UNIVERSITY OF WEST ATTICA
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Diploma Thesis

“Evaluation of the energy and environmental footprint of the global PV module production, using life cycle analysis (LCA)”

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Παράβαση της ανωτέρω ακαδημαϊκής μου ευθύνης αποτελεί ουσιώδη λόγο για την ανάκληση του διπλώματός μου.

Επιθυμώ την απαγόρευση πρόσβασης στο πλήρες κείμενο της εργασίας μου μέχρι 2 Δεκεμβρίου 2023 και έπειτα από αίτησή μου στη Βιβλιοθήκη και έγκριση του επιβλέποντος καθηγητή.»

Η Δηλούσα
ΑΙΚΑΤΕΡΙΝΑ ΓΡΙΒΑ

(Υπογραφή φοιτήτριας)

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Finally, I express my profound gratitude to my mum and grandmother who continuously supported me, and always believed in me.

Περίληψη

Η ταχεία ανάπτυξη της τεχνολογίας φωτοβολταϊκών (ΦΒ) την κατέστησε καίριο παράγοντα στην παγκόσμια παραγωγή ανανεώσιμης ενέργειας. Ωστόσο, ο περιβαλλοντικός αντίκτυπος που σχετίζεται με την παραγωγή φωτοβολταϊκών μονάδων απαιτεί προσεκτική ανάλυση. Η μελέτη που διεξάγεται στοχεύει στην αξιολόγηση των εκπομπών που παράγονται κατά τη διαδικασία παραγωγής των φωτοβολταϊκών μονάδων, εστιάζοντας στις τρεις κύριες χώρες παραγωγής: την Ευρώπη, τις Ηνωμένες Πολιτείες και την Κίνα.

Για την επίτευξη αυτού του στόχου, αξιολογήθηκαν τα μείγματα ηλεκτρικής ενέργειας καθώς και η ένταση εκπομπής αερίων του θερμοκηπίου των χωρών, λαμβάνοντας υπόψη τις διάφορες πηγές που χρησιμοποιούνται για την παραγωγή ηλεκτρικής ενέργειας. Αναλύοντας τα ενεργειακά μείγματα και χρησιμοποιώντας την ανάλυση του κύκλου ζωής της Ευρωπαϊκής Ένωσης για φωτοβολταϊκά στοιχεία και διάφορα δεδομένα κατασκευής τους, αποκτήσαμε πληροφορίες για τις εκπομπές από την καύση ντίζελ, τις εκπομπές διοξειδίου του άνθρακα (CO2), τις πτητικές οργανικές ενώσεις μη μεθανίου (NMVOC) και την κατανάλωση ενέργειας που σχετίζεται με την παραγωγή φωτοβολταϊκών μονάδων. Τα δεδομένα συμπεριέλαβαν ολόκληρο τον κύκλο ζωής, από την εξόρυξη πρώτων υλών έως το τελικό προϊόν.

Τα ευρήματα αποκάλυψαν σημαντικές διακυμάνσεις στα προφίλ εκπομπών μεταξύ των χωρών παραγωγής. Η Ευρώπη επέδειξε μικρότερο οικολογικό αποτύπωμα λόγω της μεγαλύτερης αξιοποίησης ανανεώσιμων πηγών ενέργειας στη διαδικασία κατασκευής. Αντίθετα, οι Ηνωμένες Πολιτείες εμφάνισαν μέτριες εκπομπές, επηρεασμένες από ένα μείγμα ανανεώσιμων και μη ανανεώσιμων πηγών ενέργειας. Η Κίνα, παρόλο που είναι ένας κυρίαρχος παραγωγός, εμφάνισε υψηλότερες εκπομπές, κυρίως λόγω της μεγαλύτερης εξάρτησής της από εργοστάσια παραγωγής ηλεκτρικής ενέργειας με άνθρακα.

Συνολικά, αυτή η διπλωματική επιδιώκει να ρίξει φως στις περιβαλλοντικές επιπτώσεις της παραγωγής φωτοβολταϊκών πάνελ, προσφέροντας μια συνολική κατανόηση των παραγόντων που επηρεάζουν τη βιωσιμότητά τους. Μέσα από αυστηρή ανάλυση και εξερεύνηση πιθανών λύσεων, επιδιώκει να συμβάλει στον ευρύτερο στόχο της μετάβασης προς ένα πιο πράσινο και βιώσιμο μέλλον ενέργειας.

Λέξεις – κλειδιά

Φωτοβολταϊκά πάνελ, εκπομπές, ενεργειακό μείγμα, CO2, ανάλυση κύκλου ζωής, παραγωγή φωτοβολταϊκών

Abstract

The rapid growth of photovoltaic (PV) technology has established it as a key player in global renewable energy production. However, the environmental impact associated with the production of PV modules warrants careful analysis. This study aims to assess the emissions generated during the manufacturing process of PV modules, focusing on three major production countries: Europe, the United States, and China.

To achieve this objective, the electricity mixes as well as the greenhouse gas emission intensity of the countries were evaluated, considering the various sources used for electricity generation. By analyzing the energy mixes and by using European Union's life cycle analysis for photovoltaic modules and various datasheets, we gained insights into the emissions from diesel combustion, carbon dioxide (CO2) emissions, non-methane volatile organic compounds (NMVOC), and energy consumption associated with PV module production. The data encompassed the entire lifecycle, from raw material extraction to the final product.

The findings revealed significant variations in emissions profiles among the production countries. Europe demonstrated a lower carbon footprint due to a higher utilization of renewable energy sources in the manufacturing process. Conversely, the United States exhibited moderate emissions, influenced by a mix of renewable and non-renewable energy sources. China, while a dominant producer, displayed higher emissions, primarily driven by a greater reliance on coal-fired power plants.

Overall, this thesis seeks to shed light on the environmental implications of PV module production, offering a comprehensive understanding of the factors influencing their sustainability. Through rigorous analysis and exploration of potential solutions, it aspires to contribute to the broader goal of transitioning towards a greener and more sustainable energy future.

Keywords

Photovoltaic modules, emissions, energy mixes, CO2, life cycle analysis, photovoltaic production

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Introduction

Since the onset of the industrial era, considerable damage has been inflicted on the planet by incessant human exploitation. To mitigate this damage, alternative resources must be harnessed to prevent the depletion of fossil fuels and water. Some of those renewable sources are geothermal, hydropower, bioenergy, wind, solar power, and some emerging renewables. Solar power is associated with photovoltaic modules due to the never-ending source of their power which is the sun. While every renewable energy source has its limitations, this thesis focuses specifically on the emissions generated during the manufacturing stage of PV modules, delving into their drawbacks.

