.7	3078	9.272037603	460.6887589	78,467.89	148,929.98	227397.8679
	Failure of bypass diode and junction box	Quarterly manual electrical inspection	2160	0	24	8	8000	0	0.33	20	6533	2058721	0.003173329	2.7	3078	5.945891653	460.6887589	50,319.20	28,940.76	79259.96873
	Overheating junction box	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	6714	2058721	0.003261248	2.7	3078	0.370340941	460.6887589	3,134.14	29,742.58	32876.72365
	Broken module	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	5555	2058721	0.002698277	2.7	3078	0.336715462	460.6887589	2,849.57	24,608.29	27457.86164
	Corrosion in the junction box	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	354	2058721	0.000171951	2.7	3078	0.003325937	460.6887589	28.15	1,568.20	1596.343864
	Theft or vandalism	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	431	2058721	0.000209353	2.7	3078	0.026124998	460.6887589	221.09	1,909.30	2130.393945
B Inverter	Inverter failure	Real time data monitoring (Inverter analytics)	24	0	24	16	16000	0	1	1	-	-	0.2	1	15	0.016419612	94533.33333	28,513.93	48,000.00	76513.92657
C DC Cabling	UV aging	Quarterly manual electrical inspection	2160	0	24	24	24000	0	0.01	1	2967	246084	0.012056859	2.7	324	0.003603035	8753.08642	579.35	34,723.75	35303.09995
	Theft of cables	Monthly visual inspection	720	0	24	24	24000	0	1	1	3	246084	1.2191E-05	2.7	324	0.000124106	8753.08642	19.96	35.11	55.06547276
	Damaged cables	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	9006	246084	0.036597259	2.7	324	0.024036512	8753.08642	3,864.93	105,400.11	109265.039
	Damaged connectors	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	5333	246084	0.021671462	2.7	324	0.01423348	8753.08642	2,288.66	62,413.81	64702.47092
D DC Combiner Boxes	Switch disconector/ breaker failure	Real time data monitoring (Inverter analytics)	24	0	24	8	8000	0	1	1			0.0014	1	15	0.000114937	94533.33333	199.60	168.00	367.597486
															Total CPN Value (LKR/ Annum)					1,746,932.96

C. 1 MWp Micro Inverter Model

Component	Failure Mode	Detection Mean	Time to detect (h)	Cost of detect(LKR)	Time to repair/ substitute (h)	Labor Requirement to fix (Man Days)	Cost of labor to fix (LKR)	Cost of transport	Performance Loss (1 = Total loss)	Multiplier	Number of failures (In reference database)	Number of total components (In reference database)	Component Failure Rate (In reference database)	Sample Time Frame (In reference database)	Number of components in 1 MW model	Occurance	Specific yield per component (kWh/anum)	Cost of downtime (LKR/anum)	Cost of fixing (LKR/anum)	CPN Value (LKR/anum)
A Module	Hot spot	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	13311	2058721	0.006465665	2.7	3078	0.734228219	461.3385315	6,222.43	58,966.86	65189.29251
	Delamination	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	16045	2058721	0.007793674	2.7	3078	0.150747603	461.3385315	1,277.55	71,078.31	72355.85952
	Glass breakage	Monthly visual inspection	720	0	24	8	8000	0	0.1	20	43851	2058721	0.021300118	2.7	3078	4.119933407	461.3385315	34,915.57	194,257.08	229172.6407
	Soiling losses	Real time data monitoring and analytics	24	0	672	0	0	0	0.05	20	158578	2058721	0.077027436	2.7	3078	6.968831105	461.3385315	59,059.37	-	59059.37197
	Shading losses	Real time data monitoring and analytics	24	0	48	2	2000	0	0.1	20	113982	2058721	0.055365443	2.7	3078	1.036350183	461.3385315	8,782.85	126,233.21	135016.0588
	Snail track	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	28975	2058721	0.014074272	2.7	3078	0.272228844	461.3385315	2,307.08	128,357.36	130664.4456
	Cell cracks	Real time data monitoring and analytics	24	0	24	8	8000	0	0.01	20	921	2058721	0.000447365	2.7	3078	0.000558263	461.3385315	4.73	4,079.97	4084.701198
	PID	Real time data monitoring and analytics	720	0	24	8	8000	0	0.1	20	33619	2058721	0.016330042	2.7	3078	3.158606217	461.3385315	26,768.52	148,929.98	175698.5019
	Failure of bypass diode and junction box	Real time data monitoring and analytics	24	0	24	8	8000	0	0.33	20	6533	2058721	0.003173329	2.7	3078	0.130678937	461.3385315	1,107.48	28,940.76	30048.24108
	Overheating junction box	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	6714	2058721	0.003261248	2.7	3078	0.370340941	461.3385315	3,138.56	29,742.58	32881.14416
	Broken module	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	5555	2058721	0.002698277	2.7	3078	0.336715462	461.3385315	2,853.59	24,608.29	27461.88078
	Corrosion in the junction box	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	354	2058721	0.000171951	2.7	3078	0.003325937	461.3385315	28.19	1,568.20	1596.383563
	Theft or vandalism	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	431	2058721	0.000209353	2.7	3078	0.026124998	461.3385315	221.40	1,909.30	2130.705782
B Inverter	Inverter failure	Real time data monitoring (Inverter analytics)	24	0	2	0.25	250	0	1	1	-	-	0.04	1	3078	0.365007982	461.3385315	3,093.37	30,780.00	33873.36556
C DC Cabling	UV aging	Quarterly manual electrical inspection	2160	0	24	24	24000	0	0.01	1	2967	246084	0.012056859	2.7	0	0	8765.432099	-	-	0
	Theft of cables	Monthly visual inspection	720	0	24	24	24000	0	1	1	3	246084	1.2191E-05	2.7	0	0	8765.432099	-	-	0
	Damaged cables	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	9006	246084	0.036597259	2.7	0	0	8765.432099	-	-	0
	Damaged connectors	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	5333	246084	0.021671462	2.7	0	0	8765.432099	-	-	0
D DC Combiner Boxes	Switch disconector/ breaker failure	Real time data monitoring (Inverter analytics)	24	0	24	8	8000	0	1	1			0.0014	1	0	0	94666.66667	-	-	0
															Total CPN Value (LKR/ Annum)					**999,232.59**

D. 1 MWp DCCU + String Inverter Model

Component	Failure Mode	Detection Mean	Time to detect (h)	Cost of detect(LKR)	Time to repair/ substitute (h)	Labor Requirement to fix (Man Days)	Cost of labor to fix (LKR)	Cost of transport	Performance Loss (1 = Total loss)	Multiplier	Number of failures (In reference database)	Number of total components (In reference database)	Component Failure Rate (In reference database)	Sample Time Frame (In reference database)	Number of components in 1 MW model	Occurance	Specific yield per component (kWh/anum)	Cost of downtime (LKR/anum)	Cost of fixing (LKR/anum)	CPN Value (LKR/anum)
A Module	Hot spot	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	13311	2058721	0.006465665	2.7	3078	0.734228219	463.9376218	6,257.49	58,966.86	65224.34845
	Delamination	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	16045	2058721	0.007793674	2.7	3078	0.150747603	463.9376218	1,284.75	71,078.31	72363.05701
	Glass breakage	Monthly visual inspection	720	0	24	8	8000	0	0.1	20	43851	2058721	0.021300118	2.7	3078	4.119933407	463.9376218	35,112.27	194,257.08	229369.3481
	Soiling losses	Real time data monitoring and analytics	24	0	672	0	0	0	0.05	20	158578	2058721	0.077027436	2.7	3078	6.968831105	463.9376218	59,392.10	-	59392.10082
	Shading losses	Real time data monitoring and analytics	24	0	48	2	2000	0	0.1	20	113982	2058721	0.055365443	2.7	3078	1.036350183	463.9376218	8,832.33	126,233.21	135065.5396
	Snail track	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	28975	2058721	0.014074272	2.7	3078	0.272228844	463.9376218	2,320.08	128,357.36	130677.4432
	Cell cracks	Real time data monitoring and analytics	24	0	24	8	8000	0	0.01	20	921	2058721	0.000447365	2.7	3078	0.000558263	463.9376218	4.76	4,079.97	4084.727853
	PID	Real time data monitoring and analytics	720	0	24	8	8000	0	0.1	20	33619	2058721	0.016330042	2.7	3078	3.158606217	463.9376218	26,919.33	148,929.98	175849.3105
	Failure of bypass diode and junction box	Real time data monitoring and analytics	24	0	24	8	8000	0	0.33	20	6533	2058721	0.003173329	2.7	3078	0.130678937	463.9376218	1,113.72	28,940.76	30054.48038
	Overheating junction box	Quarterly aerial thermal imaging	2160	0	24	8	8000	0	0.02	20	6714	2058721	0.003261248	2.7	3078	0.370340941	463.9376218	3,156.24	29,742.58	32898.8262
	Broken module	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	5555	2058721	0.002698277	2.7	3078	0.336715462	463.9376218	2,869.67	24,608.29	27477.95736
	Corrosion in the junction box	Monthly visual inspection	720	0	24	8	8000	0	0.01	20	354	2058721	0.000171951	2.7	3078	0.003325937	463.9376218	28.35	1,568.20	1596.542361
	Theft or vandalism	Real time data monitoring (string shutdown)	24	0	24	8	8000	0	1	20	431	2058721	0.000209353	2.7	3078	0.026124998	463.9376218	222.65	1,909.30	2131.953127
B Inverter	Inverter failure	Real time data monitoring (Inverter analytics)	24	0	24	16	16000	0	1	1	-	-	0.083333333	1	33	0.015051311	43272.72727	11,964.59	44,000.00	55964.58837
	Optimizer failure	Real time data monitoring (Inverter analytics)	24	0	2	0.25	250	0	1	2			0.01	1	1539	0.091251995	927.8752437	1,555.40	3,847.50	5402.896488
C DC Cabling	UV aging	Quarterly manual electrical inspection	2160	0	24	24	24000	0	0.01	1	2967	246084	0.012056859	2.7	186	0.002068409	7677.419355	291.72	19,934.01	20225.72265
	Theft of cables	Monthly visual inspection	720	0	24	24	24000	0	1	1	3	246084	1.2191E-05	2.7	186	7.1246E-05	7677.419355	10.05	20.16	30.20383932
	Damaged cables	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	9006	246084	0.036597259	2.7	186	0.013798739	7677.419355	1,946.09	60,507.47	62453.56297
	Damaged connectors	Real time data monitoring (Inverter analytics)	24	0	24	24	24000	0	1	1	5333	246084	0.021671462	2.7	186	0.008171072	7677.419355	1,152.40	35,830.15	36982.55067
D DC Combiner Boxes	Switch disconector/ breaker failure	Real time data monitoring (Inverter analytics)	24	0	24	8	8000	0	1	1			0.0014	1	33	0.000252862	42969.69697	199.60	369.60	569.197486
															Total CPN Value (LKR/ Annum)					**1,082,590.01**

Annexure C – Manufacturer’s Product Warranty Documentation

The SolarEdge inverter warranty is extendable to 20 or 25 years, depending on inverter model:

20 Years Warranty Extension	
Product	**USD**
HD-Wave 1Ø inverter < 4 kW	144
HD-Wave 1Ø inverter 4-6 kW	188
HD-Wave 1Ø inverter 8-10 kW	311
1Ø inverter 7.3 Kw	320
1Ø StorEdge inverter with Backup	692
3Ø inverter <15 kW	399
3Ø inverter ≥ 15 kW, <25 kW	414
3Ø inverter 25-27.6 kW with DCD	450
3Ø inverter with synergy technology 50-66.6kW	970
3Ø inverter with synergy technology 82.8-100kW	1,455

25 Years Warranty Extension	
Product	**USD**
HD-Wave 1Ø inverter < 4 kW	229
HD-Wave 1Ø inverter 4-6 kW	301
HD-Wave 1Ø inverter 8-10 kW	497
1Ø inverter 7.3 Kw	512
1Ø StorEdge inverter with Backup	1,109
3Ø inverter <15 kW	649

The inverter warranty extension applies to the inverter only and does not apply to any built-in communication accessories.

For more information please contact SolarEdge support at info@solaredge.com.

ORDER FORM
SMA WARRANTY EXTENSION

Warranty Extensions for SMA America Sunny Boy Products

Order Conditions:
Extended warranties can be purchased any time during the SMA America factory warranty period. If the inverter already has an extended warranty, it can be extended again to a maximum of 20 years. Warranty extensions are not available for Windy Boy, Sunny Island, or Legacy Sunny Boy models. SMA reserves the right to alter these prices.

Instructions:

Distributors –

Please refer to the SMA Price Lists and submit your Purchase Order with this completed form to:
US-Warranty@SMA-America.com

Installers and/or Homeowners –

Please contact US-Warranty@SMA-America.com for your quote on extended warranties.

Please mail the completed form with your check to:
6020 West Oaks Blvd. Suite 300
Rocklin, CA 95765
Attention: Warranty Department
US-Warranty@SMA-America.com

Payment Methods:

Enclosed is my check # __________ made payable to SMA America, LLC for the warranty purchase.
OR
Here is my credit card information for the warranty purchase.

☐ Visa ☐ Master Card ☐ American Express

Credit Card Number: CVV:___________
Expiration Date:
Name as it appears on card:
Credit card billing address:
Zip code:
Amount: *to be provided by SMA America* (US-Warranty@SMA-America.com)

ORDER FORM

SMA WARRANTY EXTENSION

Extended Warranty:

Extends the full SMA America factory warranty, does not include a service call rebate. Please see SMA America's factory warranty document for detailed terms and conditions.

Inverter Size	Extended Warranty		Extended Warranty	
W	**GV5US-D/I/E**		**GV10US-D/I/E**	
	5 year extension	**Quantity**	**10 year extension**	**Quantity**
Micro Inverter SB240	$18.00		$30.00	
MG-XT1E-US-10	$42.00		$60.00	
MG-XT2E-US-10 or MG-XT2S-US-10	$84.00		$120.00	
MG-XT3S-US-10	$126.00		$180.00	
MG-XT4S-US-10	$168.00		$240.00	

*Prices listed above are in USD.

Extended Warranty Plus:

Extends the full SMA America factory warranty, including a service call rebate. Please see SMA America's factory warranty document for detailed terms and conditions.

Inverter Size	Extended Warranty Plus		Extended Warranty Plus		Extended Warranty Plus	
kW	**GV5US-D/I/E PLUS**		**GV10US-D/I/E PLUS**		**GV15US-D/I/E PLUS**	
	5 year extension	**Quantity**	**10 year extension**	**Quantity**	**15 year extension**	**Quantity**
2/2.5/3kW	$200.00		$400.00		Not available	
3.8kW	$253.33		$506.67		Not available	
4/5kW	$266.67		$533.33		Not available	
6kW	$320.00		$640.00		Not available	
7kW	$373.33		$746.67		Not available	
7.7/8kW	$426.67		$853.33		Not available	
9kW	$480.00		$960.00		Not available	
10kW	$533.33		$1066.67		Not available	
11kW	$586.67		$1173.33		Not available	
12kW	$640.00		$1280.00		Not available	
15kW	$700.00		$1400.00		Not available	
20/24kW	$800.00		$1600.00		Not available	
60kW**	$ 1120.00		$2240.00		$3360.00	

*Prices listed above are in USD.

** Standard 5 year warranty.

SMA Solar Technology America, LLC
6020 West Oaks Blvd, Ste 300
Rockiln, CA 95765
Tel. +1 916 625 0870
Tel. +1 877-MY SMA TECH

ORDER FORM

SMA WARRANTY EXTENSION

Owner's Information
Company Name/Legal Name:
Last Name, First Name:
Address:
City/State/Zip Code:
Country:
Telephone Number:
Email Address:

SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	
SMA Model Part Number		Serial Number	

Signature	Date when the device was purchased

(Please attach a copy of the invoice)

☐ Yes, I would like a warranty certificate sent to the address above.

OR

☐ No thank you, an order confirmation will suffice, will be sent to the address above.

Via: ☐ Email OR ☐ US Mail

SMA Solar Technology America, LLC
6020 West Oaks Blvd, Ste 300
Rockling, CA 95765
Tel. +1 916 625 0870
Tel. +1 877-MY SMA TECH

ABB string inverters
Single and three-phase warranty programs
STANDARD, ASSURE and PROFIL

STANDARD warranty

The STANDARD warranty level is available for any ABB inverter worldwide.
The customer is responsible for the replacement for any unit in need of repair under the warranty.
Customer takes the shipment costs to the next logistic Hub defined by ABB.
To shorten the outage time during repair the customer can purchase spare parts for quick exchange on site.

The STANDARD warranty agreement for ABB string inverters includes:

- Five (5) year parts warranty depending on product and market
- Repaired units / parts are typically ready to ship within ten (10) days at ABB repair center after reception
- The repair and material is covered during the warranty period
- Technical hotline for support and troubleshooting
- Accessibility to global field service and partner network for on-site troubleshooting (fees apply)

ASSURE warranty

In addition to the STANDARD warranty benefits, the ASSURE warranty level provides customers in some installation countries with advance spare parts delivery. ABB will provide within their sole discretion new or completely reconditioned inverters.

