TERI Internship Report

A study on different communication technologies available for implementation in hybrid PV systems

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May - August 2022

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Mr. Yatharth Sharma

Acknowledgement

I would like to express my sincerest gratitude toward, Dr. G R Narasimha Rao, Director, for encouraging me and providing me with the opportunity to expand my knowledge in the field of renewable energy & solar PV by working on this project.

I would also like to extend my deepest thanks to Mr. Yatharth Kumar Sharma, Associate Fellow, whose continued support & valuable guidance have been significant contributions towards the successful completion of this project.

Abstract

This report presents an overview of the current most widely used communication technologies for implementation in hybrid photovoltaic systems. A brief introduction to the different PV technologies along with the basic design of different types of PV systems used today is provided. The different generations of PV technology along with the types of PV systems available are reviewed to gain an insight into the operation & design of modern PV systems. A brief outline of the most widely used communication technologies along with the advantages/disadvantages each pose is provided. LoRa technology, a relatively recent advancement in the field of communication, is introduced & the architecture of LoRaWAN is comprehensively discussed. Finally, to coherently link together all the concepts covered thus far & elucidate the role of communication networks in PV systems, a remote monitoring system based on WiFi & a LoRaWAN based hybrid PV system are explored & examined.

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1 Introduction to Photovoltaic technology

Solar energy is quickly garnering widespread popularity as a renewable source of energy capable of overcoming the shortcomings posed by fossil fuels. Solar energy offers several advantages: It is efficient, safe, reliable & can be widely distributed. The development of Photovoltaic (PV) technology has facilitated great advances towards the goal of achieving clean, sustainable, & renewable energy.

PV technology made the extraction of electrical power from the sun possible through the advent of solar cells. Solar cells are essentially photovoltaic semiconductor devices which operate upon the photovoltaic effect which enables the conversion of solar energy into electrical power. The photovoltaic effect can be divided into three basic processes: (i) Generation of charge carriers in semiconductor materials though absorption of photons, (ii) Separation of photo-generated charge carriers by the electric field in the depletion region, (iii) Collection of photo-generated carriers at terminals of the junction.

The global production of PV modules has seen a massive increase in recent years as a result of international efforts undertaken by several countries aimed at introducing renewable energy conversion technologies & promoting clean energy production. PV power is predicted to become one of the primary sources of renewable energy all around the globe within this century.

1.1 Types of PV technology / PV Modules

A photovoltaic module (PV) consists of multiple PV cells connected in either series or parallel depending upon the requirement of producing higher voltage or current. The commercial production technologies currently in use for PV modules have been briefly summarized below:

1.1.1 *Crystalline Silicon PV Technology*

The most commonly used solar cells in commercially available PV modules are made from crystalline silicon structures, which form the basis for the first generation of PV technology. The fabrication process of these is as follows: Metallurgical silicon powder is subjected to Siemens process which leads to formation of silicon material with a high level of purity known as polysilicon. Then, monocrystalline silicon ingots possessing a uniform

& continuous lattice structure are produced using the polysilicon through fabrication methods such as the Czochralski process or float zone process. The obtained crystal is then mechanically sawed or undergoes processes such as the silicon ribbon technique to form thin silicon wafers. Finally, metal grid/contacts along with an anti-reflective coating are added into the structure before being packaged into a monocrystalline silicon PV cell. According to [1], monocrystalline silicon PV cells offers the highest conversion efficiency ($\sim$ 26.7%) compared to all other commercial PV technologies however due to their low production rates they are not typically preferred over polycrystalline silicon PV cells.

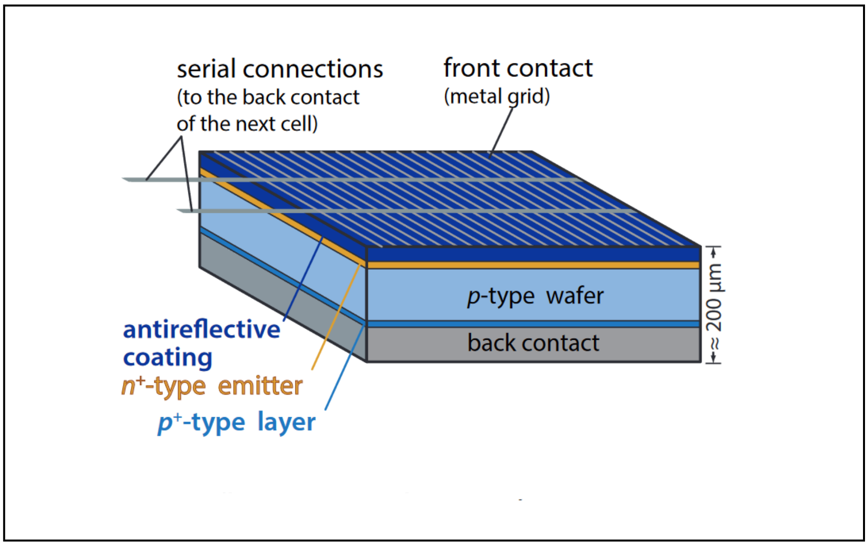


Figure 1.1: Layer structure of a crystalline silicon solar cell.

Polycrystalline silicon are crystalline solids in which the crystal lattice has several small crystalline grains. Polycrystalline silicon cells can be fabricated by melting highly purified silicon into a cubic-shaped polycrystalline ingot which may then be mechanically sawn & packaged similar to monocrystalline silicon PV cells. Polycrystalline silicon cells that make use high efficiency PERL concept still offer lower conversion efficiencies (of around $\sim$ 22.3% [2]) as compared to monocrystalline silicon cells due to the presence of large number of grain boundaries that give rise to many defects & lattice mismatches. However, polycrystalline based solar cells still constitute a considerable market share of solar PV technology due to their high production rate & steadily declining manufacturing costs.

1.1.2 *Thin film PV technology*

The second generation of PV technologies introduced thin film PV modules are comprised of solar cells fabricated using films of thicknesses varying from a few nanometres (nm) to tens of micrometres (µm). In contrast, the first generation crystalline silicon-solar cells use wafers of thicknesses up to 200 µm. The thin-film solar cells are housed in carrier materials such as glass, polymer or steel to provide them with mechanical durability &

flexibility. In thin film solar cells the active region or depletion layer is sandwiched between an electrical contact on one side & a transparent conductive oxide layer on the other side.

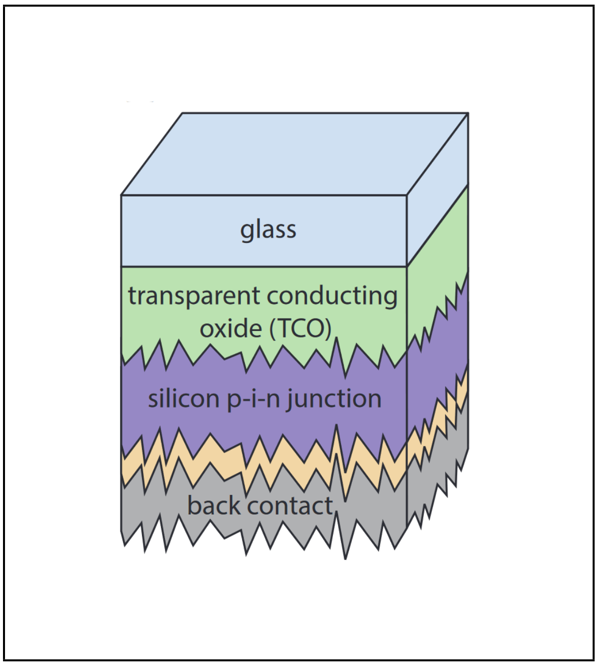


Figure 1.2: Layer structure of thin film silicon solar cell which illustrates the nano-textured interface between subsequent layers.

Since thin film PV cells are composed of thin layers, the raw material required for fabrication is significantly reduced. Also, the complexity of the fabrication process of thin film structures is significantly diminished via chemical vapour deposition methods such as epitaxial lift-off technique.

Examples of thin-film PV cells currently in commercial use include gallium arsenide (GaAs), amorphous silicon (a-Si), copper indium gallium diselenide (CIGS), & cadmium telluride (CdTe). Gallium arsenide thin film cells have efficiencies of $28.8 \pm 0.8\%$. [2]

1.1.3 *Multi-junction PV Technology*

Thermalisation processes & dissipation of photons which possess insufficient energy to be absorbed by the semiconductor material cause a spectral mismatch between the band gap of the semiconductor wafer & the energy distribution of photons in the solar spectrum. This spectral mismatch leads to the formulation of a fundamental limit on energy conversion efficiency of single-junction solar cells referred to as the Shockley-Queisser limit.

