BACHELOR'S THESIS ASSIGNMENT

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Study program: **Electrical Engineering and Computer Science**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Economic effect of oversizing solar panels on an inverter in case of medium climate and low feed-in.

Bachelor's thesis title in Czech:

Ekonomický efekt poddimenzování střídače ve fotovoltaických systémech pro případ mírného klimatu a nízkého výkupního tarifu.

Guidelines:

procedure
- literature survey
- market survey of household PV system costs depending on system size in India
- market survey of electricity prices in India
- market survey of PV modules
- simulation of household PV system yield in India and Czech Republic with various level of oversizing in PV*SOL software
- economical evaluation of oversizing by either increasing number of PV modules or increasing efficiency of installed modules

The aim is to evaluate economical effect of replacing mainstream technology by novel high-efficient technology of photovoltaic (PV) module. The idea is to use innovative graphical simplifying method that assumes constant cost of inverter and variable cost of PV module (depending on efficiency). This condition however leads to oversizing effect. The oversizing might be however economically beneficial when the energy during peaks of production has no use, such as in the case of low feed-in tariff. The aim is to simulate in PV*Sol range of typical Indian PV systems and the apply oversizing. From statistics on the results the effect of oversizing on energy yield as well on yield of directly usable energy should be plotted. Combined with graphical method this should give a diagram evaluating the economical potential of efficiency increase by applying e.g. additional layer of hybrid perovskite on top of crystalline silicon solar cell. The work is partially following thesis of Lenka Šterberová and should arrive to similar results, but more elaborated and applied to India.

Bibliography / sources:

[1] E-book: K. Jäger, O. Isabella, A. Smets, R. van Swaaij, M. Zeman, Solar Energy: Fundamentals, Technology, and Systems
[2] Book: Konrad Mertens, Photovoltaics: Fundamentals, Technology and Practice, ISBN: 978-1118634165
[3] article: Frank Andorka, Increasing Your Array-To-Inverter Ratio Improves Solar Economics, Solar Power World, June 24, 2013,
https://www.solarpowerworldonline.com/2013/06/supersize-it-oversize-your-array-to-inverter-ratio-to-improve-solar-system-performance
[4] White paper SMA: https://www.sma.de/fileadmin/content/global/specials/documents/oversizing/ Whitepaper Oversizing_EN_180530_01.pdf
[5] master thesis of Lenka Šterberová: "Evaluation of the Effect of Photovoltaic Module Efficiency on the Economic Return of the Domestic PV System"

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Assignment valid until: **30.09.2022**

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III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

.	
Date of assignment receipt	Student's signature

Bachelor Project

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Electrotechnology

Economic effect of oversizing solar panels on an inverter in case of medium climate and low feed-in.

Taha Naved Mujtaba

Supervisor: doc. Mgr. Jakub Holovský, Ph.D.
January 2021

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Last but not the least, I could not have completed this thesis without the support of my parents, who provided me with their wise counsel and sympathetic ear. Thank you for always being there for me and providing happy distractions to rest my mind outside of my work.

I thank the CTU in Prague for being a very good *alma mater*.

Declaration

I declare that this project is all my own work and I have cited all sources I have used in the bibliography.

Prague, January 05, 2021

Prohlašuji, že jsem předloženou práci vypracoval samostatně, a že jsem uvedl veškerou použitou literaturu.

V Praze, 05. ledna 2021

Abstract

The project aims to provide an insight into a grid-connected Photo-voltaic system in Delhi, India. A thorough market survey was done to gain various costs and input parameters which were then simulated in the solar Photo-voltaic design and simulation software **PV*SOL**.

The economic study for the PV systems in India was done as a followup of the project '*Evaluation of the Effect of Photovoltaic Module Efficiency on the Economic Return of the Domestic PV System*' [1] by Lenka Šterberova, i.e., Keeping a constant **B**alance-**O**f-**S**ystem cost for the PV System. Furthermore, Two case studies were done to compare Cell technology differences and its economic effect, and, the other being increasing the **number** of modules and evaluating its economic effect. Thus, analysing systems at different Oversizing Ratios with the inverter.

The project is divided into two major parts. The first one elaborates about the motivation and theory behind solar systems. The second part consists of practical simulations and their results.

Keywords: Solar System, New Delhi, Grid-Connected, PV*Sol, Oversizing

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Abstrakt

Cílem projektu je poskytnout pohled na fotovoltaický systém připojený k síti v indickém Dillí. Byl proveden důkladný průzkum trhu s cílem získat různé náklady a vstupní parametry, které byly poté simulovány v solárním fotovoltaickém návrhovém a simulačním softwaru **PV * SOL**.

Ekonomická studie pro FV systémy v Indii byla zpracována v návaznosti na projekt "Hodnocení vlivu účinnosti fotovoltaického modulu na ekonomickou návratnostsystému rodinného domu" [1] Lenky Šterberové, tj. Uvážením různých modulů s různou účinností při zachování všech ostatních nákladů na FV systém. Dále byly provedeny dvě případové studie, které porovnávaly rozdíly v technologiích a jejich ekonomický efekt. A v druhém případě porovnávaly vliv zvyšování počtu modulů. Nepřímo je tak studován vliv poddimenzování střídače vůči FV generátoru.

Projekt je rozdělen do dvou hlavních částí. První rozebírá motivaci a teorii využití solárních systémů. Druhá část se skládá z praktických simulací a jejich výsledků.

Klíčová slova: Fotovoltaický systém, Nové Dillí, Systémy připojené k síti, PV * Sol, Poddimenzování střídače

Překlad názvu: Ekonomický efekt poddimenzování střídače ve fotovoltaických systémech pro případ mírného klimatu a nízkého výkupního tarifu.

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Chapter 1

Motivation

1.1 Energy Consumption of India

With the soaring World population, Humans today have an essential need to overcome their ever-growing Energy requirements. Recalling the first law of thermodynamics, i.e., 'Energy is conserved, and its form is converted'; We meet our Energy requirements from various sources via conversion.

An average adult requires 10 000 Kilo-joules or 2390 Kilo-calories everyday to meet it's energy requirements. [2] In the present times, humans not only need energy limited to their body functioning, but also for other purposes like having running heated water at 6 AM in the morning or switching on a lamp to read. These energy demands of humans have been met with various sources since the beginning of time; Dry leaves for the early man to highly enriched Uranium 235 isotope in the present day.

Country	**Energy consumption** (kWh/Capita)	**Average power use** (W/capita)
U.S.A	81,642	9,319
Netherlands	53,963	6,160
Germany	44,310	5,058
China	23,608	2,695
India	**6,987**	**797**

Table 1.1: Total primary energy consumption and average power used per capita of some countries. [3]

Table 3.3 shows the energy consumption of some countries per capita, where we specifically look into the data about India,i.e., 6,987 kWh/capita. Also, The average human in the U.S.A uses ten times more the energy than an average person in India consumes.

Important Concepts
Power [kW] = Energy [kWh] / Time [Hour]
Energy [kWh] = Power [kW] x Time [Hour]
1kWh = 3600 kJ

According to the International Statistics and Analysis, by the *US Energy Information Administration*, India being the third-largest energy consumer in the world after China and United States has an increasing demand for Energy as a result of the population and economic growth despite millions without the provision of Electricity. To meet this demand, the country strives to use different energy sources as shown in Figure 1.1.

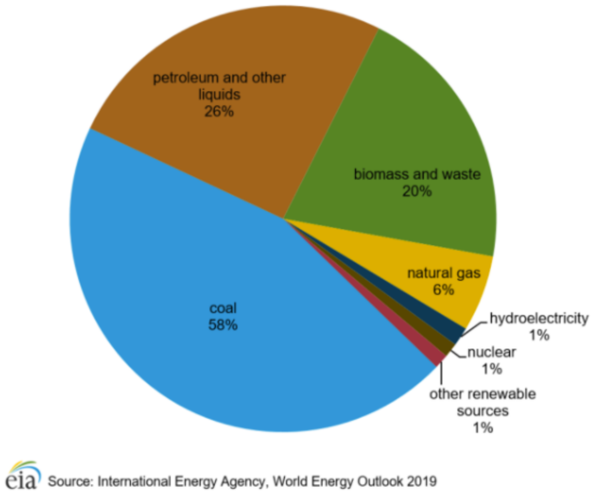

Figure 1.1: India's total primary energy consumption by fuel type [4]

Primary energy consumption in India has tripled from 1990 to 2018, reaching an estimated 916 Million Tons of Oil equivalent. The bulk, i.e., 45 % of which is provided by Coal, 52 % by other non-renewable sources , 1 % by Nuclear Fuel, and a mere 2 % by **Renewable Energy Resources** including Hydroelectricity.[4]

Another article by *The Economic Times*, from India Times says that the Global Energy Demand will increase by 30% till 2035, out of which 9% is held by India. India is also expected to overtake China as the largest growth market for energy in volume terms by 2030.[5] It also points out the analysis from *BP Energy Outlook*, where the following projections are stated:

- " Oil imports to rise by 165% and account for 56% of the increase in imports, followed by increasing imports of gas(173%) and Coal(105%). "
- " By 2035, India's energy intensity of GDP will be 36% lower than today's level, similar to non-OECD* average. "

* Organisation for Economic Co-operation and Development

Having seen the growing energy demands of India, we will come to the topic of **Availability of Energy** where we see how much of the masses still have no access to Electricity as of today.

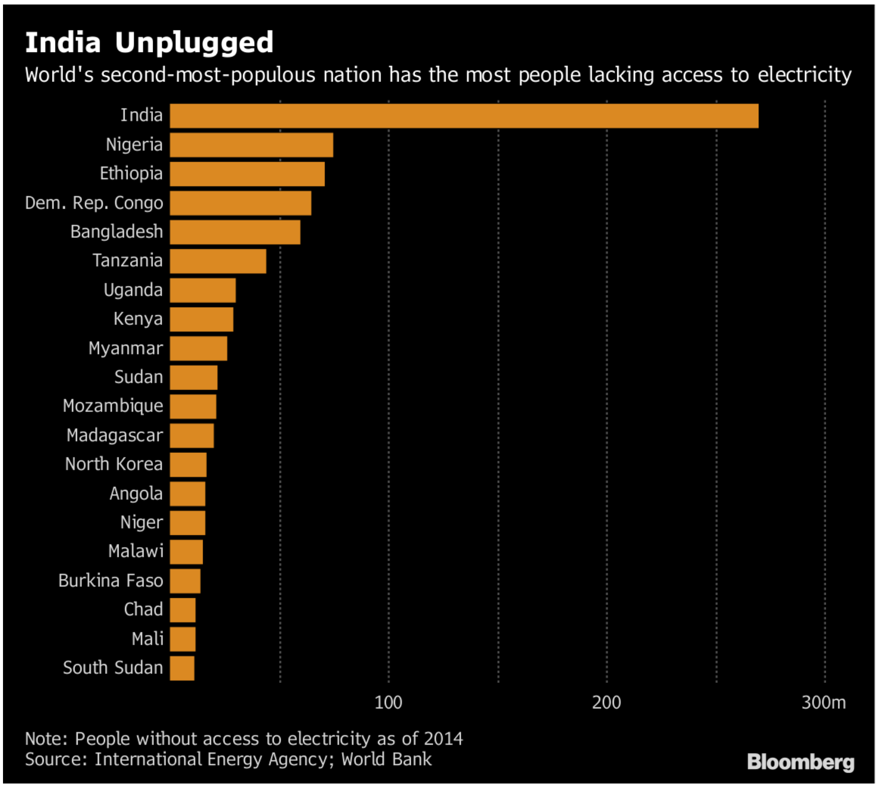

Figure 1.2: Top 20 countries with lack of Electricity [6]

According to Figure 1.2, more than 250 million people in India lack access to Electricity.[6] Despite being the second most populous nation, having a reasonable development rate, and being rich in natural resources, there is a long way to go in order to provide a running Bulb at every household. This scarcity of an essential commodity is not only hampering its growth and economic progress but causing hurdles for international trade, which is a cascading way of being detrimental on a global scale.