The ASSURE warranty also provides the customer with re-installation support through either (decision by ABB):

- Payment of a fixed reimbursement amount paid to the installer based on geographic location and product
- Dispatching an ABB certified technician to perform repairs or replacement of units / parts

Under the ASSURE warranty, customers receive the needed parts in advance, allowing single site visit for swap.
Access to the technical hotline for support and troubleshooting, the security of replacement parts and labour is available at any time a warranty need arises

The ASSURE warranty agreement from ABB includes all the attributes of the STANDARD warranty agreement with the added benefits of:

- Advanced material replacement: typically ready to ship within 3 working days after ABB´s authorization to replace defect material
- Dispatching, labour and material freight costs are included

PROFIL additional services

Additional services to meet customer specific needs not covered by the STANDARD and ASSURE warranty levels are offered complementary under customer / site specific service contracts upon request, like:

- Rapid on-site response time
- Technical availability 97%, 98% and 99%
- Preventive maintenance

For further information about the additional services and service contracts please contact your local sales agent.

Service levels ABB string inverters: PVI, UNO, TRIO, PRO

Services	1	2	3
Type	Product warranty		Additional services Available upon request A service contract is required
	STANDARD warranty	**ASSURE warranty**	**PROFIL contract Response time uptime, etc.**
Standard duration (years)	5	5	1
Extended duration (years)	10	10	Contract duration to be agreed
Technical availability (%)	-	-	97, 98, 99
Preventive maintenance	-	-	According to product manual
Corrective action	Included	Included	-
Ready to ship Typical availability of material but allow additional days to account for weekends and holidays	10 days	3 days	On a case by case basis
Remote support	Included	Included	Included
Where available	Worldwide	Ask your local ABB Representative	Available upon request

The factory reserves the right to decline providing extended warranty would the inverter not be installed in accordance with the factory installation guidelines.

Maintenance parts and consumables are not covered by warranty (i.e. Fans for PRO-33, fuses).

For PRO-33.0 we are offering a material-kit for periodic fan-replacement (price available on request). We also offer the workmanship (fee applies).

Our product warranties, including coverage terms and warranty limitations, are set forth in the Product Terms and Conditions of Sale. For complete warranty coverage information, requirements and limitations relating to a specific product or service please refer to the contractual terms and conditions governing the purchase and sale of said product or service. The information set forth herein is a summation of, and subject to, the terms and conditions governing the purchase and sale of the product. Should there be any conflict between this document and the Terms and Conditions of Sale, the Terms and Conditions of Sale shall prevail.

PVP Warranty service level agreements_String_LBU_20150618 29-06-2015 Rev. B

For more information please contact your local ABB representative or visit:
www.abb.com/solar
www.abb.com/solarinverters
www.abb.com

Annexure D – Variable Cost Breakdown for 1 MWp PV Plant Models

Annexure D - Variable Balance of System Cost Breakdown of 1 MWp PV Plant Models

A. 1 MWp Central Inverter Model

	Item	Price Reference	Quantity	Unit	Unit Rate (LKR)	Cost (LKR)
1	DC Combiner 1000 V	Supplier - Sierra Cables	14	item	313,560.00	4,389,840.00
2	DC Cables 1C 4 sqmm	Supplier - Sierra Cables	5,908	m	124.00	732,592.00
3	DC Cables 1C 50 sqmm	Supplier - Sierra Cables	616	m	3,500.00	2,156,000.00
4	DC MC4 Connectors	Online quotations	336	pcs	150.00	50,400.00
5	DC Cabling - Trunking/ Hot Dip Galvanized (150x50mm)	Supplier - Vee Power	1,228	m	6,081.00	7,467,468.00
					Total Variable BoS Cost (LKR)	**14,796,300.00**

B. 1 MWp String Inverter Model

	Item	Price Reference	Quantity	Unit	Unit Rate (LKR)	Cost (LKR)
1	Inverter Manager	Online quotations	1	kit	278,892.38	278,892.38
2	DC Combiner 1000 V	Online quotations	15	kit	58,714.00	880,710.00
3	DC Cables 1C 4 sqmm	Supplier - Sierra Cables	5,748	m	124.00	712,752.00
4	DC MC4 Connectors	Online quotations	162	pcs	150.00	24,300.00
5	DC Cabling - Trunking/ Hot Dip Galvanized (150x50mm)	Supplier - Vee Power	1,102	m	6,081.00	6,701,262.00
6	LV Main Combiner Panel Board - 1600A/ 400V	Supplier - Vee Power	1	pcs	479,000.00	479,000.00
7	LV Sub Combiner Panel Board - 125A/ 400V	Supplier - Vee Power	15	pcs	25,300.00	379,500.00
8	AC Cable Laying Materials	Subcontractor Quotations	90	m	400.00	36,000.00
9	AC Cables Cu/XLPE/PVC/Steel 4C 25 sqmm	Supplier - Sierra Cables	104	m	2,375.00	247,000.00
10	AC Cables Cu/XLPE/PVC/Steel 4C 35 sqmm	Supplier - Sierra Cables	56	m	2,875.00	161,000.00
11	AC Cables Cu/XLPE/PVC/Steel 4C 50 sqmm	Supplier - Sierra Cables	148	m	3,937.00	582,676.00
12	AC Cables Cu/XLPE/PVC/Steel 4C 70 sqmm	Supplier - Sierra Cables	46	m	5,343.00	245,778.00
					Total Variable BoS Cost (LKR)	**10,728,870.38**

C. 1 MWp Micro Inverter Model

	Item	Price Reference	Quantity	Unit	Unit Rate (LKR)	Cost (LKR)
1	Communication Gateway	Online quotations	5.00	kit	234,000.00	1,170,000.00
2	20 A - 4P Lockable AC Isolators	Online quotations	86	kit	13,680.00	1,176,480.00
3	AC Cabling - Trunking/ Hot Dip Galvanized (150x50mm)	Supplier - Vee Power	512	m	6,081.00	3,113,472.00
4	LV Main Combiner Panel Board - 1600A/ 400V	Supplier - Vee Power	1	pcs	479,000.00	479,000.00
5	LV Sub Combiner Panel Board - 125A/ 400V	Supplier - Vee Power	15	pcs	31,500.00	472,500.00
6	AC Cable Laying Materials	Subcontractor Quotations	95	m	400.00	38,000.00
7	AC Cables Cu/XLPE/PVC/Steel 4C 2.5 sqmm	Supplier - Sierra Cables	114	m	490.00	55,860.00
8	AC Cables Cu/XLPE/PVC/Steel 4C 4 sqmm	Supplier - Sierra Cables	2,116	m	735.00	1,555,260.00
9	AC Cables Cu/XLPE/PVC/Steel 4C 25 sqmm	Supplier - Sierra Cables	46	m	2,375.00	109,250.00
10	AC Cables Cu/XLPE/PVC/Steel 4C 35 sqmm	Supplier - Sierra Cables	32	m	2,875.00	92,000.00
11	AC Cables Cu/XLPE/PVC/Steel 4C 50 sqmm	Supplier - Sierra Cables	44	m	3,937.00	173,228.00
12	AC Cables Cu/XLPE/PVC/Steel 4C 70 sqmm	Supplier - Sierra Cables	204	m	5,343.00	1,089,972.00
					Total Variable BoS Cost (LKR)	**9,525,022.00**

D. 1 MWp DCCU + String Inverter Model

	Item	Price Reference	Quantity	Unit	Unit Rate (LKR)	Cost (LKR)
1	Communication Gateway	Online quotations	1	kit	221,760.00	221,760.00
2	DC Combiner 1000 V	Online quotations	31	kit	29,357.00	910,067.00
3	DC Cables 1C 4 sqmm	Supplier - Sierra Cables	2,260	m	124.00	280,240.00
4	DC MC4 Connectors	Online quotations	93	pcs	150.00	13,950.00
5	DC Cabling - Trunking/ Hot Dip Galvanized (150x50mm)	Supplier - Vee Power	522	m	6,081.00	3,174,282.00
6	LV Main Combiner Panel Board - 1600A/ 400V	Supplier - Vee Power	1	pcs	477,000.00	477,000.00
7	LV Sub Combiner Panel Board - 125A/ 400V	Supplier - Vee Power	16	pcs	25,300.00	404,800.00
8	AC Cable Laying Materials	Subcontractor Quotations	114	m	400.00	45,600.00
9	AC Cables Cu/XLPE/PVC/Steel 4C 25 sqmm	Supplier - Sierra Cables	104	m	2,375.00	247,000.00
10	AC Cables Cu/XLPE/PVC/Steel 4C 35 sqmm	Supplier - Sierra Cables	84	m	2,875.00	241,500.00
11	AC Cables Cu/XLPE/PVC/Steel 4C 50 sqmm	Supplier - Sierra Cables	148	m	3,937.00	582,676.00
12	AC Cables Cu/XLPE/PVC/Steel 4C 70 sqmm	Supplier - Sierra Cables	46	m	5,343.00	245,778.00
					Total Variable BoS Cost (LKR)	**6,844,653.00**

Annexure E – Fixed Cost Breakdown for 1 MWp PV Plant Models

Annexure E - Fixed Balance of System Cost Breakdown for 1 MWp PV Plant Models

Item Description	Qnt	Unit	Unit Cost (LKR)	Total Cost (LKR)
1. PV module				
Supply of PV module - 325Wp Multi Crystalline	3078	Nos.	16,575.00	51,017,850.00
Supply and construction of PV module mounting structure	3078	Nos.	4,767.46	14,674,240.00
Sub Total				65,692,090.00
2. PV inverter				Included in Variable BoS Cost
Supply of central inverter - 850 kW/ 400V				
Extended warranty upto 20 years				
Supply of monitoring equipment				
Sub Total				-
3. Low voltage equipment and AC/DC cablling				Included in Variable BoS Cost
Supply of DC combiners, DC cable trunking and DC cables from PV module to inverters				
Supply of AC cable trunking/ UG cabling and AC cables from inverters to main LV combiner				
Supply of main LV combiners and sub LV combiners				
Sub Total				-
4. Medium voltage equipment and cabling				
Supply, installation, testing and commissioning of 1 MVA, 33000/480 V transformer	1	Item	3,120,864.00	3,120,864.00
Supply, installation, testing and commissioning of MV switchgear including protection devices	1	Item	3,130,400.00	3,130,400.00
Supply, installation, testing and commissioning of LV cabling from main LV combiner to transformer	1	Item	657,210.00	657,210.00
Supply, installation of MV cabling from transformer to PCC (maximum 100 m)	1	Item	2,464,748.00	2,464,748.00
Supply and Installation of balance of system for the installation	1	Item	1,987,790.00	1,987,790.00
Construction of Meter cubicle	1	Item	600,000.00	600,000.00
Construction of Transformer foundation	1	Item	200,000.00	200,000.00
Sub Total				12,161,012.00
5. Logistics				
Transport of PV modules, inverters trasnformer and other electrical/ civil equipment	1	Item	910,000.00	
Sub Total				910,000.00
6. Labor				

Installation work fee	1	Item	2,579,000.00	
Sub Total				2,579,000.00
7. Civil Works				
Civil and construction work				
Sub Total				3,720,000.00
8. Project Management				
Project management fee Health and safety management fee	1	Item	2,400,000.00	
Sub Total				2,400,000.00
9. Auxiliary Systems				
Supply and installation of earthing system	1	Item	2,500,000.00	2,500,000.00
Supply and installation of lighting protection system	1	Item	2,800,000.00	2,800,000.00
Supply and installation of fire alarming system	1	Item	700,000.00	700,000.00
Supply and installation of plumbing system	1	Item	1,000,000.00	1,000,000.00
Supply and installation of weather stations and other communication systems	1	Item	873,000.00	873,000.00
Sub Total				7,873,000.00
Insurance Cost				
Total Fixed BoS Cost (LKR)				**95,335,102.00**

Annexure F – Total Upfront Cost of 1 MWp PV Plant Models

Annexure E - Total PV Plant Upfront Cost Breakdown for 1 MWp PV Plant Models

A. 1 MWp Central Inverter Model

Item Description	Qnt	Unit	Unit Cost (LKR)	Total Cost (LKR)
1. PV module				
Supply of PV module - 325Wp Multi Crystalline	3078	Nos.	16,575.00	51,017,850.00
Supply and construction of PV module mounting structure	3078	Nos.	4,767.46	14,674,240.00
Sub Total				65,692,090.00
2. PV inverter				
Supply of central inverter - 850 kW/ 400V				
Extended warranty upto 20 years				
Supply of monitoring equipment				
Sub Total				26,775,000.00
3. Low voltage equipment and AC/DC cablling				
Supply of DC combiners, DC cable trunking and DC cables from PV module to inverters				
Supply of AC cable trunking/ UG cabling and AC cables from inverters to main LV combiner				
Supply of main LV combiners and sub LV combiners				
Sub Total				14,796,300.00
4. Medium voltage equipment and cabling				
Supply, installation, testing and commissioning of 1 MVA, 33000/480 V transformer	1	Item	3,120,864.00	3,120,864.00
Supply, installation, testing and commissioning of MV switchgear including protection devices	1	Item	3,130,400.00	3,130,400.00
Supply, installation, testing and commissioning of LV cabling from main LV combiner to transformer	1	Item	657,210.00	657,210.00
Supply, installation of MV cabling from transformer to PCC (maximum 100 m)	1	Item	2,464,748.00	2,464,748.00
Supply and Installation of balance of system for the installation	1	Item	1,987,790.00	1,987,790.00
Construction of Meter cubicle	1	Item	600,000.00	600,000.00
Construction of Transformer foundation	1	Item	200,000.00	200,000.00
Sub Total				12,161,012.00
5. Logistics				
Transport of PV modules, inverters trasnformer and other electrical/ civil equipment	1	Item	910,000.00	
Sub Total				910,000.00
6. Labor				
Installation work fee	1	Item	2,579,000.00	
Sub Total				2,579,000.00
7. Civil Works				
Civil and construction work				
Sub Total				3,720,000.00

8. Project Management				
Project management fee Health and safety management fee	1	Item	2,400,000.00	
Sub Total				2,400,000.00
9. Auxiliary Systems				
Supply and installation of earthing system	1	Item	2,500,000.00	2,500,000.00
Supply and installation of lighting protection system	1	Item	2,800,000.00	2,800,000.00
Supply and installation of fire alarming system	1	Item	700,000.00	700,000.00
Supply and installation of plumbing system	1	Item	1,000,000.00	1,000,000.00
Supply and installation of weather stations and other communication systems	1	Item	873,000.00	873,000.00
Sub Total				7,873,000.00
Insurance Cost				
			Total Fixed BoS Cost (LKR)	**136,906,402.00**

B. 1 MWp String Inverter Model

Item Description	Qnt	Unit	Unit Cost (LKR)	Total Cost (LKR)
1. PV module				
Supply of PV module - 325Wp Multi Crystalline	3078	Nos.	16,575.00	51,017,850.00
Supply and construction of PV module mounting structure	3078	Nos.	4,767.46	14,674,240.00
Sub Total				65,692,090.00
2. PV inverter				
Supply of string inverters - 60 kW/ 400V				
Extended warranty upto 20 years				
Supply of monitoring equipment				
Sub Total				20,808,000.00
3. Low voltage equipment and AC/DC cablling				
Supply of DC combiners, DC cable trunking and DC cables from PV module to inverters				
Supply of AC cable trunking/ UG cabling and AC cables from inverters to main LV combiner				
Supply of main LV combiners and sub LV combiners				
Sub Total				10,728,870.00
4. Medium voltage equipment and cabling				
Supply, installation, testing and commissioning of 1 MVA, 33000/480 V transformer	1	Item	3,120,864.00	3,120,864.00
Supply, installation, testing and commissioning of MV switchgear including protection devices	1	Item	3,130,400.00	3,130,400.00
Supply, installation, testing and commissioning of LV cabling from main LV combiner to transformer	1	Item	657,210.00	657,210.00
Supply, installation of MV cabling from transformer to PCC (maximum 100 m)	1	Item	2,464,748.00	2,464,748.00
Supply and Installation of balance of system for the installation	1	Item	1,987,790.00	1,987,790.00
Construction of Meter cubicle	1	Item	600,000.00	600,000.00
Construction of Transformer foundation	1	Item	200,000.00	200,000.00
Sub Total				12,161,012.00
5. Logistics				
Transport of PV modules, inverters trasnformer and other electrical/ civil equipment	1	Item	910,000.00	
Sub Total				910,000.00
6. Labor				
Installation work fee	1	Item	2,579,000.00	
Sub Total				2,579,000.00
7. Civil Works				
Civil and construction work				
Sub Total				3,720,000.00
8. Project Management				
Project management fee Health and safety management fee	1	Item	2,400,000.00	
Sub Total				2,400,000.00