The third generation of PV technology introduced multi-junction cells capable of overcoming the aforementioned limit by incorporating various semiconductor materials each with different bandgaps into a single multi-junction structure. The different bandgaps ensure the absorption of photons with a range of energy levels & hence prevent losses due to spectral mismatch. Multi-junction PV cells are structurally composed of multiple cells stacked on top of each other, with the top most layer possessing the largest bandgap energy & successive lower layers possessing lower bandgap energies.

The amount of incoming photons from the sun that are converted into useable power, in other words the operating frequency of these devices is hence greater than that of both first generation & second generation PV technologies. However due to reasons such as higher material and manufacturing costs of multi-junction cells, they are not widely used in commercial applications. III–V compound based multi-junction semiconductor solar cells with 5 junctions have produced high efficiencies of upto 38.8%. [2]

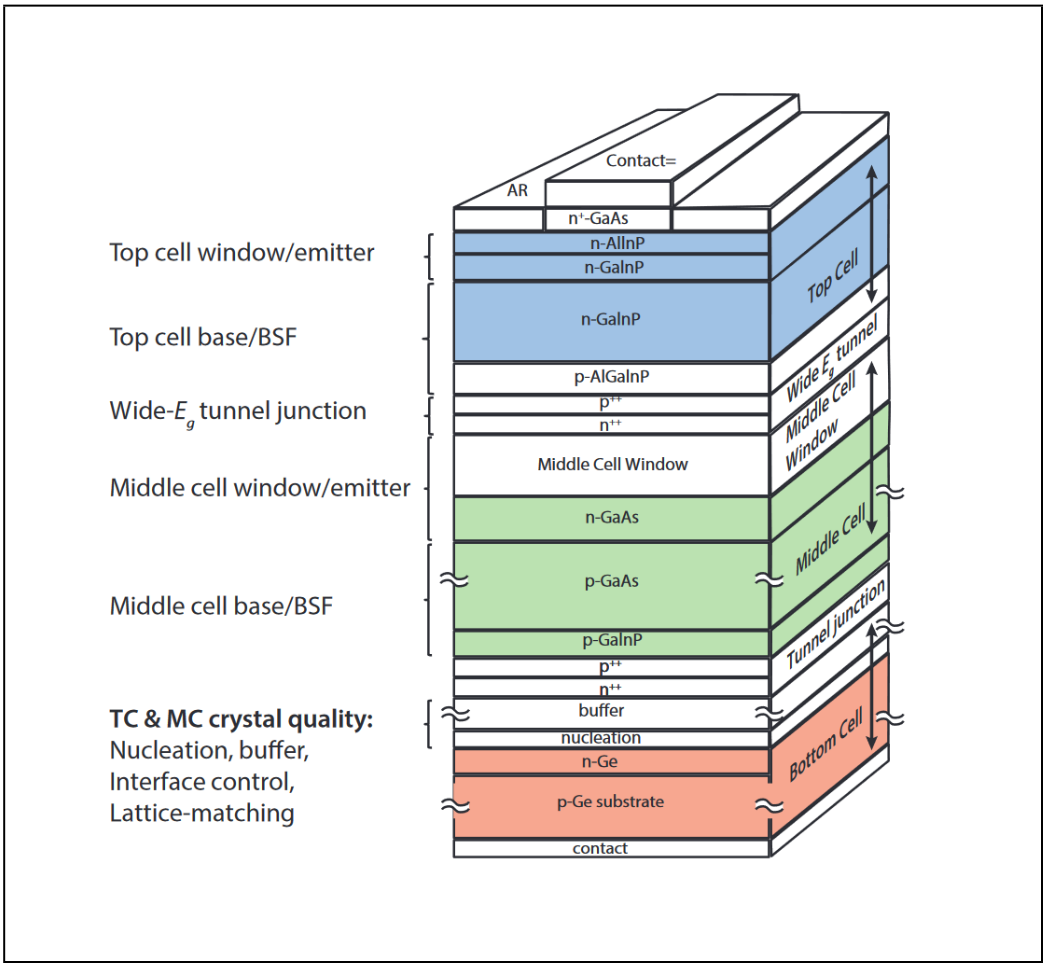


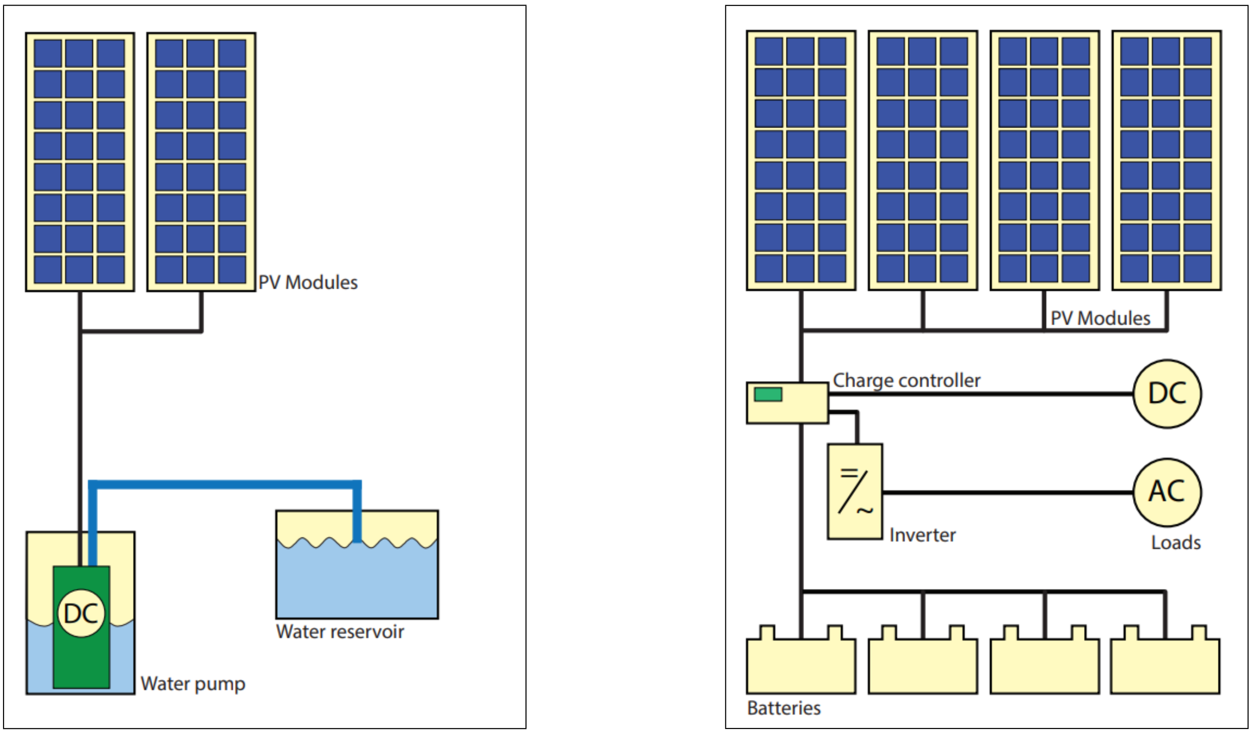
Figure 1.3: Layer structure a typical III-V triple-junction solar cell.

1.2 Types of PV Systems

A typical solar-energy system consists of a solar panel, a solar controller, and a battery or a series of batteries. If the output power is 220 V (AC) or 110 V, an inverter is also required in the setup. However, different types of PV systems may be employed to meet particular requirements. Three main types of PV systems are classified based on system configuration: stand-alone, grid-connected and hybrid.

1.2.1 *Stand-alone systems*

Stand-alone systems rely only upon solar power. The components used in stand-alone systems are PV modules, load, battery/batteries (for storing energy) & charge regulators. The charge regulators ensure that the batteries are only charged/discharged up to a certain limit by switching off the PV modules/load automatically when required. Figure 1.4 shows schematically examples of stand-alone systems; (a) a simple DC PV system without a battery and (b) a large PV system with both DC and AC loads.



(a) (b)

Figure 1.4: Schematic representation of (a) a simple DC PV system to power a water pump with no energy storage and (b) a complex PV system including batteries, power conditioners, and both DC and AC loads.

