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Institutional Rooftop Solar

NIAS Experience with a 100 kWp Solar System

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National Institute of Advanced Studies
Bengaluru, India

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By

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Message from the Director

Karnataka is deficit in electricity causing economic loss and inconveniences. Industries, educational institutes, offices, shopping complexes, market spaces, houses, etc. offer enormous opportunities to harness solar energy. This must be coupled with efficient building design and implementation based on life cycle concepts.

We, at National Institute of Advanced Studies (NIAS) have a 100kWp grid tied roof top solar photovoltaic plant operational since October 2014. The plant was installed with 30% financial support from Ministry of New and Renewable Energy (MNRE). Presently 40-50% of NIAS's monthly electricity consumption comes from solar. A substantial amount of solar generated electricity is exported to the grid during the day. The stipulated payback period assuming present trends continue, works out to be eight years.

This report evaluates the performance of 100kWp grid tied roof top solar plant located at NIAS from generation, economic and maintenance perspective. This plant is not only financially beneficial for NIAS but also one of the pioneers of green energy initiative of educational institutions at Bangalore. This report shares the benefits accrued from this plant. We, at NIAS, encourage other educational institutions and entities to participate in the green initiative based on our experiences, lessons learnt and new technologies and opportunities.

Prof. Baldev Raj
Director, NIAS

Foreword

Chronic shortages and load shedding have always characterized distribution of electricity across India, partly due to the mismatch between production and demand of electric power and partly due to the poor distribution infrastructure. As a result, urban centers like Bengaluru not only suffer unavoidable inconvenience to the public but also large economic loss to the Industry and to the country. The Government has been encouraging roof top solar installations, both solar thermal and solar electricity through PV panels, to reduce demand on the grid. Bengaluru is endowed with ample sunlight throughout the year with moderate temperatures with a very few cloudy days.

Academic Institutions like NIAS have a unique advantage that they have a steady electricity demand during working hours, low demand during the nights, weekends (Saturday, Sunday) and holidays. They also have a fairly large unutilized terrace space. Installation of solar panels on the terraces will not only cater to their electricity requirement during the day but also surplus energy produced during weekends that could be pumped into the grid. Installation of solar panels on institutional rooftops seems to be an appropriate choice not only to reduce their power bills but also to reduce deficits in the city.

With these objectives in mind, we in the National Institute of Advanced Studies (NIAS) decided to install a PV based solar power plant on the terrace of our institute building with a dual objective to generate substantial part of our electricity consumption and save on our electricity bill and also serve as a model for other educational institutes in Bangalore.

I congratulate both the authors and the Energy Environment Programme at NIAS for coming out with this booklet. In this booklet we share our experience to encourage other educational institutions to come forward and participate in this green initiative. It would be their contribution, even though small, to reduce Karnataka's growing power deficit sustainably. But if all the institutions in Karnataka make this small effort in having solar plants at their unused rooftops, this initiative would definitely reduce Karnataka's future electricity deficits substantially.

Prof. VS Ramamurthy
Emeritus Professor, NIAS

1. Introduction

Karnataka is the most power deficit state in the Southern regional grid. The average and peak deficit has been higher than the national average for the last five years[1,2]. Chronic power deficits result in load shedding leading to not only inconveniences, but also economic losses (Bose et al, 2006). One of the solutions to address power deficits is to utilize vacant rooftops and install solar panels. Institutions like schools, colleges, universities, and offices are suited specifically for this purpose as these have their major electricity requirement during the day when the sun is available (8am to 6pm). Rooftop solar power can meet a substantial portion of institutional electricity demand on working days; also it can be exported to the grid during weekends and holidays, when the institutes' activities are minimal.

At the National Institute of Advanced Studies (NIAS), we decided to go green by installing a solar PV (photovoltaic) system on our institute buildings. This plant was installed with two objectives. The first objective was to generate a substantial part of our electricity consumption and make the system economically rewarding. The second objective was to motivate institutes in Bangalore and elsewhere by being a pioneer in undertaking green energy initiative in terms of rooftop solar. We installed a 100kWp grid-tied rooftop solar PV plant which has been operational since October 2014. The plant was installed with 30% financial support from Ministry of New and Renewable Energy (MNRE).

The average monthly (30 days) generation from the plant from April 2015 to June 2016 is 11191 kWh. This typically accounts for 60-65% of NIAS's monthly electricity consumption. This has resulted in a monthly saving of Rs 60,000 to 70,000 in the electricity bill of NIAS. The plant exported a monthly average of 3676 kWh, i.e., approximately one-third of the generation to the grid. However, NIAS is a net importer from the grid as its electricity consumption is more than the solar generation. The plant has been running since its inception in October 2014 to June 2016 with an average capacity utilization factor of 16.3%. The stipulated payback period of a typical system like that of NIAS with 30% subsidy and 50 lakh investment turns out to be eight years.

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1 These deficit values are the difference between requirement and availability expressed as a percentage of requirement. The requirement is based on the unmet demand of the connected load. It does not include the households and other entities which are outside the grid access. In this sense, energy deficit is indicative of load-shedding.

2 Karnataka's power deficits (electricity energy deficit and peak power deficit) in last five years, viz., 2011-12, 2012-13, 2013-14, 2014-15, and 2015-16 are (11.2 and 18.9), (13.9 and 13.5), (9.5 and 7.2), (4.3 and 4.5), and (5.2 and 6.8), respectively, whereas the corresponding figures for the entire country are (8.5 and 10.6), (8.7 and 9.0), (4.2 and 4.5), (3.6 and 4.7), and (2.1 and 3.2), respectively (MoP 2014; 2015; CEA 2015; 2016). The actual shortages in Karnataka in the last two years are lower because of lower energy requirement; not because of the higher availability (CEA 2015; 2016).

2. Basics of Solar PV System

2.1 Solar PV Technology

In solar PV system, sun light is used to generate electricity with the help of PV cells (also called solar cells). The solar energy is directly converted to electrical energy based on the principle of 'photovoltaic effect'.[3] When sunlight falls on solar cells that are made of semiconductor materials, solar energy knocks out elections to be free to flow through the material to produce current (Renewable Energy World, 2016). The generated electricity is of DC type. An inverter can be used to convert this to AC.

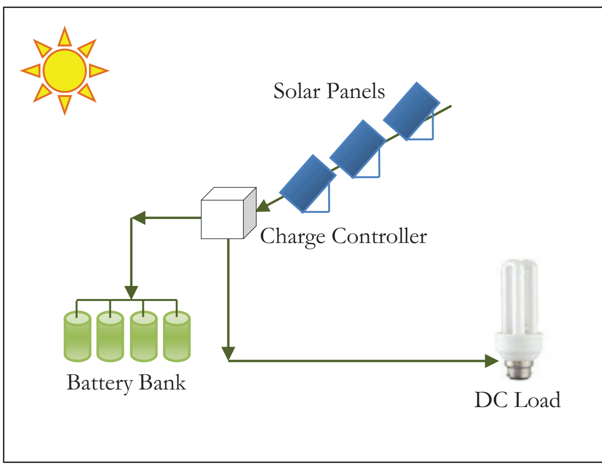

Figure 1(a): Off grid solar plant with DC Load

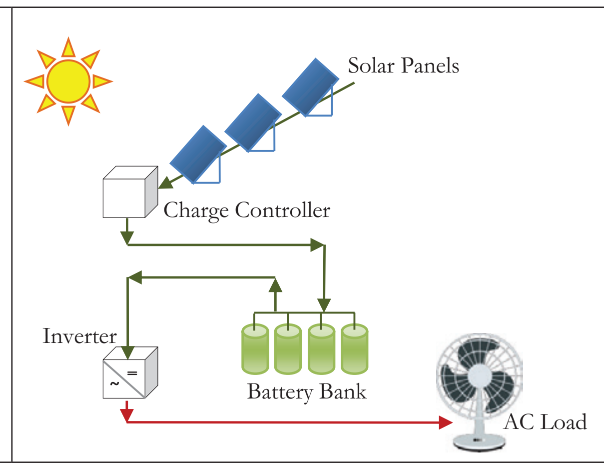

Figure 1(b): Off grid solar plant with AC Load

Figures 1(a) and 1(b) are the schematic sketches of a solar system with DC and AC electrical load, respectively. The components of the solar system are described in the next section.

2.2 Components of Solar PV System

The components of Solar PV system are listed below:

- Solar PV Array
- Battery Bank and Charge Controller
- Inverter
- Mounting structure

2.2.1 Solar PV Array

This is the most important component in solar PV system, which converts solar energy to electrical energy. The basic elements in the PV array are solar cells, which are connected electrically to form

[3] Photovoltaic effect is the process of converting light to electricity: when photons of incident light gets absorbed by solar cells—that comprises of p-type and n-type semiconductors joined together to create a p-n junction— energy from photons is transformed to electrons which escape their bonds to create pairs of electron-hole which in the presence of p-n junction move in opposite directions to produce electric current (Enis-PV, 2017; electrical4u, 2017; Energy Education, 2017).

PV module or PV panel.[4] Solar PV modules are the building blocks of PV system, which are wired in series and parallel into PV array (NREL, 1997).

The three main types of solar modules that are commercially available are: monocrystalline, polycrystalline, and thin film. Monocrystalline solar modules are made out of the highest-grade silicon; hence possessing the highest efficiency (15-20%), but most expensive (Maehlum, 2015). Polycrystalline solar modules are considered best valued as with a little lower efficiency (13-16%), it has significant cost advantages over monocrystalline solar panels (half the cost in some cases) (Maehlum, 2015; Pickerel, 2015). Compared to crystalline modules, thin film modules are simpler to produce; but are less efficient (7-13%), lower in space-efficiency, degrade faster, and have a shorter life (Maehlum, 2015).[5] The market shares of the three types of modules are: monocrystalline (36%), polycrystalline (55%), and thin film (9%) (Shah, 2016). The market share of polycrystalline is on the rise in recent years expectedly because of its lower cost and reasonably higher energy and space efficiency.

2.2.2 Battery Bank

A battery is used, particularly in the off-grid solar PV system, to store energy. Solar energy is only available during the day time; while electricity is also needed in the night, making storage necessary. Also, during the day depending on the cloud cover, the panel output would vary. A battery can smoothen out the variable output of the panels. The typical life of a battery is five years; use of battery increases the cost and maintenance requirement of the solar PV system.[6]

There are a few battery types which are used in solar PV system. The choice of type of battery depends on the cost, cycle life, and its installation and maintenance features (Zipp, 2015). Typical deep cycle lead-acid batteries have been used for decades for solar applications worldwide for decades, and will continue to dominate the market in the near future, mainly due to its lower cost (it costs as much as half of lithium ion), and reasonable reliability.[7]

Charge controller is used to regulate the flow of electricity from PV modules to batteries (NREL, 1997). It protects the batteries from overcharging or completely draining out and increases their life and performance.[8] It is required only when batteries are used in solar PV system.