9. Auxiliary Systems				
Supply and installation of earthing system	1	Item	2,500,000.00	2,500,000.00
Supply and installation of lighting protection system	1	Item	2,800,000.00	2,800,000.00
Supply and installation of fire alarming system	1	Item	700,000.00	700,000.00
Supply and installation of plumbing system	1	Item	1,000,000.00	1,000,000.00
Supply and installation of weather stations and other communication systems	1	Item	873,000.00	873,000.00
Sub Total				7,873,000.00
Insurance Cost				
			Total Fixed BoS Cost (LKR)	**126,871,972.00**

C. 1 MWp Micro Inverter Model

Item Description	Qnt	Unit	Unit Cost (LKR)	Total Cost (LKR)
1. PV module				
Supply of PV module - 325Wp Multi Crystalline	3078	Nos.	16,575.00	51,017,850.00
Supply and construction of PV module mounting structure	3078	Nos.	4,767.46	14,674,240.00
Sub Total				65,692,090.00
2. PV inverter				
Supply of micro inverters				
Extended warranty upto 20 years				
Supply of monitoring equipment				
Sub Total				45,209,664.00
3. Low voltage equipment and AC/DC cablling				
Supply of DC combiners, DC cable trunking and DC cables from PV module to inverters				
Supply of AC cable trunking/ UG cabling and AC cables from inverters to main LV combiner				
Supply of main LV combiners and sub LV combiners				
Sub Total				9,525,022.00
4. Medium voltage equipment and cabling				
Supply, installation, testing and commissioning of 1 MVA, 33000/480 V transformer	1	Item	3,120,864.00	3,120,864.00
Supply, installation, testing and commissioning of MV switchgear including protection devices	1	Item	3,130,400.00	3,130,400.00
Supply, installation, testing and commissioning of LV cabling from main LV combiner to transformer	1	Item	657,210.00	657,210.00
Supply, installation of MV cabling from transformer to PCC (maximum 100 m)	1	Item	2,464,748.00	2,464,748.00
Supply and Installation of balance of system for the installation	1	Item	1,987,790.00	1,987,790.00
Construction of Meter cubicle	1	Item	600,000.00	600,000.00
Construction of Transformer foundation	1	Item	200,000.00	200,000.00
Sub Total				12,161,012.00
5. Logistics				
Transport of PV modules, inverters trasnformer and other electrical/ civil equipment	1	Item	910,000.00	
Sub Total				910,000.00
6. Labor				
Installation work fee	1	Item	2,579,000.00	
Sub Total				2,579,000.00
7. Civil Works				
Civil and construction work				
Sub Total				3,720,000.00
8. Project Management				
Project management fee Health and safety management fee	1	Item	2,400,000.00	
Sub Total				2,400,000.00

9. Auxiliary Systems				
Supply and installation of earthing system	1	Item	2,500,000.00	2,500,000.00
Supply and installation of lighting protection system	1	Item	2,800,000.00	2,800,000.00
Supply and installation of fire alarming system	1	Item	700,000.00	700,000.00
Supply and installation of plumbing system	1	Item	1,000,000.00	1,000,000.00
Supply and installation of weather stations and other communication systems	1	Item	873,000.00	873,000.00
Sub Total				7,873,000.00
Insurance Cost				
Total Fixed BoS Cost (LKR)				**150,069,788.00**

D. 1 MWp DCCU + String Inverter Model

Item Description	Qnt	Unit	Unit Cost (LKR)	Total Cost (LKR)
1. PV module				
Supply of PV module - 325Wp Multi Crystalline	3078	Nos.	16,575.00	51,017,850.00
Supply and construction of PV module mounting structure	3078	Nos.	4,767.46	14,674,240.00
Sub Total				65,692,090.00
2. PV inverter				
Supply of DCCU + string inverters				
Extended warranty upto 20 years				
Supply of monitoring equipment				
Sub Total				25,643,820.00
3. Low voltage equipment and AC/DC cablling				
Supply of DC combiners, DC cable trunking and DC cables from PV module to inverters				
Supply of AC cable trunking/ UG cabling and AC cables from inverters to main LV combiner				
Supply of main LV combiners and sub LV combiners				
Sub Total				6,844,653.00
4. Medium voltage equipment and cabling				
Supply, installation, testing and commissioning of 1 MVA, 33000/480 V transformer	1	Item	3,120,864.00	3,120,864.00
Supply, installation, testing and commissioning of MV switchgear including protection devices	1	Item	3,130,400.00	3,130,400.00
Supply, installation, testing and commissioning of LV cabling from main LV combiner to transformer	1	Item	657,210.00	657,210.00
Supply, installation of MV cabling from transformer to PCC (maximum 100 m)	1	Item	2,464,748.00	2,464,748.00
Supply and Installation of balance of system for the installation	1	Item	1,987,790.00	1,987,790.00
Construction of Meter cubicle	1	Item	600,000.00	600,000.00
Construction of Transformer foundation	1	Item	200,000.00	200,000.00
Sub Total				12,161,012.00
5. Logistics				
Transport of PV modules, inverters trasnformer and other electrical/ civil equipment	1	Item	910,000.00	
Sub Total				910,000.00
6. Labor				
Installation work fee	1	Item	2,579,000.00	
Sub Total				2,579,000.00
7. Civil Works				
Civil and construction work				
Sub Total				3,720,000.00
8. Project Management				
Project management fee Health and safety management fee	1	Item	2,400,000.00	
Sub Total				2,400,000.00

9. Auxiliary Systems				
Supply and installation of earthing system	1	Item	2,500,000.00	2,500,000.00
Supply and installation of lighting protection system	1	Item	2,800,000.00	2,800,000.00
Supply and installation of fire alarming system	1	Item	700,000.00	700,000.00
Supply and installation of plumbing system	1	Item	1,000,000.00	1,000,000.00
Supply and installation of weather stations and other communication systems	1	Item	873,000.00	873,000.00
Sub Total				7,873,000.00
Insurance Cost				
Total Fixed BoS Cost (LKR)				**127,823,575.00**

Annexure G – Cash Flow Analysis for 1 MWp PV Plant Models

Annexure G.1 - Cash Flow Analysis for 1 MWp Central Inverter Model (Average Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
Energy Supplied (MWh)						1,414.00	1,409.00	1,403.00	1,397.00	1,390.00	1,382.00	1,374.00	1,365.00	1,356.00
Tariff Paid By CEB														
Tier 1	18.27	LKR/ kWh				25,833,780.00	25,742,430.00	25,632,810.00	25,523,190.00	25,395,300.00	25,249,140.00	25,102,980.00	24,938,550.00	24,774,120.00
O&M cost	1%	From project cost	6%	of annual increment		1,369,064.02	1,451,207.86	1,538,280.33	1,630,577.15	1,728,411.78	1,832,116.49	1,942,043.48	2,058,566.09	2,182,080.05
Depreciation						(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)
Finance cost						(14,375,172.21)	(11,500,137.77)	(8,625,103.33)	(5,750,068.88)	(2,875,034.44)				
Profit before tax						5,982,351.71	8,848,179.99	11,700,666.91	14,558,378.17	17,403,357.24	20,235,936.39	20,199,703.38	20,151,795.99	20,110,879.95
Tax			28%			1,675,058.48	2,477,490.40	3,276,186.73	4,076,345.89	4,872,940.03	5,666,062.19	5,655,916.95	5,642,502.88	5,631,046.39
Profit after tax						**4,307,293.23**	**6,370,689.60**	**8,424,480.17**	**10,482,032.28**	**12,530,417.21**	**14,569,874.20**	**14,543,786.43**	**14,509,293.11**	**14,479,833.57**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
Profit after tax						**4,307,293.23**	**6,370,689.60**	**8,424,480.17**	**10,482,032.28**	**12,530,417.21**	**14,569,874.20**	**14,543,786.43**	**14,509,293.11**	**14,479,833.57**
Add														
Depreciation						6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10
Finance cost						14,375,172.21	11,500,137.77	8,625,103.33	5,750,068.88	2,875,034.44	-	-	-	-
Net flow of project					**(136,906,402.00)**	**25,527,785.54**	**24,716,147.46**	**23,894,903.60**	**23,077,421.27**	**22,250,771.75**	**21,415,194.30**	**21,389,106.53**	**21,354,613.21**	**21,325,153.67**
Project IRR					**15.82%**									
Less														
Finance Cost						(14,375,172.21)	(11,500,137.77)	(8,625,103.33)	(5,750,068.88)	(2,875,034.44)				
Capital Repayments						(20,535,960.30)	(20,535,960.30)	(20,535,960.30)	(20,535,960.30)	(20,535,960.30)				
Cash Inflow					**(34,226,600.50)**	**(9,383,346.97)**	**(7,319,950.60)**	**(5,266,160.03)**	**(3,208,607.92)**	**(1,160,222.99)**	**21,415,194.30**	**21,389,106.53**	**21,354,613.21**	**21,325,153.67**
Equity IRR					**16.70%**									

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00
Costs Over Lifetime														
Capital Repayment		LKR			34,226,600.50	20,535,960.30	20,535,960.30	20,535,960.30	20,535,960.30	20,535,960.30	-	-	-	-
Finance Cost		LKR				14,375,172.21	11,500,137.77	8,625,103.33	5,750,068.88	2,875,034.44	-	-	-	-
O&M Cost		LKR				1,369,064.02	1,451,207.86	1,538,280.33	1,630,577.15	1,728,411.78	1,832,116.49	1,942,043.48	2,058,566.09	2,182,080.05
Taxation		LKR				1,675,058.48	2,477,490.40	3,276,186.73	4,076,345.89	4,872,940.03	5,666,062.19	5,655,916.95	5,642,502.88	5,631,046.39
Total Costs		LKR			34,226,600.50	37,955,255.01	35,964,796.33	33,975,530.69	31,992,952.22	30,012,346.55	7,498,178.68	7,597,960.42	7,701,068.96	7,813,126.44
Present Value of Costs Over Lifetime		LKR			34,226,600.50	34,504,777.28	29,722,972.17	25,526,319.08	21,851,616.85	18,635,305.93	4,232,526.39	3,898,955.07	3,592,605.51	3,313,528.31
Electricity Generation Over Lifetime														
Energy Supplied		kWh				1,414,000.00	1,409,000.00	1,403,000.00	1,397,000.00	1,390,000.00	1,382,000.00	1,374,000.00	1,365,000.00	1,356,000.00
Present Value of Energy Over Lifetime						1,285,454.55	1,164,462.81	1,054,094.67	954,169.80	863,080.64	780,102.97	705,079.25	636,782.57	575,076.37
LCOE				**17.47**	**LKR/kWh**									

10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,347.00	1,338.00	1,329.00	1,320.00	1,312.00	1,303.00	1,295.00	1,288.00	1,281.00	1,274.00	1,264.00
24,609,690.00	24,445,260.00	24,280,830.00	24,116,400.00	23,970,240.00	23,805,810.00	23,659,650.00	23,531,760.00	23,403,870.00	23,275,980.00	23,093,280.00
2,313,004.86	2,451,785.15	2,598,892.26	2,754,825.79	2,920,115.34	3,095,322.26	3,281,041.59	3,477,904.09	3,686,578.34	3,907,773.04	4,142,239.42
(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)
20,077,374.76	20,051,725.05	20,034,402.16	20,025,905.69	20,045,035.24	20,055,812.16	20,095,371.49	20,164,343.99	20,245,128.24	20,338,432.94	20,390,199.32
5,621,664.93	5,614,483.01	5,609,632.60	5,607,253.59	5,612,609.87	5,615,627.40	5,626,704.02	5,646,016.32	5,668,635.91	5,694,761.22	5,709,255.81
14,455,709.82	**14,437,242.03**	**14,424,769.55**	**14,418,652.10**	**14,432,425.37**	**14,440,184.75**	**14,468,667.48**	**14,518,327.67**	**14,576,492.33**	**14,643,671.71**	**14,680,943.51**

10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
14,455,709.82	**14,437,242.03**	**14,424,769.55**	**14,418,652.10**	**14,432,425.37**	**14,440,184.75**	**14,468,667.48**	**14,518,327.67**	**14,576,492.33**	**14,643,671.71**	**14,680,943.51**
6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10
-	-	-	-	-	-	-	-	-	-	-
21,301,029.92	**21,282,562.13**	**21,270,089.65**	**21,263,972.20**	**21,277,745.47**	**21,285,504.85**	**21,313,987.58**	**21,363,647.77**	**21,421,812.43**	**21,488,991.81**	**21,526,263.61**
21,301,029.92	**21,282,562.13**	**21,270,089.65**	**21,263,972.20**	**21,277,745.47**	**21,285,504.85**	**21,313,987.58**	**21,363,647.77**	**21,421,812.43**	**21,488,991.81**	**21,526,263.61**

10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
2,313,004.86	2,451,785.15	2,598,892.26	2,754,825.79	2,920,115.34	3,095,322.26	3,281,041.59	3,477,904.09	3,686,578.34	3,907,773.04	4,142,239.42
5,621,664.93	5,614,483.01	5,609,632.60	5,607,253.59	5,612,609.87	5,615,627.40	5,626,704.02	5,646,016.32	5,668,635.91	5,694,761.22	5,709,255.81
7,934,669.79	8,066,268.16	8,208,524.86	8,362,079.38	8,532,725.20	8,710,949.66	8,907,745.61	9,123,920.41	9,355,214.24	9,602,534.26	9,851,495.23
3,059,158.69	2,827,177.78	2,615,488.99	2,422,196.54	2,246,933.23	2,085,332.09	1,938,584.98	1,805,119.01	1,682,617.51	1,570,091.08	1,464,361.99
1,347,000.00	1,338,000.00	1,329,000.00	1,320,000.00	1,312,000.00	1,303,000.00	1,295,000.00	1,288,000.00	1,281,000.00	1,274,000.00	1,264,000.00
519,326.81	468,960.84	423,460.36	382,356.98	345,490.61	311,927.84	281,829.73	254,823.93	230,399.11	208,309.18	187,885.55

Annexure G.1 - Cash Flow Analysis for 1 MWp Central Inverter Model (Best Case)

Profit and Loss Statement

Year					**-**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**
Energy Supplied (MWh)						1,496.25	1,490.96	1,484.61	1,478.26	1,470.86	1,462.39	1,453.93	1,444.40	1,434.88	1,425.35
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				27,336,530.98	27,239,867.15	27,123,870.56	27,007,873.96	26,872,544.60	26,717,882.47	26,563,220.35	26,389,225.45	26,215,230.56	26,041,235.67
O&M cost	1%	From project cost	6%	of annual increment		1,369,064.02	1,451,207.86	1,538,280.33	1,630,577.15	1,728,411.78	1,832,116.49	1,942,043.48	2,058,566.09	2,182,080.05	2,313,004.86
Depreciation						(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)
Finance cost						(14,375,172.21)	(11,500,137.77)	(8,625,103.33)	(5,750,068.88)	(2,875,034.44)					
Profit before tax						7,485,102.69	10,345,617.15	13,191,727.46	16,043,062.13	18,880,601.84	21,704,678.86	21,659,943.72	21,602,471.44	21,551,990.51	21,508,920.42
Tax			28%			2,095,828.75	2,896,772.80	3,693,683.69	4,492,057.40	5,286,568.52	6,077,310.08	6,064,784.24	6,048,692.00	6,034,557.34	6,022,497.72
Profit after tax						**5,389,273.94**	**7,448,844.35**	**9,498,043.77**	**11,551,004.73**	**13,594,033.33**	**15,627,368.78**	**15,595,159.48**	**15,553,779.44**	**15,517,433.17**	**15,486,422.70**