1.2.2 *Grid-Connected Systems*

In grid-connected systems, the solar PV system is integrated with a grid (which refers to the conventional electricity infrastructure) via inverters. In these systems the inverter is linked to a distribution board which transfers the PV generated power to either AC appliances or the electricity grid. The grid will supply electricity when there is insufficient generation of power by the PV system & hence the need of batteries in these systems is eliminated.

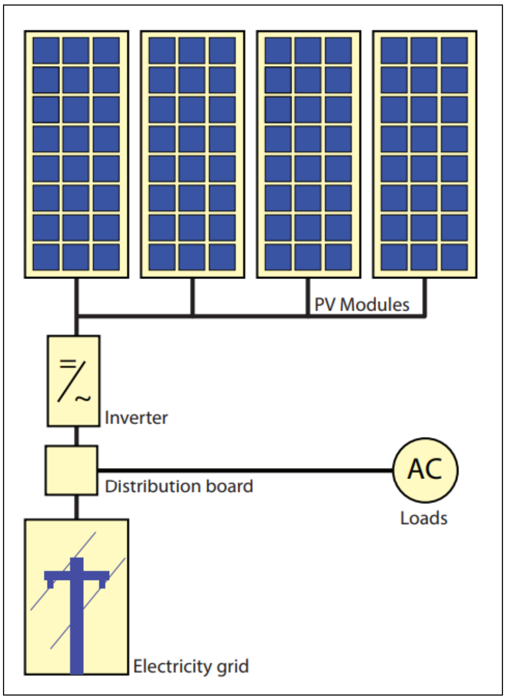


Figure 1.5: Schematic representation of a grid-connected PV system.

Several grid-connected systems linked together to form large PV fields can generate PV electricity with peak powers of the order of several MW's.

Grid connected solar systems are classified on the basis of size & overall power output into 3 categories:

i Residential: These are the smallest types of installations of hybrid systems which are capable of supplying power equal to 10kW.

ii Commercial: The commercial scale hybrid systems generate peak power between the range of 10 to 100 kW. These are found on top of large buildings.

iii Utility: Utility scale systems are typically utilized in large scale terrain based installations such as solar farms. They hence provide the greatest amount of power output on the scale of roughly ∼100kW.

1.2.3 *Hybrid Systems*

Hybrid Systems combine PV modules with complementary methods of power generation such as diesel, hydro or wind generator. A hybrid system combines the schematics of complex off-grid (stand-alone) systems and grid-connected systems. Figure 1.6 shows a hybrid system in which a diesel generator provides an alternate source of energy. This back-up generator can be used to either supply power to the load or to recharge the batteries.

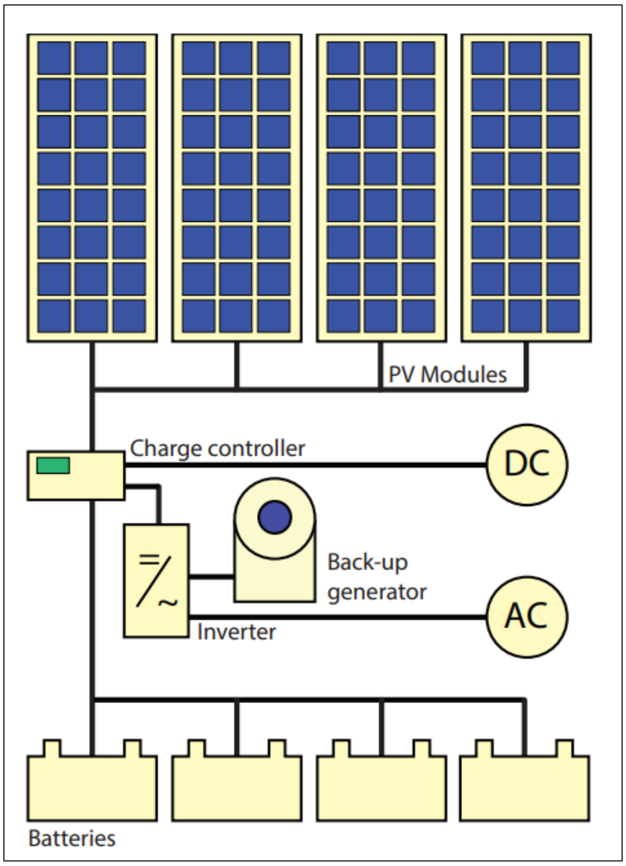


Figure 1.6: Schematic representation of a hybrid PV system that has a diesel generator as alternative electricity source.

Hybrid Systems may hence be thought of as grid connected systems that generate power with solar Photovoltaic modules as their primary source & employ other complementary renewable technologies such as diesel generator sets, hydro generators or wind turbines as their secondary source/backup source.

1.3 Role of communication in PV systems

Communication systems play a crucial role in the grid integration of renewable energy based hybrid systems. Various types of communication technologies are used to relay information between interconnected components of the grid (such as sensors, meters, voltage detectors, etc). Thus communication technologies form the basis for grid integration of renewable energy sources, & hence facilitate other important aspects such as surveillance, data acquisition, protection, & control of equipment in the grid through a automated energy delivery network. Apart from these applications, communication technologies are also integral in hybrid PV systems to control the output power & switch the primary source of energy supply between the Diesel Generator set & the PV module array.

Communication technologies enable the implementation of remote monitoring & surveillance based applications through transmitting important data pertaining to the operation of solar modules/arrays that is obtained from sensors & meters integrated into the framework of hybrid systems through the same communications systems. Examples of two such solar sensors that are suitable for such applications are the GaAs and Silicon based solar reference cells produced by ReRa solutions[1]. These type of solar sensors are capable of providing high-quality precise measurements of solar irradiance levels incident on solar PV modules. However one major disadvantage linked with the ReRa based solar sensors are that they are only capable of transmitting the collected data over WiFi which severely limits the deployability of these types of sensors in specific environments. A solution to this issue would be to implement such solar sensors using better suited alternative communication systems such as LoRa technology which is explained in detail in section 3.2 of this report.

Appendix A explains in detail the derivation & methodology involved in calculation of the solar intensity/direct irradiance incident on PV modules, which can be reviewed to gain a deeper insight to how these type of solar sensors measure important IV characteristics & operating efficiency of a PV system.

[1]https://www.rerasolutions.com/solar-cell-measurement-tools/

2 Types of Communication Technologies

The global demand of renewable energy resources has seen a massive increase in recent years as a result of international efforts undertaken by several countries aimed at introducing renewable energy conversion technologies & promoting clean energy production. The major disadvantage of relying completely on renewable energy sources is that due to their inconsistent & intermittent nature, they are not viable for continuous energy generation & supply. This issue is resolved through the advent of so called *hybrid systems* which provide continuous & cleaner energy through grid integration of one or more renewable energy sources into the main power grid infrastructure.

Communication systems play a crucial role in the grid integration of renewable energy based hybrid systems. Various types of communication technologies are used to relay information between interconnected components of the grid (such as sensors, meters, voltage detectors, etc). Thus communication technologies form the basis for grid integration of renewable energy sources, & hence facilitate other important aspects such as surveillance, protection & control of equipment in the grid through a automated energy delivery network.

Problem Description

Communication systems play an integral role in grid integration, remote monitoring, system diagnostics & data acquisition based applications in hybrid PV systems. In rural or isolated regions where the grid is inaccessible, Hybrid PV systems often utilize diesel generator sets with fully integrated data loggers. These diesel generator sets or *'DG sets'* in short are used as standby output sources that supply power when when the output from the solar PV system is below a certain threshold. These type of hybrid systems thus make use of PV solar energy & diesel generators to provide a more stable, reliable, & overall cost effective solution for an all-weather uninterrupted power supply.

There are however several problems/challenges that may arise with such types of Hybrid systems. A practical example of such a problem may be discerned through the following case: Consider a hybrid solar farm installed in a rural/under-developed area which has no power grid in close proximity. This specific hybrid system would be required to operate with a DG set due to the in-availability of a main power grid to facilitate power generation when the PV module is not functional. Due to harsh weather conditions a few solar panels might be damaged, due to which the DG set would need to be operated with a higher output. Moreover, the communication link established through optical fiber could also potentially be compromised due to certain accidents. In such cases where the communication links are vulnerable to damage from sources such as harsh weather & irregular terrain it is important to consider alternative forms of communication technologies that may be implemented into hybrid PV systems.