2.2.3 Inverter

Inverters convert DC electricity output from the PV panels or that is stored in the battery, to AC electricity. This is done so that it can be used by AC load or appliances, and can be fed to the grid in case the system is connected to utility grid. Grid-tied inverters have safety feature such that it shuts down transmission of power from the solar PV array to the utility grid during load-shedding

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4 For further details on difference between solar cell, module, and array, see (Samlex, 2017).

5 Recent studies by NCPRE (2013-14) show thin films are having lesser degradation rates as compared to c-Si technologies.

6 The battery can add up to 25-30% of the initial cost of solar rooftop PV system (EAI, 2017; Solar Mango, 2017a; 2017b).

7 The further comparison of different types of solar batteries, see Zipp (2015), Solar Mango (2017b), among others.

8 If battery gets overcharged the charge controller cuts the circuit to the PV module. Similarly if the battery gets over discharged, the battery gets disconnected from the load.

(anti-islanding protection) (Renewable Edge, 2015). The role of inverters is expanding with added features enabling performance monitoring, battery management in case of storage, and providing diagnostic information to help operation and maintenance (Zipp, 2016).

Based on interactions with grid, inverters can be classified into three categories: off-grid inverter (no need of anti-islanding protection), on-grid inverter (synchronizes with the grid have anti-islanding protection), and hybrid inverter (additional feature of charging critical loads during load shedding).[9] Depending on the size and location, inverters are of three types: micro-inverter (one inverter per solar module/panel), string inverter (one inverter per string of panels), and central inverter (one inverter for typical large scale system) (Zipp, 2016). Irrespective of shading issues,[10] string inverters are commonly used by in residential and commercial sectors for its lower cost and greater reliability (Zipp, 2016).

2.2.4 Mounting Structure

The mounting structure is an important component and the following points must be taken into consideration in its design[11]: (i) adequate strength, (ii) panels in the northern hemisphere face south and vice versa, (iii) the tilt in the panel is same as the latitude, (iv) space for air circulation for cooling, (v) access for maintenance, (vi) include tracking cautiously as it increases cost of installation and maintenance, and (vii) whether the mounting roof is flat or sloped. Also, mounting of panels can be done either in landscape or portrait orientation; however the latter is preferred as it has less adverse impact of dirt shading compared to the former (Vikram Solar, 2017). Also, the panels are kept at an inclination of less than 1:2.4 to maintain the fire class rating (Vikram Solar, 2017).[12]

Barring the primary components explained above, there are other components such as UV resistant solar cables, other electrical cables, distribution boxes, switch gears, and other accessories. These components account for 6-7% of the total project cost for residential and commercial installations (Chung *et al*., 2015). Although in the past, the cost reduction in solar was driven by module price reduction, many argue that it is innovations in components other than panel which will drive further cost reduction (Munsell, 2014).

2.3 Site Selection and Area Requirement

Location of a solar plant plays a vital role in determining the generation from the plant. Most of India receives considerably good insolation (Figure 2). Hence, it is suitable for solar installations.

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9 For details on the three types of inverters, see Maehlum (2013).

10 Shading refers to a situation where one module gets shaded for a portion of the day reducing its performance then the output of every panel on the string is reduced to the shaded panels' level (Zipp, 2016).

11 Some of these points are inspired from Solar Mango (2017)

12 For details on the fire class and slope of panels, see Sherwood et al. (2013)

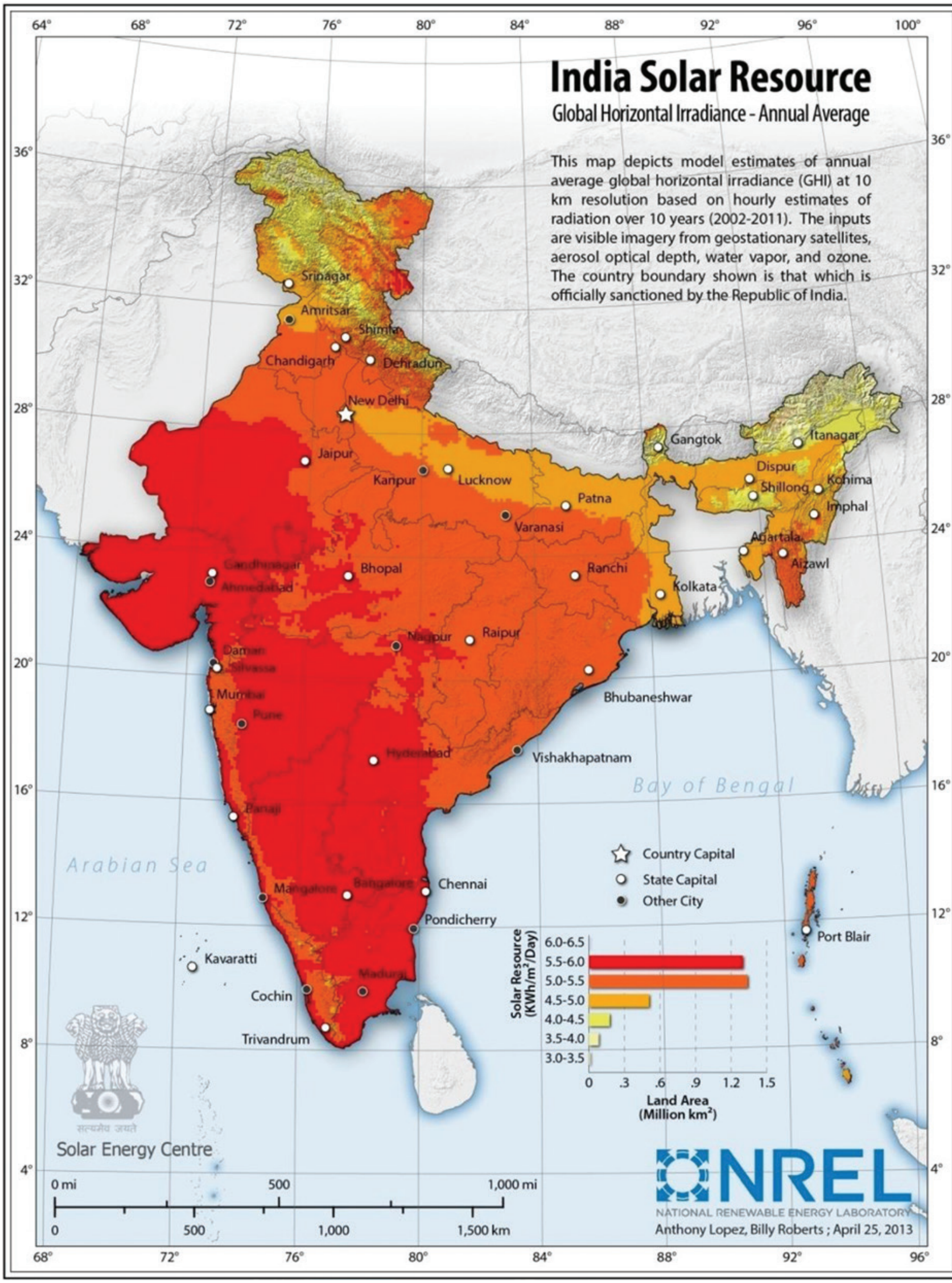


Figure 2 Solar resource in India

Map Source: NREL (2016)

On an average, installation of 1 kWp solar plant needs approximately 10 sqm of shadow free area (Gupta, 2012; MNRE, 2014; World Bank, 2015; Krishnan, 2016). Partial shadow on the panels increases the risk of hot spot creation on the panel damaging the panel partially and lead to module degradation (Maeda, 2011; NCPRE, 2013-14). This would result in reduced generation from the plant.

While choosing site for the plant, the following things have to be kept in mind (Vikram Solar, 2017):

- In case of any obstruction, the distance between the obstruction element and the solar array needs to be more than three times the height of the obstruction PV modules so that no or minimal shading occurs throughout the year.[13]
- No conflict with existing infrastructure like blocking of drainage holes.
- No possibility of panels immersed under water under any circumstances.
- Not to be installed on moving vehicles/vessels.

2.4 Interaction with the Grid

On the basis of interaction with the grid, solar PV systems can be divided into two categories (i) Off-grid systems and (ii) On grid systems. We describe them in turn.

2.4.1 Off-grid Type Solar Power Plants

Figure 3 gives a schematic representation of the off grid roof top solar power plant. The plant has no connection with the grid allowing for no import or export from the grid. It uses a dedicated battery storage unit for backup and firming up this intermittent power. Unlike on-grid plants, in this plant, any excess generation, when the battery is fully charged, is wasted. The batteries used for this purpose are mostly tubular type lead acid batteries. These battery banks need regular maintenance with distilled water.

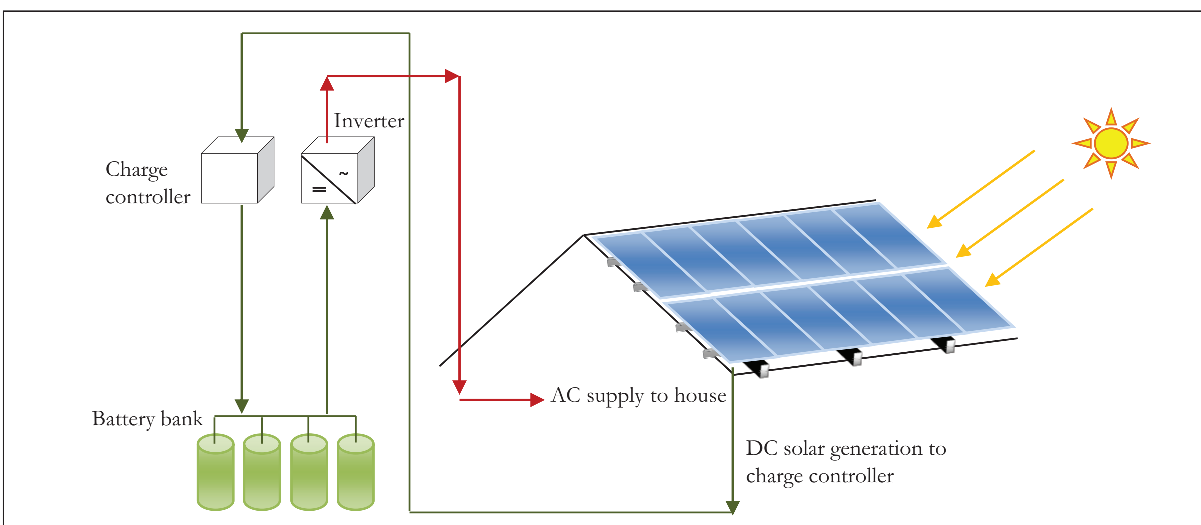


Figure 3 Off grid solar power plant

[13] Obstructions in the south side can cause more shading issues compared to the ones in the north since the sun path in northern hemisphere is mostly inclined to the south of the location.