Thus, we do have an understanding of the importance of the rising need for Energy for mankind as Graham Zabel says, that **Energy resource extraction experiences declining marginal returns.**[7] What does this mean? This means that due to the growing demands of Energy, it exerts a massive demand for energy resources, depleting them day by day; Coal mines dug deeper and Oil wells drilled in more complex locations. Of course, it does not need to be forgotten that these depleting natural resources may end one day depriving all of us not only from the luxuries but from the essential basics as well.

1.2 Need for Renewable Energy

The rising demands of energy have also taken a significant toll on the Environment, as over-harnessing fossil fuels not only befalls an extravagant loss of depleting resources but releasing gases which cause the greenhouse effect. Burning of fossil fuels leads to the release of greenhouse gases such as Carbon Dioxide, which in turn trap heat in the atmosphere.

Evidence of rising temperatures is visible as thermometer records from the past century show that the earth's temperature has risen over 1 °F (0.9 °C) and twice of that in the arctic regions. [8]

The Arctic regions may not look significant from an individual's point of view, but the value these regions hold is paramount. An excerpt from an article written by Eddy Carmack, a Senior Research Scientist Emeritus for the *Department of Fisheries and Oceans in British Columbia, Canada* has shown that, despite holding 1% of the world's marine water in the form of frozen glaciers and 3% of the world's ocean surface area, it scoops over 10% of global river runoff and claims 20 of the world's 100 longest rivers. [9]

The melting of arctic ice not only will lead to rising sea-levels (72 Cubic Miles of Water to the Ocean annually) which may one day turn the low-lying lands into Atlantis, but also the following effects which can even be seen within five years. [10]

- **Albedo Effect:** The melting of ice, turns the white area to blue, which absorbs more heat, again increasing the already seen increased temperatures.
- **Methane Release:** The melting of ice, starts to thaw offshore permafrost that contains large amounts of Methane, which is also a greenhouse gas.
- **Increase in Water Vapor:** Warmer air holds more moisture, so this means that the arctic atmospheres now contain more Vapor than ever. Water Vapor itself is a greenhouse gas, as it traps more heat by confining more long-wave radiation.
- **Warming Rivers:** The melted ice runoff and snowmelt from waterways flow through warmer land, increasing the temperatures of large, north-flowing rivers in Siberia and Canada. These warmer waters inject even more heat into the Arctic Ocean.

Spotlighting the issue with regards to **India**, 6.65% of the total global Carbon emissions are done by India, thus ranking fourth in the World just behind China (26.83%), U.S.A (14.36%) and the E.U (9.66%). [12]

Thus, we need to realize that there's a strong need to shift to Renewable Resources of Energy, after looking at the hugely growing demand of Energy, and the impact of Fossil-Fuels on environment. The advocacy of Nuclear energy which is also a Non-Renewable Source of Energy by some, is a highly debatable issue with both sides having strong points. Those arguing against it, claim some of these reasons:

"Nuclear energy has no place in a safe, clean, sustainable future. Nuclear energy is both expensive and dangerous, and just because nuclear pollution is invisible doesn't mean it's clean. Renewable energy is better for the environment, the economy, and doesn't come with the risk of a nuclear meltdown." [11]

1.3 Types of Renewable Energy

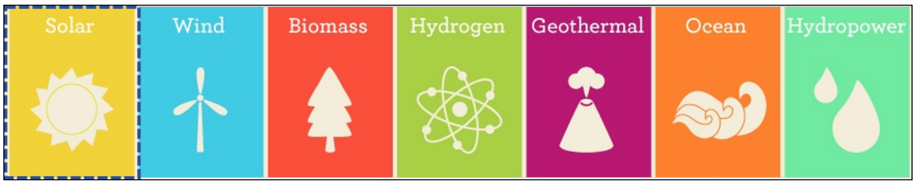

Figure 1.3: Some types of Renewable Energy [13]

Many types of Renewable Energy technologies are at humanity's disposal in today's world. These technologies operate on various principles, from the complex Photoelectric effect in Solar Cells to the basic principle of stored potential energy in Hydro-power plants. All of these resources hold their own value and benefit, but the scope of this project will be limited to **Solar Energy**.

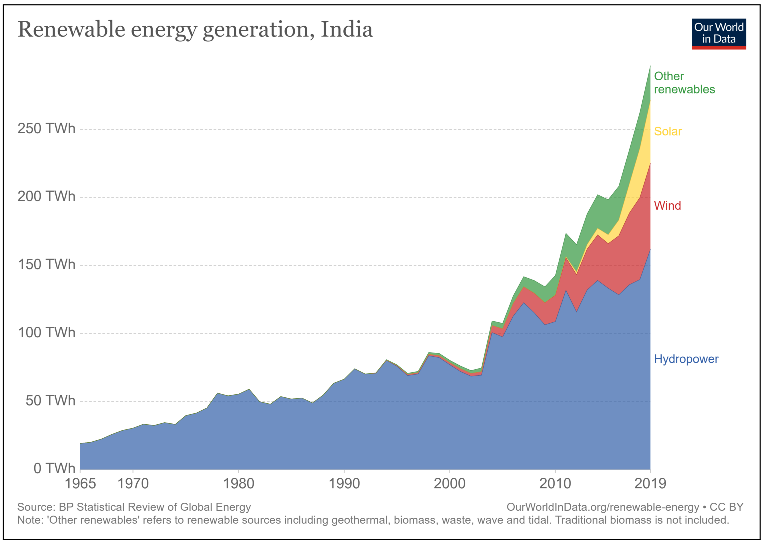

Figure 1.4: Share of Renewable Energy Generation in India [14]

Chapter 2

Theory

2.1 Major types of Solar Cells

A solar cell is the most elemental type of device, that converts light into Electrical Energy. It is based on the concept of the **Photoelectric effect**, which was initially discovered by Alexandre-Edmond Becquerel in 1839. [2] There are many different types of Solar Cells which, when combined, form a solar module / solar panel. The three major types of which are:

- **Monocrystalline Cells** (mono-Si)
- **Multicrystalline Cells** (multi-Si)
- Thin-film Solar Cells (TFSC)

2.1.1 Monocrystalline Cells

A Monocrystalline solar cell is produced by pulling out a seed crystal out of a mass of molten silicon creating a cylindrical ingot with a single, continuous, crystal lattice structure *(Czochralski method)*. This crystal is then mechanically sawn into thin wafers, polished and doped to create the required p-n junction. After an anti-reflective coating and the front and rear metal contacts are added, the cell is finally wired and packaged alongside many other cells into a full *Monocrystalline* PV module.[15] These cells are highly efficient, but due to their less sustainable production, i.e., Labor Intensive and time consuming process, they cost higher to produce and thus they are expensive than their counterparts. Due to this reason of being made from the same single silicon ingot, they also have a uniform look.

2.1.2 Multicrystalline Cells

In contrast to Monocrystalline Silicon, Multicrystalline-Silicon consists of many small crystalline grains with random orientations. Between these grains, the grain boundaries exist. And for this reason, In the Figure 2.1, we see that various grains are clearly visible in multi-Si Cell as opposed to mono-Si. At the grain boundaries, we find lattice mismatches, resulting in many defects at these boundaries. As a consequence, the charge carrier lifetime for multi-Si cells is shorter than multi-Si cells due to SRH (Shockley-Read-Hall) recombination. Hence, the grain size plays an important role in the recombination rate. As with larger grain size, the longer the charge carrier lifetime becomes leading to a larger band gap utilization. Thus having a higher open circuit voltage. Due to this reason of absence of grain boundaries, mono-Si Cells can obtain much larger Open Circuit Voltage and hence be more efficient.

Due to the size of their crystallites it is more appropriate to term them as Multicrystalline Cells. Connecting them together results in a Polycrystalline Module. These type of modules are cheaper to manufacture because of a simpler manufacturing process from cast square ingots, produced by cooling and solidifying molten silicon. The liquid silicon is poured into blocks which are cut into thin plates. Therefore costing much less than a mono-Si module to the end customer. In 2015 alone, approximately 70% of the World-wide PV production was taken by these multi-Si modules.[15]

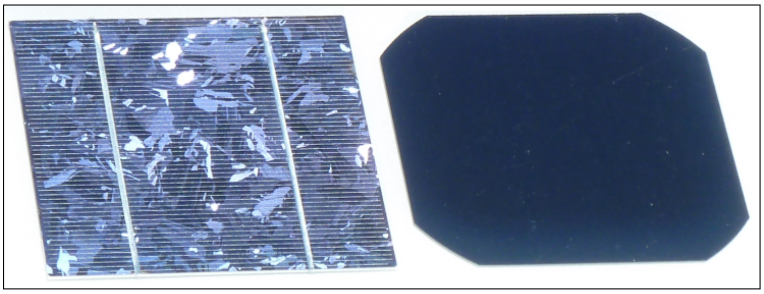

Figure 2.1: A Polycrystalline Cell (Left) vs Monocrystalline Cell (Right).[15]

2.2 Efficiency of Modules

2.2.1 Standard Test Conditions

STC are a set of conditions under which modules are tested, in order to find various parameter ratings. This helps in standardising the comparison of modules in an unbiased way with each other as they are rated under the same conditions. The conditions are as follows:

- **Temperature:** 25 °C
- **Solar Irradiation:** 1000 W/m^2
- **Air Mass:** 1.5

2.2.2 Factors affecting efficiency

The efficiency of a solar module under STC can be calculated using the equation 2.1: [1]

$$\frac{P_{max}}{E * A_m} * 100\% \tag{2.1}$$

, where: P_{max} is the Maximum Power Output [W]
E is the Solar Irradiation (1000 @ STC) $[W/m^2]$
A_m is the area of the module $[m^2]$ We must understand that the calculation of parameters like Efficiency, Open-Circuit Voltage, Short-Circuit Current in the data-sheet of manufacturers is only valid under the STCs. Therefore, these ratings are not always valid for practical usage as many other factors affect the parameters like: [18]

- Shadowing
- High ambient temperatures
- Pollution of the modules
- Suboptimal orietation of the modules throughout the day
- Module degradation
- Mismatching losses, e.g. Cable Losses

2.2.3 Maximum Power Point Tracking

An MPPT controller is a necessary device to allow the module to operate at the maximum power point. *This maximum operating power point is the maximum of the P-V Curve as shown in figure 2.2.*

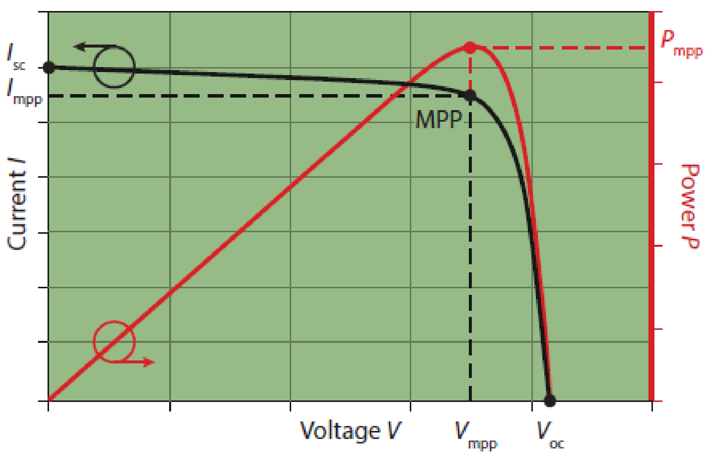

Figure 2.2: A generic I-V curve and the associated P-V Curve. The *Maximum Power Point* is indicated. [2]

2.2.4 Types of Losses

It is very crucial to understand, why solar modules don't convert 100% of the incoming solar energy into Electrical energy. As the Shockley–Queisser limit reduces the efficiency to 33.1% already (at AM 1.5 spectrum) [2], we take a look at some other losses:

- **Optical Losses:** These losses chiefly consist of light that could have been utilised to generate an electron-hole pair, but are not due to the loss of light by *Reflection*, *Shadowing*, or *Parasitic Absorption* [19, 20].