Figure 2.1: Damaged/Burnt Solar Panel caused due to Lightning Strikes & Harsh Weather conditions

There are several types of communication technologies & systems which may be implemented for grid integration of hybrid systems. In this section, a few of these different communication technologies are highlighted & their related standards are discussed.

2.1 *Power Line Communications (PLC)*

Power line communication systems transport information through existing electrical channels such as power lines. The key advantage that PLC systems offer is that they allow for transmission of information along the same wires which supply electricity. PLC can be used in several important applications: broadband Internet access, indoor wired local area networks, utility metering and control, real-time pricing, distributed energy generation.[3]

The IEEE Standard 1901-2010 is a standard for high speed (up to 500 Mbit/s at the physical layer) communication devices operating via power lines. The IEEE P1901 working group is currently working on developing PLC medium access control and physical layer specifications.

The key advantages that PLC systems offer have been listed as follows:

i PLC based hybrid systems allow for transmission of information along the same wires which also supply electricity.

ii The grid infrastructure network in PLC operated hybrid systems is capable of operating with a higher level of synchronization since the information & power is transmitted along the same channel.

iii The cost of integrating additional wires & labour is significantly reduced through power line communications.

The drawbacks/disadvantages of Power Line Communication systems may be summarized as follows:

i Power line cables are often un-shielded & hence more susceptible to electromagnetic interference.

ii The installation of PLC modules may also be more difficult in areas with irregular terrain.

iii The transmission speeds of information through PLC systems is not as high as those offered by other modern communication technologies.

iv While costs of integrating additional wiring & labour are reduced, maintenance & repair of PLC modules which house expensive components such as capacitors & inductors can be appreciably high.

2.2 *Optical Fiber Communication Systems*

Optical fiber communication systems use modulated pulses of light to transmit information from transmitter to receiver through fiber optic cables. Most Hybrid PV systems employ optical fibers for communication between DG sets & solar PV panels. Optic fibers are also used in hybrid systems for grid integration & remote monitoring applications. The advantages that have led to optical fibers being the preferred mode of communication in hybrid systems may be summarised as follows:

i Optical fibers provide high bandwidth & bit-rates which make them the most suitable choice for applications with high data transmission requirements.

ii Optical fibers enable long distance transmission with minimum power losses.

iii Optical fibers do not suffer from effects due to electromagnetic interference

iv Fiber optic communication is more secure than PLC systems since hijacking or tampering with light signals propagating within optic fibers is not possible.

v Optic fiber cables are mechanical stable & flexible which makes them more resistant to stress or pressure caused due to bending or deformation.

The potential drawbacks/disadvantages of optical fiber Communication systems may be listed as follows:

i Optical fibers are more brittle & delicate as compared to the cables used in other communication technologies such as PLC systems.

ii Several challenges arise during the installation process of optical fibers such as damage/splintering of fibers, difficulty in splicing, & bending during installation.

iii At large transmitting distances losses due to attenuation & dispersion become considerable enough to alter the optical signal. Thus, investments into additional components such as repeaters or EDFA's are often required.

iv Maintenance & repair of optical fibers can be quite difficult & expensive. For example, fault detection through methods such as OTDR (optical time domain reflectrometry) requires expensive equipment & involves high investment costs.

2.3 Wireless Area Networks

2.3.1 *Wireless Local Area Networks (WLAN)*

A Wireless-LAN is a computer network that links two or more devices within a bounded radius to form a local area network through wireless communication. The most widely used Wireless-LAN's are based on the IEEE802.11 standards. One such wireless network protocol based on the IEEE801.22 family of standards is WiFi which has recently become the standard for modern laptops & mobile devices due to the high bit rates it is capable of providing.

However, unlike other wireless low-power technologies such as Bluetooth or ZigBee, the power consumption of Wi-Fi is considerably higher & an important aspect to consider when implementing Wi-Fi based communication systems.

The key advantages that WLAN systems offer have been listed as follows:

i WLAN based systems offer high bit rates. For example, the WLAN protocol 802.11n operating at frequencies 2.4 or 5 GHz can achieve speeds of upto 72 Mbps.

ii WLAN systems are less expensive & comparatively easier to install as compared to wired communication systems such as optical fibers since WLAN systems completely remove the need along with the costs involved in installation of physical wiring.

iii WLAN systems offer a more versatile & flexible form of communication as WLAN's enable changes in the positions of workstations & components without interfering with their connection to the network.

The potential disadvantages of wireless LAN systems may be summarized as follows:

i The coverage range of WLAN is less than that of other communication systems such as WAN. Due to this WLAN based systems can not be implemented in applications (for ex. hybrid PV system in rural area) that require long range communication.

ii Harsh weather conditions such as excessive rain or thunder can cause interference & reduce operability of WLAN systems.

iii WLAN systems like all wireless communication systems are vulnerable to breaches in security. Several extra measures are required to ensure safe transmission of data through WLAN systems.

2.3.2 *Wireless Wide Area Networks (WWAN)*

A Wireless Wide Area Network (WWAN) is a telecommunications network that facilitates communication over a large geographical areas. A key difference between WWAN & WLAN is that WWAN often uses mobile telecommunication cellular network technologies such as 2G, 3G, 4G LTE, and 5G to transfer data. WiMAX is a type of WWAN based on the IEEE 802.16 standard, enabling the delivery of wireless broadband communications. WiMAX uses licensed wireless spectrum which provides greater security and is more reliable as compared to wireless networking technologies that use unlicensed spectrum such as Silver Spring & Trilliant. The primary disadvantage of using a licensed network is that it is more expensive. In addition, compared to cellular technologies, WiMAX has yet to be deployed at scale, which in turn can lead to some risks when implementing it into certain utilities.

2.4 *Long Range WAN (LoRaWAN)*

LoRaWAN *(acronym for Long Range Wide Area Network)* has recently garnered significant attention among the scientific community & network industry due to some of the advantages it offers in Machine-to-machine (M2M) & IOT network based applications. LoRa as a wireless networking protocol enables long range, bi-directional & low power communication between multiple devices. LoRaWAN is still undergoing development & several advancements in LoRa network architecture along with modelling techniques are being investigated in order to maximize energy optimization and also to evaluate the performance & limitations of LoRa technology in renewable energy based implementations.

While wired connections provide a high bit rate capacity & jitterless transmission, the high wiring costs involved along with the hindrances in network expansion imposed by wired communication systems such as optical fibers justify studies into the feasibility of new technologies such as LoRaWAN. Lack of cellular reception & difficulty of access at remote locations such as villages or other rural areas are some of the limitations faced by typical wireless WAN communication systems or satellite communications. Such limitations validate the implementation of LoRa technology in solar PV systems which require long range coverage, low power, & high energy efficiency requirements.

Some key advantages of LoRa technology over other communication technologies for applications in hybrid PV systems have been listed below:

i LoRa based hybrid systems enable long range transmission of information wirelessly between several miles ($\sim$ 2-5km urban & 15km sub-urban) with low power consumption.

ii LoRa technology offers duplex (bi-directional) communication along with end to end security between the two devices/nodes.

iii LoRa based modules are cost efficient & use constant envelope modulation which allow for usage of power amplifier stages with low power & high efficiency.

iv Deployment of LoRa based systems is easy since the architecture of LoRa WAN networks is rather simple as may be seen through figure 2.3. The steps involved in deployment of a LoRaWAN system are briefly covered in 3.2.1

The potential drawbacks/disadvantages of LoRa WAN based communication systems may be summarized as follows:

i LoRa based wireless networks provide low bit rates ranging from 0.3 kbit/s to 50 kbit/s per channel. Thus LoRa WAN is only capable of supporting hybrid systems applications which require low data rates.

ii LoRa WAN's are also susceptible to interference & data misplacement issues. Also like all wireless communication protocols LoRa is vulnerable to several security risks & issues. (A detailed study on the security risks of LoraWAN has been done by X.Yang [4])

iii LoRa technology is not suitable for supporting real time applications that have lower latency & bounded jitter requirements since LoRa protocol does not allow continuous transmission of signals as per the rules of the frequency band it utilizes. Thus LoRa is only suitable for applications that require periodic communication.