Cash Flow

Year					**-**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**
Profit after tax						**5,389,273.94**	**7,448,844.35**	**9,498,043.77**	**11,551,004.73**	**13,594,033.33**	**15,627,368.78**	**15,595,159.48**	**15,553,779.44**	**15,517,433.17**	**15,486,422.70**
Add															
Depreciation						6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10
Finance cost						14,375,172.21	11,500,137.77	8,625,103.33	5,750,068.88	2,875,034.44	-	-	-	-	-
Net flow of project					**(136,906,402.00)**	**26,609,766.25**	**25,794,302.21**	**24,968,467.20**	**24,146,393.72**	**23,314,387.87**	**22,472,688.88**	**22,440,479.58**	**22,399,099.54**	**22,362,753.27**	**22,331,742.80**
Project IRR					**16.72%**										
Less															
Finance Cost						(14,375,172.21)	(11,500,137.77)	(8,625,103.33)	(5,750,068.88)	(2,875,034.44)					
Capital Repayments						(20,535,960.30)	(20,535,960.30)	(20,535,960.30)	(20,535,960.30)	(20,535,960.30)					
Cash Inflow					**(34,226,600.50)**	**(8,301,366.26)**	**(6,241,795.85)**	**(4,192,596.43)**	**(2,139,635.47)**	**(96,606.87)**	**22,472,688.88**	**22,440,479.58**	**22,399,099.54**	**22,362,753.27**	**22,331,742.80**
Equity IRR					**18.09%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					**-**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**
Costs Over Lifetime															
Capital Repayment		LKR			34,226,600.50	20,535,960.30	20,535,960.30	20,535,960.30	20,535,960.30	20,535,960.30	-	-	-	-	-
Finance Cost		LKR				14,375,172.21	11,500,137.77	8,625,103.33	5,750,068.88	2,875,034.44	-	-	-	-	-
O&M Cost		LKR				1,369,064.02	1,451,207.86	1,538,280.33	1,630,577.15	1,728,411.78	1,832,116.49	1,942,043.48	2,058,566.09	2,182,080.05	2,313,004.86
Taxation		LKR				2,095,828.75	2,896,772.80	3,693,683.69	4,492,057.40	5,286,568.52	6,077,310.08	6,064,784.24	6,048,692.00	6,034,557.34	6,022,497.72
Total Costs		LKR			34,226,600.50	38,376,025.28	36,384,078.73	34,393,027.65	32,408,663.73	30,425,975.04	7,909,426.57	8,006,827.72	8,107,258.09	8,216,637.40	8,335,502.57
Present Value of Costs Over Lifetime		LKR			34,226,600.50	34,887,295.71	30,069,486.55	25,839,990.72	22,135,553.40	18,892,136.68	4,464,665.10	4,108,768.65	3,782,095.73	3,484,656.35	3,213,697.08
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,496,252.38	1,490,961.53	1,484,612.51	1,478,263.49	1,470,856.30	1,462,390.94	1,453,925.58	1,444,402.05	1,434,878.52	1,425,354.99
Present Value of Energy Over Lifetime						1,360,229.44	1,232,199.61	1,115,411.35	1,009,673.85	913,286.04	825,481.56	746,093.71	673,824.22	608,528.56	549,536.05
LCOE				**16.79**	**LKR/kWh**										

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,415.83	1,406.31	1,396.78	1,388.32	1,378.80	1,370.33	1,362.92	1,355.52	1,348.11	1,337.53
25,867,240.77	25,693,245.88	25,519,250.99	25,364,588.86	25,190,593.97	25,035,931.84	24,900,602.48	24,765,273.12	24,629,943.76	24,436,616.10
2,451,785.15	2,598,892.26	2,754,825.79	2,920,115.34	3,095,322.26	3,281,041.59	3,477,904.09	3,686,578.34	3,907,773.04	4,142,239.42
(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)
21,473,705.82	21,446,818.04	21,428,756.68	21,439,384.10	21,440,596.13	21,471,653.33	21,533,186.47	21,606,531.35	21,692,396.69	21,733,535.41
6,012,637.63	6,005,109.05	6,000,051.87	6,003,027.55	6,003,366.92	6,012,062.93	6,029,292.21	6,049,828.78	6,073,871.07	6,085,389.92
15,461,068.19	**15,441,708.99**	**15,428,704.81**	**15,436,356.55**	**15,437,229.21**	**15,459,590.40**	**15,503,894.26**	**15,556,702.57**	**15,618,525.62**	**15,648,145.50**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
15,461,068.19	**15,441,708.99**	**15,428,704.81**	**15,436,356.55**	**15,437,229.21**	**15,459,590.40**	**15,503,894.26**	**15,556,702.57**	**15,618,525.62**	**15,648,145.50**
6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10
-	-	-	-	-	-	-	-	-	-
22,306,388.29	**22,287,029.09**	**22,274,024.91**	**22,281,676.65**	**22,282,549.31**	**22,304,910.50**	**22,349,214.36**	**22,402,022.67**	**22,463,845.72**	**22,493,465.60**
22,306,388.29	**22,287,029.09**	**22,274,024.91**	**22,281,676.65**	**22,282,549.31**	**22,304,910.50**	**22,349,214.36**	**22,402,022.67**	**22,463,845.72**	**22,493,465.60**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,451,785.15	2,598,892.26	2,754,825.79	2,920,115.34	3,095,322.26	3,281,041.59	3,477,904.09	3,686,578.34	3,907,773.04	4,142,239.42
6,012,637.63	6,005,109.05	6,000,051.87	6,003,027.55	6,003,366.92	6,012,062.93	6,029,292.21	6,049,828.78	6,073,871.07	6,085,389.92
8,464,422.78	8,604,001.31	8,754,877.66	8,923,142.89	9,098,689.17	9,293,104.53	9,507,196.30	9,736,407.11	9,981,644.11	10,227,629.33
2,966,728.55	2,741,499.97	2,535,976.21	2,349,742.41	2,178,153.85	2,022,450.31	1,880,948.10	1,751,178.40	1,632,078.57	1,520,271.93
1,415,831.46	1,406,307.93	1,396,784.40	1,388,319.04	1,378,795.51	1,370,330.15	1,362,922.96	1,355,515.77	1,348,108.58	1,337,526.88
496,240.29	448,093.05	404,598.69	365,587.79	330,072.68	298,223.77	269,647.04	243,801.43	220,426.53	198,814.85

Annexure G.1 - Cash Flow Analysis for 1 MWp Central Inverter Model (Worst Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Energy Supplied (MWh)						1,331.75	1,327.04	1,321.39	1,315.74	1,309.14	1,301.61	1,294.07	1,285.60	1,277.12	1,268.65	1,260.17	1,251.69	1,243.22	1,235.68
Tariff Paid By CEB																			
Tier 1	18.27	LKR/ kWh				24,331,029.02	24,244,992.85	24,141,749.44	24,038,506.04	23,918,055.40	23,780,397.53	23,642,739.65	23,487,874.55	23,333,009.44	23,178,144.33	23,023,279.23	22,868,414.12	22,713,549.01	22,575,891.14
O&M cost	1%	From project cost	6%	of annual increment		1,369,064.02	1,451,207.86	1,538,280.33	1,630,577.15	1,728,411.78	1,832,116.49	1,942,043.48	2,058,566.09	2,182,080.05	2,313,004.86	2,451,785.15	2,598,892.26	2,754,825.79	2,920,115.34
Depreciation						(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)
Finance cost						(14,375,172.21)	(11,500,137.77)	(8,625,103.33)	(5,750,068.88)	(2,875,034.44)									
Profit before tax						4,479,600.73	7,350,742.84	10,209,606.35	13,073,694.21	15,926,112.64	18,767,193.92	18,739,463.03	18,701,120.53	18,669,769.39	18,645,829.09	18,629,744.27	18,621,986.27	18,623,054.70	18,650,686.38
Tax			28%			1,254,288.20	2,058,208.00	2,858,689.78	3,660,634.38	4,459,311.54	5,254,814.30	5,247,049.65	5,236,313.75	5,227,535.43	5,220,832.14	5,216,328.40	5,214,156.16	5,214,455.32	5,222,192.19
Profit after tax						**3,225,312.52**	**5,292,534.84**	**7,350,916.57**	**9,413,059.83**	**11,466,801.10**	**13,512,379.62**	**13,492,413.38**	**13,464,806.78**	**13,442,233.96**	**13,424,996.94**	**13,413,415.88**	**13,407,830.12**	**13,408,599.39**	**13,428,494.19**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Profit after tax						**3,225,312.52**	**5,292,534.84**	**7,350,916.57**	**9,413,059.83**	**11,466,801.10**	**13,512,379.62**	**13,492,413.38**	**13,464,806.78**	**13,442,233.96**	**13,424,996.94**	**13,413,415.88**	**13,407,830.12**	**13,408,599.39**	**13,428,494.19**
Add																			
Depreciation						6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10
Finance cost						14,375,172.21	11,500,137.77	8,625,103.33	5,750,068.88	2,875,034.44	-	-	-	-	-	-	-	-	-
Net flow of project					**(136,906,402.00)**	**24,445,804.83**	**23,637,992.71**	**22,821,340.00**	**22,008,448.81**	**21,187,155.64**	**20,357,699.72**	**20,337,733.48**	**20,310,126.88**	**20,287,554.06**	**20,270,317.04**	**20,258,735.98**	**20,253,150.22**	**20,253,919.49**	**20,273,814.29**
Project IRR					**14.92%**														
Less																			
Finance Cost						(14,375,172.21)	(11,500,137.77)	(8,625,103.33)	(5,750,068.88)	(2,875,034.44)									
Capital Repayments						(20,535,960.30)	(20,535,960.30)	(20,535,960.30)	(20,535,960.30)	(20,535,960.30)									
Cash Inflow					**(34,226,600.50)**	**(10,465,327.68)**	**(8,398,105.36)**	**(6,339,723.63)**	**(4,277,580.37)**	**(2,223,839.10)**	**20,357,699.72**	**20,337,733.48**	**20,310,126.88**	**20,287,554.06**	**20,270,317.04**	**20,258,735.98**	**20,253,150.22**	**20,253,919.49**	**20,273,814.29**
Equity IRR					**15.34%**														

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Costs Over Lifetime																			
Capital Repayment		LKR			34,226,600.50	20,535,960.30	20,535,960.30	20,535,960.30	20,535,960.30	20,535,960.30	-	-	-	-	-	-	-	-	-
Finance Cost		LKR				14,375,172.21	11,500,137.77	8,625,103.33	5,750,068.88	2,875,034.44	-	-	-	-	-	-	-	-	-
O&M Cost		LKR				1,369,064.02	1,451,207.86	1,538,280.33	1,630,577.15	1,728,411.78	1,832,116.49	1,942,043.48	2,058,566.09	2,182,080.05	2,313,004.86	2,451,785.15	2,598,892.26	2,754,825.79	2,920,115.34
Taxation		LKR				1,254,288.20	2,058,208.00	2,858,689.78	3,660,634.38	4,459,311.54	5,254,814.30	5,247,049.65	5,236,313.75	5,227,535.43	5,220,832.14	5,216,328.40	5,214,156.16	5,214,455.32	5,222,192.19
Total Costs		LKR			34,226,600.50	37,534,484.73	35,545,513.92	33,558,033.74	31,577,240.71	29,598,718.06	7,086,930.79	7,189,093.13	7,294,879.84	7,409,615.48	7,533,837.00	7,668,113.54	7,813,048.41	7,969,281.11	8,142,307.52
Present Value of Costs Over Lifetime		LKR			34,226,600.50	34,122,258.85	29,376,457.79	25,212,647.44	21,567,680.29	18,378,475.18	4,000,387.67	3,689,141.50	3,403,115.28	3,142,400.28	2,904,620.30	2,687,627.02	2,489,478.00	2,308,416.87	2,144,124.05
Electricity Generation Over Lifetime																			
Energy Supplied		kWh				1,331,747.62	1,327,038.47	1,321,387.49	1,315,736.51	1,309,143.70	1,301,609.06	1,294,074.42	1,285,597.95	1,277,121.48	1,268,645.01	1,260,168.54	1,251,692.07	1,243,215.60	1,235,680.96
Present Value of Energy Over Lifetime						1,210,679.65	1,096,726.01	992,777.98	898,665.74	812,875.24	734,724.38	664,064.79	599,740.93	541,624.18	489,117.57	441,681.39	398,827.67	360,115.28	325,393.42
LCOE				**18.23**	**LKR/kWh**														

15.00	16.00	17.00	18.00	19.00	20.00
1,227.20	1,219.67	1,213.08	1,206.48	1,199.89	1,190.47
22,421,026.03	22,283,368.16	22,162,917.52	22,042,466.88	21,922,016.24	21,749,943.90
3,095,322.26	3,281,041.59	3,477,904.09	3,686,578.34	3,907,773.04	4,142,239.42
(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)	(6,845,320.10)
18,671,028.19	18,719,089.65	18,795,501.51	18,883,725.12	18,984,469.18	19,046,863.22
5,227,887.89	5,241,345.10	5,262,740.42	5,287,443.03	5,315,651.37	5,333,121.70
13,443,140.30	**13,477,744.55**	**13,532,761.09**	**13,596,282.08**	**13,668,817.81**	**13,713,741.52**

15.00	16.00	17.00	18.00	19.00	20.00
13,443,140.30	**13,477,744.55**	**13,532,761.09**	**13,596,282.08**	**13,668,817.81**	**13,713,741.52**
6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10	6,845,320.10
-	-	-	-	-	-
20,288,460.40	**20,323,064.65**	**20,378,081.19**	**20,441,602.18**	**20,514,137.91**	**20,559,061.62**
20,288,460.40	**20,323,064.65**	**20,378,081.19**	**20,441,602.18**	**20,514,137.91**	**20,559,061.62**

15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-
-	-	-	-	-	-
3,095,322.26	3,281,041.59	3,477,904.09	3,686,578.34	3,907,773.04	4,142,239.42
5,227,887.89	5,241,345.10	5,262,740.42	5,287,443.03	5,315,651.37	5,333,121.70
8,323,210.15	8,522,386.70	8,740,644.51	8,974,021.37	9,223,424.41	9,475,361.12
1,992,510.34	1,854,719.65	1,729,289.92	1,614,056.62	1,508,103.59	1,408,452.05
1,227,204.49	1,219,669.85	1,213,077.04	1,206,484.23	1,199,891.42	1,190,473.12
293,783.00	265,435.70	240,000.83	216,996.79	196,191.84	176,956.24

Annexure G.2 - Cash Flow Analysis for 1 MWp String Inverter Model (Average Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,418.00	1,413.00	1,407.00	1,401.00	1,394.00	1,386.00	1,378.00	1,369.00	1,360.00	1,351.00
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				25,906,860.00	25,815,510.00	25,705,890.00	25,596,270.00	25,468,380.00	25,322,220.00	25,176,060.00	25,011,630.00	24,847,200.00	24,682,770.00
O&M cost	1%	From project cost	6%	of annual increment		1,268,719.72	1,344,842.90	1,425,533.48	1,511,065.49	1,601,729.42	1,697,833.18	1,799,703.17	1,907,685.36	2,022,146.48	2,143,475.27
Depreciation						(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)
Finance cost						(13,321,557.06)	(10,657,245.65)	(7,992,934.24)	(5,328,622.82)	(2,664,311.41)					
Profit before tax						7,510,424.06	10,159,508.66	12,794,890.64	15,435,114.06	18,062,199.40	20,676,454.58	20,632,164.57	20,575,716.76	20,525,747.88	20,482,646.67
Tax			28%			2,102,918.74	2,844,662.42	3,582,569.38	4,321,831.94	5,057,415.83	5,789,407.28	5,777,006.08	5,761,200.69	5,747,209.41	5,735,141.07
Profit after tax						**5,407,505.32**	**7,314,846.23**	**9,212,321.26**	**11,113,282.12**	**13,004,783.57**	**14,887,047.30**	**14,855,158.49**	**14,814,516.07**	**14,778,538.48**	**14,747,505.60**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**5,407,505.32**	**7,314,846.23**	**9,212,321.26**	**11,113,282.12**	**13,004,783.57**	**14,887,047.30**	**14,855,158.49**	**14,814,516.07**	**14,778,538.48**	**14,747,505.60**
Add															
Depreciation						6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60
Finance cost						13,321,557.06	10,657,245.65	7,992,934.24	5,328,622.82	2,664,311.41	-	-	-	-	-
Net flow of project					**(126,871,972.00)**	**25,072,660.98**	**24,315,690.48**	**23,548,854.10**	**22,785,503.55**	**22,012,693.58**	**21,230,645.90**	**21,198,757.09**	**21,158,114.67**	**21,122,137.08**	**21,091,104.20**
Project IRR					**17.09%**										
Less															
Finance Cost						(13,321,557.06)	(10,657,245.65)	(7,992,934.24)	(5,328,622.82)	(2,664,311.41)					
Capital Repayments						(19,030,795.80)	(19,030,795.80)	(19,030,795.80)	(19,030,795.80)	(19,030,795.80)					
Cash Inflow					**(31,717,993.00)**	**(7,279,691.88)**	**(5,372,350.97)**	**(3,474,875.94)**	**(1,573,915.08)**	**317,586.37**	**21,230,645.90**	**21,198,757.09**	**21,158,114.67**	**21,122,137.08**	**21,091,104.20**
Equity IRR					**18.67%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			31,717,993.00	19,030,795.80	19,030,795.80	19,030,795.80	19,030,795.80	19,030,795.80	-	-	-	-	-
Finance Cost		LKR				13,321,557.06	10,657,245.65	7,992,934.24	5,328,622.82	2,664,311.41	-	-	-	-	-
O&M Cost		LKR				1,268,719.72	1,344,842.90	1,425,533.48	1,511,065.49	1,601,729.42	1,697,833.18	1,799,703.17	1,907,685.36	2,022,146.48	2,143,475.27
Taxation		LKR				2,102,918.74	2,844,662.42	3,582,569.38	4,321,831.94	5,057,415.83	5,789,407.28	5,777,006.08	5,761,200.69	5,747,209.41	5,735,141.07
Total Costs		LKR			31,717,993.00	35,723,991.32	33,877,546.77	32,031,832.89	30,192,316.05	28,354,252.46	7,487,240.46	7,576,709.25	7,668,886.05	7,769,355.89	7,878,616.34
Present Value of Costs Over Lifetime		LKR			31,717,993.00	32,476,355.74	27,997,972.54	24,065,990.15	20,621,758.11	17,605,759.95	4,226,352.05	3,888,049.86	3,577,591.94	3,294,965.33	3,037,547.66
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,418,000.00	1,413,000.00	1,407,000.00	1,401,000.00	1,394,000.00	1,386,000.00	1,378,000.00	1,369,000.00	1,360,000.00	1,351,000.00
Present Value of Energy Over Lifetime						1,289,090.91	1,167,768.60	1,057,099.92	956,901.85	865,564.32	782,360.87	707,131.89	638,648.60	576,772.76	520,868.98