- **Recombination Losses:** These losses affect both the Short-Circuit Current and the Open-Circuit Voltage. They typically occur at the surface *(Surface Recombination)* or in the bulk of the solar cell [19, 20].

- **Electrical Losses:** Resistive effects in solar cells reduce the efficiency of the solar cell by dissipating power in the resistances. Most common paraitic resistances are *Series Resistance* and *Low Shunt Resistance.* The *Series Resistance* may be due to the movement of current through p-n material of the cell, contact resistance between metal contact and Silicon, or even the resistance of top and rear metallic contacts [20, 21].
  Cables Losses, AC Losses at the output of inverters are also few of the reasons that affect the overall efficiency of a PV system.

2.2.5 Solutions

Passivated Emitter and Rear Cell

PERC modules are a new standard type of Crystalline-Silicon Cells. These modules have a passivation layer that is spearating large area metal contact from the absorber. Additionally, it reduce optical losses by trapping more light by having an extra layer beneath the solar cell, thereby reflecting some of the sun rays back into the cell and giving them an opportunity to be converted into Electrical Energy. They can help increase the energy production by 6 to 12 %. [20, 22]

These can be of two types, i.e., Monofacial: Producing energy from one side and Bifacial: Can produce energy from both sides.

Module	Type
Canadian Solar CS3W-415P	multi-Si
JA Solar JAM78S10-440/MR/1500V	mono-Si
Vikram SOMERA VSM.72.370.05	mono-Si
GOLDI-72GN1	mono-Si
RenewSys DESERV 3S6H	mono-Si
Panasonic ANCHOR AE14H380VHB5B	mono-Si

Table 2.1: Filtered PERC modules used in our study.

As seen in table 2.1, we also used modules in our project constructed using PERC technology. All of these modules were Monofacial in nature.

Bypass Diodes

These parallel connected diodes serve as a protection mechanism in case one of the solar-cell is shaded or damaged. Thus, they are a good solution for the problem of **Partial Shading**. [2] These are not to be confused with *Blocking Diodes* which are series connected and serve the purpose of verification of current flowing only in one direction, i.e., out of the series array. [23]

PID Resistant

Potential Induced Degradation is an undesirable effect that can occur when the module's voltage potential and leakage current drive ion mobility within the module between the semiconductor material and other elements of the module (e.g. glass, mount and frame), thus causing the module's power output capacity to degrade. [24] In some cases the degradation factor can make a power plant to lose 70% of the total power generation. [25] It also reduces the Maximum Power Point and the Open-Circuit voltage of the module along with a reduction in shunt resistance.
Most of the filtered modules in our study, including the ones in Table 2.1 are PID-Resistant as per the IEC standard.

Half-Cell Modules

Half-Cell modules contain double the number of solar cells as opposed to the traditional Full-Cell modules. Full-Cell Modules usually consist of 60 or 72 Cells, whereas a Half-Cell module may contain 120 or 140 Cells. This bisection of cells is done due to the factor of resistance. As they have more number of cells, they tend to have lower resistance which allows to capture more energy than their counterparts.

Manufacturers also claim to offer many other benefits when choosing Half-Cell modules like: Excellent performance in low-light situations, More Durability, Better performance in high-heat conditions, Less heat accumulation below the individual cells on the module. [26]

Figure 2.3, from the *International Technology Roadmap for Photovoltaic* gives us a good overview about the rising trends of Half-Cell modules in the PV Market.

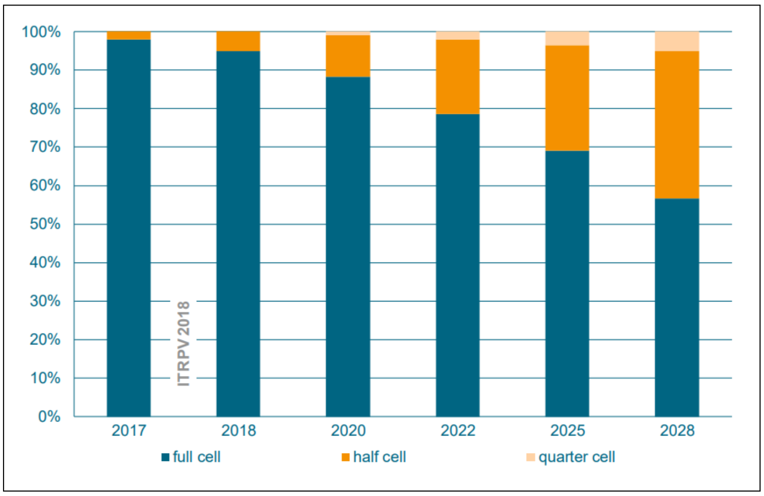

Figure 2.3: Predicted market shares for modules with full, half and quarter cells.[27]

2.3 PV Systems

2.3.1 Types of PV Systems

PV System can range from simple designs like charging a smart phone during the day when connected to a mini flexible panel to providing AC power in a household. The household may require power from the system day and night, thus employing a battery to support at night or the system may be required to provide power only during the day. Depending on these requirements PV systems can be distinguished by varying in their configuration.

Stand-alone Systems

Off-Grid or Stand-alone systems rely on solar power only without the input of AC power from the grid. These type of systems require batteries to store power for usage at night, and a charge-controller which switches off the PV-modules when batteries are fully charged or switches off the loads when batteries are discharged below a certain limit. [2]

Grid-Connected Systems

On-Grid or Grid-Connected systems are connected to the grid via inverters, where the inverter provides the PV-generated power into the grid or to AC appliances in the house. These systems do not require the use of batteries and they can act as a buffer by supplying electricity feed-in to the grid if an oversupply of PV-Power is generated. Meanwhile, the grid can also provide electricity to the household at times of insufficient PV-Power.[2] They are also the more popular type of PV systems among homeowners due to their lower cost because of absence of batteries and the assurance of providing electricity irrespective of the production by the PV-System. [28]

Our study solely focuses on this specific type of PV System and with regards to the surplus feed-in to the grid option, we overlook this part in our study due to the absence of feed-in policies from rooftop PV Systems in India.

Hybrid PV Systems

Hybrid PV Systems consist of a combination of the PV-Modules along with a complimentary power generator using Diesel, Gas or even Wind. In contrast to their peers, these systems require a more complex type of installation due to several reasons. e.g. Starting of the Diesel generator only when the battery reaches a certain discharge level. The generators can also be used to recharge the batteries, thus not only being limited to power the AC appliances.

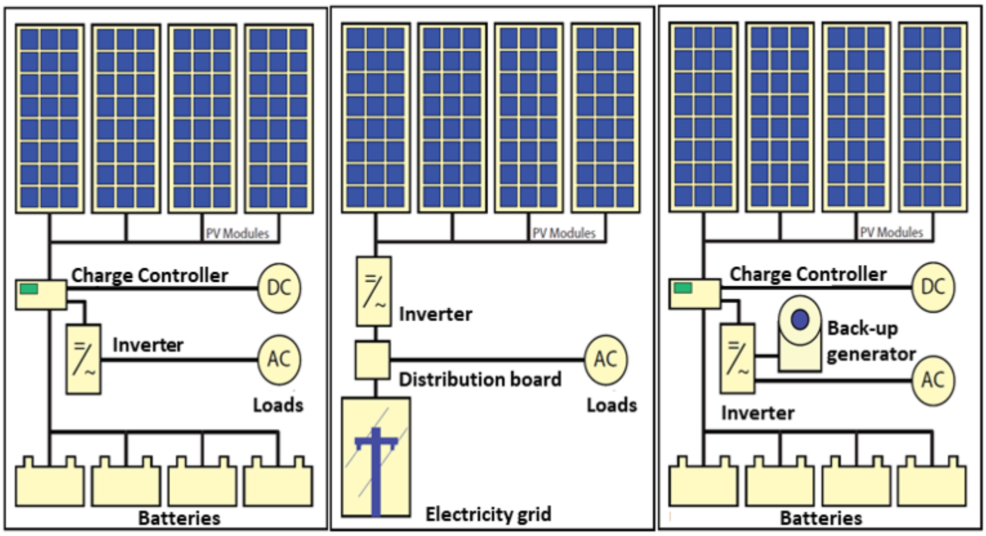

Figure 2.4: Schematics for Off-Grid, **On-Grid** and Hybrid Systems from L→R [2]

2.3.2 Components in a PV System

Despite the PV-Modules being the heart of a PV-System, there exist many other components which are required for proper functioning and installation of a PV-System. All of these components apart from the PV-modules are collectively called as **Balance Of System**.
The BOS Costs are vital in financial analyses of solar systems.

Mounting Structure and Cables

A Mounting structure is the skeleton used to fix and hold the modules in their proper place with the desired orientation and angle.
Cables on the other hand connect the various components with each other to transport Current. Cables of sufficient thickness and low resistivity materials must be used in order to minimise resistive losses discussed in section 2.2.2.

Inverters

As opposed to a rectifier in electronics which converts AC power → DC power, an **Inverter** is a device that converts PV-module-generated DC Power into AC Power fit for household consumption. These inverters also have a power rating from the manufacturer, which is essential to know for our study.
Some of the most popular brands of inverters in India are: Huawei, Delta, Sungrow, Sineng and Kehua.

2.3.3 Oversizing

What is Oversizing an array? Why do we do it?

Well, to begin with we need to understand that oversizing doesn't mean increasing the area of a module or length of the cables. **Oversizing an array means to increase the DC input power to an inverter more than it's rated AC output power.** *This is also at times called as Undersizing the inverter.*

For an inverter with maximum AC power output $P_{AC,max}$ connected to a PV array with STC power $P_{DC,(STC)}$, the inverter is oversized if: [29]

$$P_{DC(STC)} > P_{AC,max} \tag{2.2}$$

As discussed in section 2.2.1, PV Modules at the time of their manufacturing are rated according to the STC. Nevertheless, in real life, these conditions hold a mere reference value as the day-to-day conditions broadly differ in different parts of the world. So, a module with a manufacturer's claim of producing 320 Wp with 20% efficiency may not necessarily produce 320 Wp during day-to-day conditions but may only generate 250 Wp. This can be due to many factors that affect efficiency, as shown in Section 2.3.2.
In order to mitigate this issue, the DC input power can be increased such that, despite the less production, the inverter is still utilized at its full capacity.
This can be achieved by:

- Using modules with higher efficiencies. This can be done by using newer technologies like a Half-Cell, PERC Module, or using Perovskite in silicon-based tandem cells.
- **Increasing the number of Modules to effectively increase the total combined DC input power to the inverter**.

Oversizing Ratio

DC → AC ratio / DC load ratio or Overloading ratio is how much DC capacity (the quantity and wattage of solar panels) is installed to the inverter's AC power rating.

$$\text{Oversizing Ratio} = \frac{P_{DC(STC)}}{P_{AC,max}} \tag{2.3}$$

Inverter Clipping

What would happen on a very sunny day, if the oversized arrays produce more energy than an inverter is rated at? Will the system shutdown?