Off-grid systems are usually smaller in size. Under Jawaharlal Nehru National Solar Mission (JNNSM), there was a target of 2 GW of off grid solar installation in India by 2022 (MNRE, 2010). However, within the Government of India's new 100GW solar target by 2022 (MNRE, 2016), off-grid systems did not feature.[14]

2.4.2 On-grid or Grid-interactive Type Solar Power Plant

Grid connected solar PV system can be of two kinds: Utility scale system and Rooftop system. Utility scale systems constitute 60GW of 100GW solar target by 2022 (MNRE, 2016). These systems are of large size and the same is not covered in this booklet. The other component of 100GW target is 40GW grid interactive rooftop projects. These systems are from 1 kWp to 500-1000 kWp size (MNRE, 2014).

Figure 4 gives a schematic representation of on grid rooftop solar system. These systems can avoid any other storage as the grid itself acts as the storage. The reference voltage for this type of plant is provided by the grid. The generated power is used in-house and the excess gets exported to the grid. Similarly, if the generation falls short of consumption, the required balance amount of electricity is imported from the grid. The premise installing the rooftop system becomes net exporter (importer) if the total generation exceeds (falls behind) the total consumption.

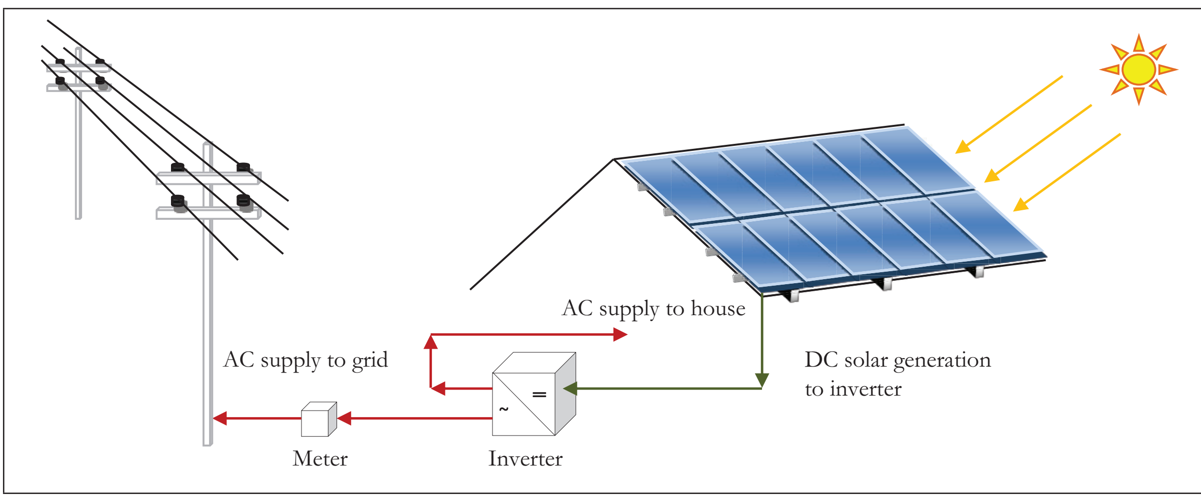


Figure 4 Grid-tied or grid interactive solar power plant

During load shedding or power outage, the solar inverters stop working (anti islanding protection) and the solar plants stop generating electricity. It results in a situation wherein regardless of the presence of the rooftop solar system, the consumer cannot get electricity during the load shedding hours. There are two ways to solve this: we may use a battery (Figure 5) or a diesel generator set (Figure 6) to provide the reference voltage while the grid is unavailable. This will make a local grid available for the inverter and the solar panels will resume operation.[15]

[14] With more and more grid penetration, the trend will be towards grid-interactive power. The proportion of completely isolated off-grid systems is expected to fall in future.

[15] In this case, there are special controllers to be used (eg. DEIF, SMA's fuel save controller etc.); otherwise if there is no load requirement, the solar power may feed into the DG/battery system causing damages.

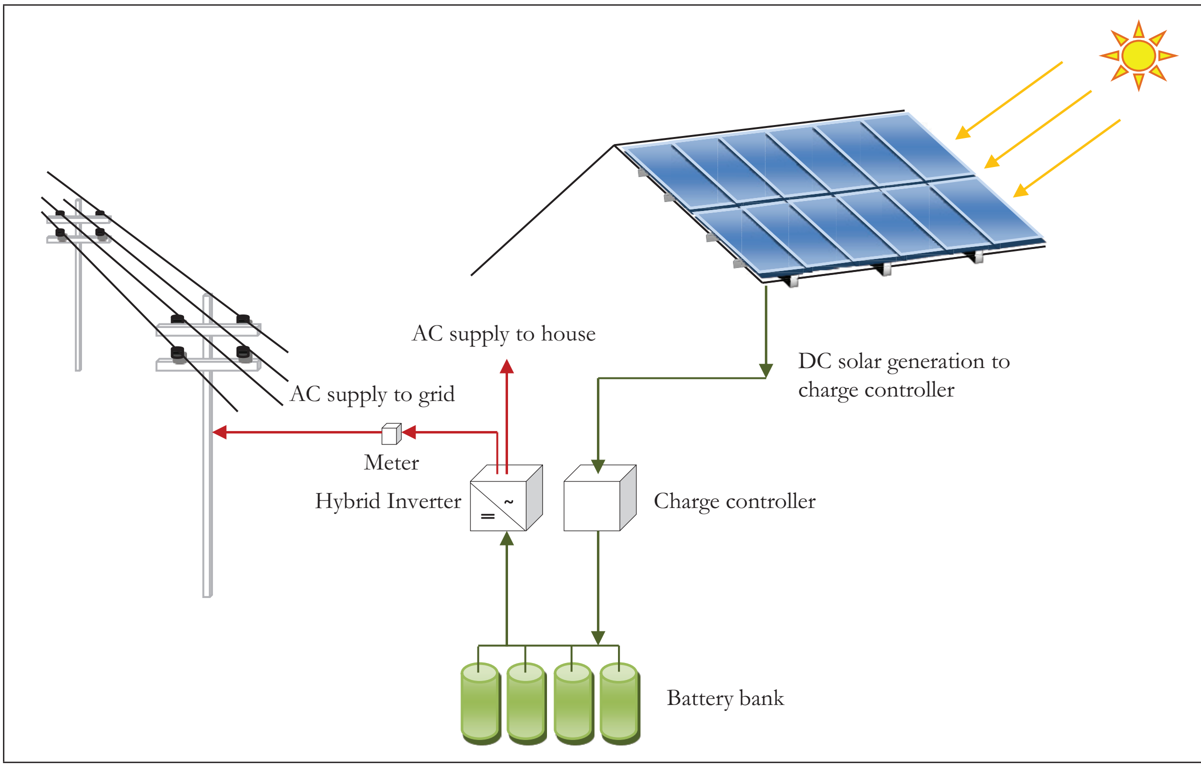


Figure 5 Grid-tied system with battery

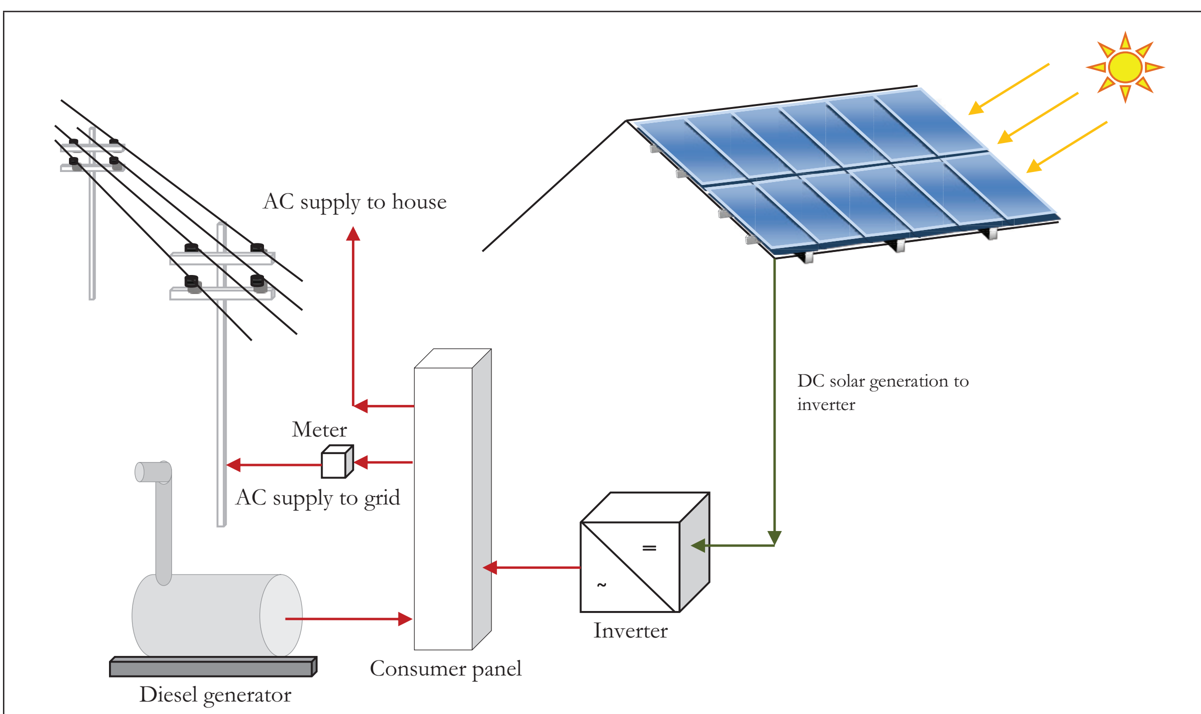


Figure 6 Grid tied system with diesel generator

3. Installation of Rooftop Solar Plant at NIAS

A 100kWp grid-tied roof top solar PV plant has been installed at NIAS. This has been operational since October 2014. The plant is located in the vacant roof space of two buildings of NIAS: the guest house block and the auditorium.[16] The guest house block subsystem is of 53kWp capacity and the auditorium block subsystem is of 47kWp capacity. Figure 7 shows solar power plant of NIAS in Google Maps (the two buildings having the system are marked).