There are several types of photovoltaic cells such as mono-crystalline, poly-crystalline, and thin film modules. However, crystalline cells have become the prevailing technology due to the higher efficiency and the less complexion in the manufacturing process. It is important to focus on evaluating the environmental impact of multi-Si PV module production in the leading production countries, China, USA, and Europe from 2015 to 2020, considering that multi-crystalline PV modules dominate the PV production landscape.

Before calculating production-stage emissions, some key factors need to be analyzed such as greenhouse gas emission intensity, PV shipments of each country, their electricity mix and explore the concept of Life Cycle Analysis and Ecodesign. Calculations of emissions during the manufacturing process will be based on the results of the European Commission's Piloting of the Product Environmental Footprint method, various PV datasheets and the key factors mentioned.

To consider PVs as a green energy alternative and to benefit the environment a range of potential solutions will be discussed.

Diploma thesis subject

This diploma thesis delves into an in-depth examination of the emissions generated during PV module production, utilizing the European Commission's Piloting of the Product Environmental Footprint method. By analyzing various PV datasheets and considering PV shipments from three leading countries, namely Europe, the USA, and China, for years 2015-2020 this study aims to evaluate the environmental sustainability of PV module production. Overall, this thesis seeks to shed light on the environmental implications of PV module production, offering a comprehensive understanding of the factors influencing their sustainability. Through rigorous analysis and exploration of potential solutions, it aspires to contribute to the broader goal of transitioning towards a greener and more sustainable energy future.

Purpose and Goals

This study's purpose is to conduct a comprehensive analysis of emissions and energy requirements during the production of photovoltaic (PV) modules. By employing life cycle analysis and examining data from production plants, the study aims to evaluate the environmental impact of PV module manufacturing processes. The primary goal is to calculate and assess the emissions, including CO2 and NMVOC, as well as the electricity requirements associated with PV module production in China, the USA, and Europe for years 2015-2020. Through this analysis, the study intends to identify measures and strategies for improving and minimizing the environmental footprint of PV module manufacturing, contributing to sustainable energy production, and addressing climate change concerns.

Structure

This thesis aims to assess the emissions and energy requirements during the production of photovoltaic (PV) modules through the utilization of life cycle analysis and data obtained from production plants. The following structure will be followed. In the first chapter, we will mention the different renewable energy sources that exist and some emerging. The second chapter will focus on analyzing diverse types of PV modules, their construction methods, efficiency levels, and the leading countries involved in their production. This section aims to provide a comprehensive understanding of PV module technology. In Chapter 3, we will delve into life cycle analysis, which involves evaluating the environmental impact of PV module production from cradle to grave. We will specifically examine the electricity mix of the three leading production countries, namely China, the USA, and Europe. Additionally, we will investigate the annual PV shipments for the years 2015-2020. Lastly, the role of Ecodesign principles and key factors will be discussed. The fourth and last chapter will employ the European Commission's Piloting of the Product Environmental Footprint method, along with various PV datasheets, to calculate emissions resulting from diesel combustion, non-methane volatile organic compounds (NMVOCs), CO2 emissions, and the annual electricity requirements per kilowatt (kW) for the years 2015-2020 in China, the USA, and Europe. These calculations will help identify necessary measures to improve and reduce emissions from PV module production. By following this structure, we aim to gain valuable insights into the emissions and energy requirements associated with the production of PV modules. The findings will contribute to the development of strategies and actions to mitigate the environmental impact of PV module manufacturing.

1 Chapter 1: Renewable energy sources

There are currently three types of energy sources. Fossil fuels, nuclear resources, and renewable energy sources. As the industrial sector continues to grow and the need for earth minerals remains constant, our primary energy source, fossil fuels, is being consumed at a rate that outpaces its natural replenishment.

Renewable energy sources are considered as clean sources of energy since they have lower carbon emissions from fossil fuels and are renowned to minimize global warming by reducing greenhouse gas emissions. Their difference from the other sources is that they can be used repeatedly since they are renewed constantly. Also, fossil fuels, coal, and oil gas, take hundreds of years to form in contrast with the renewables which are already in the world around us since the sun is the key element for all renewable sources. Renewable energy sources are a feasible solution to the current energy crisis and to protect the environment.[1] Already from the fifteenth century, a primary form of renewable energy source was used, windmills.
There are currently five most known renewable energy sources: Geothermal Energy, Hydropower, Bioenergy, Wind Power, and Solar Power. Geothermal is based on the natural heat of the earth. It is a sustainable source of energy nonetheless harmful gases can be released to the atmosphere during digging and it has a substantial risk of causing earthquakes. Hydropower uses the kinetic movement of the water, it is reliable and can create lakes, but it can harm aquatic life and is costly. Bioenergy through biomass can help reduce waste and is carbon neutral but the conversion produces only ethanol. Wind turbines, which are well-known devices used to convert the wind's energy into electrical power, and solar power by photovoltaic modules, produce electricity directly from sunlight. In subsequent sections we will delve into greater depth regarding the chief drawback of PV modules, namely the emissions generated during their manufacturing phase.

There are also several emerging resources such as marine energy and enhanced geothermal. However, there are still many obstacles to be faced to be able to produce enough energy.[2]

A review of the specified sustainable energy sources ensues.