To overcome such an issue, inverters possess a feature called **Clipping**. Inverter Clipping or Power Limiting occurs when DC input power to the inverter exceeds an inverter's maximum input rating. [30] As the name suggests, this type of extra energy produced is simply clipped (and lost) without affecting the required rated energy. Minuscule value of energy production may get affected but otherwise **clipping should not damage any component of the PV system.** [31]

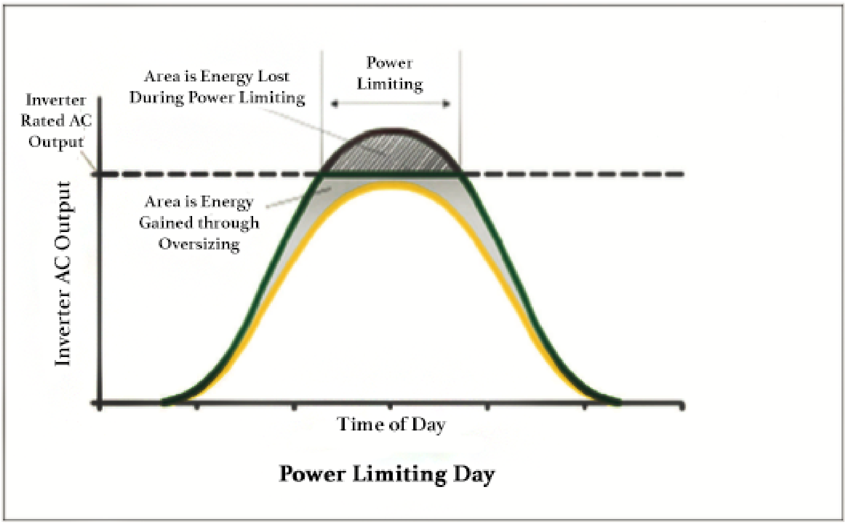

Figure 2.5: Daily Production with Clipping (Power Limiting) on a Sunny day [32]

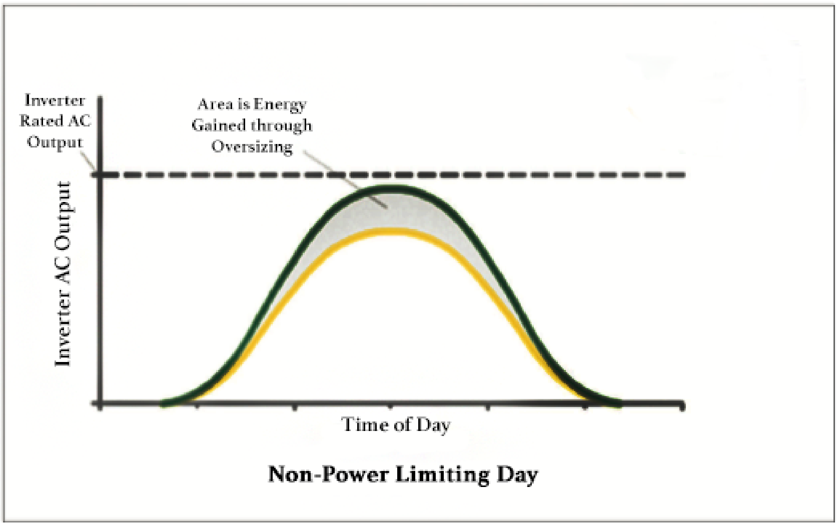

Figure 2.6: Daily Production without Clipping on a Cloudy day [32]

Optimizing

- **Clipping Losses:** The energy clipped by the inverter, at times of DC power exceeding AC rated power, is called as Clipping Loss.
- **Specific Yield:** This is the system's annual energy harvest per unit kWp of installed DC capacity.

$$\text{Specific Yield} = \frac{\text{Energy Generated [kWh]}}{\text{Installed Module Power [kWp]}} \tag{2.4}$$

For optimizing a system, we need to keep various factors in mind. These may include keeping the clipping losses to a minimum, having the maximum Specific Yield.

But it may also be interesting to know that, we cannot oversize a system irrationally as after a specific threshold the Oversizing Ratio takes a toll on the **Specific Yield value**. Different studies have found out different values to be set as the *Optimum Oversizing ratio*, so it can be said that this is not a simple deduction but rather a complex calculation depending on many factors like size of the system, inverters, location and Climate etc.

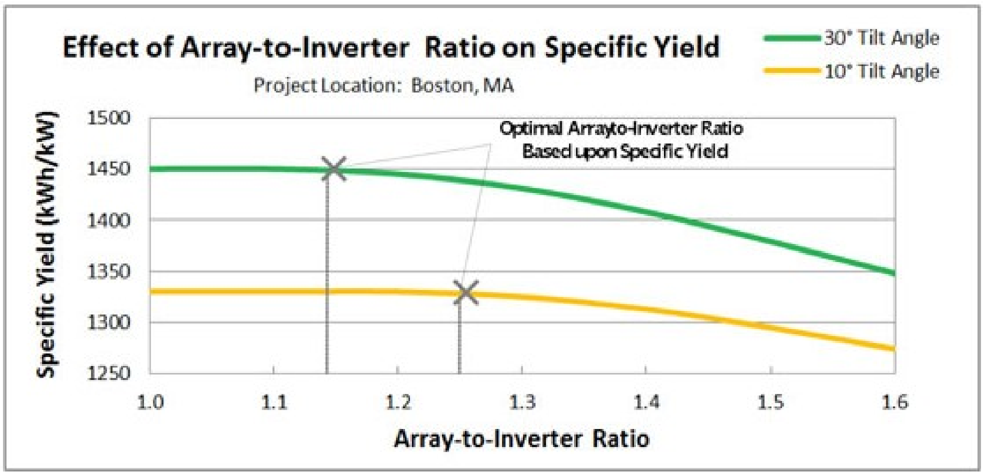

Figure 2.7: Effects of Oversizing Ratio on Specific Yield [33]

Oversizing Ratio	Energy Generated	Clipping Loss
1.0	163.06 MWh	0.0 MWh
1.3	193.86 MWh	1.8 MWh (0.9%)
1.5	217.24 MWh	11.0 MWh (4.8)%)

Table 2.2: Energy Generated out of a 100-kW inverter as a function of Oversizing Ratio. [34]

Figure 2.7 portrays the effect of Oversizing Ratio on the Specific Yield. It can be noted that the decreasing ratio becomes critical at a specific point, which depends on the cost saved by purchasing weaker inverter. Similarly Table 2.2 shows an effect of Oversizing Ratio on Clipping Loss.

2.3.4 Economics of a PV System

An essential part along with the previously described sections of PV Systems, is the Economics of a PV System. The Economic topics can be classified on various levels. Ranging from the Consumer level to Manufacturers and Installer level. Not to forget, even the macroscopic technological level is important, where it is compared with other sources of generation technologies. Our economic focus in the study for a rooftop installation is mainly limited to the consumer benefit.

Payback Time

Payback Time or Payback Period in finance is referred to the amount of time required to recover the cost of an investment. This is the most basic method of return of investment calculation at the consumer level.

$$\text{Payback Time} = \frac{\text{Initial Investment}}{\text{Annual Return}} \tag{2.5}$$

The Payback Time is strongly infulenced by various factors like: [2]

- The Location of the PV System. The sunnier the location, the more the PV Yield, and the shorter payback time.
- Grid Electricity Costs. The higher the Grid Electricity costs are in the city of PV System, the shorter the Payback Time becomes.
- Initial Costs of the PV System

NOTE: *Payback Time must not be confused with Energy Payback Time, which is a completely different concern describing the Total Invested Energy by the average Annual Energy Yield.*

However, in practice this Payback Time is not so accurate as this doesn't take into account factors like:

- **Inflation**. *1000 $ today, will not be having the same purchase power as 1000 $ in ten years time*
- Subsidies, Feed-In-Tariffs, **Interest Rates**. These play quite a pivotal role in the actual calculation of the Return of an Investment.

To have a more detailed calculation, we need complex methods which will be described in the upcoming parts.

LCoE

This parameter takes into account, the Capital Cost (Discount Rate). **Levelized Cost of Electricity** helps in comparing the lifetime costs of different Electric Energy generation technologies. It is defined as the cost per kWh of electricity produced by a particular facility. To effectively estimate the cost per kWh, LCoE allocates the costs of an Electricity generation system across its full lifecycle. Similar to the averaging of upfront costs of production over a long period of time. The calculation of LCoE can reach a very high complexity, based on the number of Variables taken into account. [2] For a simple case, we can say that the LCoE can be found using equation 2.6.

$$\mathrm{LCoE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{2.6}$$

where,
I_t are the investment expenditures in the year t
M_t are the operational and maintenance expenditures in the year t
F_t are the fuel expenditures in the year t
E_t is the Electrcity Yield in the year t
r is the discount rate

Discount rate is a factor used to discount future costs and translate them into present value. And for PV Systems, Fuel Expenditures F_t is zero.

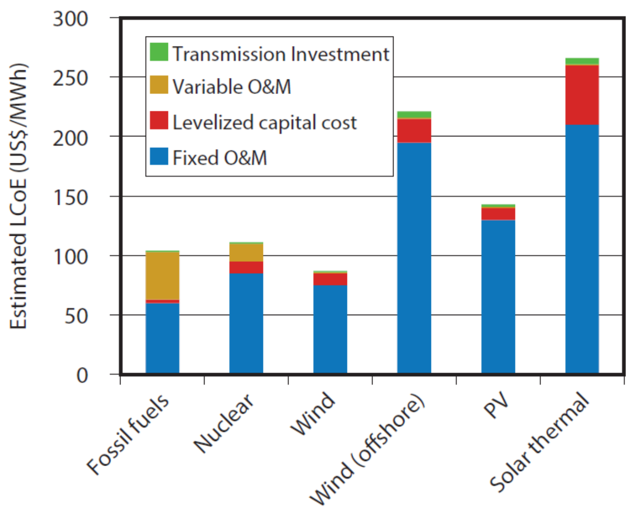

Figure 2.8: LCoE for different types of Electricity Generation Systems [2]

Figure 2.8 shows us that Wind Energy has the lowest LCoE, even below Fossil Fuels and Nuclear Systems, and PV energy is still slightly above the Non-Renewable Sources.

NPV

Net Present Value is a concept commonly used to show the value of future income or savings in a PV System installation. LCoE is different from NPV, as LCoE also shows the Net Present Value of Total Cost divided by the Total Energy produced in lifetime. Thus, giving us a Price/kWh Value. It also covers the time value of money, and the discount rate. It is calculated by subtracting the initial investment cost from the sum of the total discounted future cash flows over the lifetime of the investment.

$$\text{NPV} = \sum_{t=0}^{N} \frac{\text{Cash Flow}_t}{(1+r)^t} \tag{2.7}$$

where,

Cash Flow is the system cost in year 0 and for years t = 1 through 25 (Assuming 25 Years Lifespan of the PV System), and r is the discount rate, same like in equation 2.6
NPV is very useful not only in valuing PV Systems, but also in finding returns of investments like Real Estate and Business Ventures.

NPV is quite relatable to the numerator of LCoE. LCoE is different from NPV, as LCoE also shows the Net Present Value of Total Cost divided by the Total Energy produced in lifetime. Thus, giving us a Price/kWh Value. [35, 44]

$$\text{LCoE} = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}} \tag{2.8}$$

IRR

Internal Rate of Return is quite analagous to NPV, only different in the unit. As NPV is calculated in the currency, i.e., Dollars/Euros , IRR is a percentage return one can expect to gain or lose from an installation and the future cash flows. IRR is solved by setting the NPV close to zero, and finding the discount rate. Since this calculation is rather difficult mathematically, trial and error of different discount rates are used till we achieve NPV as close to zero as possible. [36]

Chapter 3
Practical Findings

3.1 PV*SOL

A Solar simulation software is a very useful tool that provides a user with the estimated solar energy yield, performance ratio, Comparative CO2 emissions and other important parameters of a PV System by creating a computer simulation. These tools are of high importance as it is not feasible for a designer to run trials using real modules for the whole year in order to get various results. Financial reports like ROI (Return On Investment), Years of return on assets, and more are also some of the complementary benefits that a user can generate.
Today, many Solar simulation softwares exist on the market with various features. Thus, while choosing a simulation software one must keep in mind factors like User-Friendliness, Customisable Module or Inverter database, Reliability, Flexibility and accuracy. *Some inverter companies also provide their own simulation softwares.*

Some of the top 5 Solar simulation softwares on the market are: [37]

- **PV*SOL Premium**
- PVSyst
- Helioscope
- Homer
- Solar Pro

We carried out the simulations for this project on **PV*SOL Premium 2021** made by *Valentin Software*, with the licensing under the Faculty of Electrical Engineering, CTU.

3.1.1 Accuracy

A research paper [38] published in the *International Journal of Energy and Environemntal Engineering*, calculated the accuracy of multiple different simulation software tools, by comparing the simulated results with the real observed values from a PV System Installation. In order to compare the goodness of fit between the results simulated from the softwares and the real test, various parameters were used:

- Root Mean Sqare Error (RMSE)
- Mean Absolute Deviation (MAD)
- Absolute Percentage Error (MAPE)
- Model Efficiency (EF)

According to the statistical parameters used, when the values of RMSE, MAD, MAPE is as close to zero as possible, and EF as close to 100 %, we can say that the simulations are the most precise.