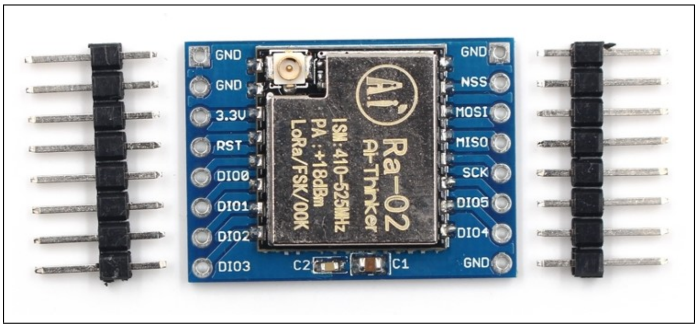
The upcoming sections discuss in detail the LoRaWAN architecture & modern LoRaWAN Environments along with one of the most important hardware component of LoRaWAN networks i.e the LoRa module which is responsible for transmission of LoRa radio signals. A brief overview of the salient features and specifications of the LoRa Ra-02 module which make it the most viable option for implementation in Hybrid pv systems is also provided.

2.4.1 *LoRa Module*

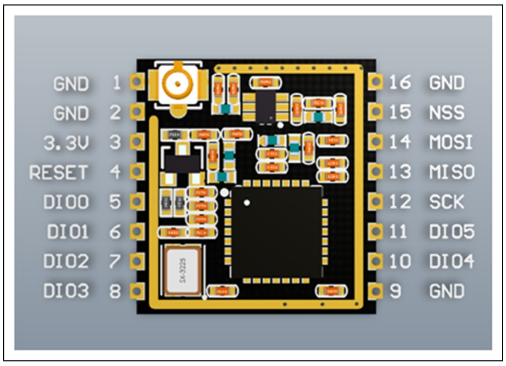
The LoRa module model typically utlized in solar PV applications for long range communication is the LoRa Ra-02 model, which is based on SEMTECH's SX1278 wireless transceiver. The Ra-02 uses advanced LoRa$^{\text{TM}}$ spread spectrum technology to offer long transmission distances (of upto 10,000 meters) and high reliablity. The LoRa Ra-02 module can be interfaced with Diesel Generator sets & solar panel arrays to facilitate communication and control of power output between the two. Some important specifications & features of LoRa modules which make them desirable for interfacing with hybrid pv systems have been listed below:

- Offers communication between distances from 10KM to 15KM.
- LoRa Ra-02 module supports FSK, GFSK, MSK, GMSK and LoRa ™ Spread Spectrum modulation techniques.
- Constant RF power output at + 20dBm-100mW voltage change
- Working temperature: The module is operational between temperature ranges of -40°C upto +80°C
- Low power consumption: Operates at voltage range 1.8-3.7V and hence offers appreciably low power consumption rates.

Figure 2.2 as seen below shows a image of the LoRa Ra-02 module along with the pin diagram of the module. The ground pins are denoted by 1, 2, 9 and 16. The pin number 3 represents input supply voltage and 4 is the reset pin. To read and write data, the module consists of five digital input and output pins. MISO represents master in slave out, in which the data is transmitted from slave to master. MOSI represents master out slave in; data is transmitted from master to slave.



(a)



(b)

Figure 2.2: (a) A typical LoRa Ra-02 module suitable for use in Hybrid solar PV systems and (b) The PIN diagram & layout of a LoRa Ra-02 module.

2.4.2 *LoRaWAN Architecture*

A typical LoRaWAN setup consists of end-devices (a.k.a end nodes), gateways, a network server and usually one or more application servers. In the context of hybrid PV systems, the end devices linked through LoRa gateways are the various meters, voltage sensors & DG-sets that are interconnected and linked to the solar PV farm/plant. Figure 2.3 as seen below gives an overview of the architecture of a LoRa wide area network.

The network facilitates communication between the end devices through an application through the following steps:

i A end-device communicates with a gateway by transmitting a LoRa Radio Frequency.

ii The gateway then proceeds to virtually link the LoRa radio frequency received from the end device with a standard IP connection (over ethernet) with the network server.

iii The network server processes and provides the end-device data to the application servers which further relay it to their applications for further processing.

iv For a hybrid PV system, this means that LoRaWAN would effectively allow intermittent communication which would facilitate power output control & switching between the diesel generator set and the solar panel array. (the end devices i.e. the data logger in the DG set along with voltage meters/sensors in the pv panels would facilitate the required responses/changes in the systems operation.)

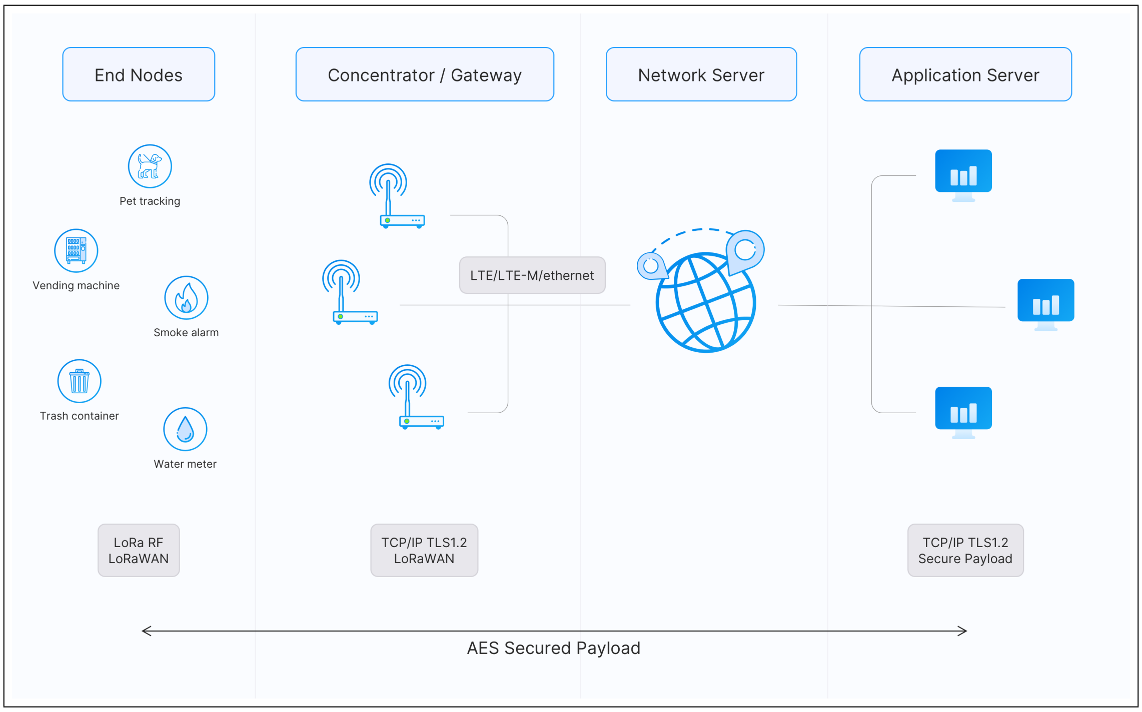


Figure 2.3: Link design & architecture of a typical LoRaWAN

2.4.3 *LoRaWAN Environments*

There are several LoRaWAN environment choices available, either a personal network may be set up, or an already existing network could be used after availing permission from the network's owner. An Example of a pre-existing network that is used all around the globe is The Things Network.

The Things Network (TTN)[1] is a global collaborative IoT ecosystem that creates networks, devices & solutions using LoRaWAN. It is an open framework network which is free to use and allows everyone to add their own gateway. The downside of this network is that its coverage as of now is limited. The final option is to set up your own network, this would, depending on the area you wish to cover, involve much larger costs.

[1] https://www.thethingsnetwork.org

3 Implementation & Applications

3.1 *Remote Monitoring system using WiFi*

Through the incorporation of web-based tools into utility scale hybrid systems, remote monitoring of several parameters such as PV array power output, panel status, peak voltage, etc is made possible. Figure 3.1 shows the schematic of how remote monitoring & system diagnostics through data acquisition of Hybrid PV systems may be achieved through incorporation of web-based tools into a PV power system. The monitoring interface gets electrical generation data from the inverters and transmits it to the server via the Internet. Some systems also provide sensors to collect data of ambient temperatures, solar irradiance, total generation, and usage data from the electrical panel. RS-485 is widely used as the protocol between the inverters and the data logger. Ethernet and Internet are typically the media for local and remote monitoring. An RS232 or USB interface is handy for the on-site debug, configuration, or monitoring for one-inverter systems.