Figure 7 100kWp solar power plant at NIAS

Source: Google Maps (2016)

The outputs from both the systems are connected to the institute grid through local AC distribution boards. This output can be used anywhere in the campus or exported to the grid. The schematic diagram of our system is similar to the scheme depicted in the Figure 6. Available diesel generator set is being used to create the local grid during load shedding.

The latitude and longitude of the installed locations are: guest house (13º 01' 44", 77º 33' 47") and auditorium (13º 01' 46", 77º 33' 50"). The rooftop areas used by the solar panels are 426sq.m. and 352sq.m., respectively. The single line diagram (SLD) of the plant is shown in Figure 8. Major components of the plant are,

- 245Wp Polycrystalline solar modules – 408 numbers
- 15kW String Inverters – 6 numbers
- Aluminium mounting structure
- Balance of System

[16] These two locations satisfied the site selection criteria identified in Section 2.3

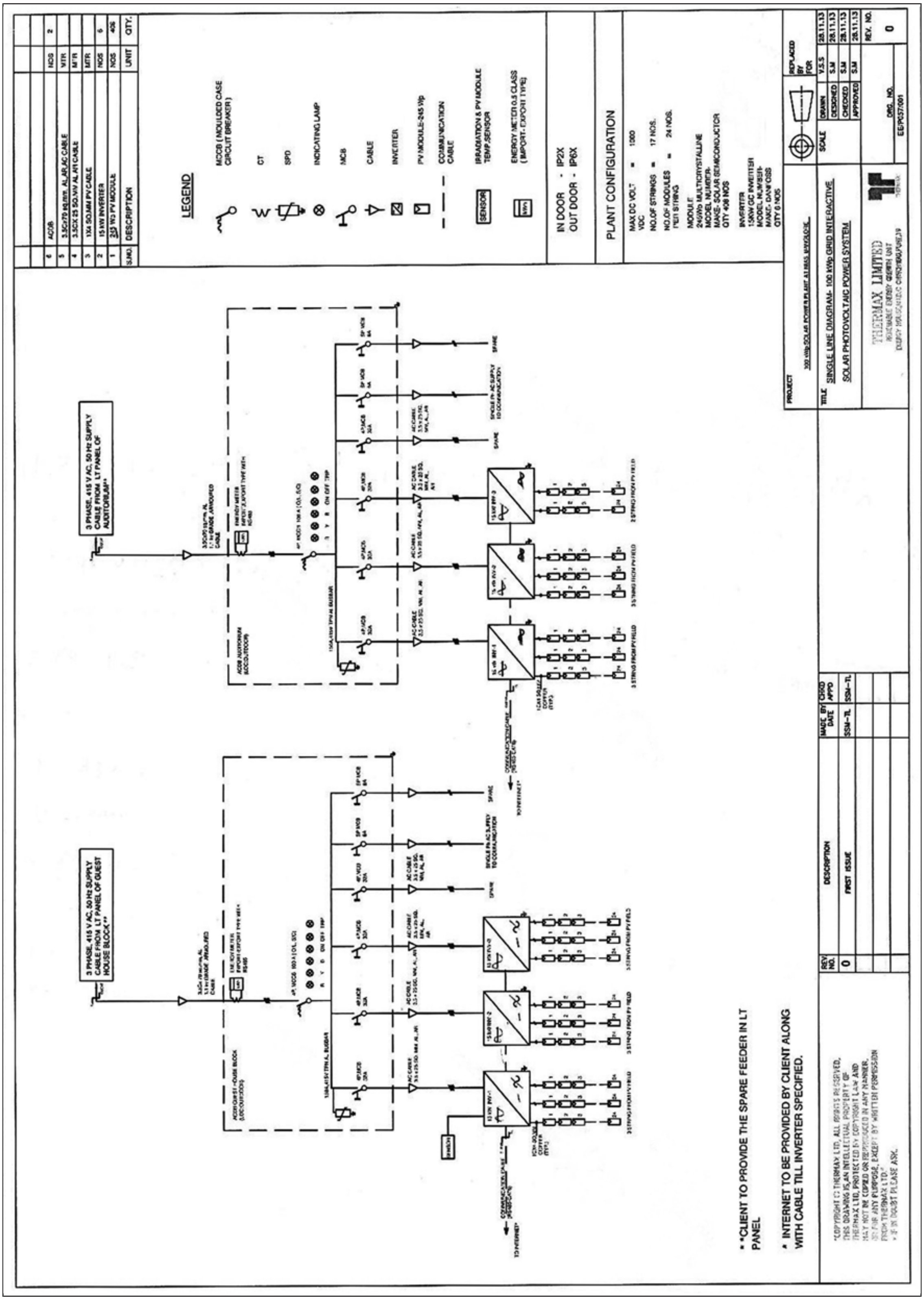


Figure 8 Single line diagram of the 100kWp solar plant at NIAS

Source: Thermax Limited (2014)

3.1 Solar Module

The NIAS solar plant has a total of 408 solar modules made of polycrystalline silicon cells. There are 216 panels located on the roof of the guest house and the remaining 192 are on the auditorium roof. The modules were supplied by M/s Vikram Solar and these are part of the ELDORA VSP.60.AAA.03 module series having a 60 cell configuration. The tilt of the panel is 14° which is approximately the latitude of Bangalore. The nameplate specification of the panel is given below in Table 1 and Table 2.

Table 1 Basic information of solar module

Solar Cell	Multi Crystalline
Solar Cell Shape	Full Square
Colour class of cell	Blue (Bright or Medium or dark)
Module Dimensions	1639*982*36 (mm)
Fire rating	Class C
NOCT	45°C

Table 2 Technical Specification of solar module

Open Circuit Voltage	Voc	36.86 V
Short Circuit Current	Isc	8.48 amp
Rated Voltage	Vmp	31.01 V
Rated Current	Imp	7.93 amp
Peak Power	Pmax	245 W
Fill Factor		78.38
Operating Voltage		600 V (UL)
Maximum System Voltage		1600 V (TUV)
Efficiency		15.22%

Data source Vikram Solar (2016)

Note: Some of these values are obtained from the specification table given on the module. For explanation of some of these terms, see Glossary section in the end.

The rated power output is generated at standard test condition (STC), which is defined as 1000 W/m^2 irradiance, 25°C cell temperature, AM 1.5g spectrum according to EN 60904-3 (Vikram Solar, 2016).[17] However, the field parameters are different: the typical operating temperature is higher and insolation level is lower (PV Education, 2017). The expected operating temperature for the module is referred to as the Nominal Operating Cell Temperature (NOCT).[18] NOCT is required to determine the power output of the solar cell (PV Education, 2017).

[17] AM 1.5g stands for Air Mass 1.5 global; for details see (Green Rhino Energy, 2017)

[18] NOCT is defined as is defined as the temperature reached by open circuited cells in a module under the conditions as listed below: Irradiance on cell surface = 800 W/m^2; Air Temperature = 20°C; Wind Velocity = 1 m/s and Mounting to be open back side (PV Education, 2017).

3.2 Solar Inverters

The plant uses string inverters. These grid-tied type inverters are manufactured by M/s Danfoss. There are total six 15kW three-phase inverters. Each of the two building rooftops has three of these inverters. The inverter model name is TLX Pro 15.0k. The inverter specification and connection details are elaborated in Table 3 and Table 4, respectively.

Table 3 Inverter specification

Number of units	6
Maximum power	15.5kW
Maximum power AC	15KW
Input Voltage range	1000V DC
Output Voltage range	690V AC
Frequency	50Hz
Maximum Efficiency	98%

Table 4 Inverter connections at NIAS

Inverter name	Location	Strings connected to inverter	Panels in each string	Panels connected to inverters
Inverter 1	Auditorium	3	24	72
Inverter 2	Auditorium	3	24	72
Inverter 3	Auditorium	2	24	48
Inverter 4	Guest house	3	24	72
Inverter 5	Guest house	3	24	72
Inverter 6	Guest house	3	24	72
Total panels				**408**

All inverters have built-in monitoring system and are able to function as the system master providing the monitoring interface for the complete plant. Connecting the other inverters in the system to the master via Ethernet LAN can make the installation, communication and monitoring simpler and minimize the error (Danfoss, 2011a). At NIAS, one inverter (inverter 3) has been identified as the master inverter.

3.3 Aluminium Mounting Structure

Panel mounting structure is also an important part of the plant. It must be suitably designed for the applicable wind load, and the weight of the solar plant per square meter needs to be well within the load bearing capacity of the roof. The aluminium structures used for this 100kWp plant are suitable for flat roof and do not cause any damage to the roof. The structure is designed to keep the panels at a tilt angle of 14°. The panel arrangement is depicted in the Figure 9.