Software	RMSE	MAD	MAPE (%)	EF (%)
Archelios	5.41	4.85	3.70	98.94
Polysun	4.27	3.52	2.67	99.31
PVSyst	4.80	4.29	3.22	99.21
PV*SOL	**3.07**	**2.67**	**2.47**	**99.66**
PVGIS	18.96	15.07	12.81	88.00

Table 3.1: Analysis of Solar irradiation at 30 ° [38]

Software	RMSE	MAD	MAPE (%)	EF (%)
TRNSYS	47.46	29.72	1.24	99.69
Archelios	141.23	126.67	5.14	97.16
Polysun	200.34	186.90	7.41	94.30
PVSyst	234.23	225.92	9.16	92.47
PV*SOL	**230.92**	**223.18**	**9.08**	**92.66**
PVGIS	244.88	221.42	9.24	89.93

Table 3.2: Energy generation error analysis [38]

From Tables 3.1 and 3.2, we can see that **PV*SOL** displayed the most accurate calculation of the global irradiation received by the system. But, in terms of the energy generated it was the third most inaccurate.

3.1.2 Model

Due to the lack of *Google Street View* in India, and a proper satellite view of the household location, a 3D-Model with a flat roof building was created as

most of the buildings in Delhi are flat-roof. This 3D-Model in the software did not have any nearby high-rise buildings or towers that would have caused **Significant** external shadowing on the roof. Nonetheless, some trees were placed outside the building area.
Also, as the location is in the Northern Hemisphere, modules were placed facing South. The tilting of assembly system for placing the modules (30°) were default as in the **PV*SOL** software and were not changed.

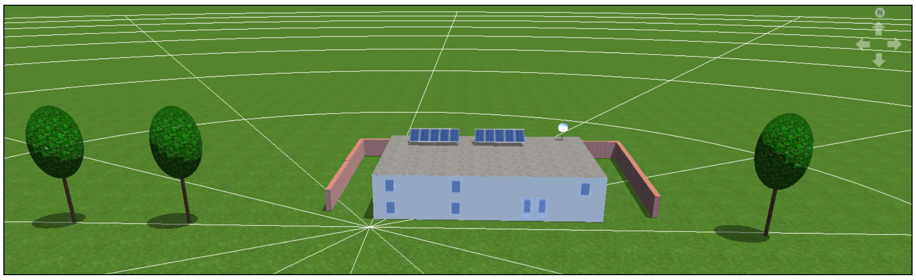

Figure 3.1: House Model adapted in PV*SOL

Climate Data

The temperature and irradiation data was acquired from **Meteonorm** Software made by *Meteotest AG*. **PV*SOL** has a built-in option to directly adapt this data from **Meteonorm**. Unfortunately, the data was recorded from 1991-2010, which makes it quite old, keeping in mind the annual temperatue deviations described in section 1.2.

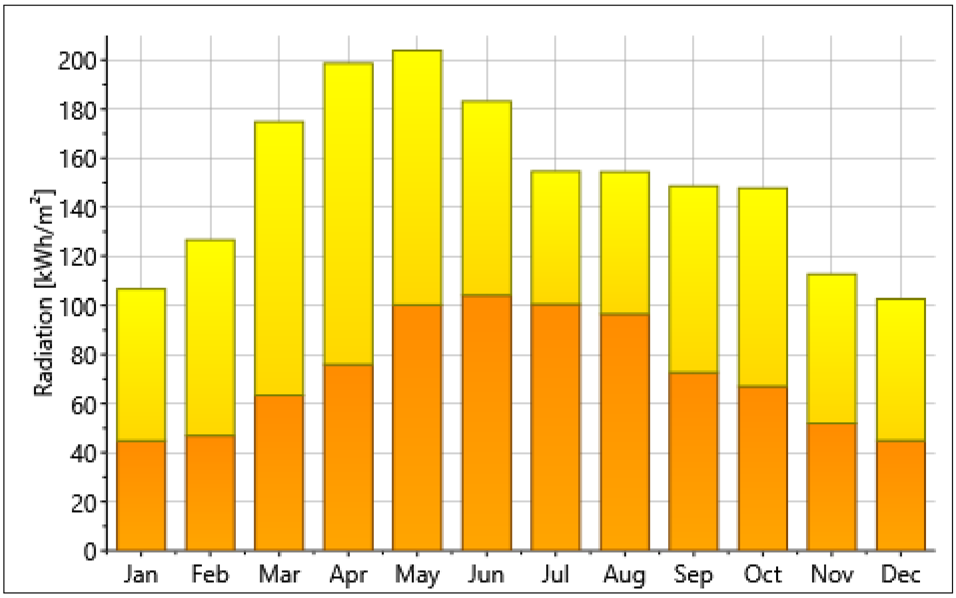

Figure 3.2: Radiation data imported from the **Meteonorm** software.
Yellow: Global radiation & Orange: Diffuse Radiation

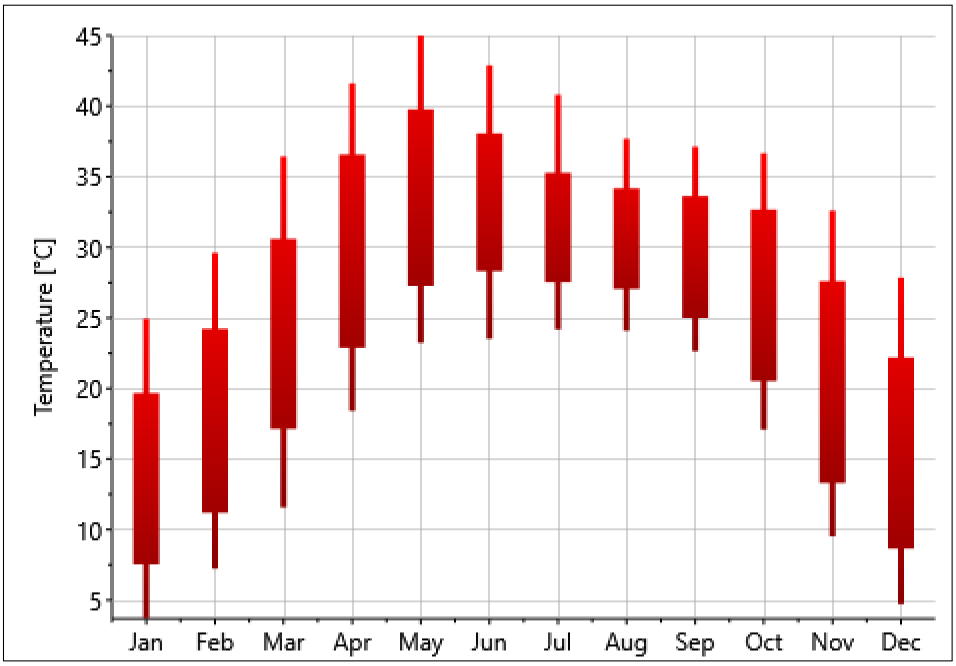

Figure 3.3: Temperature data imported from the **Meteonorm** software.

Figure 3.2 & 3.3 contain the Radiation and temperature data of Delhi, India measured during 1991-2010.

- **Annual Sum of Global Irradiation**: 1959 kWh/m^2
- **Annual Average Temperature**: 25.9 °C

Electrical Parameters

- **Mains Voltage between phase and neutral**: 230 V
- **Number of Phases**: Three
- **Displacement Power Factor** ($\cos\phi$): 1

Consumption

The Yearly energy Consumption plan of the household is set at 3929 kWh considering the household composed of 3 members, i.e., Two Adults and One Child.

3.1.3 Calculations

BOS [A01]

Average Module (€/m^2)	Average Module (€/Wp)	Average PV System [45] (€/Wp)
138.17	0.4337	1.16052

Table 3.3: Values of required **Costs**, in order to calculate BOS Cost

From Table 3.3, we calculate the BOS cost per area using Equation 3.1, i.e.,

$$\frac{\text{Avg Module } (€/m^2) * [\text{Avg PV System } (€/\text{Wp}) - \text{Avg Module } (€/\text{Wp})]}{\text{Avg Module } (€/\text{Wp})} \quad (3.1)$$

We see that we have the BOS Cost per area as **208.25** €/m^2. This will be very important for us, in order to have the innovative graphical interpretation of the Project. The calculations and references for price points can be found in the Annex Excel File [A01]

LCoE [A02]

The LCoE Calculations were conducted on an Excel Template from the *Corporate Finance Institute* which is only for educational purposes. It can be found in the Annex Excel File [A02].

Investment Parameters for LCoE
Optimization and Maintenance Costs: 2500 INR / Year [46]
Project Lifespan: 25 years
Discount Rate 8.77% [47]

3.2 Market Survey Evaluation & Simulation [A01]

3.2.1 Market Survey of Modules in India

After conducting a market survey of Monocrystalline modules in India, it was found out that the **average price per Watt** for locally manufactured modules was INR: 25.0942 /- **or** 0.28542 €. The average price per Watt for internationally manufactured Monocrystalline modules was 0.28399 €.

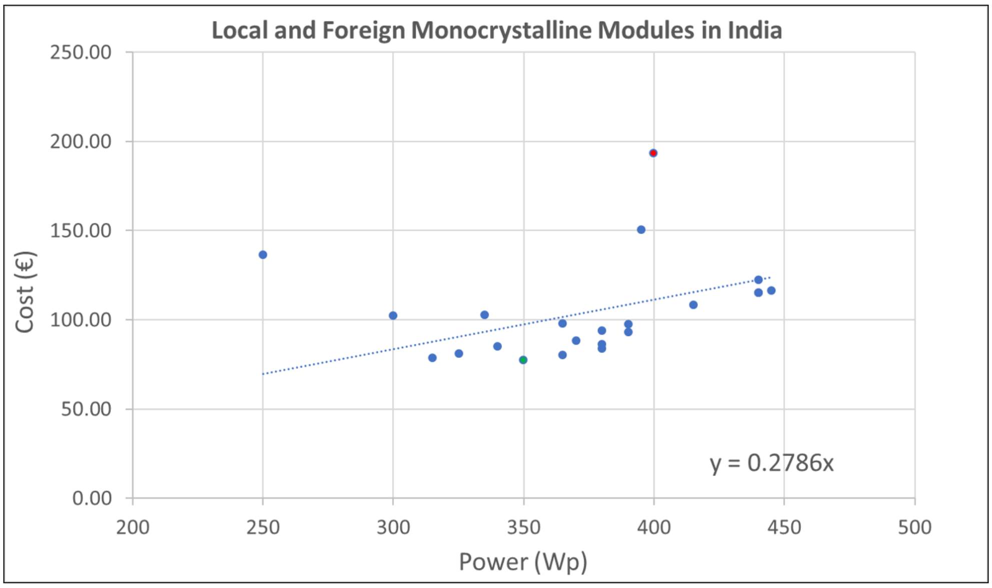

Figure 3.4: Price-Power analysis of most popular Monocrystalline modules in India. [A01]

The results for Multicrystalline Modules in India, also showed no significant difference between the average price per Watt of locally manufactured Polycrystalline modules and internationally manufactured Polyycrystalline Modules. The average price per Watt of locally manufactured Polycrystalline Modules was around 0.26101 €, and the average price per Watt of internationally manufactured Modules was 0.26819 €.
NOTE: The modules that appear to be in a straight line, are from the same manufacturer, with the same base price (INR/Wp) and from the same Product Series. (Just with different Power Ratings, i.e., **Wp (Watt Peak)**)

Exchange Rate* [16]
1 Euro = 87.9213 Indian Rupees
1 Indian Rupee = 0.0113738 Euros
* Rates are always subjected to fluctuations

Also, the modules selected from the local Indian manufacturers are from the category of Tier 1 Manufacturers with ISO and IEC certifications.[17]