1.1 Geothermal Energy

Geothermal energy is based on the natural heat within the earth. Due to the slow decay of radioactive particles in rocks at the center of the planet, the earth's core is as hot as the sun's surface. This heat is used by drilling deep wells and then extraction of hot fluids to generate electricity, to heat spaces and even for powering generators. [3] Although its function seems simple (as shown in Figure 1: Geothermal steam field with its components), there are several factors to be taken into consideration because the risk of causing an earthquake, if drilled too much, is imminent. Nonetheless, there are some countries that receive over 20% of their electricity from geothermal. [3] Geothermal energy comes with minimal greenhouse gas emissions, it is cheap, and it is also not affected by climate, weather conditions and region. Geothermal energy will have eliminated one (1) billion tons of C02 released in the atmosphere by 2050. However, there are various environmental, political, and economic obstacles for this renewable source to participate in the energy mix actively. [4]

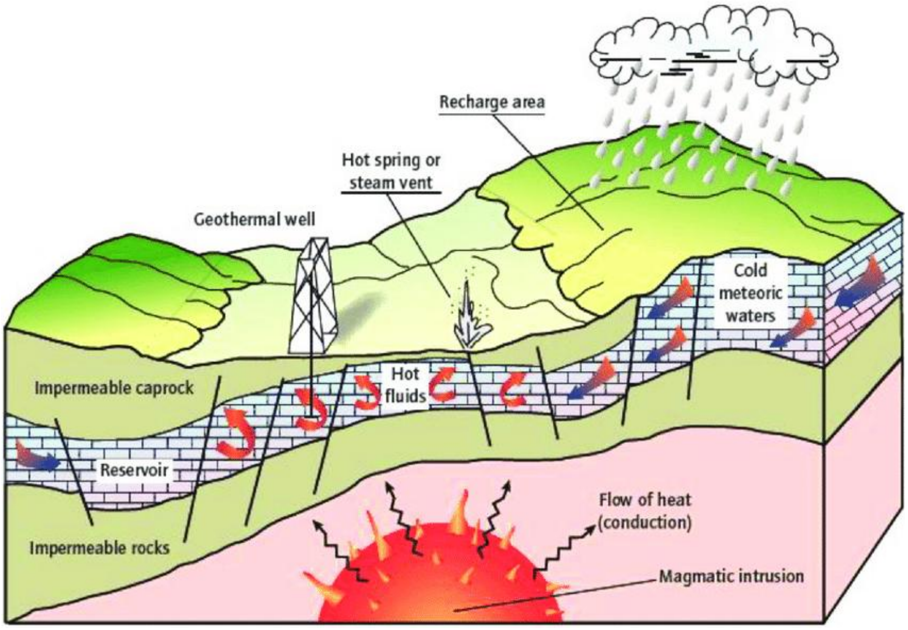

Figure 1. Geothermal steam field with its components.[59]

1.2 Hydropower

Hydropower relies on the everlasting water cycle to produce electricity using water as fuel. It also accounted for 33% of the European Union's renewable electricity production in 2020 making hydropower a significant renewable energy source.[5] Incredibly inexpensive, and the principle behind hydroelectricity is as follows: water flows from a higher elevation to a lower elevation and a facility uses turbines and generators to convert this motion into electricity. Then, the water returns to the river on the downstream side of the dam. In Figure 2, a basic hydroelectric facility is shown. Also, some structures can be used for flood control. Water can be recycled in many ways with two of them being a dam and a diversion. On the other hand, if not enough measures are taken, hydropower can be very harmful for the river ecosystem. Hydropower technology is always improving to increase efficiency of the generators or to find a way for dams to work together and produce more energy. [6]

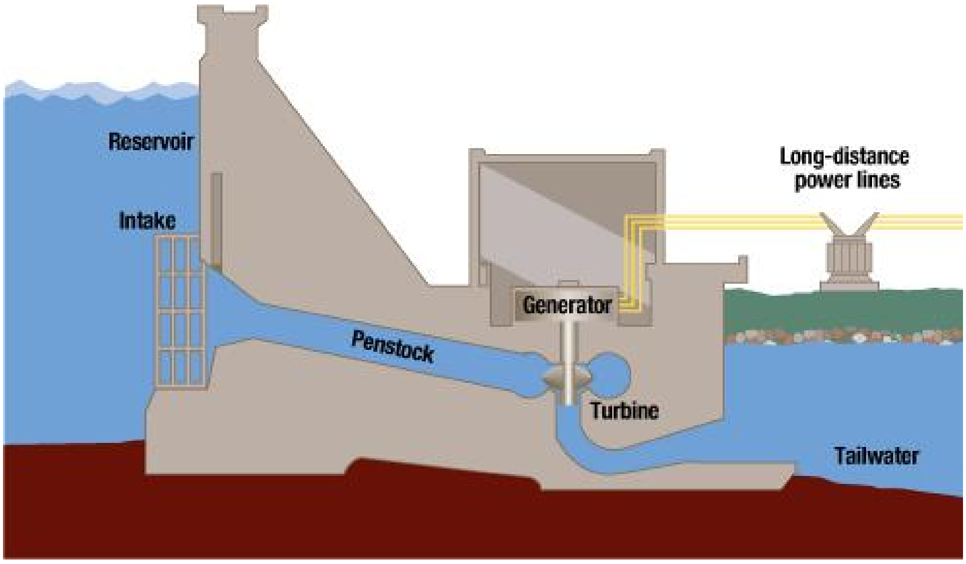

Figure 2. Basic hydroelectric facility.[60]

1.3 Bioenergy

Bioenergy is the energy produced by biological sources and it includes biomass and biofuels. It can aid the fuel shortage with biofuels in the form of gas, liquid, or solid fuels. The three types of converting biomass to fuels are: thermal conversion, biochemical conversion, and mechanical conversion. [7] Thermal conversion is used to convert biomass to biofuels using heat through combustion, gasification or pyrolysis and decomposing the materials used.[8] Biochemical conversion produces only ethanol and biogas and is a slow process compared to thermal conversion due to the need of pretreatment stages. Unlike Geothermal Energy, Bioenergy requires large areas of land, and is affected by weather and location.

Renewable energy derived from the conversion of organic matter such as living or dead organisms, garbage, crops, and animal fats is known as bioenergy, which represents the stored chemical energy from the sun. Organisms produce biomass through photosynthesis. It can be used to produce heat, electricity, and liquid fuel. It is interesting to note that in the mid 1800s biomass was the primary energy source.[9] *The International Energy Agency (IEA)* forecasted that biomass will lead the markets in the following years, however, several issues remain that includes political obstacles, as well as technical limitations that must be overcome to ensure success. These challenges are complex and multifaceted and require a comprehensive approach that considers the factors that contribute to their persistence. [10]