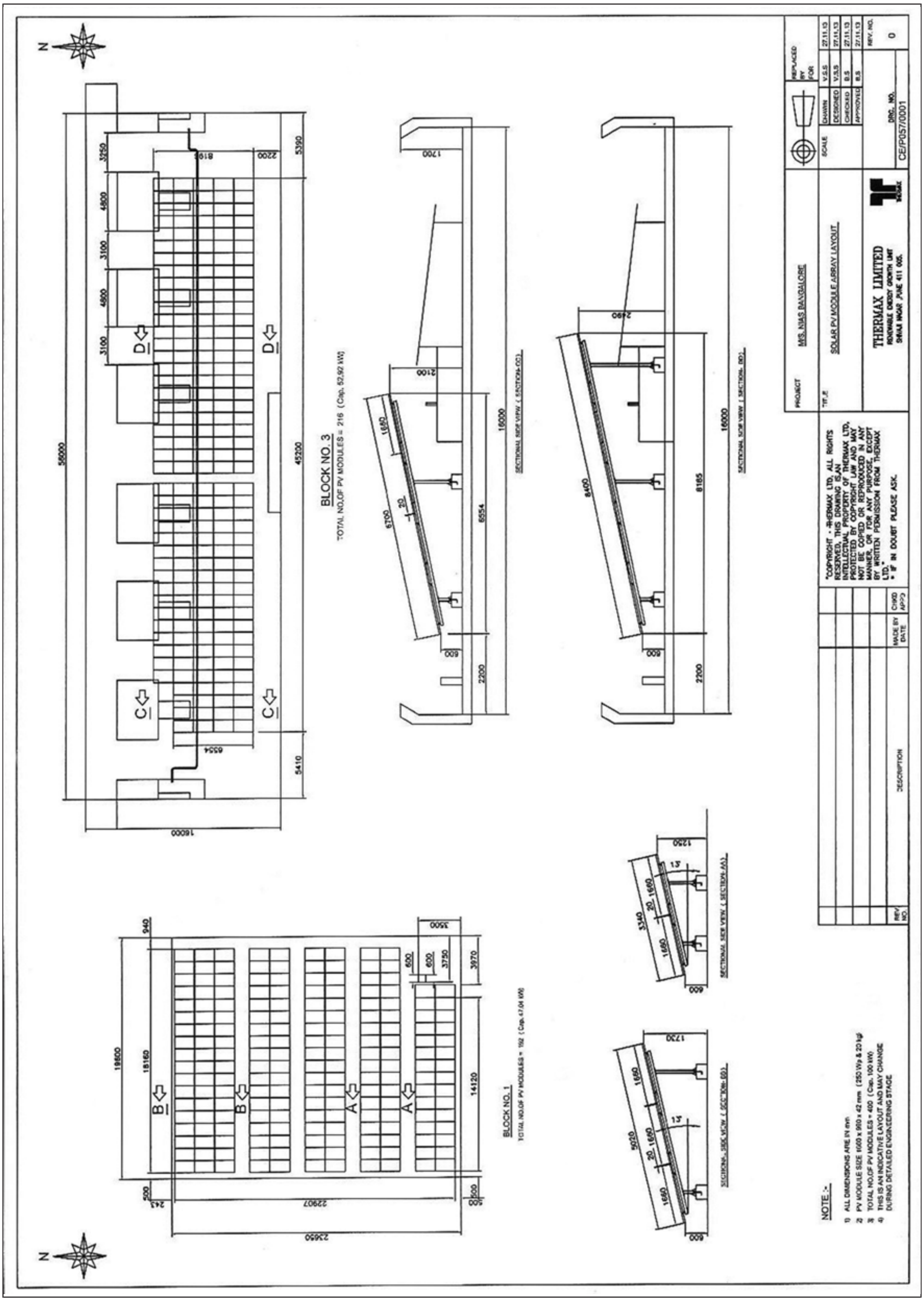


Figure 9 Solar PV module array layout

Source: Thermax Limited (2014)

3.4 Balance of System (BOS)

The balance of system is required for connecting the major components of the system. These components should be selected carefully by the installer to enhance system reliability. The BOS at NIAS system consists of:

- UV resistant solar cables
- DC Copper Cables
- AC Aluminium Cables
- MC4 (Multi-Contact and a 4 mm^2 contact assembly pin) connectors for solar cables[19]
- Cable trays, cable ties, lugs and glands for AC and DC Cables
- DC and AC distribution boards
- Lightning arrestors
- Earthing system including earth flats and earth pits
- Safety equipment like fire extinguisher

3.5 Installation and Commissioning

The NIAS rooftop system was installed under an MNRE subsidy scheme. The project execution started after the contract was signed with one of the MNRE approved vendors. The construction of the plant has few steps, such as design approval from the owner institute, supply of material, installation of the panels and inverter, installation of bidirectional meter with permission from ESCOM, and final commissioning of the plant. It took nine months from the date of contract for the final commissioning of 100kWp plant at NIAS.

While installing the plant, mechanical and electrical safety norms need to be observed strictly. There are specific safety guidelines with respect to solar modules, inverters, installation environment, connections, and maintenance.[20] The manuals supplied by the manufacturers and system integrators need to be followed.

After completion of installation of solar roof top system, permission was sought from Bangalore Electricity Supply Company (BESCOM) Ltd. to change the main meter of the campus. With BESCOM's approval, the old unidirectional meter was changed to a bidirectional meter. Two bidirectional meters (L&T make) were installed, one as the main meter and the other as a check meter. The meter constant was also modified accordingly.

[19] MC4 allows strings of panels to be easily connected by hand, but require a tool to disconnect them so as to ensure they do not accidentally disconnect when the cables are pulled (Solaronics Green Energy, 2017).

[20] In the specific case of NIAS, such guidelines are followed in consideration with Danfoss (2011a; 2011b), Vikram Solar (2017), among others.

4. Functional Description of Solar Rooftop System at NIAS

Since the operationalization of the solar plant at NIAS in October 2014, we have collected data at 10 minutes intervals on the voltage current and power generation (except the days when the inverter communication failed). The data showed certain patterns which we describe below.

4.1 Power Plant DC side

Polycrystalline solar panels generate DC and are connected in series and parallel connections to feed the electricity generated to the inverter (Figure 8). There are three strings, each consisting of 24 panels in series connected to each inverter except for inverter3. Inverter 3 has two strings connected to its input. The maximum open circuit string voltage would be 36.86 x 24 V = 885 V which is reasonable high and hence, the panels need to be handled safely during the day while they are generating electricity. The maximum output DC power from each string will be 245 x 24 W = 5880 W at STC. The string current is 7.93 Amp at STC.

4.1.1 DC Voltage

Figure 10 shows the average PV string voltage for three seasons. In Bangalore, one can consider December-January as the winter season, February-March as the summer and June July as the monsoon. The voltage starts building up as soon as the sunlight falls on the panels. In the winter season, the starting time is late compared to summer and monsoon due to late sunrise. The panels have a negative temperature coefficient for open circuit voltage (-0.31%/° C), i.e., the voltage reduces with increase in temperature. In the figure, we can see a slight dip in the string voltage during the noon in summer compared to winter and monsoon.

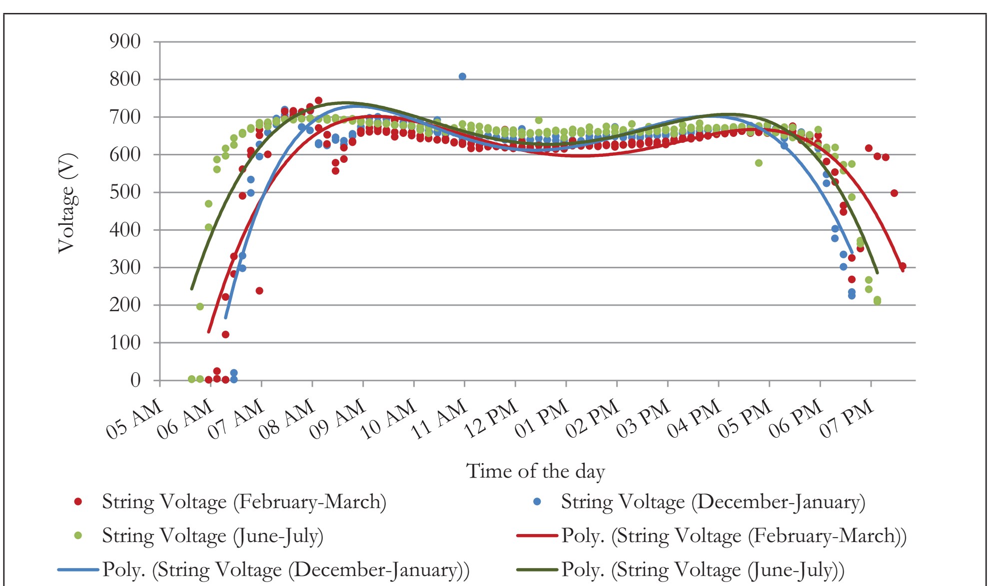


Figure 10 Average seasonal string voltage

4.1.2 DC Current

Figure 11 depicts the average seasonal string currents for three seasons. The peak current is lowest in monsoon and highest in summer. The peak current occurs between 12 pm to 1 pm when the solar irradiance is at its peak.

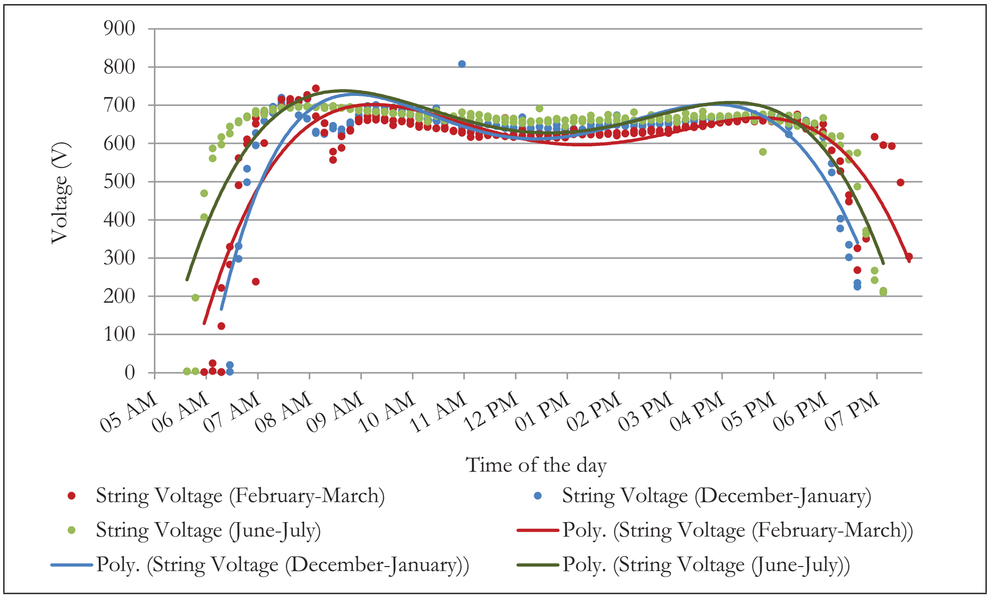


Figure 11 Average seasonal string current

4.2 Power Plant AC side

4.2.1 Inverters

The DC generated by the panels is converted to AC with the help of inverter and used for energizing the grid. The grid is under constant surveillance when the inverter energizes the grid. The parameters monitored during surveillance are - Grid voltage magnitude (instantaneous and 10-minute average), Grid voltage frequency, Three-phase Loss-of-Mains detection, Rate-of-Change-of-Frequency, DC content of grid current, and Residual Current Monitoring Unit.[21] If any of the above parameters violates the grid code, the inverter would not energize the grid. Other than these parameters, during the self-test, the insulation resistance between the PV arrays and earth is also tested. If the resistance value falls under certain threshold, the inverter does not energize the grid and waits for 10 minutes before making a fresh attempt to energize (Danfoss, 2011b).

There are four modes of inverter operation.[22] The LEDs signal those modes. The off-grid or night mode (LEDs off) is a situation when the inverter switches off if no power is delivered to it for 10 minutes. Under normal circumstances when it attempts to connect to the grid, the green LED starts flashing and remains on when inverter energizes the grid. In case of any failure, it gets disconnected and goes to safe mode (Red LED flashing).

[21] These parameters are taken from Danfoss (2011b)

[22] We borrow the information on inverter modes from Danfoss (2011b; 2011c).

The inverters used at NIAS are equipped with maximum power point trackers (MPPTs) (Danfoss, 2011b). These MPPTs with the help of an algorithm ensure maximum power generation controlling the operating point of the panel near the knee point of the I-V curve of the panel (Figure 12).