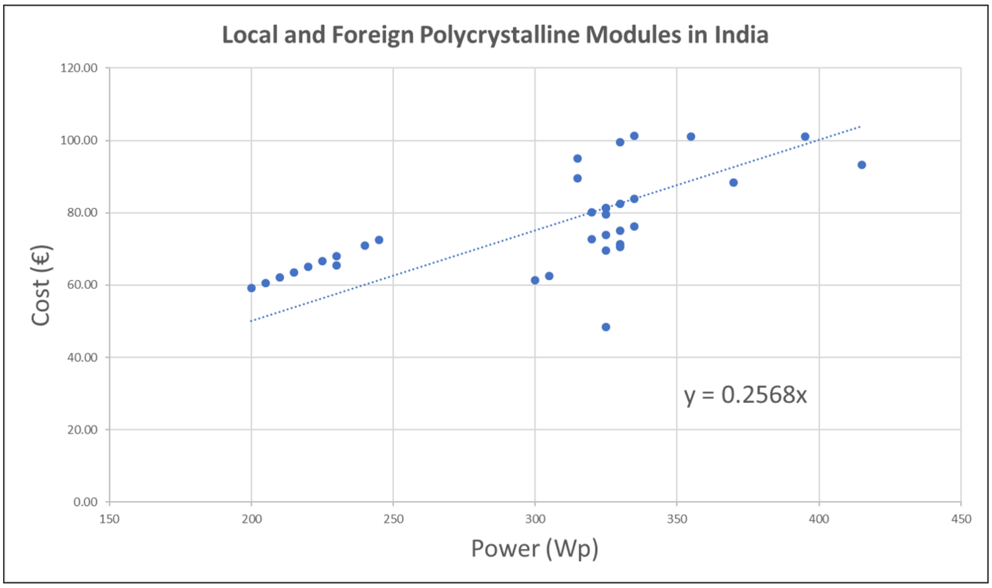

Figure 3.5: Price-Power analysis of most popular Multicrystalline modules in India. [A01]

Many of them, are PID resistant, half-cell and PERC modules and have a linear power output for 25 years. Detailed information about each module can be found in the supplementary files with data-sheets of each selected module.

3.2.2 Investment dependence on the basis of Efficiency [1]

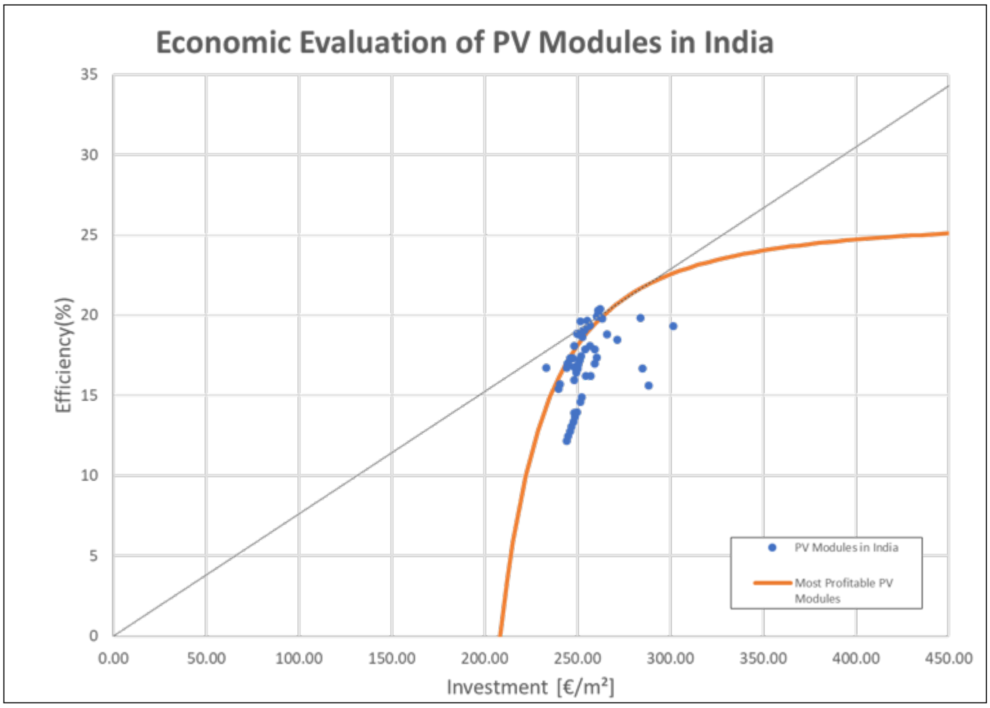

Figure 3.6: Investment dependence of Modules based on Efficiency with constant BOS in Indian Market [A01]

Having looked at Figures 3.4 and 3.5, where we plot out the multi-Si and mono-si modules in India, we created the Graph in Figure 3.6. The Curve keeps a constant BOS, i.e., 208.25 €$/m^2$ and evaluates the PV system investment based on the Module Efficiency. The Hyperbolic envelope Curve in Orange color has it's origin at the BOS Price, essentially symbolizing that we have Zero Efficiency (Y-Axis) at this Cost. The Curve asymptotically rises to a theoretical assumption of maximum 26% efficiency.

From an economic perspective in the graph, the straight black tangent line represents the given fixed Efficiency per Investment ratio. Thus, the touching point, i.e., Tangent touching the curve is the most advantageous point. Points lying slightly above the curve are some modules which offer high advantage, but are quite exceptional taken during the market survey.

For selecting the modules as an investment decision for a consumer ideally, the modules at the bulge of the curve, i.e., Intersection with the tangent line are the most economically advantageous modules and we can say that when most modules will lie in this region, the market will become consolidated.

3.2.3 Annual Energy Yield found by PV*SOL Simulations dependence on the Investment Cost of PV System

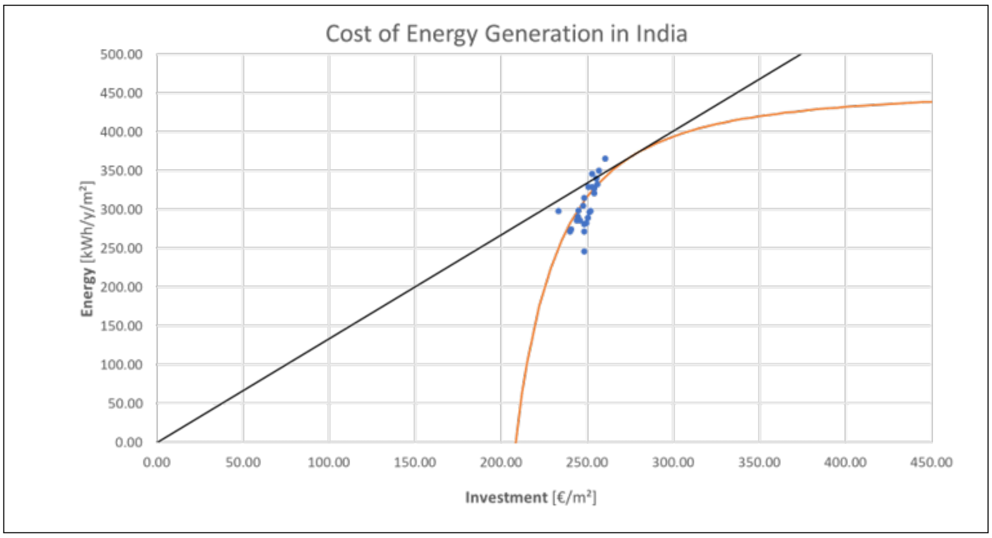

Figure 3.7: Energy Yield of the PV System on the basis of Investment (Also on the Efficiency of Modules) [A01]

Similar to the concept of the previous Graph in Figure 3.6, where the graph was not yet perfectly evaluating the cost of produced energy, we conduct some simulations and now the Black tangent line represents Energy per Investment. Thus, directly representing produced energy cost.

Here the graph in Figure 3.7, shows us the analysis of some of the listed Modules in India with a constant priced BOS System. The BOS cost remaining the same as 208.25 €/m^2.
The simulations in **PV*SOL** provided us with the Annual Energy Yield per Area, which were then plotted against the Investment per Area. The envelope curve here also has it's origin at the BOS Price, at which obviously the system yields an annual energy of 0 kWh/Year/m^2. The curve was plotted by multiplying an arbitrary factor of 17.5, using the curve parameters from previous graph.

After having these simulations and graphical analysis, we realize that we might have an accompanying issue of Oversizing Effect as overlooked. This is because we have been considering the same BOS Cost for all Modules which definitely are different in their output Parameters due to ranging efficiency.
In order to study the economic effect of Oversizing for a rooftop small PV system, we will be forming a Case study which will be in the upcoming section of Approach II. This will help us decide if Oversizing has a positive benefit or negative drawback to the Household consumer.

3.3 Approach I. Using Modules of higher Efficiency - Case Study

3.3.1 Theory: Efficiency Curve Differences in Modules

Just for understanding the difference in Efficiency, we take a look at the **Relative Efficiency - Irradiance** dependence curve of two modules, having the same type of Silicon Cell (mono-Si). The only difference being the presence of Half-Cell technology in one type of module.

- HHV Solar HSTFF24315M (12x6 = 72 Cells)(Efficiency: 15.93%)
- JA Solar JAM78S10-440/MR (26x6 = 156 Cells)(Efficiency: 20.3%)

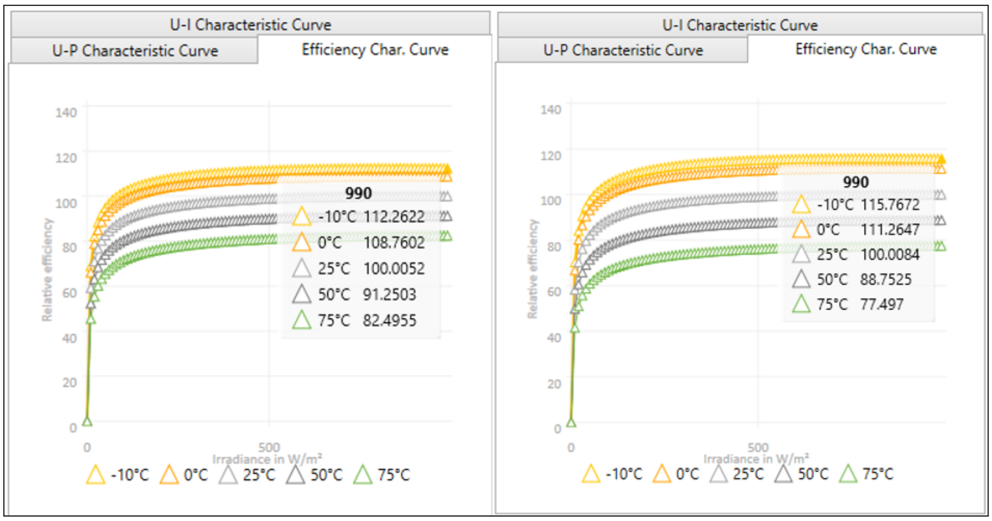

Figure 3.8: Relative Efficiency dependence on the temperature and Irradiance of Half-Cell Module (Left) and Full-Cell Module (Right)

NOTE: Relative Efficiency is not the same as Nominal Efficiency. Nominal efficiency is calculated at STC, and if conditions are different the nominal efficiency must be multiplied with the Relative Efficiency factor. [40]

From Figure 3.8, we can see that the Relative Efficiency with irradiance 990 W/m^2 and temperature 25°C is not so different in the Modules.

Whereas, for higher temperatures, i.e., 50 or 75 °C, Half-Cell Module has higher relative efficiency. Meaning that at a temperature of 75°C, the Full cell Module will be 12.34% efficient as opposed to its 15.93 % efficiency at STC. And the Half-Cell Module will be 16.74 % efficient as opposed to 20.3 at STC. Importantly, the effect at a very low irradiance of 200 W/m^2 is also visible and in correlation with the theory behind Half-Cell Modules. At 200 W/m^2 and temperature 25 °C, Half-Cell Modules had a relative efficiency of 94.32, meaning an Efficiency of 19.14% as opposed to 20.3%. Full-Cell Modules at this low level of Irradiance had a relative efficiency of 94.30, thus having an Efficiency of 15.02%.