1.4 Wind Power

Wind power is a technology based on the kinetic energy of air to produce electricity. The main drawback of this renewable is that it solely depends on environmental conditions. It is a complicated renewable source as it depends on height, terrain, climate in the area where wind turbines are installed. There are two types of wind turbines: horizontal-axis turbines and vertical-axis turbines yet, horizontal-axis turbines have prevailed. The first emergence of wind turbines occurred in the 1830s. The operation of horizontal-axis wind turbines relies on the movement of air flowing through their blades, which causes the blades to rotate and activate the embedded turbine. Then a transformer is used to convert electricity to the appropriate voltage. [11] Its function is illustrated in Figure 3. Some advantages of wind power are that it causes economic growth and can create jobs. On top of that they can distribute electricity even in the more inaccessible areas. Despite their many benefits, such as producing clean energy and reducing dependence on fossil fuels, wind turbines are known to produce a significant amount of noise during operation. As a result, it is recommended that wind turbines be in isolated or remote areas, away from densely populated urban areas where noise pollution can be a concern for nearby residents. In addition, wind turbines are typically large, which can disrupt the surrounding area's appearance and natural landscape. Furthermore, the construction and maintenance of wind turbines can be quite challenging and require specialized expertise and equipment, which can increase the overall cost and complexity of the project. [12]

In the past two decades energy production from wind has increased from 7.5 GW in 1997 to 564GW by 2018 according to IRENA. In 2020 about 1.000.000 GWh of renewable energy was produced by wind turbines.

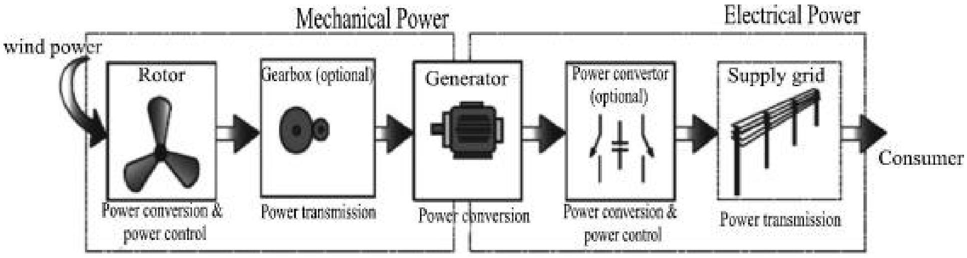

Figure 3. Basic conversion from wind power to electricity.[61]

1.5 Emerging Renewable Energy Sources

Apart from the abovementioned renewable energy sources, the following nascent renewables are also being studied:

1.5.1 Marine Renewable Energy

Marine renewable energy refers to renewable energy that is installed and operated at sea. This can be from offshore wind, tides, and currents. However, the sea moves in chaotic movements and that is one thing to overcome. The biggest problem though is the high probability of the sea and its waves destroying the installed equipment. [13] Moreover, the negative results for the sea ecosystem are colossal since the noise from projects and from the electrical cables could be devastating.[14] To this day, there has not been a significant breakthrough regarding marine energy and more research must be conducted.

1.5.2 Enhanced Geothermal

Enhanced Geothermal energy is the future of Geothermal Energy. The main difference between Geothermal and Enhanced Geothermal is that the latter is manufactured. In Geothermal systems, the location must be found and examined to drill and extract the needed fluid, not unlike mining for oil. Due to the limitations of geothermal energy, a solution had to be found. In geothermal systems, a hot rock must be drilled whereas in enhanced geothermal systems a survey is being done to specify a rock that has not fractured naturally enough.[15] [16] A fluid is injected into the rock to make it porous and then the fluid runs through the pathways that were made and afterwards is brought to the surface and used to generate electricity. The resources must be calculated for them not to heat up or pressurized too high. [17] A basic layout of an enhanced geothermal system is depicted in Figure 4.

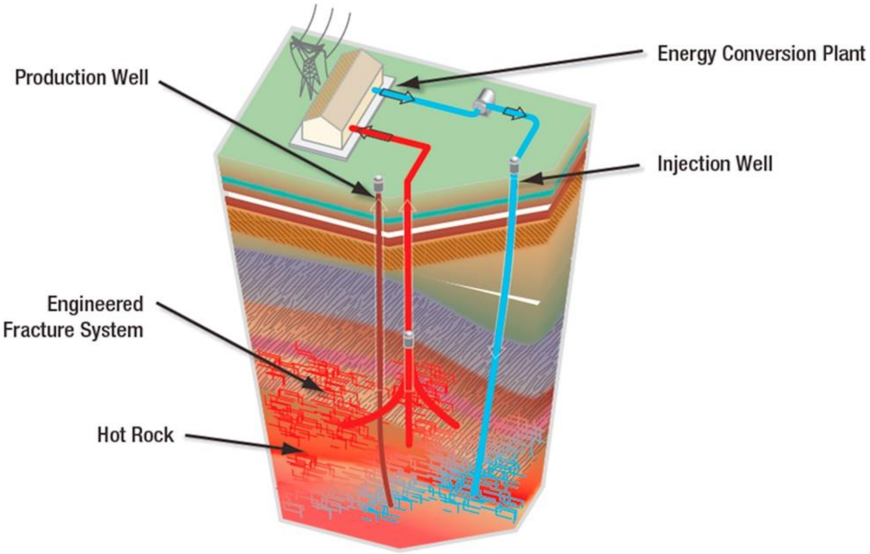

Figure 4. Basic layout of Enhanced Geothermal System [16]

1.6 Solar Power

Solar energy holds particular significance as it plays a critical role in enabling the other renewable energy sources discussed earlier. In addition to the primary benefit shared by all renewable sources, namely their environmentally friendly nature, solar energy is also economical, hygienic, adaptable, and quiet. Solar power is the conversion from sunlight to electricity. One of the main uses of solar power is Photovoltaic modules, which is the basic element of this study, and they will be analyzed further in Chapter 2. On a grander scale, solar-thermal power plants can harness the sun's energy as a source of heat, which can be utilized to vaporize water and channel it to a steam turbine that generates power for numerous individuals. Additional applications of solar energy include cooking, and its widespread use in water heating can potentially prevent around one metric ton of carbon dioxide emissions annually. In 2020, over 800.000 GWh of electricity were produced by Photovoltaic Modules.[18] Recognizing the immense potential of solar power, the European Union has devised an EU solar energy strategy with the objective of overcoming the lingering challenges in the solar sector and expediting the adoption of solar energy throughout the European Union. The three (3) main initiatives are the following: [19]

- European Solar Rooftops Initiative aims to increase the number of buildings that have integrated various sources to produce clean energy on rooftops.
- EU large-scale skills partnership aims to promote clean energy and help people acquire skills that will accommodate future jobs that are depended on renewables.
- EU solar PV industry alliance aims to increase the gigawatts of electricity that are produced from photovoltaics to 600GW by 2030. This alliance is the priciest of the three but also the most profitable and it will create about 400000 new jobs.