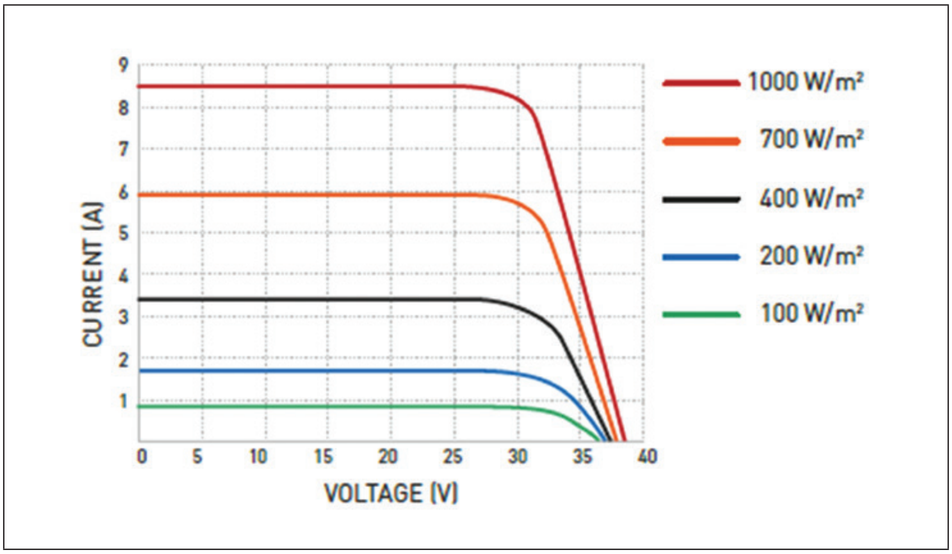


Figure 12. I-V curve of polycrystalline solar module

Source: Vikram Solar (2016)

4.2.2 AC Power Generation

Power generated on a typical summer day from the solar plant is shown in Figure 13. As the power production is proportional to the irradiance value, the generation would vary continuously with change in solar irradiance. To derive a pattern from these values, we have calculated the average power generation for three different seasons.

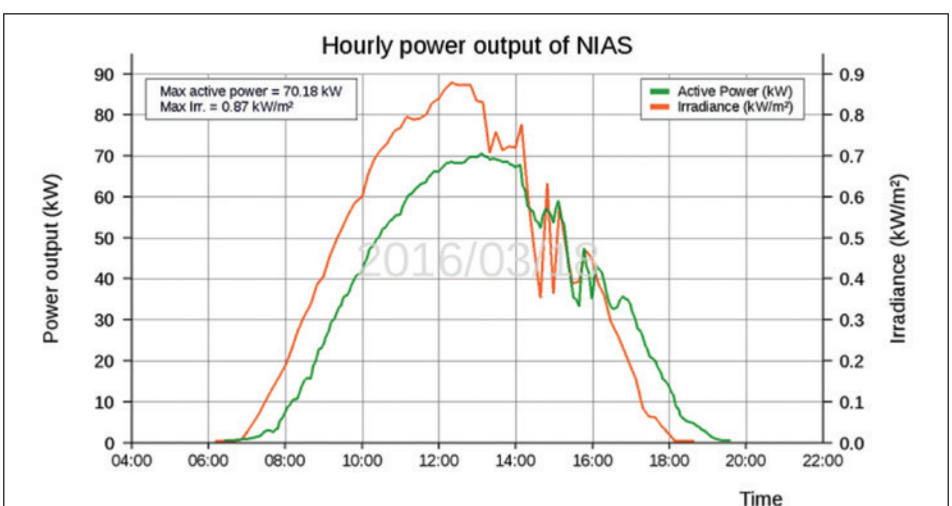


Figure 13 Solar power generation on a typical summer day (18th Mar 2016)

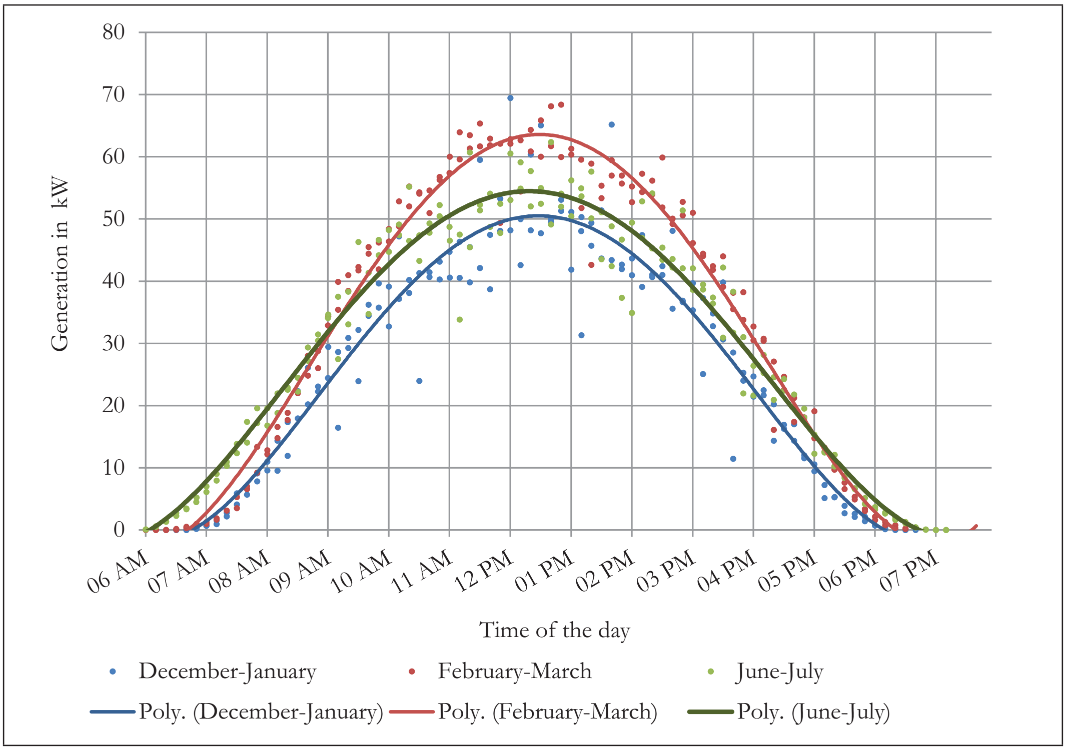


Figure 14 Solar power generation at NIAS plant during different seasons

In Figure 14, the average power generations in different months have been plotted. The data are taken from the inverters. The winter period (December- January), depicted in blue, has the smallest peak. During winters, due to the sun's location in the southern hemisphere, the sun light has to travel through the atmosphere for a longer distance and the global horizontal irradiance (GHI) at noon is less compared to other seasons. Hence, the peak generation during winter was less compared to monsoon (depicted in green) and summer (depicted in red). In the summer time, the clear sky combined with high solar irradiance makes the generation higher compared to other seasons. During monsoon, the generation is low compared to summer due to greater cloud cover.[23]

4.2.3 Capacity Utilization Factor (CUF)

Capacity utilization factor (CUF) is the ratio of energy generated by a plant in a certain period to the hypothetically maximum amount of energy the plant could produce in that period. The formula is given below,

Monthly solar CUF = (Monthly solar energy produced in kWh) / (Rated monthly solar energy production in kWh)

For calculation purpose the above formula can be written as,

CUF = Monthly solar generation / [(Rated capacity (100kW) x 24 x Number of days in a month)]

[23] The trends in the AC power (Figure 14) for the three seasons can be observed from the trends in voltage (Figure 10) and current (Figure 11) as AC Power is nothing but multiplication of voltage by current and power factor. As per the inverter data sheet the power factor is 1 for the solar plant.

The monthly CUFs are listed in Table 5 and the same is graphically represented in Figure 15. A seasonal pattern is visible in the graph having peaks during February. The monsoon shows a low CUF due to low generation values.

Table 5 Monthly capacity utilization factors (CUFs) for solar plant at NIAS

Month	Solar generation (kWh)	CUF	Month	Solar generation (kWh)	CUF
Oct-14	12236	16%	Sep-15	11161	16%
Nov-14	12810	18%	Oct-15	11993	16%
Dec-14	12342	17%	Nov-15	6736	9%
Jan-15	14154	19%	Dec-15	10855	15%
Feb-15	14752	22%	Jan-16	13483	18%
Mar-15	13037	18%	Feb-16	18125	26%
Apr-15	11090	15%	Mar-16	13442	18%
May-15	10501	14%	Apr-16	13654	19%
Jun-15	9605	13%	May-16	9993	13%
Jul-15	9066	12%	Jun-16	11113	15%
Aug-15	9665	13%	Average CUF		16.3%

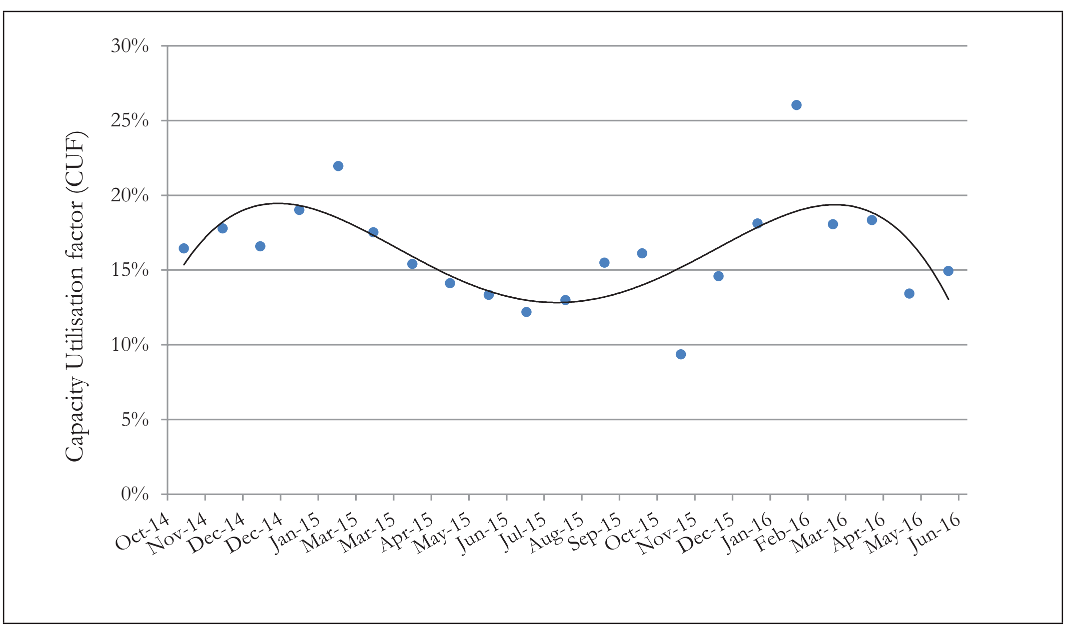


Figure 15 Capacity utilization factors for solar plant at NIAS

5 Financial Aspects

The electricity demands at NIAS is primarily during the day. This coincides with the power generation from the rooftop solar plant. As a matter of fact, during the peak solar generation hours (noon and afternoon) on most of the days (except those days when the auditorium air conditioner is operating), the generation exceeds the demand. During those periods there is no import from grid and NIAS rather exports electricity to the grid which may be used at some other place. Similarly, during holidays and weekends, NIAS exports electricity during the day. On the contrary, during the evening and night time, when there is no solar generation, the NIAS electricity requirement albeit smaller compared to the daytime comes from the grid. Also, when the auditorium air conditioner operates in evening hours on some special occasions, NIAS import from the grid shoots up. Overall, on a monthly basis, NIAS continue to be net importer of electricity. Nevertheless, the electricity bill of NIAS has gone down drastically.