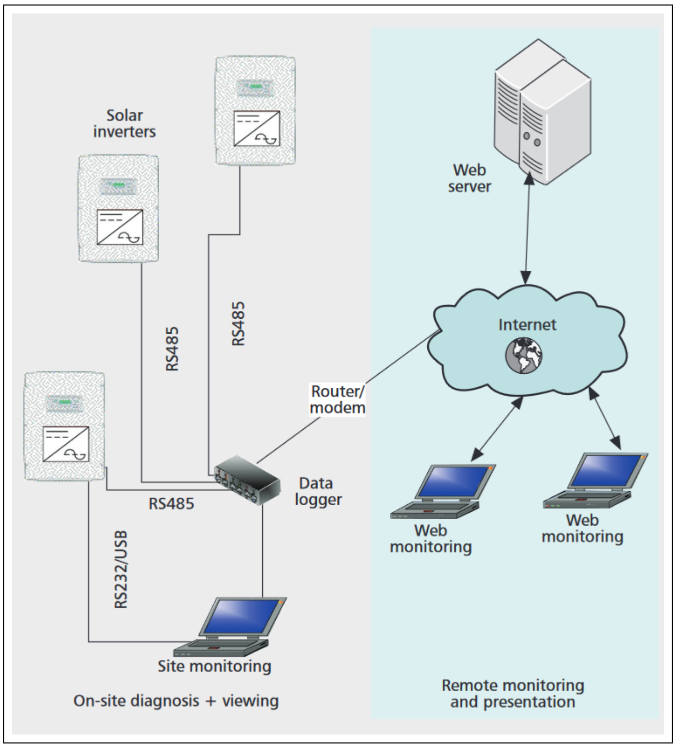


Figure 3.1: Schematic representation of a typical monitoring application of grid-tied photovoltaic power systems.

These systems are used to monitor the following variables: the solar irradiance, PV module power production, weather forecast data, temperature & status of key components (for ex. inverter, sensors, meters), AC grid conditions, etc.Remote monitoring & surveillance systems are also crucially important in ensuring the safety & protection of PV systems from cyber attacks & security risks. Modern power systems may have various vulnerabilities to cyber attacks. [5] Remote monitoring & proper surveillance can act as defense mechanisms against these vulnerabilities.

From the schematic shown in Figure 3.1 it may be concluded that one of the main applications of communication systems is enabling remote monitoring & data acquisition of important variables pertaining to hybrid solar systems. In future reports, other applications of implementing communication systems into hybrid PV systems along with the advantages/disadvantages of different types of communication systems in grid implementation will be discussed & explored.

3.2 *LoRaWAN based Hybrid PV system*

The scenario involved with the incompatibility of communication technologies such as WiFi with solar sensors such as ReRa solar reference cells was briefly introduced in section 1.3. The main issue with using wireless network protocols such as WiFi is that each end device/component in a hybrid PV systems such as the data loggers, voltage meters, & solar sensors each require a password protected WiFi router to communicate their data through WiFi. This setup leads to a few challenges:

i The deployment of the routers required for WiFi networks is restricted by the fact that WiFi based systems have limited range.

ii Since deployment of the routers is difficult often adaptations to the structure/topology of the network are made to incorporate the routers within a operational range of the end devices. This can lead to further increase in costs involved.

iii If the password of the would be exposed to a security risk, manual reconfiguration of the passwords of each router tied with a component of the hybrid system would be required to ensure a secure & safe communication network.

Solar sensors typically send float type data pertaining to current operating efficiency of the PV module array to the data logger integrated into the secondary source of power generation say a Diesel Generator set in a hybrid system. This data is ideally to be transmitted in real time at regular intervals with minimum amount of time delay & the size of this multi-variable data is around 32 bytes. Thus the low bandwidth limitation of LoRa is not of a concern when integrating it into hybrid systems. (while the range coverage it offers is a significant upgrade over WiFi).

The sensor should be operable for at least 5 years without user intervention due to the low power consumption of LoRaWAN systems. Moreover, LoRaWAN-sensors can easily be deployed on a large scale without the need of extra equipment since all settings (including network keys) are coded into the sensors and automatically change if network settings happen to change. Encryption of the data is done using AES and data integrity is achieved through CMAC and is automatically enforced in LoRaWAN.

The first step in creating a LoRaWAN based communication link between the components of hybrid systems is to deploy & configure a network server along with gateways within said server. However, pre-existing networks such as The Things Network^{TM} introduced in section 2.4.3 allow for immediate deployment & integration of LoRaWAN with end-devices. Once an end-device is deployed, it has to be activated within a certain LoRaWAN environment.

3.2.1 *LoRaWAN Communication*

LoRaWAN specifies several different types of communication between network server and end-devices, each with a specific use-case in mind.

Activating an End-Device: As shown in Figure 3.2, an end-device needs to be activated before it is able to send or receive data. There are two ways to activate an end-device, either by manually configuring the network details, called Authentication By Personalisation (ABP), or by allowing for Over-the-Air-Activation (OT AA), in which after selecting a network, the rest of the configuration is done automatically.

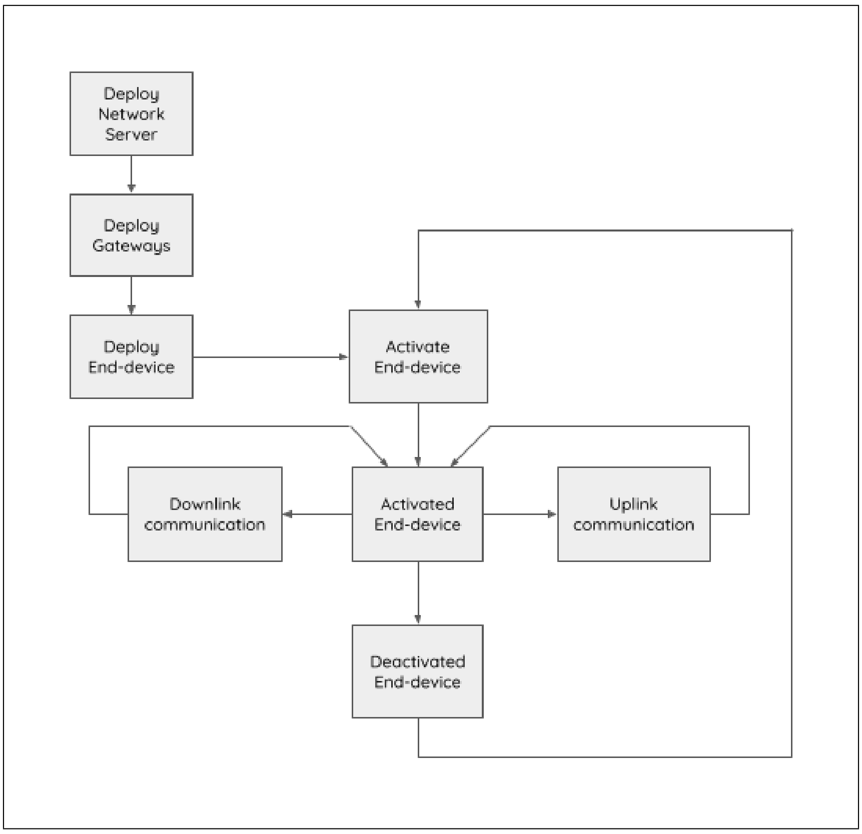


Figure 3.2: Block diagram of LoRaWAN setup & deployment of End-devices

Sending data: The reason this network exists is to be able to transfer data. This is possible, both as an uplink transmission (end-device to network server) and as a downlink transmission (network server to end-device).

Multiple End-Device communication: If a group of end-devices are assigned the same device address, downlink communication to multiple end-devices at once is possible if required. In hybrid systems often more than one source of complementary power is used & hence Multiple End-Device communication is integral for these different sources of power to operate in conjunction with one another.

3.2.2 *Proposed Model*

Once the LoRaWAN environment has been properly configured & the end-devices activated, the end-devices of the network can engage in uplink/downlink communication through the LoRaWAN gateways at regular intervals. Figure 3.3 illustrates a potential implementation of LoRaWAN into a hybrid Pv system with a diesel generator set as its complementary source of power.