2 Chapter 2: Photovoltaics

The sun plays a vital role in sustaining life on Earth, and its energy is crucial for the existence of all renewable energy sources, as highlighted earlier. The growth of plants, which can be used for biomass, is dependent on the energy from the sun. Additionally, solar radiation is responsible for creating the appropriate conditions for the generation of wind power and hydroelectric renewable energy by inducing air movements and powering up hydroelectric turbines through the vaporization of water. Moreover, solar energy has the advantage of being stored to produce power when needed, such as during the night or on cloudy days. In the subsequent chapter, we will delve into an analysis of the photovoltaic effect, types of photovoltaic cells, and provide data regarding their production. To construct a PV module several cells, need to be connected, typically sixty or seventy-two, and the resulting module is then equipped with other equipment as well. The energy generated by photovoltaic arrays can serve as an alternative to coal-based electricity. Most countries worldwide produce photovoltaics in varying proportions. By gaining an insight on the PV modules, we can analyze the several factors that must be taken into consideration regarding their production.

2.1 Photovoltaic effect

During the mid-19th century, a new energy resource appeared by Edmond Becquerel who discovered the Photovoltaic effect when, during some experiments he did with wet cells he discovered that voltage increased when exposed to sunlight. [20]

The principal behind the PV effect is based on the conversion of electromagnetic radiation, without any reactions, to electrical energy. A simple diagram of photovoltaic effect is presented in Figure 5.

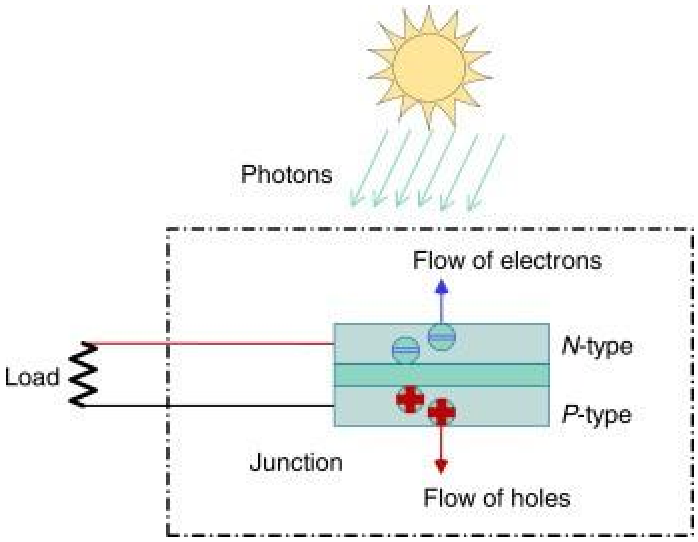

Figure 5. The photovoltaic effect. [20]

A fundamental aspect of photovoltaic technology is the absorption of light by a semiconductor material, which leads to the release of negative and positive electrons. These newly formed electric charge carriers typically recombine, thereby generating heat.[21] However, to produce electricity, it is necessary to separate these pairs before recombination. This is the basic principle underlying the photovoltaic effect. The separated electrons and holes are then extracted from the semiconductor as electric current. Although crystallized silicon is the most used material for solar cells, it is not an efficient current conductor. Therefore, photovoltaic manufacturers utilize metallurgical silicon with impurities to enhance the cell's ability to absorb and conduct electric current, resulting in greater efficiency.

In the 1950s, silicon made its appearance followed by the integration of photovoltaic effect to create p-n junctions which is used until now to manufacture photovoltaics. PV cells have two surfaces. The one is P-Type, enhanced with boron to produce positive electrons and the other is N-Type enhanced with phosphorous to produce negative electrons.[22] The movement of the electrons trying to reach from type p to type n junction box generates current. Minority carriers become majority carriers on the other side of the connector, and they create the voltage and current of a solar cell.

However, since voltage output from an individual cell is negligible, to achieve sufficient voltage output, multiple cells are electrically connected and encapsulated. Typically, photovoltaic modules consist of 60 or 72 cells. To achieve system integrated, multiple modules are serially connected and for final construction of a PV array multiple PVs are connected in parallel.[23]

Various techniques are employed in the production of photovoltaic cells, yet the electrical current generated within the PV cell is invariably direct current (DC) and not alternating current (AC). Consequently, each photovoltaic setup comprises an array of modules, inverters that transform DC current into AC, cables, and connectors to facilitate the transportation of electrical current, transformers, and energy storage devices. Moreover, mounting structures are also deployed to ensure the stability and secure positioning of the PV panels.[24]

It is interesting to mention that the first uses of PV modules were in the US space program where they were used to power satellites and in the late 1960s there is reference for use of photovoltaics in residence. [25]

Various kinds of photovoltaics exist depending on the construction material utilized in the PV cells. A comprehensive analysis of the predominant types is provided in the following section.

2.2 Types of PV Modules

More than 25 types of solar cells and modules are currently in use. The most common technology of construction is monocrystalline and polycrystalline silicon cells and will continue to prevail over other technologies in massive quantities as the raw materials needed are in abundance and inexpensive. Thin film PV modules such as CdTe and CIG are highly competitive to the silicon ones as the efficiency cost ratio is much higher. On the other hand, PV cells whose construction is based on rare mineral materials are a challenge because they are expensive and expendable. [26] Furthermore, depending on the material on which the solar cell is produced there are different efficiencies.

The production process of each silicon-based photovoltaic starts with the preparation of wafers which are pieces of semiconductor,180μm thick and with a surface of 15.6 x 15.6cm^2. These wafers are then processed into cells, usually 60 or 72. World silicon-based PV production is around 95% at a price of less than 1$/W.[26]

Solar cells consist of the following elements: [27]

- Silicon-based wafers (monocrystalline or polycrystalline) with p-n junction on the surface.
- Front and rear contact, where the front must have the appropriate shape to absorb as much incident radiation as possible.
- Anti-reflective layer that covers the front surface.

In the below sub-chapters, an analysis of each type of electrolytic cell and the corresponding PV module follows.