LCOE **16.53** **LKR/kWh**

11.00	**12.00**	**13.00**	**14.00**	**15.00**	**16.00**	**17.00**	**18.00**	**19.00**	**20.00**
1,342.00	1,333.00	1,324.00	1,316.00	1,307.00	1,300.00	1,293.00	1,286.00	1,279.00	1,270.00
24,518,340.00	24,353,910.00	24,189,480.00	24,043,320.00	23,878,890.00	23,751,000.00	23,623,110.00	23,495,220.00	23,367,330.00	23,202,900.00
2,272,083.79	2,408,408.82	2,552,913.34	2,706,088.14	2,868,453.43	3,040,560.64	3,222,994.28	3,416,373.93	3,621,356.37	3,838,637.75
(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)
20,446,825.19	20,418,720.22	20,398,794.74	20,405,809.54	20,403,744.83	20,447,962.04	20,502,505.68	20,567,995.33	20,645,087.77	20,697,939.15
5,725,111.05	5,717,241.66	5,711,662.53	5,713,626.67	5,713,048.55	5,725,429.37	5,740,701.59	5,759,038.69	5,780,624.58	5,795,422.96
14,721,714.14	**14,701,478.56**	**14,687,132.22**	**14,692,182.87**	**14,690,696.28**	**14,722,532.67**	**14,761,804.09**	**14,808,956.64**	**14,864,463.20**	**14,902,516.19**

11.00	**12.00**	**13.00**	**14.00**	**15.00**	**16.00**	**17.00**	**18.00**	**19.00**	**20.00**
14,721,714.14	**14,701,478.56**	**14,687,132.22**	**14,692,182.87**	**14,690,696.28**	**14,722,532.67**	**14,761,804.09**	**14,808,956.64**	**14,864,463.20**	**14,902,516.19**
6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60
-	-	-	-	-	-	-	-	-	-
21,065,312.74	**21,045,077.16**	**21,030,730.82**	**21,035,781.47**	**21,034,294.88**	**21,066,131.27**	**21,105,402.69**	**21,152,555.24**	**21,208,061.80**	**21,246,114.79**
21,065,312.74	**21,045,077.16**	**21,030,730.82**	**21,035,781.47**	**21,034,294.88**	**21,066,131.27**	**21,105,402.69**	**21,152,555.24**	**21,208,061.80**	**21,246,114.79**

11.00	**12.00**	**13.00**	**14.00**	**15.00**	**16.00**	**17.00**	**18.00**	**19.00**	**20.00**
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,272,083.79	2,408,408.82	2,552,913.34	2,706,088.14	2,868,453.43	3,040,560.64	3,222,994.28	3,416,373.93	3,621,356.37	3,838,637.75
5,725,111.05	5,717,241.66	5,711,662.53	5,713,626.67	5,713,048.55	5,725,429.37	5,740,701.59	5,759,038.69	5,780,624.58	5,795,422.96
7,997,194.84	8,125,650.48	8,264,575.87	8,419,714.82	8,581,501.99	8,765,990.01	8,963,695.87	9,175,412.63	9,401,980.95	9,634,060.72
2,802,968.00	2,589,082.66	2,393,953.24	2,217,174.06	2,054,343.35	1,907,734.83	1,773,419.44	1,650,278.61	1,537,299.01	1,432,041.74
1,342,000.00	1,333,000.00	1,324,000.00	1,316,000.00	1,307,000.00	1,300,000.00	1,293,000.00	1,286,000.00	1,279,000.00	1,270,000.00
470,362.81	424,734.88	383,515.64	346,543.93	312,885.41	282,917.88	255,813.16	231,298.40	209,126.72	188,777.41

Annexure G.2 - Cash Flow Analysis for 1 MWp String Inverter Model (Best Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,500.49	1,495.19	1,488.85	1,482.50	1,475.09	1,466.62	1,458.16	1,448.63	1,439.11	1,429.59
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				27,413,862.05	27,317,198.22	27,201,201.62	27,085,205.03	26,949,875.66	26,795,213.54	26,640,551.41	26,466,556.52	26,292,561.62	26,118,566.73
O&M cost	1%	From project cost	6%	of annual increment		1,268,719.72	1,344,842.90	1,425,533.48	1,511,065.49	1,601,729.42	1,697,833.18	1,799,703.17	1,907,685.36	2,022,146.48	2,143,475.27
Depreciation						(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)
Finance cost						(13,321,557.06)	(10,657,245.65)	(7,992,934.24)	(5,328,622.82)	(2,664,311.41)					
Profit before tax						9,017,426.11	11,661,196.87	14,290,202.26	16,924,049.09	19,543,695.07	22,149,448.12	22,096,655.98	22,030,643.28	21,971,109.51	21,918,443.40
Tax			28%			2,524,879.31	3,265,135.12	4,001,256.63	4,738,733.74	5,472,234.62	6,201,845.47	6,187,063.67	6,168,580.12	6,151,910.66	6,137,164.15
Profit after tax						**6,492,546.80**	**8,396,061.75**	**10,288,945.63**	**12,185,315.34**	**14,071,460.45**	**15,947,602.64**	**15,909,592.31**	**15,862,063.16**	**15,819,198.84**	**15,781,279.25**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**6,492,546.80**	**8,396,061.75**	**10,288,945.63**	**12,185,315.34**	**14,071,460.45**	**15,947,602.64**	**15,909,592.31**	**15,862,063.16**	**15,819,198.84**	**15,781,279.25**
Add															
Depreciation						6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60
Finance cost						13,321,557.06	10,657,245.65	7,992,934.24	5,328,622.82	2,664,311.41	-	-	-	-	-
Net flow of project					**(126,871,972.00)**	**26,157,702.46**	**25,396,906.00**	**24,625,478.47**	**23,857,536.77**	**23,079,370.46**	**22,291,201.24**	**22,253,190.91**	**22,205,661.76**	**22,162,797.44**	**22,124,877.85**
Project IRR					**18.04%**										
Less															
Finance Cost						(13,321,557.06)	(10,657,245.65)	(7,992,934.24)	(5,328,622.82)	(2,664,311.41)					
Capital Repayments						(19,030,795.80)	(19,030,795.80)	(19,030,795.80)	(19,030,795.80)	(19,030,795.80)					
Cash Inflow					**(31,717,993.00)**	**(6,194,650.40)**	**(4,291,135.45)**	**(2,398,251.57)**	**(501,881.86)**	**1,384,263.25**	**22,291,201.24**	**22,253,190.91**	**22,205,661.76**	**22,162,797.44**	**22,124,877.85**
Equity IRR					**20.22%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			31,717,993.00	19,030,795.80	19,030,795.80	19,030,795.80	19,030,795.80	19,030,795.80	-	-	-	-	-
Finance Cost		LKR				13,321,557.06	10,657,245.65	7,992,934.24	5,328,622.82	2,664,311.41	-	-	-	-	-
O&M Cost		LKR				1,268,719.72	1,344,842.90	1,425,533.48	1,511,065.49	1,601,729.42	1,697,833.18	1,799,703.17	1,907,685.36	2,022,146.48	2,143,475.27
Taxation		LKR				2,524,879.31	3,265,135.12	4,001,256.63	4,738,733.74	5,472,234.62	6,201,845.47	6,187,063.67	6,168,580.12	6,151,910.66	6,137,164.15
Total Costs		LKR			31,717,993.00	36,145,951.89	34,298,019.48	32,450,520.15	30,609,217.85	28,769,071.25	7,899,678.65	7,986,766.85	8,076,265.48	8,174,057.14	8,280,639.42
Present Value of Costs Over Lifetime		LKR			31,717,993.00	32,859,956.26	28,345,470.64	24,380,556.08	20,906,507.65	17,863,329.78	4,459,162.66	4,098,474.25	3,767,637.45	3,466,598.17	3,192,544.96
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,500,485.06	1,495,194.21	1,488,845.19	1,482,496.17	1,475,088.98	1,466,623.62	1,458,158.26	1,448,634.73	1,439,111.20	1,429,587.67
Present Value of Energy Over Lifetime						1,364,077.33	1,235,697.69	1,118,591.43	1,012,564.83	915,914.20	827,870.80	748,265.75	675,798.79	610,323.63	551,167.93

LCOE **15.90** **LKR/kWh**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,420.06	1,410.54	1,401.02	1,392.55	1,383.03	1,375.62	1,368.21	1,360.81	1,353.40	1,343.88
25,944,571.84	25,770,576.94	25,596,582.05	25,441,919.92	25,267,925.03	25,132,595.67	24,997,266.31	24,861,936.95	24,726,607.59	24,552,612.69
2,272,083.79	2,408,408.82	2,552,913.34	2,706,088.14	2,868,453.43	3,040,560.64	3,222,994.28	3,416,373.93	3,621,356.37	3,838,637.75
(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)
21,873,057.03	21,835,387.16	21,805,896.80	21,804,409.47	21,792,779.86	21,829,557.71	21,876,661.99	21,934,712.28	22,004,365.36	22,047,651.85
6,124,455.97	6,113,908.40	6,105,651.10	6,105,234.65	6,101,978.36	6,112,276.16	6,125,465.36	6,141,719.44	6,161,222.30	6,173,342.52
15,748,601.06	**15,721,478.76**	**15,700,245.69**	**15,699,174.82**	**15,690,801.50**	**15,717,281.55**	**15,751,196.63**	**15,792,992.84**	**15,843,143.06**	**15,874,309.33**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
15,748,601.06	**15,721,478.76**	**15,700,245.69**	**15,699,174.82**	**15,690,801.50**	**15,717,281.55**	**15,751,196.63**	**15,792,992.84**	**15,843,143.06**	**15,874,309.33**
6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60
-	-	-	-	-	-	-	-	-	-
22,092,199.66	**22,065,077.36**	**22,043,844.29**	**22,042,773.42**	**22,034,400.10**	**22,060,880.15**	**22,094,795.23**	**22,136,591.44**	**22,186,741.66**	**22,217,907.93**
22,092,199.66	**22,065,077.36**	**22,043,844.29**	**22,042,773.42**	**22,034,400.10**	**22,060,880.15**	**22,094,795.23**	**22,136,591.44**	**22,186,741.66**	**22,217,907.93**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,272,083.79	2,408,408.82	2,552,913.34	2,706,088.14	2,868,453.43	3,040,560.64	3,222,994.28	3,416,373.93	3,621,356.37	3,838,637.75
6,124,455.97	6,113,908.40	6,105,651.10	6,105,234.65	6,101,978.36	6,112,276.16	6,125,465.36	6,141,719.44	6,161,222.30	6,173,342.52
8,396,539.76	8,522,317.22	8,658,564.45	8,811,322.80	8,970,431.80	9,152,836.80	9,348,459.63	9,558,093.37	9,782,578.67	10,011,980.27
2,942,935.96	2,715,472.90	2,508,077.70	2,320,296.68	2,147,450.05	1,991,923.96	1,849,542.90	1,719,107.11	1,599,529.78	1,488,217.07
1,420,064.14	1,410,540.61	1,401,017.08	1,392,551.72	1,383,028.19	1,375,621.00	1,368,213.81	1,360,806.62	1,353,399.43	1,343,875.90
497,723.82	449,441.71	405,824.74	366,702.39	331,085.95	299,375.21	270,693.81	244,753.03	221,291.62	199,758.59

Annexure G.2 - Cash Flow Analysis for 1 MWp String Inverter Model (Worst Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,335.51	1,330.81	1,325.15	1,319.50	1,312.91	1,305.38	1,297.84	1,289.37	1,280.89	1,272.41
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				24,399,857.95	24,313,821.78	24,210,578.38	24,107,334.97	23,986,884.34	23,849,226.46	23,711,568.59	23,556,703.48	23,401,838.38	23,246,973.27
O&M cost	1%	From project cost	6%	of annual increment		1,268,719.72	1,344,842.90	1,425,533.48	1,511,065.49	1,601,729.42	1,697,833.18	1,799,703.17	1,907,685.36	2,022,146.48	2,143,475.27
Depreciation						(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)
Finance cost						(13,321,557.06)	(10,657,245.65)	(7,992,934.24)	(5,328,622.82)	(2,664,311.41)					
Profit before tax						6,003,422.01	8,657,820.44	11,299,579.02	13,946,179.04	16,580,703.74	19,203,461.04	19,167,673.16	19,120,790.24	19,080,386.26	19,046,849.94
Tax			28%			1,680,958.16	2,424,189.72	3,163,882.13	3,904,930.13	4,642,597.05	5,376,969.09	5,366,948.49	5,353,821.27	5,342,508.15	5,333,117.98
Profit after tax						**4,322,463.85**	**6,233,630.72**	**8,135,696.89**	**10,041,248.91**	**11,938,106.69**	**13,826,491.95**	**13,800,724.68**	**13,766,968.98**	**13,737,878.11**	**13,713,731.96**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**4,322,463.85**	**6,233,630.72**	**8,135,696.89**	**10,041,248.91**	**11,938,106.69**	**13,826,491.95**	**13,800,724.68**	**13,766,968.98**	**13,737,878.11**	**13,713,731.96**
Add															
Depreciation						6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60
Finance cost						13,321,557.06	10,657,245.65	7,992,934.24	5,328,622.82	2,664,311.41	-	-	-	-	-
Net flow of project					**(126,871,972.00)**	**23,987,619.51**	**23,234,474.96**	**22,472,229.73**	**21,713,470.33**	**20,946,016.70**	**20,170,090.55**	**20,144,323.28**	**20,110,567.58**	**20,081,476.71**	**20,057,330.56**
Project IRR					**16.12%**										
Less															
Finance Cost						(13,321,557.06)	(10,657,245.65)	(7,992,934.24)	(5,328,622.82)	(2,664,311.41)					
Capital Repayments						(19,030,795.80)	(19,030,795.80)	(19,030,795.80)	(19,030,795.80)	(19,030,795.80)					
Cash Inflow					**(31,717,993.00)**	**(8,364,733.35)**	**(6,453,566.48)**	**(4,551,500.31)**	**(2,645,948.29)**	**(749,090.51)**	**20,170,090.55**	**20,144,323.28**	**20,110,567.58**	**20,081,476.71**	**20,057,330.56**
Equity IRR					**17.16%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			31,717,993.00	19,030,795.80	19,030,795.80	19,030,795.80	19,030,795.80	19,030,795.80	-	-	-	-	-
Finance Cost		LKR				13,321,557.06	10,657,245.65	7,992,934.24	5,328,622.82	2,664,311.41	-	-	-	-	-
O&M Cost		LKR				1,268,719.72	1,344,842.90	1,425,533.48	1,511,065.49	1,601,729.42	1,697,833.18	1,799,703.17	1,907,685.36	2,022,146.48	2,143,475.27
Taxation		LKR				1,680,958.16	2,424,189.72	3,163,882.13	3,904,930.13	4,642,597.05	5,376,969.09	5,366,948.49	5,353,821.27	5,342,508.15	5,333,117.98
Total Costs		LKR			31,717,993.00	35,302,030.74	33,457,074.07	31,613,145.64	29,775,414.24	27,939,433.67	7,074,802.27	7,166,651.66	7,261,506.63	7,364,654.64	7,476,593.26
Present Value of Costs Over Lifetime		LKR			31,717,993.00	32,092,755.22	27,650,474.44	23,751,424.22	20,337,008.57	17,348,190.12	3,993,541.44	3,677,625.48	3,387,546.43	3,123,332.49	2,882,550.36
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,335,514.94	1,330,805.79	1,325,154.81	1,319,503.83	1,312,911.02	1,305,376.38	1,297,841.74	1,289,365.27	1,280,888.80	1,272,412.33
Present Value of Energy Over Lifetime						1,214,104.49	1,099,839.50	995,608.42	901,238.87	815,214.45	736,850.94	665,998.03	601,498.41	543,221.89	490,570.04
LCOE				**17.23**	**LKR/kWh**										