The solar reference sensor calculates data pertaining to the solar irradiance incident on the PV module in a float type format. This data is both transmitted & received by the LoRa Ra-02 module which forwards this data through LoRaWAN gateways to the data logger. The data logger processes this data & accordingly alters the output power generation of the secondary source in the hybrid system, say a diesel generator. This communication channel allows for bi-directional exchange of information between the components of the hybrid PV system & enables switching & adjustment of output power between the PV module & multiple secondary sources of power.

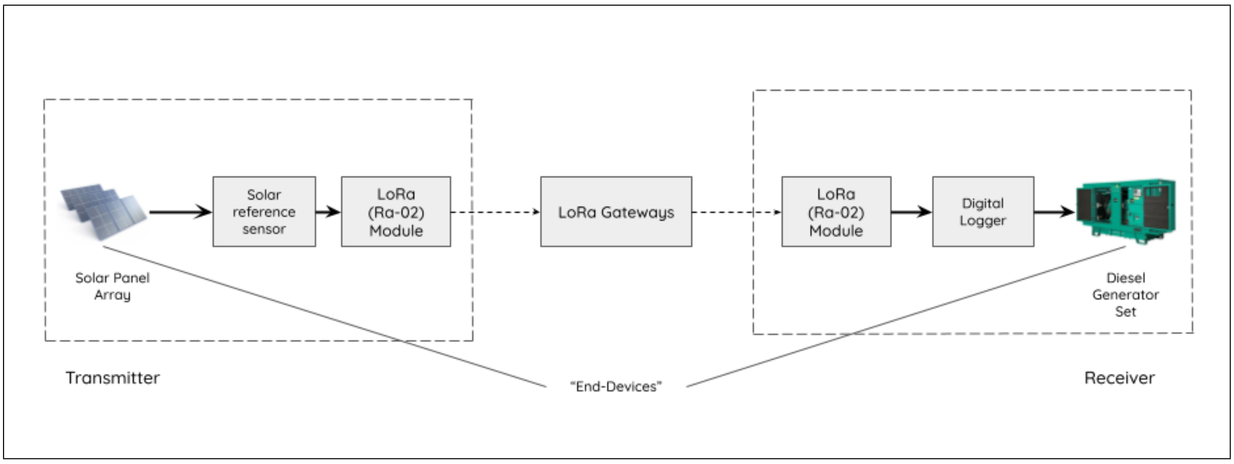


Figure 3.3: Schematic representation of LoRa facilitated communication between components of a Hybrid PV system

The Figure 3.3 shows only the transmission of data from the solar panel array to the diesel generator set, however in a hybrid PV system the communication channel created through LoRaWAN gateways facilitates bi-directional communication between multiple end-devices. Through periodic relay of operational parameters & inbuilt algorithms that create a suitable response to the received data, the power outputs of the solar panel module & the complementary sources are automatically adjusted every few minutes. This is the underlying working mechanism behind hybrid PV systems which effectively reduces the extent of the intermittent nature of renewable energy resources.

Naturally such systems are not without their limitations, since while LoRaWAN may offer a significant advantage in coverage range over wireless networks such as Wi-Fi, it still suffers from issues such as duty-cycle limited network size, reliability and densification drain network capacity. Several studies have highlighted these shortcomings of LoRaWAN which make it unsuitable for applications such as real time monitoring, industrial automation, critical infrastructure actuation & video surveillance. [6]

4 Conclusion

To conclude, this report provides a detailed overview on the feasibility & compatibility of the different types of communication technologies implemented into hybrid photovoltaic systems.

As research & investments into the development of novel technologies in the field of communication (such as LoRa technology) are made, the viability & significance of hybrid PV systems continues to be realized & validated in both domestic and industrial landscapes, as a direct result of which the global solar PV generation increased a record 23% in 2020. [7]

As the electricity consumption demands continue to increase with continually growing world population, several countries around the world such as China, Germany, & Japan are promoting the development & deployment of renewable technologies such as solar PV systems through implementing various PV initiative policies. [8] Hence as the global initiative towards reducing carbon emissions, becoming energy independent and achieving clean, sustainable, & renewable energy becomes more prevalent, investments into improving solar PV system infrastructure are being fueled by improvements and developments in communication technologies. As advancements are made in the field of communication technologies, exchange of data among PV system components & grid integration based applications continue to become increasingly more efficient. This prospect leads to the belief that the future of renewable energy in the form of hybrid solar PV has a potentially promising future ahead.

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A Solar Irradiance Derivation

One of the most important factors to consider when installing & planning a PV system is the amount of solar irradiance incident on the PV module at different mounting angles. These factors play a pivotal role in determining an approximation of the amount of the average energy that may be expected from a PV system under ideal conditions. In this section, expressions for the direct irradiance incident on PV modules mounted on different planes are derived & discussed by using the concept of a celestial sphere, which is a imaginary sphere concentric to earth with some arbitrary radius. For PV applications, the celestial sphere is modeled using a horizontal coordinate system in which the horizon of the observer constitutes the fundamental plane.

A.1 PV Modules Mounted on a Horizontal Plane

To begin with a derivation of the irradiance on a PV module, let us first consider the case of a PV module mounted on a horizontal plane titled at an arbitrary angle, θ_M. We utilize the horizontal coordinate system to describe the orientation of the PV module as illustrated in figure A.1 shown below.

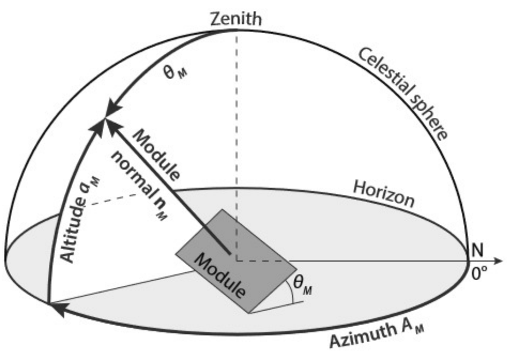

Figure A.1: Orientation of a PV module installed on a horizontal plane in a celestial sphere with horizontal coordinate system.

The azimuth angle of the module is given by A_M. The altitude of the module is given by angle $a_M = 90° - \theta$. We consider the location of the sun to be at horizontal coordinates (A_S, a_S). The direct irradiance on the PV module, G_M is then defined as:

$$G_M^{dir} = I_e^{dir} \cos\gamma \tag{A.1}$$

Where, $\gamma = \sphericalangle(A_M, a_m)(A_S, a_S)$ is the angle between the surface normal and the incident direction of the sunlight. Since we can express the cosine of the enclosed angle γ as the scalar product of two unit vectors, we may express $\cos\gamma$ as:

$$\cos\gamma = \mathbf{n}_M \cdot \mathbf{n}_S. \tag{A.2}$$

To define the two unit normal vectors $\mathbf{n}_M$ & $\mathbf{n}_S$ in terms of spherical horizontal coordinates $\mathbf{a}_M$ & $\mathbf{A}_S$ we use the relationship between Cartesian coordinates (ξ_M, ν_M, ζ_M) & spherical coordinates given by the following equation:

$$\begin{pmatrix} \xi \\ \nu \\ \zeta \end{pmatrix} = \begin{pmatrix} \cos a \cos A \\ \cos a \sin A \\ \sin a \end{pmatrix} \tag{A.3}$$

Thus using the relationship mentioned in eq. (A.3), the normal vectors $\mathbf{n}_M$ & $\mathbf{n}_S$ may be given as:

$$\mathbf{n}_M = \begin{pmatrix} \xi_M \\ \nu_M \\ \zeta_M \end{pmatrix} = \begin{pmatrix} \cos a_M \cos A_M \\ \cos a_M \sin A_M \\ \sin a_M \end{pmatrix}, \tag{A.4}$$

$$\mathbf{n}_S = \begin{pmatrix} \xi_S \\ \nu_S \\ \zeta_S \end{pmatrix} = \begin{pmatrix} \cos a_S \cos A_S \\ \cos a_S \sin A_S \\ \sin a_S \end{pmatrix} \tag{A.5}$$

Substituting eq. (A.4) & eq. (A.5) into eq. (A.2) we find,

$$\begin{aligned} \cos\gamma &= \mathbf{n}_M \cdot \mathbf{n}_S \\ &= \cos a_M \cos A_M \cos a_S \cos A_S + \cos a_M \sin A_M \cos a_S \sin A_S + \sin a_M \sin a_S \\ &= \cos a_M \cos a_S (\cos A_M \cos A_S + \sin A_M \sin A_S) + \sin a_M \sin a_S \\ &= \cos a_M \cos a_S \cos A_M - A_S + \sin a_M \sin a_S \end{aligned} \tag{A.6}$$

Substituting eq. (A.6) into the expression obtained for irradiance, G_M in eq. (A.1) we obtain:

$$G_M^{dir} = I_e^{dir}[\cos a_M \cos a_S \cos(A_M - A_S) + \sin a_M \sin a_S]$$

Simplyfing further in terms of angle θ we have:

$$G_M^{dir} = I_e^{dir}[\sin\theta cos a_S \cos(A_M - A_S) + \cos\theta \sin a_S] \tag{A.7}$$

The equation obtained above for the direct irradiance holds true only when the following conditions are satisfied:

i The altitude of the sun is greater than 0 ($a_S > 0$) (i.e the sun is above the horizon) &

ii The azimuth of the sun is within $\pm$ 90° of $A_M, A_S \in [A_S - 90°, A_S + 90°]$, otherwise $G_M = 0$.