2.2.1 Mono-Crystalline silicon (m-Si) modules

The construction of monocrystalline silicon is done with the Czochrakski method.[28] The type of silicon used for this technology is produced in a large ingot and then shredded to form wafers. Monocrystalline silicon can be treated as a continuous crystal layer.[29] The solar cells that are created have a dark blue or black color with anti-reflective coating. Their efficiency is around 15-18% and it costs more than polycrystalline silicon because it needs more resources to be built. During the cutting process of silicon, a large amount of material is wasted. The advantage of mono-crystalline silicon cells is their high efficiency. There is also the PERC cell which is the most advanced monocrystalline technology and uses more layers to increase the generator efficiency and sun absorption. In Figure 6, a monocrystalline silicon solar module is portrayed.

Figure 6. Monocrystalline PV module. [62]

2.2.2 Multi-crystalline modules

Polycrystalline silicon modules are the main objective of this study. They are more economical than mono-crystalline modules, although they are less efficient. Multi crystalline cells are mostly built with square shapes and their color is either blue or grey silver with anti-reflective coating. (Refer to Figure 7) There are two ways to produce polycrystalline silicon, the chemical and the metallurgical with which many small silicon grains are forming a bigger layer. The chemical method follows the Siemens method, but the metallurgical method is five times more efficient. With the Siemens method the trichlorosilane is decomposed while with the metallurgical way, the silicon is obtained directly from the metallurgical silicon. Each production plant chooses the preferred method of construction even though the larger factories use the metallurgical one. The problem with the chemical process method is that during the formation of polycrystalline silicon, hydrochloric acid is produced which is not only toxic but also corrosive.[30] Some other chemicals also explode in the presence of water. Hence, it is imperative to implement measures to control the emission of chlorine since it is a highly dense gas that can potentially cause poisoning if inhaled.

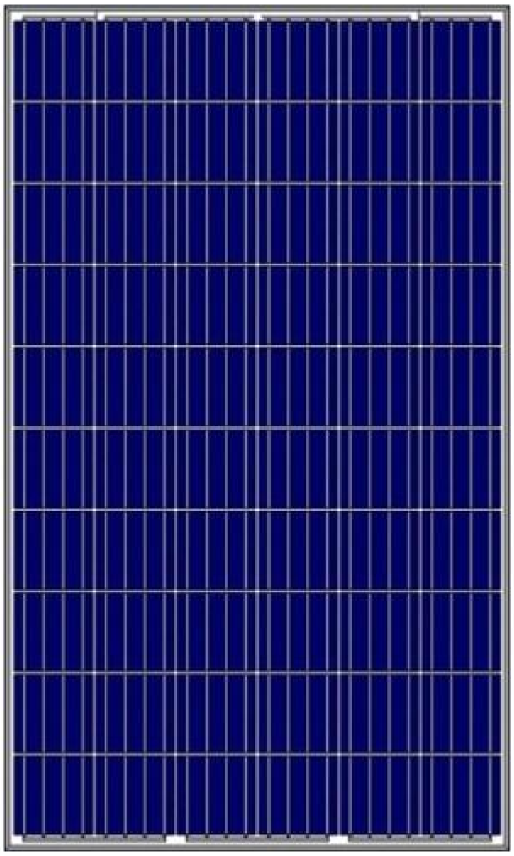

Figure 7. Polycrystalline silicon module. [63]

2.2.3 Thin Film Modules

Thin film processing is an integral part of all modern photovoltaic technologies. Silicon technologies that make optimal use of thin film such as the amorphous and crystalline technique, show increased efficiency and are of constructional interest.[31] Cadmium tellurium technologies as well as CIGS (Copper Indium Gallium Selenide) frames also belong to this category. They are manufactured by vaporizing and then putting semiconductor materials into glass, ceramic, or metal. Transparent silicon oxide films (TCOs) are required for thin film solar cells as a front contact material and must combine low resistance, high transparency, and a sufficient surface to absorb light.[32] Compared to silicone-based modules, they are more affordable due to lack of wafers and lower in mass.[33] Solar panels made exclusively of thin film coatings in 2012 accounted for 20% of the global market. Nonetheless, during the past few years, silicon-based technologies have become increasingly dominant in photovoltaic modules production.

Amorphous-silicon solar cells are used in watches and calculators. The most common method for making amorphous silicon thin film cells is the deposition of plasma-enhanced chemical vapors (PECVD) by decomposing silane gas into plasma (SiH4). This technique allows a large production of substances such as aluminum and stainless-steel sheets to be cheap and to be produced with the minimum required energy.[34] The only reason most photovoltaics are not made of amorphous silicon is that they have a low efficiency of around 6%. [33]

Cadmium Telluride is the second most used technology after crystalline silicone (5% of the world market). Its construction is like the technology of CIGS photovoltaic panels. [35] The advantage of this technology is that it is produced from a single p-n junction with a p CdTe layer bonded to a n-doped cadmium sulfide (CdS) layer. However, cadmium sulfide is extremely toxic and carcinogenic. That is why researchers are looking for new, safer, and more efficient technologies.

Finally, another category of thin film modules is copper indium gallium selenide (CIGS). The most controlled, temperature-resistant, and efficient production of these cells is the simultaneous evaporation of the following materials: Cu, In and Ga. [34] Indium and gallium are evaporated together with selenium vapor, at low temperature to form a thin layer. Copper and selenium then evaporate at elevated temperatures to form a copper-rich, thin CIGS layer. The indium, gallium selenium is then evaporated to create another layer, this time poor in copper. The technologies with which the CIGS solar cells are manufactured are quite complex and as a result they cost more, and their production time is longer. [36]

2.3 Characteristic curve of PV

Macroscopically, solar cells can be modelled via the characteristic I-V curve or P-V curve. There are some points such as open circuit voltage (Voc), short circuit current (Isc), and maximum power point (Pmpp) that can be used to compare how diverse types of photovoltaics should behave in standard test conditions. (Refer to Figure 9) Short circuit current (Isc) is the highest generated current, whereas open circuit voltage is the highest voltage in case of open circuit. Those two characteristic numbers do not correspond to the highest power produced by a panel, and they only refer to Standard test conditions.[37] The term "standard test conditions" denotes a set of predefined parameters for testing the performance of a photovoltaic module, which typically includes irradiance of $1000W/m^2$ and a module area of $1m^2$. The following curve does not apply in the field as it is impossible to manufacture two identical modules. The I-V curve and P-V characteristics portray the electrical parameters of a cell, and it is vital in the design, installation, and maintenance of photovoltaics. This characteristic is shown in Figure 8 and a comparison between several types of PV is shown in Figure 9. Maximum power in standard test conditions will be useful in the last chapter, to calculate the required energy for the manufacture process.