The solar plant at NIAS was designed to cater to NIAS load partially. It was in line with the intentions behind the NIAS installation. The intention was to address the electricity needs of the campus and set an example for other institutes to come forward. There was no intentions within NIAS to become a net exporter and generate income from selling the excess electricity. Hence, NIAS preferred to remain a net importer. The 30% subsidy from Ministry of New and Renewable Energy (MNRE) and the savings in the monthly electricity bills make the system financially viable.

The plant has been operational since October 2014. As per the first contract with BESCOM, NIAS was allowed to export excess generation free of cost. Hence, there is no record available for the energy exported to the grid. However, in the initial months due to the in campus usage of part of generated solar energy, the monthly bills were reduced. Subsequently, NIAS's contract was modified and NIAS became eligible for payment for exported energy. The billing system also got streamlined. From April 2015, the electricity bills included import from the grid as well as export and NIAS was expected to pay for the difference. This reduced NIAS's payable electricity bill substantially (monthly by Rs 60,000 to Rs 70,000).

Figure 16 depicts NIAS's monthly electricity usage from various sources. The negative values indicate exports from the solar plant. The positive values depict NIAS's electricity consumption both from conventional (brown) and solar (green). The monthly consumption value is influenced by the number of days the auditorium was occupied or the auditorium air conditioner was operational. A seasonal pattern is also observed in the consumption.

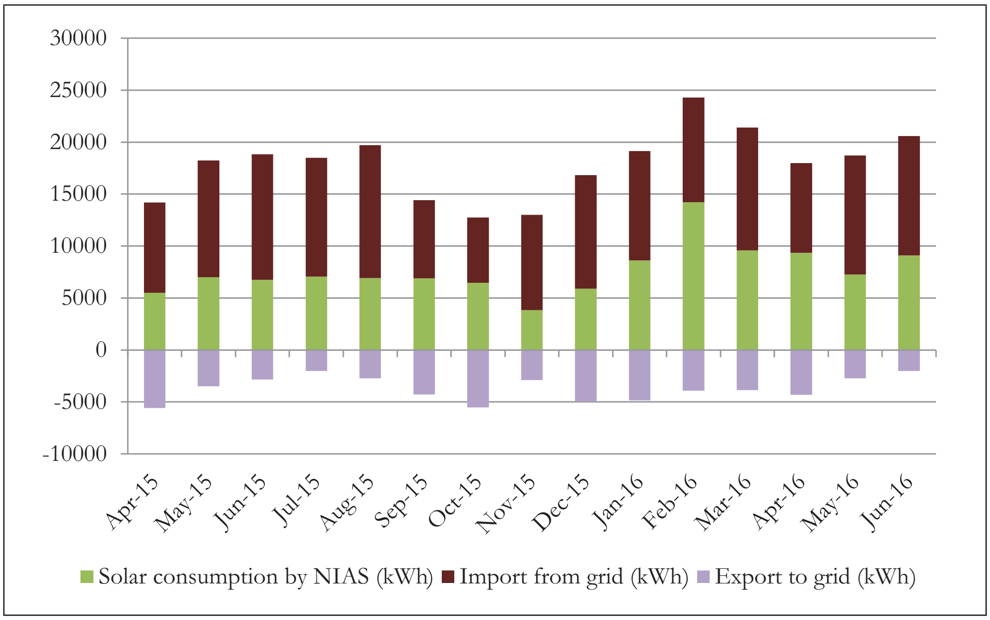


Figure 16 NIAS electricity usage from various sources.

Table 6 compares NIAS's electricity consumption and present payable units after installation of the solar plant. The reduction in payable units is substantial and the same is also depicted in Figure 18.

Table 6 Electricity consumption and generation from solar plant at NIAS

Month	Import from grid (kWh)	Export to grid (kWh)	Solar generation (kWh)	Solar consumption by NIAS (kWh)	NIAS Consumption (kWh)	To be paid by NIAS (kWh)	Reduction in payable units by NIAS
Apr-15	8700	5590	11090	5500	14200	3110	78%
May-15	11220	3490	10501	7011	18231	7730	58%
Jun-15	12070	2840	9605	6765	18835	9230	51%
Jul-15	11440	2010	9066	7056	18496	9430	49%
Aug-15	12800	2740	9665	6925	19725	10060	49%
Sep-15	7530	4270	11161	6891	14421	3260	77%
Oct-15	6280	5520	11993	6473	12753	760	94%
Nov-15	9170	2900	6736	3836	13006	6270	52%
Dec-15	10910	4950	10855	5905	16815	5960	65%
Jan-16	10500	4850	13483	8633	19133	5650	70%
Feb-16	10080	3910	18125	14215	24295	6170	75%
Mar-16	11840	3870	13442	9572	21412	7970	63%
Apr-16	8630	4300	13654	9354	17984	4330	76%
May-16	11480	2740	9993	7253	18733	8740	53%
Jun-16	11500	2020	11113	9093	20593	9480	54%

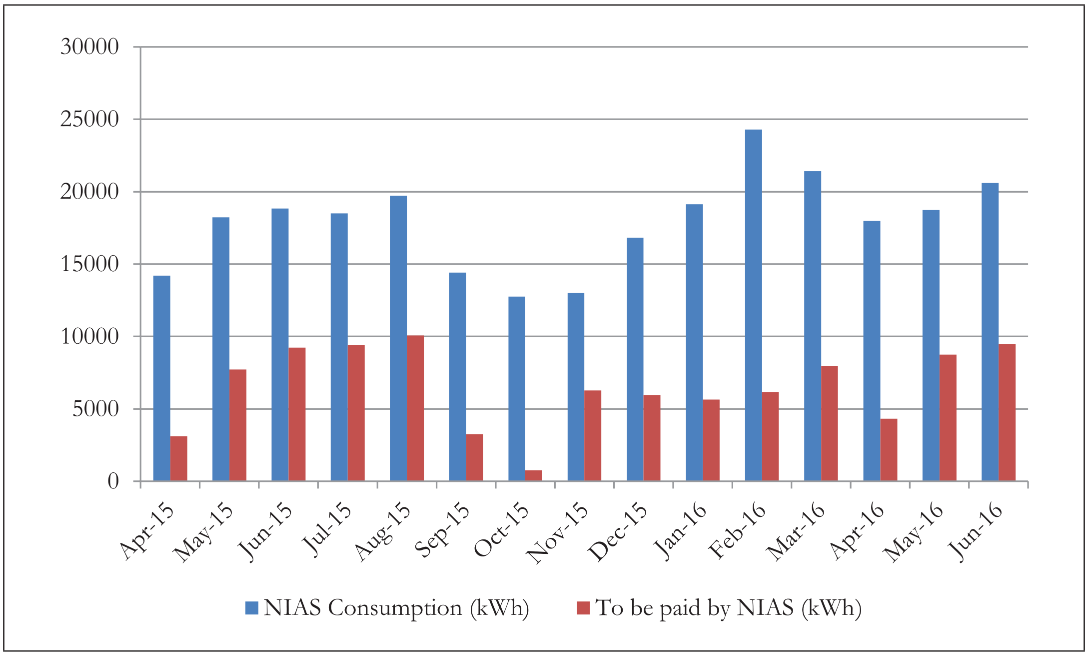


Figure 17 Monthly electricity consumption and payable units after solar installation at NIAS

To calculate the payback period of the plant, we collected the daily solar generation data and monthly electricity bills of NIAS (since April 2015). We have considered a few assumptions to calculate the payback period (Table 7).

Table 7 Assumptions considered while simulating different financial scenarios

Parameters	Value	Units/Comments
Initial parameters		
System size	100	kWp
Performance degradation	0.5%	per year
Storage	0	Grid tied system
System cost	80	Rs/W
Total capital subsidy	30%	
Interest rate on debt from bank	12%	
Interest rate for FD in bank	8%	
Starting Electricity tariff	5.92	Rs/kWh
Tariff increment raise	3%	per year
O&M Parameters		
O&M Cost	Rs 84,000	Rs/Year
O&M Escalation	5%	per year
Inverter replaced in year	13	
Inverter cost	7%	of total project cost
System cost	Rs 80,00,000	Rs

Figure 18 and Table 8 compare the annual cash flows and payback periods. At NIAS, we have received 30% of the capital cost from MNRE subsidy and the balance 70% (approximately Rs 50,00,000) has been provided by NIAS (Case 1). Case 1 shows that the payback period is eight years for NIAS solar plant. The plant is designed to run for 25 years. From 9th year onwards it provides benefit in the form of savings in electricity bill while requiring only a small expenditure on account of maintenance.

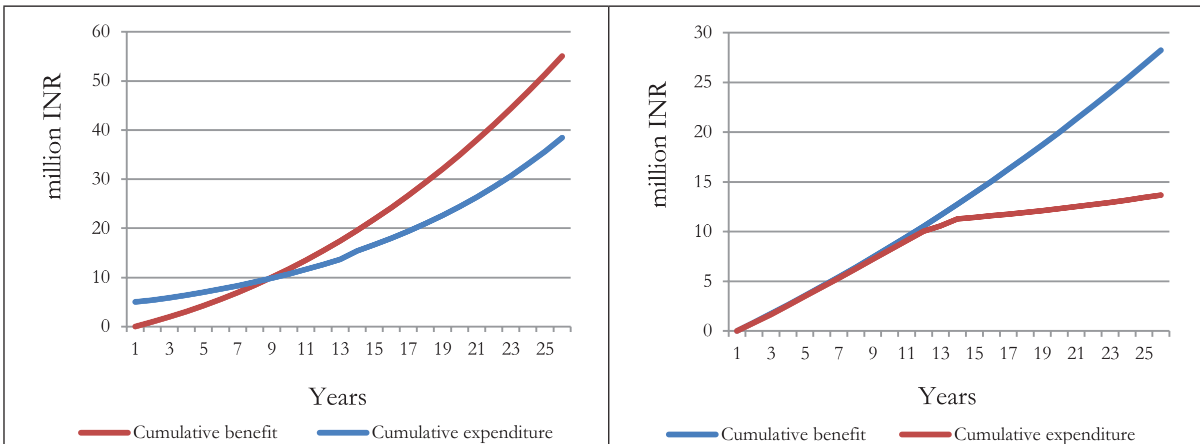
However, other institutions may not have ready funds available for investing in a solar rooftop plant. In that case they may have to arrange, for instance, 70% of the capital expenditure as a bank loan (Case 2). This case the loan is completely repayable in 12 years. No negative cash flow is envisaged in this scenario, i.e., the bank loan along with the interest is paid every year with the help of savings made by the solar plant during that period.