A.2 PV Modules Mounted on an Inclined Plane

Let us now consider the case for a PV module mounted on an inclined plane say a tilted rooftop which makes an arbitrary angle with respect to the horizontal plane.

To determine the unit normal vector $\mathbf{n}_M$ for this case we transform the normal of the module obtained through a incline plane coordinate system (in which the fundamental plane is parallel to the roof, hence also referred to as a 'roof coordinate system') to the horizontal coordinate system. Figure A.2 illustrates the orientation of the titled roof along with the mounted panels in a horizontal coordinate system.

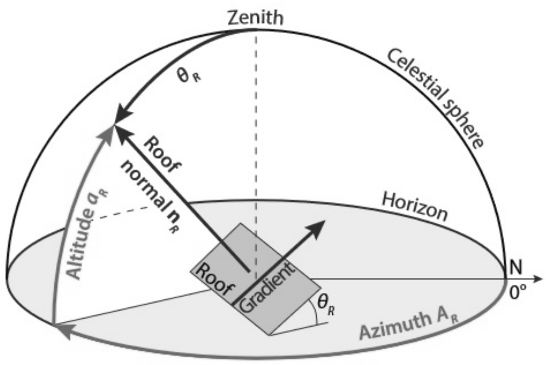

Figure A.2: Orientation of rooftop tilted at angle θ_R in horizontal coordinate system.

However, since we are required to calculate the normal of the module which is mounted on the roof we describe the orientation of the module in terms of the roof coordinate system in which the module normal is characterized by the same parameters represented with different notation: the azimuth is given by ϕ_M and the altitude is given by δ_M. The orientation of the module in the roof coordinate system is shown in Figure A.3 below.

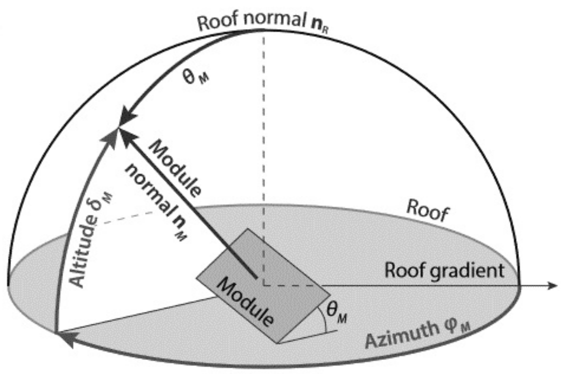

Figure A.3: Orientation of PV module mounted on a tilted roof with fundamental plane parallel to the roof & with principal direction along gradient of the roof (Hence a 'Roof Coordinate System').

To begin with the coordinate transform we start by combining two rotations:

i Firstly, We apply a transformation by rotating an angle of $(90° - a_R)$ around the axis that is perpendicular to both $\mathbf{n}_R$ and the gradient direction of the roof.

ii Secondly, we rotate with the angle $(A_R + 180°)$ along the zenith.

Applying these transformations, we obtain the normal vector as:

$$\begin{pmatrix} \xi_M \\ \nu_M \\ \zeta_M \end{pmatrix} = \begin{pmatrix} \cos a_M \cos A_M \\ \cos a_M \sin A_M \\ \sin a_M \end{pmatrix}$$

$$\begin{pmatrix} \xi_M \\ \nu_M \\ \zeta_M \end{pmatrix} = \begin{pmatrix} -\cos A_R & \sin A_R & 0 \\ -\sin A_R & -\cos A_R & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \sin a_R & 0 & -\cos a_R \\ 0 & 1 & 0 \\ \cos a_R & 0 & \sin a_R \end{pmatrix} \begin{pmatrix} \cos \delta_M \cos \phi_M \\ \cos \delta_M \sin \phi_M \\ \sin \delta_M \end{pmatrix} \tag{A.8}$$

The coordinates of the module in the horizontal coordinate system are then given by the following set of equations:

$$\xi_M = \cos a_M \cos A_M = -\cos A_R \sin a_R \cos \delta_M \cos \phi_M + \sin A_R \cos \delta_M \sin \phi_M + \cos A_R \cos a_R \sin \delta_M \tag{A.9}$$

$$\nu_M = \cos a_M \sin A_M = -\sin A_R \sin a_R \cos \delta_M \cos \phi_M - \cos A_R \cos \delta_M \sin \phi_M + \sin A_R \cos a_R \sin \delta_M \tag{A.10}$$

$$\zeta_M = \sin a_M \qquad = \cos a_R \cos \delta_M \cos \phi_M + \sin a_R \sin \delta_M \tag{A.11}$$

Dividing eq. (A.10) by eq. (A.9) to obtain an expression for the Azimuth (A_M) of the PV module in the horizontal coordinate system:

$$\tan A_M = \frac{-\sin A_R \sin a_R \cos \delta_M \cos \phi_M - \cos A_R \cos \delta_M \sin \phi_M + \sin A_R \cos a_R \sin \delta_M}{-\cos A_R \sin a_R \cos \delta_M \cos \phi_M + \sin A_R \cos \delta_M \sin \phi_M + \cos A_R \cos a_R \sin \delta_M} \tag{A.12}$$

Also we have eq. (A.11) obtained earlier which provides us with an expression for the altitude (a_M) of the PV module in the horizontal coordinate system:

$$\zeta_M = \sin a_M = \cos a_R \cos \delta_M \cos \phi_M + \sin a_R \sin \delta_M \tag{A.11 revisited}$$

Thus with eq. (A.11) & eq. (A.12) we have the expressions required to model the orientation of the module using the horizontal coordinate system.

To obtain the irradiance incident on PV module mounted on an incline plane we need to calculate the value of cosine of the angle γ, which is the angle between the module normal & the incident direction of solar radiation. This may be given as:

$$\begin{aligned}\cos\gamma = \mathbf{n}_M \cdot \mathbf{n}_S = \cos a_S \cos(A_R - A_S)(\cos a_R \sin\delta_M - \sin a_R \cos\delta_M \cos\phi_M)\\ + \cos a_S \sin(A_R - A_S)\cos\delta_M \sin\phi_M + \sin a_S(\cos a_R \cos\delta_M cos\phi_M + \sin a_R \sin\delta_M)\end{aligned} \tag{A.13}$$

Hence substituting the value of $\cos\gamma$ obtained from eq. (A.13) into the equation for direct irradiance obtained in eq. (A.1), the direct irradiance incident on a PV panel mounted on an inclined plane may be obtained as:

$$\begin{aligned}G_M^{dir} = I_e^{dir}[\cos a_S \cos(A_R - A_S)(\cos a_R \sin\delta_M - \sin a_R \cos\delta_M \cos\phi_M)\\ + \cos a_S \sin(A_R - A_S)\cos\delta_M \sin\phi_M + \sin a_S(\cos a_R \cos\delta_M cos\phi_M + \sin a_R \sin\delta_M)]\end{aligned} \tag{A.14}$$

The expressions for calculating the direct irradiation incident on PV modules mounted on both, horizontal as well as inclined planes obtained in eq. (A.7) & eq. (A.14) respectively can be used in modern PV applications for determining the approximate value of the amount of electrical energy that may be produced by a PV module under ideal conditions.

However from a practical viewpoint, there are often several factors that must be considered during calculation of the *actual* amount of energy that a PV module is expected to generate. A few examples of such factors are: attenuation of incident radiation by the atmosphere (*diffuse irradiance*) & shadowing which introduce losses in the operational efficiencies of PV modules.