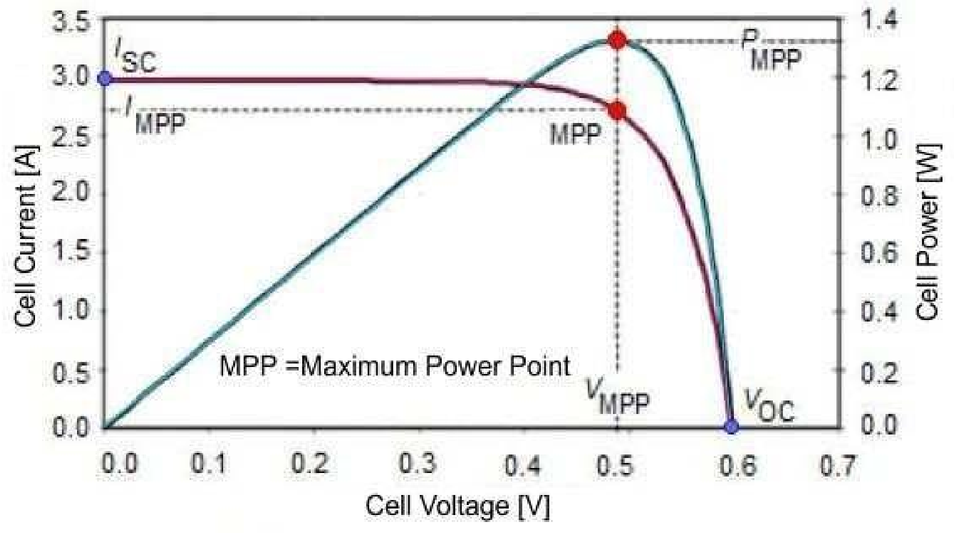

Figure 8. Characteristics of Photovoltaic module.[64]

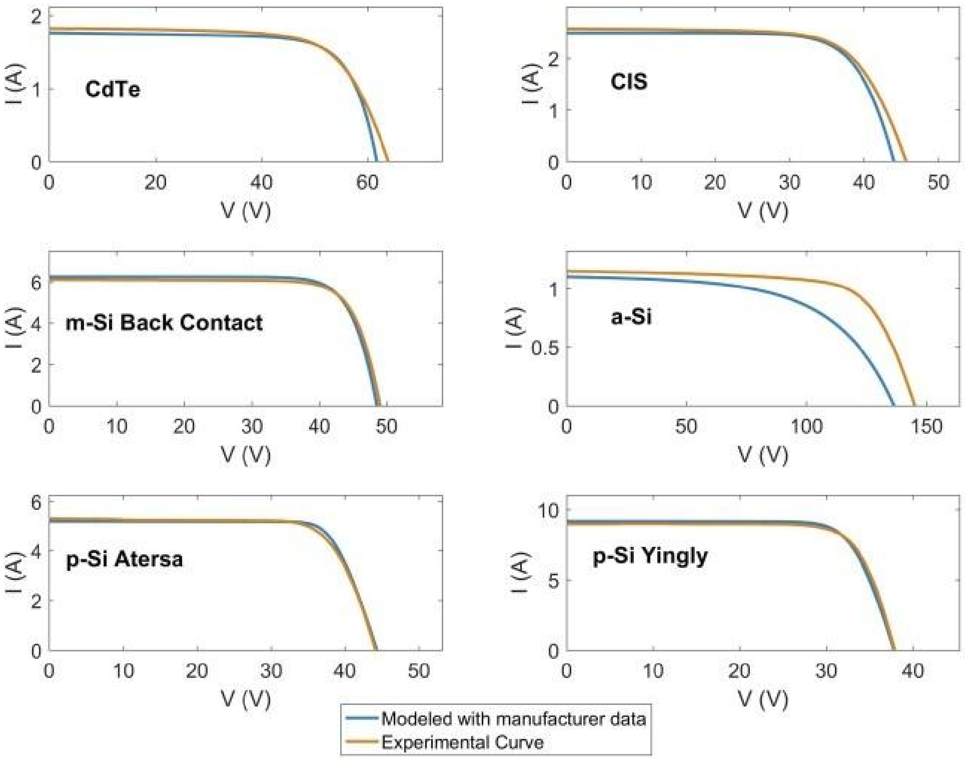

Figure 9. Comparison between diverse types of Photovoltaic modules. [65]

2.4 Efficiency of PV Modules

Module efficiency is determined by its performance, meaning the amount of absorbed sunlight that can be turned into electricity. Solar panels are normally able to process around 15-20% of solar energy into energy that can be used. Although photovoltaic modules are designed to operate under different weather conditions, there are several weather-related factors that can adversely affect their efficiency. These factors include snow, hail, extreme wind, and ice, all of which can cause a reduction in the performance of PV module. To calculate the module efficiency, panels are tested at Standard Test Conditions. Due to the massive competition worldwide in the PV market, over the last few decades, module efficiencies have increased rapidly with a price reduction. Multi-crystalline cells in 2015 had a 21.5% efficiency whereas in 2020 23.2%. Single crystalline cells in 2015 had a 25% efficiency and in 2020 they had 26.1%. Thin film crystal cells have remained with an unchanged efficiency of 21.24%. As for thin film technologies, amorphous silicon cells had an increase in their efficiency from around 10% in 2015 to 13-14% and CdTe technologies efficiency remained unchanged to 22.1%. [38]

2.5 Worldwide production and emissions during PV manufacturing process

In the past twenty years, the manufacturing of PV modules has experienced a significant surge in output. Based on the data provided by the International Energy Agency (IEA) in 2015, the global production of PV modules reached a remarkable 63 GW, with China leading the world in production. In 2021, global PV module production increased to 242 GW. In Table 1, worldwide production of PV per year is illustrated. All data have been collected from IEA PVPS trends. [39]

Even though PVs help to reduce greenhouse gas emissions during their use, the same thing does not apply during the manufacturing process. While there are no or minimal hazardous emissions during their use, there are significant emissions during their manufacturing process. Land use impacts of the construction of each module are caused by the production facilities and the end-of-life land use. Every single manufacturing process involved in photovoltaic production results in greenhouse gas emissions. Despite the emissions appearing minimal, mass production of PVs can result in highly polluted areas, even when the goal is to generate clean energy. [26] It is worth noting that greenhouse gas emissions are influenced by the amount of solar radiation in each region and can therefore vary from country to country. Those impacts will be analyzed further in the following chapters.