The subsidy received from MNRE for solar rooftop plays a very pivotal role in both the financial models.

Table 8 Annual cash flows for Case 1 and Case 2 Values are in million Rs. (million INR)

	Case 1			Case 2		
Year	Cumulative benefit	Cumulative expenditure	Net Benefit	Cumulative benefit	Cumulative expenditure	Net Benefit
0	0.00	5.00	-5.00	0.00	0.00	0.00
1	0.87	5.40	-4.53	0.87	0.83	0.05
2	1.81	5.83	-4.02	1.74	1.65	0.09
3	2.85	6.39	-3.54	2.64	2.56	0.07
4	3.97	6.98	-3.01	3.55	3.48	0.07
5	5.19	7.62	-2.44	4.48	4.40	0.08
6	6.50	8.31	-1.81	5.44	5.33	0.11
7	7.91	9.06	-1.14	6.41	6.26	0.15
8	9.42	9.85	-0.43	7.41	7.20	0.21
9	11.04	10.71	0.33	8.44	8.14	0.29
10	12.76	11.64	1.12	9.48	9.09	0.39
11	14.58	12.63	1.95	10.55	10.05	0.50
12	16.52	13.70	2.82	11.64	10.58	1.06
13	18.57	15.41	3.16	12.76	11.28	1.47
14	20.73	16.65	4.08	13.90	11.43	2.46
15	23.01	17.98	5.03	15.06	11.59	3.47
16	25.41	19.42	5.99	16.26	11.76	4.50
17	27.93	20.96	6.96	17.48	11.93	5.54
18	30.57	22.63	7.94	18.72	12.12	6.61
19	33.34	24.42	8.92	20.00	12.31	7.69
20	36.24	26.35	9.90	21.30	12.51	8.79

	Case 1			Case 2		
Year	Cumulative benefit	Cumulative expenditure	Net Benefit	Cumulative benefit	Cumulative expenditure	Net Benefit
21	39.28	28.42	10.85	22.63	12.72	9.90
22	42.45	30.66	11.79	23.99	12.95	11.04
23	45.75	33.07	12.69	25.38	13.18	12.19
24	49.20	35.66	13.54	26.79	13.43	13.37
25	52.80	38.46	14.34	28.24	13.68	14.56



Case 1: Capital provided by owner + subsidy

Case 2: Capital provided by bank + subsidy

Figure 18 Financial scenarios (Case 1 and Case 2)

6 Maintenance and Operation Care

Maintenance of the solar plant plays a pivotal role in ensuring maximum energy harvesting. It is very important to have a maintenance planning to keep the plant running effectively and maintain the efficiency over the years. For NIAS, the first two years the maintenance was in the scope of the supplier, i.e., M/s Thermax Limited.

6.1 Solar Module

The average life span of well-maintained solar modules is 25-27 years. The manufacturer M/s Vikram Solar has also provided performance warranty for modules for 27 years. The manufacturer has provided linear power warranty for 27 years with 2.5% reduction for 1st year degradation and 0.67% maximum decrease from module's nominal power output per year, ending with the 80.08% nominal power in the 27th year tested under STC. Following are the few maintenance activities, which can keep the panels functioning in long run.

6.1.1 Module Cleaning

The module has to be kept clean to ensure maximum power. In order to clean PV modules, a soft cloth with mild soft detergent can be used. The cleaning should be done on a weekly basis. If the area is frequented by birds, the bird droppings may make the panels dirty very soon. In that case, the cleaning has to be done more frequently. Water with the same temperature as that of the module needs to be used; otherwise thermal shocks can damage the module. Soft water has to be used for cleaning. The hard water may leave salt deposition on the panel which is harmful for the solar modules and reduces generation.

To ensure the module is cleaned without causing any damage such as micro-cracks in the module, the cleaning needs to be done preferably at early morning hours. During the middle of the day the panel the temperature would be typically in the range of 60° C and the string voltage would be in the range of 1000 V. Cleaning the panels during sunshine hours is harmful for the cleaning personnel as well as the panel. If the panels are cleaned during evening or night the water droplets left on the panel (if any) would take a longer time to dry compared to the morning hours and that would leave marks on the panel affecting its efficiency.

At NIAS due to specific (rectangular) shape of the guest house roof space a big panel assembly having 5 rows of panels was installed. The end point of the 5^{th} panel is at a height of 2.6 m, which poses a challenge for cleaning. A 2HP 2 piston compressor pump set fitted with a filter and nozzle is being used for cleaning these panels.

Proper access to the roof space makes the maintenance easier and increases the generation from the panels. NIAS suffers from not having the proper access.

The maintenance and care of all the aspect of modules must be taken as per the instructions given by the manufacturer.[24]

6.2 Inverter

Normally, the inverter needs no maintenance or calibration. However, at NIAS, we faced some difficulties with the inverters. One of the inverter (Inverter 4) had to be replaced twice within 1.5 years and there were certain data logging problems with other inverters. However, as six inverters were used in this plant, the plant was partially functional while one inverter was malfunctioning. An erosion of mild steel nuts used in the busbar resulted in loose connection in the concerned AC distribution box to which Inverter 4 was connected. This might have caused the repeated failure of the inverter. The erosion happened due to erroneous installation of ACDB with aluminum busbars connected to aluminum cables through copper lugs and mild steel nut bolts. Likewise the modules, the inverters and other components are to be maintained as instructed in the manufacturers' manual.[25]

[24] In case of NIAS system Maintenance and Care section of Vikram Solar (2017) needs to be considered.

[25] For NIAS system such manuals are provided for inverter by Danfoss (2011b)

Acknowledgement

Prof. V.S. Ramamurthy, the previous Director of NIAS along with members of the Energy Environment Group, especially Prof. D.R. Ahuja, Prof. D.P. Sen Gupta and Mr. Gautam Narasimhan, conceived the idea of installing a rooftop solar plant at NIAS and Prof. Ramamurthy sanctioned the required funds after Mr. Narasimhan had gone through the arduous task of planning details and checking with different vendors before the present vendor was selected. Prof. Sen Gupta and Mr. Srinivas Aithal visited Electricity Boards for securing necessary permissions. We, Anasuya Gangopadyay and Hippu Salk Kristle Nathan, were involved in the installation and later entrusted the task of producing the present report which demanded considerable amount of data which Anasuya continuously procured with the unfailing help of Sri V.A. Ramesh, the technical person-in-charge of Power system at NIAS. We acknowledge the assistance of Mr. Chetan Jois and Ms Upashana Ranjan during the drafting of the report. We are thankful to Dr. Shoibal Chakravarty, Mr. Mitavachan Hiremath, Ms. Aditi Malhotra and Mr. Vivek K, for their comments on earlier drafts of the report. We also thank Mr. Aithal and Mr. Satish Bhat for administrative support. NIAS expresses the appreciation for the support received from M/s Thermax in installation and maintenance of the plant and some data collection. Professor Baldev Raj, the present Director NIAS has encouraged and enabled the publication of this report at a short notice.

GLOSSARY

Terms	Definitions
Master inverter	With the power share buses and the power deviation controllers, the paralleled inverter can operate in a master slave configuration. All TLX Pro inverters are able to function as the system master, providing the monitoring interface for the complete plant. Connecting the other inverters in the system to the master via Ethernet LAN can make the installation and monitoring simpler and minimize the error too.
Multicrystalline/ Polycrystalline:	The poly-silicon large rods, usually broken into chunks of specific sizes are directly cast into multi-crystalline ingots. They are then sliced into thin silicon wafers and used for the production of poly crystalline solar cells. Polycrystalline cells can be recognized by a visible grain, a "metal flake effect". In opposition the mono crystalline cells being produced from a single crystal shows uniform colouring. Although the mono crystalline silicon cells are more efficient compared to poly crystalline cells, they are more expensive too.
Efficiency	The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as- $\eta = (Voc*Isc*FF)/Pin$ The input power for efficiency calculations is 1 kW/m2 or 100 mW/cm2. Thus the input power for a 100 × 100 mm2 cell is 10 W and for a 156 × 156 mm2 cell is 24.3 W. So if we have area of (1639*982) sq mm, then input power would be 1609 watt. By substituting values of all the parameters we get efficiency of 15.2%.
Fill factor (FF):	The fill factor is defined as the ratio of the maximum power from the solar cell to the product of Voc and Isc. Mathematically written as: (peak power)/(Voc*Isc). By putting the values from the above table that is peak power open circuit voltage and short circuit current we will get fill factor. Calculation- 245/(36.86*8.48)=0.7838*100=78.38%
Fire rating	A fire-resistance rating typically means the duration for which a passive fire protection system can withstand a standard fire resistance test. This can be quantified simply as a measure of time. Class A is the greatest resistance, followed by B and C.

NOCT	The Nominal Operating Cell Temperature (NOCT) is defined as the temperature reached by open circuited cells in a module under the conditions as listed below: Ø Irradiance on cell surface = 800 W/m2 Ø Air Temperature = 20 °C Ø Wind Velocity = 1 m/s Ø Mounting = open back side.
Open circuit voltage (Voc)	Open-circuit voltage (Voc) is the difference of electrical potential between two terminals of a device when disconnected from any circuit. There is no external load connected. No electric current flows between the terminals
Operating voltage	The voltage level by which an electrical system is designated and to which certain operating characteristics of the system are related.
Peak power	The maximum instantaneous power.
Rated current	Also described as current rating or current-carrying capacity, is the RMS electric current which a device or conductor can continuously carry while remaining within its temperature rating.
Rated voltage	The Rating of an electrical appliance indicates the voltage at which the appliance is designed to work. This is called rated voltage. This figure is usually displayed on a rating plate attached to the appliance
Short circuit current (Isc)	The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is short circuited). Usually written as Isc.

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