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,263.94	1,255.46	1,246.98	1,239.45	1,230.97	1,224.38	1,217.79	1,211.19	1,204.60	1,196.12
23,092,108.16	22,937,243.06	22,782,377.95	22,644,720.08	22,489,854.97	22,369,404.33	22,248,953.69	22,128,503.05	22,008,052.41	21,853,187.31
2,272,083.79	2,408,408.82	2,552,913.34	2,706,088.14	2,868,453.43	3,040,560.64	3,222,994.28	3,416,373.93	3,621,356.37	3,838,637.75
(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)	(6,343,598.60)
19,020,593.35	19,002,053.27	18,991,692.69	19,007,209.62	19,014,709.80	19,066,366.37	19,128,349.37	19,201,278.39	19,285,810.18	19,348,226.46
5,325,766.14	5,320,574.92	5,317,673.95	5,322,018.69	5,324,118.74	5,338,582.58	5,355,937.82	5,376,357.95	5,400,026.85	5,417,503.41
13,694,827.21	**13,681,478.35**	**13,674,018.74**	**13,685,190.93**	**13,690,591.06**	**13,727,783.79**	**13,772,411.55**	**13,824,920.44**	**13,885,783.33**	**13,930,723.05**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
13,694,827.21	**13,681,478.35**	**13,674,018.74**	**13,685,190.93**	**13,690,591.06**	**13,727,783.79**	**13,772,411.55**	**13,824,920.44**	**13,885,783.33**	**13,930,723.05**
6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60	6,343,598.60
-	-	-	-	-	-	-	-	-	-
20,038,425.81	**20,025,076.95**	**20,017,617.34**	**20,028,789.53**	**20,034,189.66**	**20,071,382.39**	**20,116,010.15**	**20,168,519.04**	**20,229,381.93**	**20,274,321.65**
20,038,425.81	**20,025,076.95**	**20,017,617.34**	**20,028,789.53**	**20,034,189.66**	**20,071,382.39**	**20,116,010.15**	**20,168,519.04**	**20,229,381.93**	**20,274,321.65**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,272,083.79	2,408,408.82	2,552,913.34	2,706,088.14	2,868,453.43	3,040,560.64	3,222,994.28	3,416,373.93	3,621,356.37	3,838,637.75
5,325,766.14	5,320,574.92	5,317,673.95	5,322,018.69	5,324,118.74	5,338,582.58	5,355,937.82	5,376,357.95	5,400,026.85	5,417,503.41
7,597,849.93	7,728,983.73	7,870,587.30	8,028,106.84	8,192,572.18	8,379,143.22	8,578,932.10	8,792,731.88	9,021,383.22	9,256,141.16
2,663,000.05	2,462,692.41	2,279,828.79	2,114,051.44	1,961,236.64	1,823,545.70	1,697,295.98	1,581,450.12	1,475,068.25	1,375,866.40
1,263,935.86	1,255,459.39	1,246,982.92	1,239,448.28	1,230,971.81	1,224,379.00	1,217,786.19	1,211,193.38	1,204,600.57	1,196,124.10
443,001.81	400,028.05	361,206.53	326,385.47	294,684.86	266,460.54	240,932.51	217,843.78	196,961.82	177,796.23

Annexure G.3 - Cash Flow Analysis for 1 MWp Micro Inverter Model (Average Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,420.00	1,411.00	1,405.33	1,399.67	1,394.00	1,388.33	1,382.67	1,377.00	1,371.33	1,365.67
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				25,943,400.00	25,778,970.00	25,675,440.00	25,571,910.00	25,468,380.00	25,364,850.00	25,261,320.00	25,157,790.00	25,054,260.00	24,950,730.00
O&M cost	1%	From project cost	6%	of annual increment		1,500,697.88	1,590,739.75	1,686,184.14	1,787,355.19	1,894,596.50	2,008,272.29	2,128,768.62	2,256,494.74	2,391,884.43	2,535,397.49
Depreciation						(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)
Finance cost						(15,757,327.74)	(12,605,862.19)	(9,454,396.64)	(6,302,931.10)	(3,151,465.55)					
Profit before tax						4,183,280.74	7,260,358.16	10,403,738.09	13,552,844.69	16,708,021.55	19,869,632.89	19,886,599.22	19,910,795.34	19,942,655.03	19,982,638.09
Tax			28%			1,171,318.61	2,032,900.29	2,913,046.67	3,794,796.51	4,678,246.03	5,563,497.21	5,568,247.78	5,575,022.70	5,583,943.41	5,595,138.67
Profit after tax						**3,011,962.13**	**5,227,457.88**	**7,490,691.43**	**9,758,048.18**	**12,029,775.52**	**14,306,135.68**	**14,318,351.44**	**14,335,772.65**	**14,358,711.62**	**14,387,499.43**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**3,011,962.13**	**5,227,457.88**	**7,490,691.43**	**9,758,048.18**	**12,029,775.52**	**14,306,135.68**	**14,318,351.44**	**14,335,772.65**	**14,358,711.62**	**14,387,499.43**
Add															
Depreciation						7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40
Finance cost						15,757,327.74	12,605,862.19	9,454,396.64	6,302,931.10	3,151,465.55	-	-	-	-	-
Net flow of project					**(150,069,788.00)**	**26,272,779.27**	**25,336,809.47**	**24,448,577.47**	**23,564,468.67**	**22,684,730.46**	**21,809,625.08**	**21,821,840.84**	**21,839,262.05**	**21,862,201.02**	**21,890,988.83**
Project IRR					**14.57%**										
Less															
Finance Cost						(15,757,327.74)	(12,605,862.19)	(9,454,396.64)	(6,302,931.10)	(3,151,465.55)					
Capital Repayments						(22,510,468.20)	(22,510,468.20)	(22,510,468.20)	(22,510,468.20)	(22,510,468.20)					
Cash Inflow					**(37,517,447.00)**	**(11,995,016.67)**	**(9,779,520.92)**	**(7,516,287.37)**	**(5,248,930.62)**	**(2,977,203.28)**	**21,809,625.08**	**21,821,840.84**	**21,839,262.05**	**21,862,201.02**	**21,890,988.83**
Equity IRR					**14.83%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			37,517,447.00	22,510,468.20	22,510,468.20	22,510,468.20	22,510,468.20	22,510,468.20	-	-	-	-	-
Finance Cost		LKR				15,757,327.74	12,605,862.19	9,454,396.64	6,302,931.10	3,151,465.55	-	-	-	-	-
O&M Cost		LKR				1,500,697.88	1,590,739.75	1,686,184.14	1,787,355.19	1,894,596.50	2,008,272.29	2,128,768.62	2,256,494.74	2,391,884.43	2,535,397.49
Taxation		LKR				1,171,318.61	2,032,900.29	2,913,046.67	3,794,796.51	4,678,246.03	5,563,497.21	5,568,247.78	5,575,022.70	5,583,943.41	5,595,138.67
Total Costs		LKR			37,517,447.00	40,939,812.43	38,739,970.43	36,564,095.65	34,395,551.00	32,234,776.28	7,571,769.50	7,697,016.41	7,831,517.44	7,975,827.83	8,130,536.16
Present Value of Costs Over Lifetime		LKR			37,517,447.00	37,218,011.30	32,016,504.49	27,471,146.24	23,492,624.13	20,015,259.94	4,274,066.48	3,949,786.46	3,653,460.68	3,382,529.59	3,134,673.66
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,420,000.00	1,411,000.00	1,405,333.33	1,399,666.67	1,394,000.00	1,388,333.33	1,382,666.67	1,377,000.00	1,371,333.33	1,365,666.67
Present Value of Energy Over Lifetime						1,290,909.09	1,166,115.70	1,055,847.73	955,991.17	865,564.32	783,677.97	709,526.62	642,380.66	581,579.20	526,523.62
LCOE				**18.52**	**LKR/kWh**										

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,360.00	1,354.33	1,348.67	1,343.00	1,337.33	1,331.67	1,326.00	1,320.33	1,314.67	1,309.00
24,847,200.00	24,743,670.00	24,640,140.00	24,536,610.00	24,433,080.00	24,329,550.00	24,226,020.00	24,122,490.00	24,018,960.00	23,915,430.00
2,687,521.34	2,848,772.62	3,019,698.98	3,200,880.92	3,392,933.77	3,596,509.80	3,812,300.39	4,041,038.41	4,283,500.72	4,540,510.76
(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)
20,031,231.94	20,088,953.22	20,156,349.58	20,234,001.52	20,322,524.37	20,422,570.40	20,534,830.99	20,660,039.01	20,798,971.32	20,952,451.36
5,608,744.94	5,624,906.90	5,643,777.88	5,665,520.43	5,690,306.82	5,718,319.71	5,749,752.68	5,784,810.92	5,823,711.97	5,866,686.38
14,422,487.00	**14,464,046.32**	**14,512,571.70**	**14,568,481.09**	**14,632,217.55**	**14,704,250.69**	**14,785,078.31**	**14,875,228.09**	**14,975,259.35**	**15,085,764.98**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
14,422,487.00	**14,464,046.32**	**14,512,571.70**	**14,568,481.09**	**14,632,217.55**	**14,704,250.69**	**14,785,078.31**	**14,875,228.09**	**14,975,259.35**	**15,085,764.98**
7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40
-	-	-	-	-	-	-	-	-	-
21,925,976.40	**21,967,535.72**	**22,016,061.10**	**22,071,970.49**	**22,135,706.95**	**22,207,740.09**	**22,288,567.71**	**22,378,717.49**	**22,478,748.75**	**22,589,254.38**
21,925,976.40	**21,967,535.72**	**22,016,061.10**	**22,071,970.49**	**22,135,706.95**	**22,207,740.09**	**22,288,567.71**	**22,378,717.49**	**22,478,748.75**	**22,589,254.38**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,687,521.34	2,848,772.62	3,019,698.98	3,200,880.92	3,392,933.77	3,596,509.80	3,812,300.39	4,041,038.41	4,283,500.72	4,540,510.76
5,608,744.94	5,624,906.90	5,643,777.88	5,665,520.43	5,690,306.82	5,718,319.71	5,749,752.68	5,784,810.92	5,823,711.97	5,866,686.38
8,296,266.29	8,473,679.52	8,663,476.86	8,866,401.34	9,083,240.60	9,314,829.51	9,562,053.06	9,825,849.33	10,107,212.68	10,407,197.14
2,907,790.72	2,699,975.44	2,509,500.65	2,334,800.59	2,174,455.58	2,027,178.30	1,891,801.22	1,767,265.37	1,652,610.04	1,546,963.54
1,360,000.00	1,354,333.33	1,348,666.67	1,343,000.00	1,337,333.33	1,331,666.67	1,326,000.00	1,320,333.33	1,314,666.67	1,309,000.00
476,671.70	431,532.34	390,660.69	353,653.87	320,146.97	289,809.47	262,342.03	237,473.56	214,958.51	194,574.51

Annexure G.3 - Cash Flow Analysis for 1 MWp Micro Inverter Model (Best Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,502.60	1,493.08	1,487.08	1,481.09	1,475.09	1,469.09	1,463.10	1,457.10	1,451.10	1,445.11
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				27,452,527.58	27,278,532.68	27,168,980.34	27,059,428.00	26,949,875.66	26,840,323.32	26,730,770.98	26,621,218.64	26,511,666.30	26,402,113.96
O&M cost	1%	From project cost	6%	of annual increment		1,500,697.88	1,590,739.75	1,686,184.14	1,787,355.19	1,894,596.50	2,008,272.29	2,128,768.62	2,256,494.74	2,391,884.43	2,535,397.49
Depreciation						(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)
Finance cost						(15,757,327.74)	(12,605,862.19)	(9,454,396.64)	(6,302,931.10)	(3,151,465.55)					
Profit before tax						5,692,408.32	8,759,920.85	11,897,278.44	15,040,362.69	18,189,517.21	21,345,106.21	21,356,050.21	21,374,223.99	21,400,061.33	21,434,022.06
Tax			28%			1,593,874.33	2,452,777.84	3,331,237.96	4,211,301.55	5,093,064.82	5,976,629.74	5,979,694.06	5,984,782.72	5,992,017.17	6,001,526.18
Profit after tax						**4,098,533.99**	**6,307,143.01**	**8,566,040.48**	**10,829,061.14**	**13,096,452.39**	**15,368,476.47**	**15,376,356.15**	**15,389,441.27**	**15,408,044.16**	**15,432,495.88**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**4,098,533.99**	**6,307,143.01**	**8,566,040.48**	**10,829,061.14**	**13,096,452.39**	**15,368,476.47**	**15,376,356.15**	**15,389,441.27**	**15,408,044.16**	**15,432,495.88**
Add															
Depreciation						7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40
Finance cost						15,757,327.74	12,605,862.19	9,454,396.64	6,302,931.10	3,151,465.55	-	-	-	-	-
Net flow of project					**(150,069,788.00)**	**27,359,351.13**	**26,416,494.60**	**25,523,926.52**	**24,635,481.64**	**23,751,407.34**	**22,871,965.87**	**22,879,845.55**	**22,892,930.67**	**22,911,533.56**	**22,935,985.28**
Project IRR					**15.41%**										
Less															
Finance Cost						(15,757,327.74)	(12,605,862.19)	(9,454,396.64)	(6,302,931.10)	(3,151,465.55)					
Capital Repayments						(22,510,468.20)	(22,510,468.20)	(22,510,468.20)	(22,510,468.20)	(22,510,468.20)					
Cash Inflow					**(37,517,447.00)**	**(10,908,444.81)**	**(8,699,835.79)**	**(6,440,938.32)**	**(4,177,917.66)**	**(1,910,526.41)**	**22,871,965.87**	**22,879,845.55**	**22,892,930.67**	**22,911,533.56**	**22,935,985.28**
Equity IRR					**16.06%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			37,517,447.00	22,510,468.20	22,510,468.20	22,510,468.20	22,510,468.20	22,510,468.20	-	-	-	-	-
Finance Cost		LKR				15,757,327.74	12,605,862.19	9,454,396.64	6,302,931.10	3,151,465.55	-	-	-	-	-
O&M Cost		LKR				1,500,697.88	1,590,739.75	1,686,184.14	1,787,355.19	1,894,596.50	2,008,272.29	2,128,768.62	2,256,494.74	2,391,884.43	2,535,397.49
Taxation		LKR				1,593,874.33	2,452,777.84	3,331,237.96	4,211,301.55	5,093,064.82	5,976,629.74	5,979,694.06	5,984,782.72	5,992,017.17	6,001,526.18
Total Costs		LKR			37,517,447.00	41,362,368.15	39,159,847.98	36,982,286.94	34,812,056.04	32,649,595.07	7,984,902.03	8,108,462.68	8,241,277.46	8,383,901.60	8,536,923.67
Present Value of Costs Over Lifetime		LKR			37,517,447.00	37,602,152.86	32,363,510.73	27,785,339.55	23,777,102.68	20,272,829.77	4,507,269.03	4,160,923.45	3,844,616.76	3,555,592.70	3,291,353.63
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,502,601.40	1,493,077.87	1,487,081.57	1,481,085.28	1,475,088.98	1,469,092.68	1,463,096.39	1,457,100.09	1,451,103.79	1,445,107.50
Present Value of Energy Over Lifetime						1,366,001.27	1,233,948.65	1,117,266.40	1,011,601.17	915,914.20	829,264.52	750,799.79	679,747.95	615,409.66	557,151.50
LCOE				**17.79**	**LKR/kWh**										

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,439.11	1,433.11	1,427.12	1,421.12	1,415.13	1,409.13	1,403.13	1,397.14	1,391.14	1,385.14
26,292,561.62	26,183,009.28	26,073,456.94	25,963,904.60	25,854,352.26	25,744,799.92	25,635,247.58	25,525,695.24	25,416,142.90	25,306,590.56
2,687,521.34	2,848,772.62	3,019,698.98	3,200,880.92	3,392,933.77	3,596,509.80	3,812,300.39	4,041,038.41	4,283,500.72	4,540,510.76
(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)
21,476,593.57	21,528,292.51	21,589,666.52	21,661,296.12	21,743,796.64	21,837,820.32	21,944,058.57	22,063,244.25	22,196,154.22	22,343,611.92
6,013,446.20	6,027,921.90	6,045,106.63	6,065,162.91	6,088,263.06	6,114,589.69	6,144,336.40	6,177,708.39	6,214,923.18	6,256,211.34
15,463,147.37	**15,500,370.60**	**15,544,559.90**	**15,596,133.21**	**15,655,533.58**	**15,723,230.63**	**15,799,722.17**	**15,885,535.86**	**15,981,231.04**	**16,087,400.58**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
15,463,147.37	**15,500,370.60**	**15,544,559.90**	**15,596,133.21**	**15,655,533.58**	**15,723,230.63**	**15,799,722.17**	**15,885,535.86**	**15,981,231.04**	**16,087,400.58**
7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40
-	-	-	-	-	-	-	-	-	-
22,966,636.77	**23,003,860.00**	**23,048,049.30**	**23,099,622.61**	**23,159,022.98**	**23,226,720.03**	**23,303,211.57**	**23,389,025.26**	**23,484,720.44**	**23,590,889.98**
22,966,636.77	**23,003,860.00**	**23,048,049.30**	**23,099,622.61**	**23,159,022.98**	**23,226,720.03**	**23,303,211.57**	**23,389,025.26**	**23,484,720.44**	**23,590,889.98**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,687,521.34	2,848,772.62	3,019,698.98	3,200,880.92	3,392,933.77	3,596,509.80	3,812,300.39	4,041,038.41	4,283,500.72	4,540,510.76
6,013,446.20	6,027,921.90	6,045,106.63	6,065,162.91	6,088,263.06	6,114,589.69	6,144,336.40	6,177,708.39	6,214,923.18	6,256,211.34
8,700,967.54	8,876,694.52	9,064,805.61	9,266,043.83	9,481,196.83	9,711,099.49	9,956,636.79	10,218,746.80	10,498,423.90	10,796,722.10
3,049,636.04	2,828,388.43	2,625,751.29	2,440,038.94	2,269,723.14	2,113,418.19	1,969,867.51	1,837,931.43	1,716,576.20	1,604,863.94
1,439,111.20	1,433,114.90	1,427,118.61	1,421,122.31	1,415,126.01	1,409,129.72	1,403,133.42	1,397,137.12	1,391,140.83	1,385,144.53
504,399.70	456,634.57	413,385.43	374,225.92	338,769.92	306,667.68	277,602.47	251,287.39	227,462.64	205,892.91