3.3.2 Case Study according to Approach I. [A01]

Here, using comparative analysis we try to evaluate the difference between a higher efficiency module and an average efficiency module. Selection of modules is from the Graph in Figure 3.6, where the modules lying on the Orange Curve are taken. The inverter will be the same for all 5 modules, in order to be focused on the differences in modules only. And, systems may be slightly oversized.

Module	**Type**	**Efficiency** (%)	**Power** (Wp)	**Module Cost** (€)
6 x TP300	multi-Si	15.40	300	61.42
6 x SS325P	multi-Si	16.72	325	69.49
6 x 72GN	multi-Si	17.31	335	76.20
4 x 72GN1	mono-Si	18.08	350	77.23
4 x CS3W-445MS	mono-Si	20.10	445	116.41

Table 3.4: Modules selected for Approach I.

The inverter is **SMA Sunny Boy 1.5-1VL-40** for Modules in Table 3.4. And for getting the total cost of PV System, required for the LCoE, We use the following concept: The total Cost is equal to the **sum** of the following:

- (BOS Cost per Area Without Inverter (128.48 €/m^2) * Total Area) [A01]
- (Module Price * Number of Modules)
- (Unit Inverter Price = 53000 INR/Piece) [48]

VALUES

- **TATA TP300 (15.40%)**
  Annual Energy Generation: 3086 kWh/Year
  Total Installed Power: 1.800 kWp
  Total Cost of the PV System: 2466.84 €
  Sizing Ratio of the System: 1.2
  LCoE: 8.82 INR/kWh

- **Sova Power SS325P (16.72%)**
  Annual Energy Generation: 3257 kWh/Year
  Total Installed Power: 1.950 kWp
  Total Cost of the PV System: 2515.26 €
  Sizing Ratio of the System: 1.3
  LCoE: 8.51 INR/kWh

- **Goldi 72GN (17.31%)**
  Annual Energy Generation: 3369 kWh/Year
  Total Installed Power: 2.01 kWp
  Total Cost of the PV System: 2555.52 €

Sizing Ratio of the System: 1.3
LCoE: 8.34 INR/kWh

- **Goldi 72GN1 (18.08%)**
  Annual Energy Generation: 2391 kWh/Year
  Total Installed Power: 1.400 kWp
  Total Cost of the PV System: 1908.74 €
  Sizing Ratio of the System: 1
  LCoE: 9.10 INR/kWh

- **Canadian Solar CS3W-445MS (20.10%)**
  Annual Energy Generation: 3170 kWh/Year
  Total Installed Power: 1.780 kWp
  Total Cost of the PV System: 2211.92 €
  Sizing Ratio of the System: 1.2
  LCoE: 7.80 INR/kWh

The LCoE calculations were kept in Indian Rupee per kWh in order to see a more easy and amplified difference, as Euros at such a low amount will consist of many zeroes after decimal.

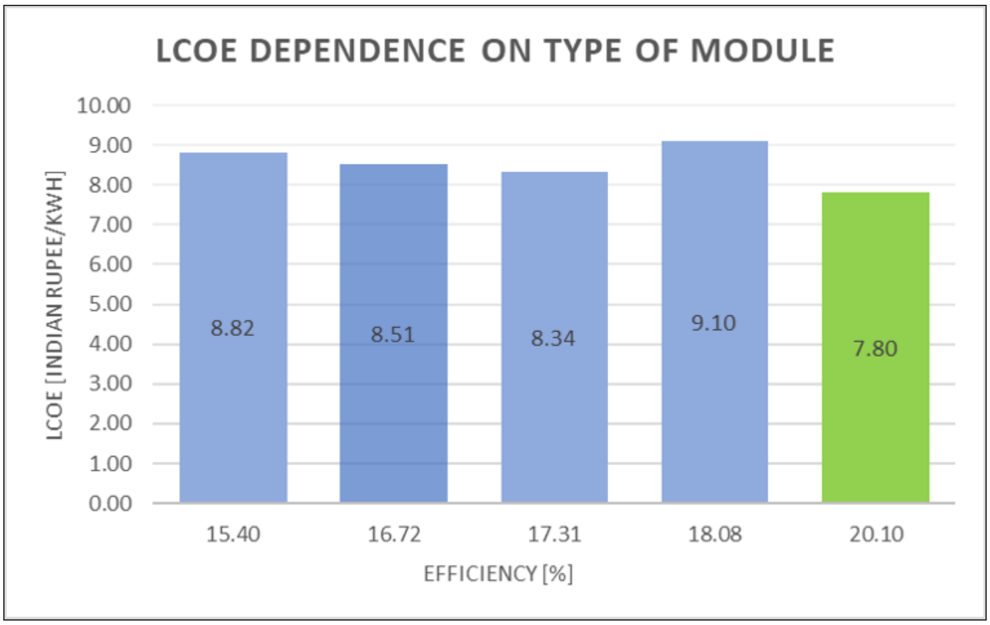

Figure 3.9: LCoE Dependence on the type of Module Used [A01, A02]

From Figure 3.9, the effect of More generated PV Power on the inverter, by using modules of various efficiency can be seen. We also have to keep in mind the slightly oversized system in each case.

Also, we observe that the module with efficiency 20.10%, from the advantageous region in graph 3.6, indeed has the lowest LCoE compared to others. ***"The Lower LCoE, the better investment for the end consumer."***

3.4 Approach II. Increasing the number of Modules - Case Study

To analyse the results of Oversizing by increasing the number of Modules, we consider the following factors for our case study:

- Module: JA Solar JAM72S01-380/PR (mono-Si)
  Power: 380W
  Efficiency: 19.00%
  Module Price: 7600 INR/Module or 86.44 €/Module

- Inverter: SMA Sunny Boy 1.5-1VL-40
  AC Rated Power: 1.5kW
  European Efficiency: 96.1%
  Inverter Price: 53000 INR/Unit

- BOS Costs (Excluding Inverter): 128.48 €/m^2

3.4.1 Is Oversizing Beneficial?

A study on the effect of Oversizing in a 100 MVA Powerplant Project, from an excerpt in a White Paper [18], Published by *SMA Solar Technology AG* shows us the numerous benefits of Oversizing by comparing different Economical Values like IRR and NPV, which were explained in the Section 2.3.4.

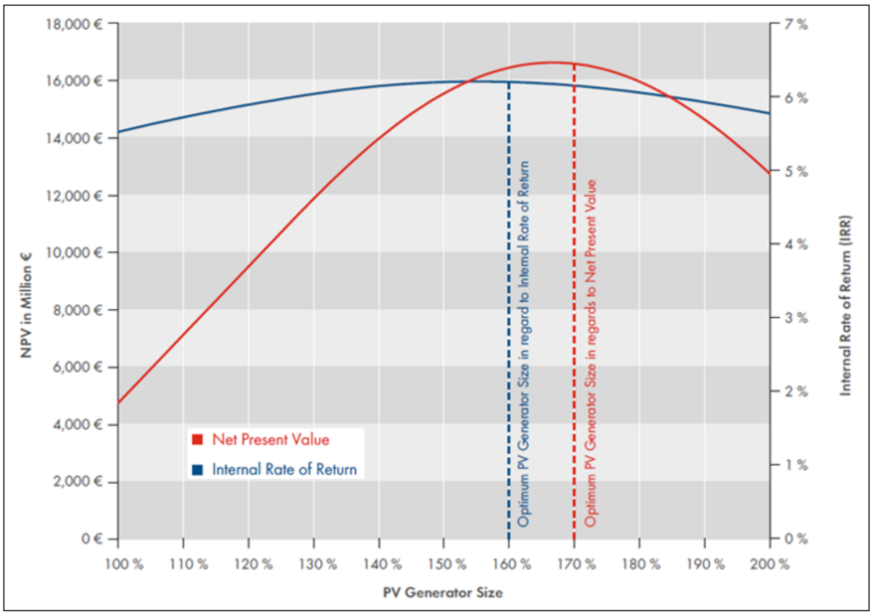

Figure 3.10: Optimum Oversizing of a 100 MVA PV Power Plant [18]

Figure 3.10 shows us that the most optimum IRR is achievable at around 160% and the most optimum NPV at around 170% for the Power Plant. The whitepaper also tells us that it depends on various factors to analyse if markets are suitable for Oversizing. This largely depends on Factors like NPV, IRR and even Project Development Costs. A fair example to consider is Japan, where Project Development Costs are incredibly high, thus promoting Oversizing because this creates an extremely favorable ratio of PV array costs.

Household Rooftop PV System

Oversizing Ratio	Annual Energy Yield (kWh)	LCoE (INR/kWh)
0.50	1319	11.780
0.76	1996	9.433
1.01	2673	8.275
1.26	3304	**7.691**
1.52	3728	7.699
1.77	4012	7.975
2.02	4224	8.354

Table 3.5: Simulated Energy Yield and LCoE for different Oversizing Ratios

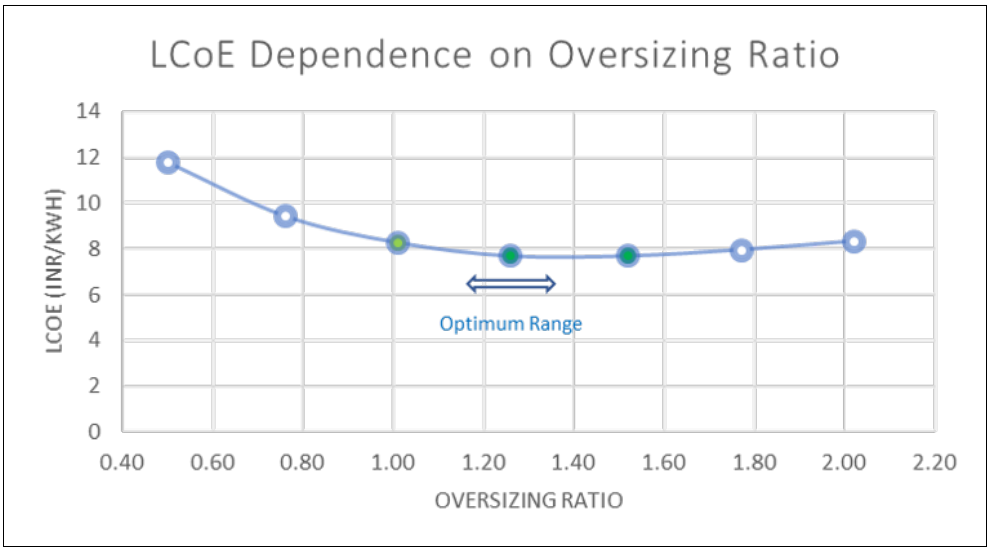

Figure 3.11: LCoE Dependence on Oversizing Ratio simulated in PV*SOL [A01, A02]

In Figure 3.11, we see the LCoE (Price in Indian Rupees/ kWh), for different Oversizing Ratios. These were calculated, after simulating the same system with different number of Modules. Analyzing the graph clearly shows us that around 1.25 is a very optimum Oversizing Ratio, in order to attain the lowest

LCoE as after this range, the value starts rising again.