Annexure G.3 - Cash Flow Analysis for 1 MWp Micro Inverter Model (Worst Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,337.40	1,328.92	1,323.59	1,318.25	1,312.91	1,307.57	1,302.24	1,296.90	1,291.56	1,286.23
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				24,434,272.42	24,279,407.32	24,181,899.66	24,084,392.00	23,986,884.34	23,889,376.68	23,791,869.02	23,694,361.36	23,596,853.70	23,499,346.04
O&M cost	1%	From project cost	6%	of annual increment		1,500,697.88	1,590,739.75	1,686,184.14	1,787,355.19	1,894,596.50	2,008,272.29	2,128,768.62	2,256,494.74	2,391,884.43	2,535,397.49
Depreciation						(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)
Finance cost						(15,757,327.74)	(12,605,862.19)	(9,454,396.64)	(6,302,931.10)	(3,151,465.55)					
Profit before tax						2,674,153.16	5,760,795.48	8,910,197.75	12,065,326.69	15,226,525.88	18,394,159.56	18,417,148.24	18,447,366.70	18,485,248.72	18,531,254.13
Tax			28%			748,762.89	1,613,022.73	2,494,855.37	3,378,291.47	4,263,427.25	5,150,364.68	5,156,801.51	5,165,262.68	5,175,869.64	5,188,751.16
Profit after tax						**1,925,390.28**	**4,147,772.74**	**6,415,342.38**	**8,687,035.21**	**10,963,098.64**	**13,243,794.89**	**13,260,346.73**	**13,282,104.02**	**13,309,379.08**	**13,342,502.97**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**1,925,390.28**	**4,147,772.74**	**6,415,342.38**	**8,687,035.21**	**10,963,098.64**	**13,243,794.89**	**13,260,346.73**	**13,282,104.02**	**13,309,379.08**	**13,342,502.97**
Add															
Depreciation						7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40
Finance cost						15,757,327.74	12,605,862.19	9,454,396.64	6,302,931.10	3,151,465.55	-	-	-	-	-
Net flow of project					**(150,069,788.00)**	**25,186,207.42**	**24,257,124.33**	**23,373,228.42**	**22,493,455.71**	**21,618,053.59**	**20,747,284.29**	**20,763,836.13**	**20,785,593.42**	**20,812,868.48**	**20,845,992.37**
Project IRR					**13.73%**										
Less															
Finance Cost						(15,757,327.74)	(12,605,862.19)	(9,454,396.64)	(6,302,931.10)	(3,151,465.55)					
Capital Repayments						(22,510,468.20)	(22,510,468.20)	(22,510,468.20)	(22,510,468.20)	(22,510,468.20)					
Cash Inflow					**(37,517,447.00)**	**(13,081,588.52)**	**(10,859,206.06)**	**(8,591,636.42)**	**(6,319,943.59)**	**(4,043,880.16)**	**20,747,284.29**	**20,763,836.13**	**20,785,593.42**	**20,812,868.48**	**20,845,992.37**
Equity IRR					**13.61%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			37,517,447.00	22,510,468.20	22,510,468.20	22,510,468.20	22,510,468.20	22,510,468.20	-	-	-	-	-
Finance Cost		LKR				15,757,327.74	12,605,862.19	9,454,396.64	6,302,931.10	3,151,465.55	-	-	-	-	-
O&M Cost		LKR				1,500,697.88	1,590,739.75	1,686,184.14	1,787,355.19	1,894,596.50	2,008,272.29	2,128,768.62	2,256,494.74	2,391,884.43	2,535,397.49
Taxation		LKR				748,762.89	1,613,022.73	2,494,855.37	3,378,291.47	4,263,427.25	5,150,364.68	5,156,801.51	5,165,262.68	5,175,869.64	5,188,751.16
Total Costs		LKR			37,517,447.00	40,517,256.71	38,320,092.88	36,145,904.35	33,979,045.95	31,819,957.49	7,158,636.96	7,285,570.13	7,421,757.42	7,567,754.07	7,724,148.65
Present Value of Costs Over Lifetime		LKR			37,517,447.00	36,833,869.73	31,669,498.25	27,156,952.93	23,208,145.59	19,757,690.11	4,040,863.94	3,738,649.46	3,462,304.61	3,209,466.48	2,977,993.68
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,337,398.60	1,328,922.13	1,323,585.09	1,318,248.06	1,312,911.02	1,307,573.98	1,302,236.95	1,296,899.91	1,291,562.87	1,286,225.84
Present Value of Energy Over Lifetime						1,215,816.91	1,098,282.75	994,429.07	900,381.16	815,214.45	738,091.43	668,253.46	605,013.38	547,748.74	495,895.74
LCOE				**19.35**	**LKR/kWh**										

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,280.89	1,275.55	1,270.21	1,264.88	1,259.54	1,254.20	1,248.87	1,243.53	1,238.19	1,232.86
23,401,838.38	23,304,330.72	23,206,823.06	23,109,315.40	23,011,807.74	22,914,300.08	22,816,792.42	22,719,284.76	22,621,777.10	22,524,269.44
2,687,521.34	2,848,772.62	3,019,698.98	3,200,880.92	3,392,933.77	3,596,509.80	3,812,300.39	4,041,038.41	4,283,500.72	4,540,510.76
(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)	(7,503,489.40)
18,585,870.32	18,649,613.94	18,723,032.64	18,806,706.91	18,901,252.11	19,007,320.48	19,125,603.40	19,256,833.77	19,401,788.41	19,561,290.80
5,204,043.69	5,221,891.90	5,242,449.14	5,265,877.94	5,292,350.59	5,322,049.73	5,355,168.95	5,391,913.45	5,432,500.76	5,477,161.42
13,381,826.63	**13,427,722.04**	**13,480,583.50**	**13,540,828.98**	**13,608,901.52**	**13,685,270.74**	**13,770,434.45**	**13,864,920.31**	**13,969,287.66**	**14,084,129.37**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
13,381,826.63	**13,427,722.04**	**13,480,583.50**	**13,540,828.98**	**13,608,901.52**	**13,685,270.74**	**13,770,434.45**	**13,864,920.31**	**13,969,287.66**	**14,084,129.37**
7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40	7,503,489.40
-	-	-	-	-	-	-	-	-	-
20,885,316.03	**20,931,211.44**	**20,984,072.90**	**21,044,318.38**	**21,112,390.92**	**21,188,760.14**	**21,273,923.85**	**21,368,409.71**	**21,472,777.06**	**21,587,618.77**
20,885,316.03	**20,931,211.44**	**20,984,072.90**	**21,044,318.38**	**21,112,390.92**	**21,188,760.14**	**21,273,923.85**	**21,368,409.71**	**21,472,777.06**	**21,587,618.77**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,687,521.34	2,848,772.62	3,019,698.98	3,200,880.92	3,392,933.77	3,596,509.80	3,812,300.39	4,041,038.41	4,283,500.72	4,540,510.76
5,204,043.69	5,221,891.90	5,242,449.14	5,265,877.94	5,292,350.59	5,322,049.73	5,355,168.95	5,391,913.45	5,432,500.76	5,477,161.42
7,891,565.03	8,070,664.52	8,262,148.12	8,466,758.85	8,685,284.36	8,918,559.53	9,167,469.34	9,432,951.87	9,716,001.47	10,017,672.18
2,765,945.40	2,571,562.44	2,393,250.01	2,229,562.23	2,079,188.02	1,940,938.40	1,813,734.94	1,696,599.31	1,588,643.88	1,489,063.14
1,280,888.80	1,275,551.76	1,270,214.73	1,264,877.69	1,259,540.65	1,254,203.62	1,248,866.58	1,243,529.54	1,238,192.51	1,232,855.47
448,943.71	406,430.10	367,935.96	333,081.83	301,524.02	272,951.25	247,081.60	223,659.72	202,454.37	183,256.11

Annexure G.4 - Cash Flow Analysis for 1 MWp DCCU + String Inverter Model (Average Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Energy Supplied (MWh)						1,428.00	1,423.00	1,417.00	1,411.00	1,406.00	1,400.00	1,394.00	1,389.00	1,383.00	1,378.00
Tariff Paid By CEB															
Tier 1	18.27	LKR/ kWh				26,089,560.00	25,998,210.00	25,888,590.00	25,778,970.00	25,687,620.00	25,578,000.00	25,468,380.00	25,377,030.00	25,267,410.00	25,176,060.00
O&M cost	1%	From project cost	6%	of annual increment		1,278,235.75	1,354,929.90	1,436,225.69	1,522,399.23	1,613,743.18	1,710,567.77	1,813,201.84	1,921,993.95	2,037,313.59	2,159,552.40
Depreciation						(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)
Finance cost						(13,421,475.38)	(10,737,180.30)	(8,052,885.23)	(5,368,590.15)	(2,684,295.08)					
Profit before tax						7,555,141.62	10,224,780.85	12,880,751.71	15,541,600.33	18,225,889.36	20,897,389.02	20,890,403.09	20,907,845.20	20,913,544.84	20,944,433.65
Tax			28%			2,115,439.66	2,862,938.64	3,606,610.48	4,351,648.09	5,103,249.02	5,851,268.93	5,849,312.87	5,854,196.66	5,855,792.55	5,864,441.42
Profit after tax						**5,439,701.97**	**7,361,842.21**	**9,274,141.23**	**11,189,952.24**	**13,122,640.34**	**15,046,120.10**	**15,041,090.23**	**15,053,648.55**	**15,057,752.28**	**15,079,992.23**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Profit after tax						**5,439,701.97**	**7,361,842.21**	**9,274,141.23**	**11,189,952.24**	**13,122,640.34**	**15,046,120.10**	**15,041,090.23**	**15,053,648.55**	**15,057,752.28**	**15,079,992.23**
Add															
Depreciation						6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75
Finance cost						13,421,475.38	10,737,180.30	8,052,885.23	5,368,590.15	2,684,295.08	-	-	-	-	-
Net flow of project					**(127,823,575.00)**	**25,252,356.10**	**24,490,201.26**	**23,718,205.21**	**22,949,721.14**	**22,198,114.16**	**21,437,298.85**	**21,432,268.98**	**21,444,827.30**	**21,448,931.03**	**21,471,170.98**
Project IRR					**17.17%**										
Less															
Finance Cost						(13,421,475.38)	(10,737,180.30)	(8,052,885.23)	(5,368,590.15)	(2,684,295.08)					
Capital Repayments						(19,173,536.25)	(19,173,536.25)	(19,173,536.25)	(19,173,536.25)	(19,173,536.25)					
Cash Inflow					**(31,955,893.75)**	**(7,342,655.53)**	**(5,420,515.29)**	**(3,508,216.27)**	**(1,592,405.26)**	**340,282.84**	**21,437,298.85**	**21,432,268.98**	**21,444,827.30**	**21,448,931.03**	**21,471,170.98**
Equity IRR					**18.79%**										

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Costs Over Lifetime															
Capital Repayment		LKR			31,955,893.75	19,173,536.25	19,173,536.25	19,173,536.25	19,173,536.25	19,173,536.25	-	-	-	-	-
Finance Cost		LKR				13,421,475.38	10,737,180.30	8,052,885.23	5,368,590.15	2,684,295.08	-	-	-	-	-
O&M Cost		LKR				1,278,235.75	1,354,929.90	1,436,225.69	1,522,399.23	1,613,743.18	1,710,567.77	1,813,201.84	1,921,993.95	2,037,313.59	2,159,552.40
Taxation		LKR				2,115,439.66	2,862,938.64	3,606,610.48	4,351,648.09	5,103,249.02	5,851,268.93	5,849,312.87	5,854,196.66	5,855,792.55	5,864,441.42
Total Costs		LKR			31,955,893.75	35,988,687.03	34,128,585.08	32,269,257.64	30,416,173.72	28,574,823.53	7,561,836.70	7,662,514.71	7,776,190.61	7,893,106.14	8,023,993.83
Present Value of Costs Over Lifetime		LKR			31,955,893.75	32,716,988.21	28,205,442.22	24,244,370.88	20,774,655.91	17,742,717.23	4,268,459.68	3,932,081.63	3,627,650.31	3,347,447.52	3,093,596.97
Electricity Generation Over Lifetime															
Energy Supplied		kWh				1,428,000.00	1,423,000.00	1,417,000.00	1,411,000.00	1,406,000.00	1,400,000.00	1,394,000.00	1,389,000.00	1,383,000.00	1,378,000.00
Present Value of Energy Over Lifetime						1,298,181.82	1,176,033.06	1,064,613.07	963,731.99	873,015.38	790,263.50	715,342.42	647,978.75	586,527.01	531,278.65
LCOE				16.44	**LKR/kWh**										

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
1,372.00	1,366.00	1,361.00	1,355.00	1,349.00	1,344.00	1,338.00	1,333.00	1,327.00	1,321.00
25,066,440.00	24,956,820.00	24,865,470.00	24,755,850.00	24,646,230.00	24,554,880.00	24,445,260.00	24,353,910.00	24,244,290.00	24,134,670.00
2,289,125.55	2,426,473.08	2,572,061.47	2,726,385.15	2,889,968.26	3,063,366.36	3,247,168.34	3,441,998.44	3,648,518.35	3,867,429.45
(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)
20,964,386.80	20,992,114.33	21,046,352.72	21,091,056.40	21,145,019.51	21,227,067.61	21,301,249.59	21,404,729.69	21,501,629.60	21,610,920.70
5,870,028.30	5,877,792.01	5,892,978.76	5,905,495.79	5,920,605.46	5,943,578.93	5,964,349.89	5,993,324.31	6,020,456.29	6,051,057.80
15,094,358.49	**15,114,322.32**	**15,153,373.96**	**15,185,560.61**	**15,224,414.05**	**15,283,488.68**	**15,336,899.71**	**15,411,405.38**	**15,481,173.31**	**15,559,862.90**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
15,094,358.49	**15,114,322.32**	**15,153,373.96**	**15,185,560.61**	**15,224,414.05**	**15,283,488.68**	**15,336,899.71**	**15,411,405.38**	**15,481,173.31**	**15,559,862.90**
6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75
-	-	-	-	-	-	-	-	-	-
21,485,537.24	**21,505,501.07**	**21,544,552.71**	**21,576,739.36**	**21,615,592.80**	**21,674,667.43**	**21,728,078.46**	**21,802,584.13**	**21,872,352.06**	**21,951,041.65**
21,485,537.24	**21,505,501.07**	**21,544,552.71**	**21,576,739.36**	**21,615,592.80**	**21,674,667.43**	**21,728,078.46**	**21,802,584.13**	**21,872,352.06**	**21,951,041.65**

11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
2,289,125.55	2,426,473.08	2,572,061.47	2,726,385.15	2,889,968.26	3,063,366.36	3,247,168.34	3,441,998.44	3,648,518.35	3,867,429.45
5,870,028.30	5,877,792.01	5,892,978.76	5,905,495.79	5,920,605.46	5,943,578.93	5,964,349.89	5,993,324.31	6,020,456.29	6,051,057.80
8,159,153.85	8,304,265.09	8,465,040.23	8,631,880.95	8,810,573.73	9,006,945.29	9,211,518.23	9,435,322.75	9,668,974.64	9,918,487.24
2,859,733.65	2,645,994.78	2,452,020.63	2,273,044.04	2,109,181.30	1,960,173.72	1,822,449.77	1,697,025.73	1,580,954.62	1,474,319.93
1,372,000.00	1,366,000.00	1,361,000.00	1,355,000.00	1,349,000.00	1,344,000.00	1,338,000.00	1,333,000.00	1,327,000.00	1,321,000.00
480,877.63	435,249.70	394,233.22	356,813.85	322,939.87	292,493.56	264,716.17	239,751.77	216,975.10	196,358.23