Also, In Figure 3.12 we take a look at an analysis conducted by *ABB*, where they arrive to a similar result of deducing the optimum region of Oversizing Ratio for an Inverter. These simulations by *ABB* were done in an another PV Simulation Softaware **PVSyst**, which is also a considerably good tool, just being slightly different in the accuracy from **PV*SOL** as shown in Tables 3.1 and 3.2. [34]

They Concluded that *"An inverter that could manage a DC-to-AC ratio up to 1.6 would be the most ideal because then the project could achieve the best economic benefit of increasing the DC capacity, without adding to the fixed cost of the system."*

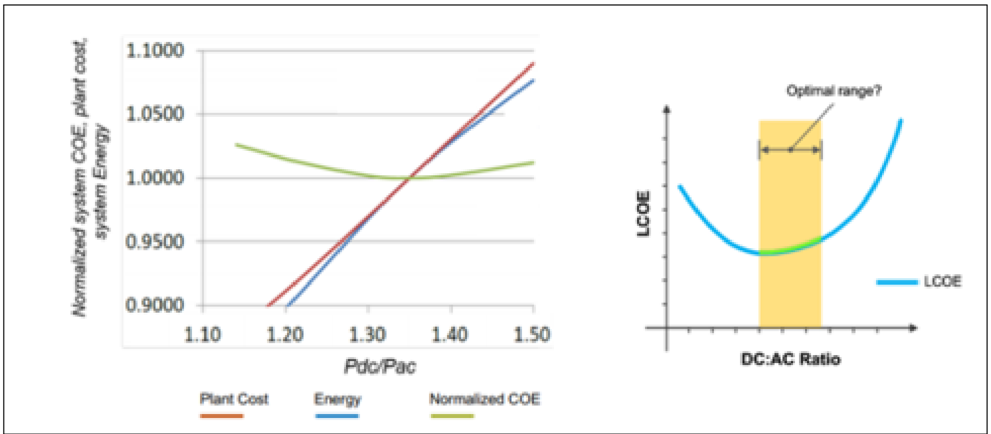

Figure 3.12: Oversizing Study Results by *ABB* [34]

Inverter Technical Parameters: As per the manufacturer datasheet of our selected Inverter, they state that the inverter can be safely oversized upto 100% without voiding the warranty, i.e., An Oversizing Ratio of 2.0 provided the Parameter conditions defined in Datasheet are met. [49]

With the parameters set in the simulation software **PV*SOL**, we made sure that the mentioned datasheet conditions are met.

Use of Energy

In order to understand the split of generated energy, we must go back to the fact in Section 2.3.1 that, **the Market that we are focused in** does not offer Feed-In Tariff Policies till date for household rooftop PV Systems. The LCoE Calculations were done keeping in mind the Equation 2.6, where we consider the Annual Energy Yield in the year t. But it's essential to know that as a Household consumer, we don't utilise the Total Annual Energy Yield, rather use a small part of it, and provide the Extra Energy to the Grid; which in our case can be quite more or less considered as Energy Lost.

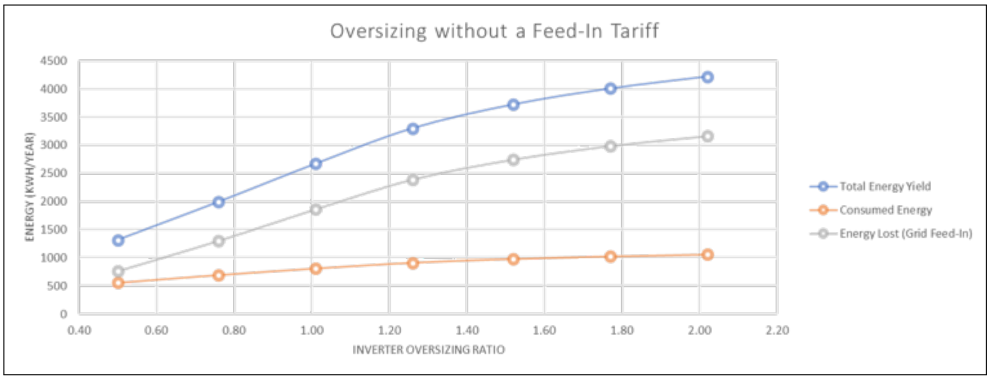

Figure 3.13: Graph showing the Total Energy Yield, Energy Consumed and the Energy Lost (Grid Feed-In) at different Oversizing Ratios [A01]

The Average Rate of Energy Consumption for Households in Delhi, India ranges from 3000 kWh/Year to 3240 kWh/Year, which is also the highest in the country compared to other cities, due to the higher usage of Air Conditioners and Air Coolers. [41]

Recalling the Equation 2.4, where we saw the optimized system in Figure 2.7, we also plotted a dependence of the Specific Yield on the Oversizing Ratio, as seen in Figure 3.15. We can say that our results were quite relative to the one in Figure 2.7.

To have a better overview of the Energy Flow, We analyse the Graph in Figure 3.16 for an yearly overview. It can be observed that the lowest Energy generation is in the month of July due to the *Monsoon* months.

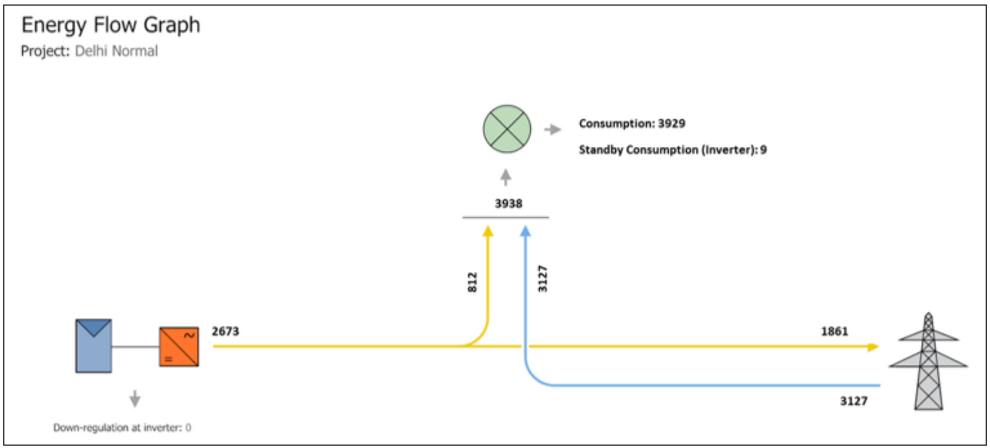

Figure 3.14: Energy Flow Graph for Oversizing Ratio 1.0

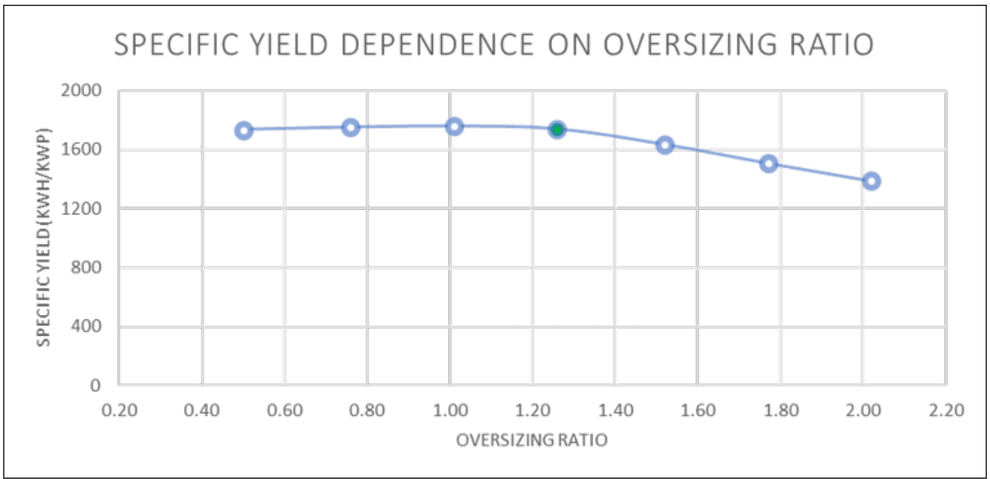

Figure 3.15: Specific Yield Dependence on Oversizing Ratio [A01]

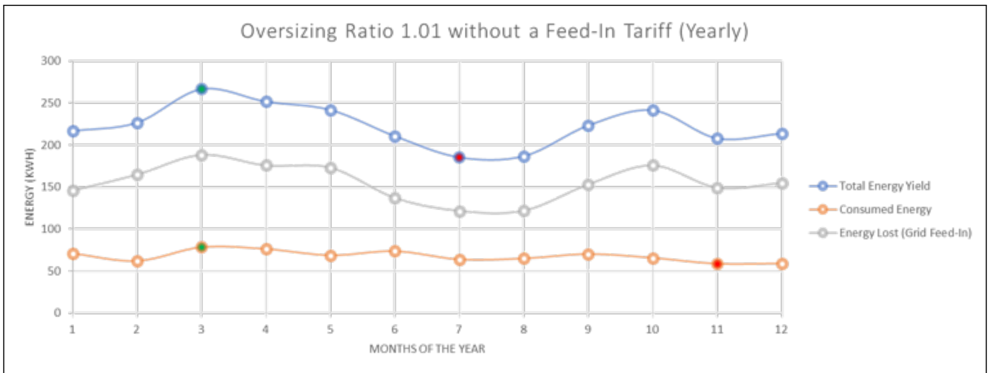

Figure 3.16: Energy Flow for Oversizing Ratio 1.01 across the Year [A01]

Chapter 4
Conclusion

The Project was devoted to the Economic Effect of Oversizing a PV System in New Delhi, India. The aim was to analyse if Oversizing is beneficial from an economic perspective for the consumer if they set up a rooftop PV Grid-Connected System.

The project was split into 3 Chapters, beginning from illustrating the Motivation and Theory behind the Project, and then effectively presenting the Simulated Results.

Chapter 1 solely focuses on the Need for Renewable Energy Resources, which was also spotlighted regarding the Climate Effects and Need of Energy Sources. The Literature Review shows us that in the modern-day society, Mankind has an ever-growing need for energy, due to which Natural Resources are being exploited, thus being detrimental to not only the future but also to the Present generation. Having Seen the analysis and predictions by Climate Scientists, there is an urgent need to shift our thinking towards the path of Sustainable Renewable Energy Resources. In Particular, the use of Solar Energy.

Chapter 2 describes the theory behind PV Systems, i.e. , The types of systems available in the market, and their functioning. We also review the various components of a PV System, which are essential for selecting and installing a PV System and their effect on the total Investment needed for the Project. It also contains an insight into the emerging technologies, that significantly have increased the PV Systems' efficiency over the past decades. Inevitably, Science has accomplished an outstanding achievement as we have reached Cell efficiencies much higher than the first practical solar cell invented by Bell Technologies in 1954, with a mere efficiency of 6% [42]. No doubt, today, the Market offers a plethora of choices to a consumer with an average range of 3 times the first solar cell's efficiency. An explanation of investment parameters like NPV, IRR, LCoE and ROI is also exhibited, which is fundamental for understanding the Economic effects, before investing in a PV System.

Chapter 3 is the most crucial section of the Project as it contains the Simulations by the Solar Simulation Software **PV*SOL**. We also describe the analysis of the PV Market survey. The Thesis by Lenka Šterberova [1] was a great piece of help to understand the pattern needed to proceed in order to effectively study the Market. The survey of Modules of various types depends on the assumption of a constant BOS, and an innovative method shown in Figures 3.6 and 3.7 represents it graphically. However, this approach leads to Oversizing as maybe at some configurations we provide a more amount of power than the inverter is rated at. We then study the effect of Oversizing, in a rooftop PV System by increasing the number of Modules while keeping the same inverter. This is presented by comparing the LCoE at different Oversizing Ratios, as shown in Figure 3.11. Here, the lowest LCoE was attained around an Oversizing Ratio of 1.2.

We also saw that in Figure 3.15, we plotted the Specific Yield on the Oversizing Ratio, and it's quite visible that the Optimal Oversizing Ratio based upon Specific Yield is around 1.2 as also in the Figure 2.7.

Even though the Project was not so Scientific oriented but instead Economically focussed, this Project helped a lot in understanding the comprehensive theory and Economics behind the PV System. It is thus enabling to heighten the concepts which I lacked in the past. Also, in Section 3.3.2 of Approach I., a comparison of systems with different module efficiencies was made, to analyse if indeed a Module with better Efficiency can enhance its LCoE. And through the Graph in Figure 3.9, we can say that we found quite significant differences in the LCoE for Modules with different Efficiency.

All of the calculations, simulations, and data-sheets for each device can be found in the accompanying Annex Files.

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[A01] Annex File for Calculations and Results. Microsoft Excel

[A02] Annex File for LCoE Calculation. Microsoft Excel