Annexure G.4 - Cash Flow Analysis for 1 MWp DCCU + String Inverter Model (Best Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Energy Supplied (MWh)						1,511.07	1,505.78	1,499.43	1,493.08	1,487.79	1,481.44	1,475.09	1,469.80	1,463.45	1,458.16	1,451.81	1,445.46	1,440.17	1,433.82
Tariff Paid By CEB																			
Tier 1	18.27	LKR/ kWh				27,607,189.71	27,510,525.88	27,394,529.28	27,278,532.68	27,181,868.86	27,065,872.26	26,949,875.66	26,853,211.84	26,737,215.24	26,640,551.41	26,524,554.81	26,408,558.22	26,311,894.39	26,195,897.79
O&M cost	1%	From project cost	6%	of annual increment		1,278,235.75	1,354,929.90	1,436,225.69	1,522,399.23	1,613,743.18	1,710,567.77	1,813,201.84	1,921,993.95	2,037,313.59	2,159,552.40	2,289,125.55	2,426,473.08	2,572,061.47	2,726,385.15
Depreciation						(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)
Finance cost						(13,421,475.38)	(10,737,180.30)	(8,052,885.23)	(5,368,590.15)	(2,684,295.08)									
Profit before tax						9,072,771.33	11,737,096.72	14,386,690.99	17,041,163.01	19,720,138.21	22,385,261.28	22,371,898.76	22,384,027.04	22,383,350.08	22,408,925.06	22,422,501.61	22,443,852.55	22,492,777.11	22,531,104.20
Tax			28%			2,540,375.97	3,286,387.08	4,028,273.48	4,771,525.64	5,521,638.70	6,267,873.16	6,264,131.65	6,267,527.57	6,267,338.02	6,274,499.02	6,278,300.45	6,284,278.71	6,297,977.59	6,308,709.18
Profit after tax						**6,532,395.36**	**8,450,709.64**	**10,358,417.52**	**12,269,637.37**	**14,198,499.51**	**16,117,388.13**	**16,107,767.10**	**16,116,499.47**	**16,116,012.06**	**16,134,426.05**	**16,144,201.16**	**16,159,573.84**	**16,194,799.52**	**16,222,395.02**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Profit after tax						**6,532,395.36**	**8,450,709.64**	**10,358,417.52**	**12,269,637.37**	**14,198,499.51**	**16,117,388.13**	**16,107,767.10**	**16,116,499.47**	**16,116,012.06**	**16,134,426.05**	**16,144,201.16**	**16,159,573.84**	**16,194,799.52**	**16,222,395.02**
Add																			
Depreciation						6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75
Finance cost						13,421,475.38	10,737,180.30	8,052,885.23	5,368,590.15	2,684,295.08	-	-	-	-	-	-	-	-	-
Net flow of project					**(127,823,575.00)**	**26,345,049.48**	**25,579,068.69**	**24,802,481.49**	**24,029,406.27**	**23,273,973.34**	**22,508,566.88**	**22,498,945.85**	**22,507,678.22**	**22,507,190.81**	**22,525,604.80**	**22,535,379.91**	**22,550,752.59**	**22,585,978.27**	**22,613,573.77**
Project IRR					**18.12%**														
Less																			
Finance Cost						(13,421,475.38)	(10,737,180.30)	(8,052,885.23)	(5,368,590.15)	(2,684,295.08)									
Capital Repayments						(19,173,536.25)	(19,173,536.25)	(19,173,536.25)	(19,173,536.25)	(19,173,536.25)									
Cash Inflow					**(31,955,893.75)**	**(6,249,962.14)**	**(4,331,647.86)**	**(2,423,939.98)**	**(512,720.13)**	**1,416,142.01**	**22,508,566.88**	**22,498,945.85**	**22,507,678.22**	**22,507,190.81**	**22,525,604.80**	**22,535,379.91**	**22,550,752.59**	**22,585,978.27**	**22,613,573.77**
Equity IRR					**20.34%**														

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Costs Over Lifetime																			
Capital Repayment		LKR			31,955,893.75	19,173,536.25	19,173,536.25	19,173,536.25	19,173,536.25	19,173,536.25	-	-	-	-	-	-	-	-	-
Finance Cost		LKR				13,421,475.38	10,737,180.30	8,052,885.23	5,368,590.15	2,684,295.08	-	-	-	-	-	-	-	-	-
O&M Cost		LKR				1,278,235.75	1,354,929.90	1,436,225.69	1,522,399.23	1,613,743.18	1,710,567.77	1,813,201.84	1,921,993.95	2,037,313.59	2,159,552.40	2,289,125.55	2,426,473.08	2,572,061.47	2,726,385.15
Taxation		LKR				2,540,375.97	3,286,387.08	4,028,273.48	4,771,525.64	5,521,638.70	6,267,873.16	6,264,131.65	6,267,527.57	6,267,338.02	6,274,499.02	6,278,300.45	6,284,278.71	6,297,977.59	6,308,709.18
Total Costs		LKR			31,955,893.75	36,413,623.35	34,552,033.53	32,690,920.64	30,836,051.27	28,993,213.21	7,978,440.93	8,077,333.49	8,189,521.52	8,304,651.61	8,434,051.42	8,567,426.00	8,710,751.80	8,870,039.06	9,035,094.33
Present Value of Costs Over Lifetime		LKR			31,955,893.75	33,103,293.95	28,555,399.61	24,561,172.53	21,061,437.93	18,002,504.31	4,503,621.91	4,144,949.26	3,820,472.23	3,521,982.97	3,251,691.93	3,002,830.55	2,775,513.97	2,569,334.36	2,379,222.72
Electricity Generation Over Lifetime																			
Energy Supplied		kWh				1,511,066.76	1,505,775.91	1,499,426.89	1,493,077.87	1,487,787.02	1,481,438.00	1,475,088.98	1,469,798.13	1,463,449.11	1,458,158.26	1,451,809.24	1,445,460.22	1,440,169.37	1,433,820.35
Present Value of Energy Over Lifetime						1,373,697.05	1,244,442.90	1,126,541.62	1,019,792.28	923,798.68	836,233.13	756,953.89	685,671.68	620,645.28	562,183.13	508,850.28	460,568.17	417,165.77	377,569.71
LCOE				**15.82**	**LKR/kWh**														

15.00	16.00	17.00	18.00	19.00	20.00
1,427.47	1,422.18	1,415.83	1,410.54	1,404.19	1,397.84
26,079,901.20	25,983,237.37	25,867,240.77	25,770,576.94	25,654,580.35	25,538,583.75
2,889,968.26	3,063,366.36	3,247,168.34	3,441,998.44	3,648,518.35	3,867,429.45
(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)
22,578,690.71	22,655,424.98	22,723,230.37	22,821,396.64	22,911,919.95	23,014,834.45
6,322,033.40	6,343,518.99	6,362,504.50	6,389,991.06	6,415,337.59	6,444,153.65
16,256,657.31	**16,311,905.98**	**16,360,725.86**	**16,431,405.58**	**16,496,582.36**	**16,570,680.81**

15.00	16.00	17.00	18.00	19.00	20.00
16,256,657.31	**16,311,905.98**	**16,360,725.86**	**16,431,405.58**	**16,496,582.36**	**16,570,680.81**
6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75
-	-	-	-	-	-
22,647,836.06	**22,703,084.73**	**22,751,904.61**	**22,822,584.33**	**22,887,761.11**	**22,961,859.56**
22,647,836.06	**22,703,084.73**	**22,751,904.61**	**22,822,584.33**	**22,887,761.11**	**22,961,859.56**

15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-
-	-	-	-	-	-
2,889,968.26	3,063,366.36	3,247,168.34	3,441,998.44	3,648,518.35	3,867,429.45
6,322,033.40	6,343,518.99	6,362,504.50	6,389,991.06	6,415,337.59	6,444,153.65
9,212,001.66	9,406,885.35	9,609,672.84	9,831,989.50	10,063,855.93	10,311,583.10
2,205,279.96	2,047,212.33	1,901,222.54	1,768,369.73	1,645,520.86	1,532,751.12
1,427,471.33	1,422,180.48	1,415,831.46	1,410,540.61	1,404,191.59	1,397,842.57
341,725.29	309,507.91	280,114.71	253,698.13	229,596.55	207,780.39

Annexure G.4 - Cash Flow Analysis for 1 MWp DCCU + String Inverter Model (Worst Case)

Profit and Loss Statement

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Energy Supplied (MWh)						1,344.93	1,340.22	1,334.57	1,328.92	1,324.21	1,318.56	1,312.91	1,308.20	1,302.55	1,297.84	1,292.19	1,286.54	1,281.83	1,276.18
Tariff Paid By CEB																			
Tier 1	18.27	LKR/ kWh				24,571,930.29	24,485,894.12	24,382,650.72	24,279,407.32	24,193,371.14	24,090,127.74	23,986,884.34	23,900,848.16	23,797,604.76	23,711,568.59	23,608,325.19	23,505,081.78	23,419,045.61	23,315,802.21
O&M cost	1%	From project cost	6%	of annual increment		1,278,235.75	1,354,929.90	1,436,225.69	1,522,399.23	1,613,743.18	1,710,567.77	1,813,201.84	1,921,993.95	2,037,313.59	2,159,552.40	2,289,125.55	2,426,473.08	2,572,061.47	2,726,385.15
Depreciation						(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)
Finance cost						(13,421,475.38)	(10,737,180.30)	(8,052,885.23)	(5,368,590.15)	(2,684,295.08)									
Profit before tax						6,037,511.92	8,712,464.97	11,374,812.43	14,042,037.65	16,731,640.50	19,409,516.76	19,408,907.43	19,431,663.37	19,443,739.60	19,479,942.24	19,506,271.98	19,540,376.11	19,599,928.33	19,651,008.61
Tax			28%			1,690,503.34	2,439,490.19	3,184,947.48	3,931,770.54	4,684,859.34	5,434,664.69	5,434,494.08	5,440,865.74	5,444,247.09	5,454,383.83	5,461,756.16	5,471,305.31	5,487,979.93	5,502,282.41
Profit after tax						**4,347,008.58**	**6,272,974.78**	**8,189,864.95**	**10,110,267.10**	**12,046,781.16**	**13,974,852.07**	**13,974,413.35**	**13,990,797.62**	**13,999,492.51**	**14,025,558.42**	**14,044,515.83**	**14,069,070.80**	**14,111,948.40**	**14,148,726.20**

Cash Flow

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Profit after tax						**4,347,008.58**	**6,272,974.78**	**8,189,864.95**	**10,110,267.10**	**12,046,781.16**	**13,974,852.07**	**13,974,413.35**	**13,990,797.62**	**13,999,492.51**	**14,025,558.42**	**14,044,515.83**	**14,069,070.80**	**14,111,948.40**	**14,148,726.20**
Add																			
Depreciation						6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75
Finance cost						13,421,475.38	10,737,180.30	8,052,885.23	5,368,590.15	2,684,295.08	-	-	-	-	-	-	-	-	-
Net flow of project					**(127,823,575.00)**	**24,159,662.71**	**23,401,333.83**	**22,633,928.93**	**21,870,036.00**	**21,122,254.99**	**20,366,030.82**	**20,365,592.10**	**20,381,976.37**	**20,390,671.26**	**20,416,737.17**	**20,435,694.58**	**20,460,249.55**	**20,503,127.15**	**20,539,904.95**
Project IRR					**16.21%**														
Less																			
Finance Cost						(13,421,475.38)	(10,737,180.30)	(8,052,885.23)	(5,368,590.15)	(2,684,295.08)									
Capital Repayments						(19,173,536.25)	(19,173,536.25)	(19,173,536.25)	(19,173,536.25)	(19,173,536.25)									
Cash Inflow					**(31,955,893.75)**	**(8,435,348.92)**	**(6,509,382.72)**	**(4,592,492.55)**	**(2,672,090.40)**	**(735,576.34)**	**20,366,030.82**	**20,365,592.10**	**20,381,976.37**	**20,390,671.26**	**20,416,737.17**	**20,435,694.58**	**20,460,249.55**	**20,503,127.15**	**20,539,904.95**
Equity IRR					**17.28%**														

Assumptions:

1. 100% depreciation over 20 years with unit rate.
2. O&M is 1% from total project cost with 6% annual escalation
3. USD 1 = 170 LKR
4. Tax rate 28% from total income

LCOE

Year					-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00	13.00	14.00
Costs Over Lifetime																			
Capital Repayment		LKR			31,955,893.75	19,173,536.25	19,173,536.25	19,173,536.25	19,173,536.25	19,173,536.25	-	-	-	-	-	-	-	-	-
Finance Cost		LKR				13,421,475.38	10,737,180.30	8,052,885.23	5,368,590.15	2,684,295.08	-	-	-	-	-	-	-	-	-
O&M Cost		LKR				1,278,235.75	1,354,929.90	1,436,225.69	1,522,399.23	1,613,743.18	1,710,567.77	1,813,201.84	1,921,993.95	2,037,313.59	2,159,552.40	2,289,125.55	2,426,473.08	2,572,061.47	2,726,385.15
Taxation		LKR				1,690,503.34	2,439,490.19	3,184,947.48	3,931,770.54	4,684,859.34	5,434,664.69	5,434,494.08	5,440,865.74	5,444,247.09	5,454,383.83	5,461,756.16	5,471,305.31	5,487,979.93	5,502,282.41
Total Costs		LKR			31,955,893.75	35,563,750.71	33,705,136.64	31,847,594.65	29,996,296.17	28,156,433.85	7,145,232.47	7,247,695.92	7,362,859.69	7,481,560.68	7,613,936.23	7,750,881.70	7,897,778.39	8,060,041.40	8,228,667.57
Present Value of Costs Over Lifetime		LKR			31,955,893.75	32,330,682.47	27,855,484.82	23,927,569.23	20,487,873.90	17,482,930.16	4,033,297.45	3,719,214.00	3,434,828.39	3,172,912.06	2,935,502.02	2,716,636.75	2,516,475.59	2,334,706.89	2,166,865.35
Electricity Generation Over Lifetime																			
Energy Supplied		kWh				1,344,933.24	1,340,224.09	1,334,573.11	1,328,922.13	1,324,212.98	1,318,562.00	1,312,911.02	1,308,201.87	1,302,550.89	1,297,841.74	1,292,190.76	1,286,539.78	1,281,830.63	1,276,179.65
Present Value of Energy Over Lifetime						1,222,666.58	1,107,623.21	1,002,684.53	907,671.70	822,232.08	744,293.87	673,730.95	610,285.83	552,408.73	500,374.17	452,904.98	409,931.22	371,300.67	336,057.99
LCOE				17.14	**LKR/kWh**														

15.00	16.00	17.00	18.00	19.00	20.00
1,270.53	1,265.82	1,260.17	1,255.46	1,249.81	1,244.16
23,212,558.80	23,126,522.63	23,023,279.23	22,937,243.06	22,833,999.65	22,730,756.25
2,889,968.26	3,063,366.36	3,247,168.34	3,441,998.44	3,648,518.35	3,867,429.45
(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)	(6,391,178.75)
19,711,348.31	19,798,710.24	19,879,268.82	19,988,062.75	20,091,339.25	20,207,006.94
5,519,177.53	5,543,638.87	5,566,195.27	5,596,657.57	5,625,574.99	5,657,961.94
14,192,170.79	**14,255,071.37**	**14,313,073.55**	**14,391,405.18**	**14,465,764.26**	**14,549,045.00**

15.00	16.00	17.00	18.00	19.00	20.00
14,192,170.79	**14,255,071.37**	**14,313,073.55**	**14,391,405.18**	**14,465,764.26**	**14,549,045.00**
6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75	6,391,178.75
-	-	-	-	-	-
20,583,349.54	**20,646,250.12**	**20,704,252.30**	**20,782,583.93**	**20,856,943.01**	**20,940,223.75**
20,583,349.54	**20,646,250.12**	**20,704,252.30**	**20,782,583.93**	**20,856,943.01**	**20,940,223.75**

15.00	16.00	17.00	18.00	19.00	20.00
-	-	-	-	-	-
-	-	-	-	-	-
2,889,968.26	3,063,366.36	3,247,168.34	3,441,998.44	3,648,518.35	3,867,429.45
5,519,177.53	5,543,638.87	5,566,195.27	5,596,657.57	5,625,574.99	5,657,961.94
8,409,145.79	8,607,005.23	8,813,363.61	9,038,656.01	9,274,093.34	9,525,391.39
2,013,082.64	1,873,135.11	1,743,677.01	1,625,681.73	1,516,388.37	1,415,888.74
1,270,528.67	1,265,819.52	1,260,168.54	1,255,459.39	1,249,808.41	1,244,157.43
304,154.46	275,479.21	249,317.63	225,805.41	204,353.66	184,936.07