The capacity of photovoltaic (PV) modules is continuously increasing and the cost of producing photovoltaics is decreasing. However, the demand for silicon, a key material used in the production of PV modules, is causing environmental pollution issues, particularly in China, which is the leading country in terms of production. Therefore, there is a need for increased awareness and implementation of sustainable manufacturing practices in the PV industry, to address these environmental concerns and ensure a more sustainable future for the industry. [40]

Year	2015	2016	2017	2018	2019	2020	2021
Worldwide production of PV (GW)	63	77	104	116	140	178	242

Table 1. Worldwide production of PVs

Below follows an analysis on the leading production countries and plants for years 2015-2021.

2.5.1 Leading production countries and plants

Even though every country uses photovoltaics not every country produces them. We will analyze the main countries of PV production, according to IEA, throughout the years 2015-2021.

- In 2015, there were three top cell manufacturers; Hanwha Q Cells, Trina Solar, and JA Solar with their plants located in China, Malaysia, Germany, and South Korea. The need of polysilicon for 1W of solar cell was 5.6g. Trina Solar was also the largest producer with a shipment of 5873 MW of PV modules. Thin film modules were also produced in the USA with the main plant being First Solar. First Solar achieved an efficiency of 22.1% in Cd-Te modules in the laboratory.
- China remained the top global producer and consumer of polysilicon in 2016, with a usage rate of 5.4g per 1W of solar cell. The top manufacturers were SunPower followed by Jinko Solar, Hanwha Q-cells and JA Solar. About 4.9 GW of thin film modules were produced in Malaysia, Japan, USA, and Germany.
- In 2017, China outranked every country in the production of solar cells, followed by Malaysia, Thailand, South Korea, Japan Germany, and USA. The need of polysilicon per 1W of solar cell was 4.9g. As for manufacture plants, the top five were JinkoSolar, LONGi Green Energy Technology, Hanwha Q Cells, JA Solar and COMTEC.
- China maintained its position as the leading global manufacturer of solar cells in 2018, with a dominant market share of 74%. This is consistent with the country's leading role in the solar industry in previous years. Following China are the same countries that held the respective positions in 2017. In this stage, 4g of polysilicon is used for 1W of solar cell. Main suppliers of PV were JinkoSolar, JA Solar, Trina Solar, Canadian Solar and LONGi Green Energy Technology. In 2018, a patent is used to produce modules with higher efficiency. Silicon-based cells are commonly halved, and their resistance is reduced to increase power output under elevated temperatures. This process, which is typically carried out under controlled conditions, can lead to a significant improvement in the overall performance of silicon-based solar cells.

- In 2019, China maintains its first place in solar cell production followed by Malaysia, South Korea, Japan, India USA, and Thailand. The usage of polysilicon has decreased to 3.2g/1W of solar cells. The top five manufacturers continue to be the same as in 2018. Innovative technologies are used to increase output power and minimize the levelized cost of energy of PVs. Bifacial PV modules achieve those two goals and tend to extend their share by 2023.
- In 2020, China with a 22% of increase in its cell production continued to be in the first place of production followed by Malasia, Vietnam, South Korea, and Thailand with the respective plants being LONGi, Jinko Solar, Trina Solar, JA Solar Technology and Canadian Solar. In line with developments in 2019, half-cut cell technology is still being widely used, along with 1/3 cut technology, which involves cutting solar cells into smaller pieces. These innovative technologies are being increasingly employed to enhance the efficiency and performance of solar cells, with ongoing research and development aimed at further improving their effectiveness.
- China maintained its preeminent position in the global solar market in 2021, with Vietnam ranking as the second-largest producer followed by Malaysia, Korea, and the USA. An extra increase in half cut technology is observed with more than 80% of the total share.

A summary table (Table 2) follows with the module production of each of the top five countries per year.

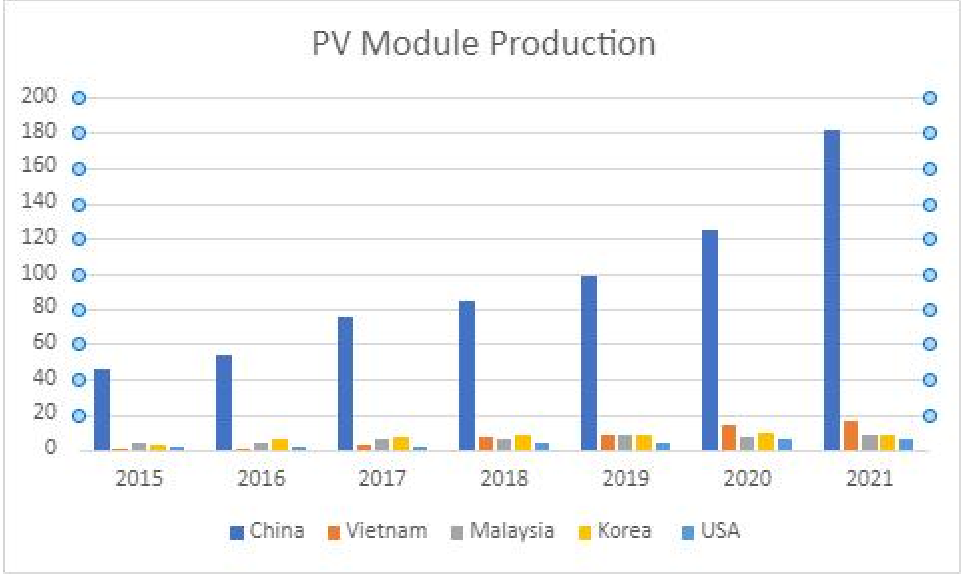

Table 2. Module production per Country for years 2015-2021.

As shown from the above Table, China is the leading production country regarding photovoltaics. Leading companies in the production of mono and poly crystalline cells are Hanwha Solar, Rene Solar, Jinergy, Canadian Solar, Zhongli, Eging PV, Talesun with plants over the world.

3 Chapter 3: Emissions during production of PV modules

In the second chapter of this document, we referenced the global production of photovoltaic (PV) modules. However, to accurately determine the quantity of emissions that arise during the manufacturing process, it is necessary to investigate a range of other contributing factors. This chapter explores several key aspects related to the environmental impact of photovoltaic (PV) modules. It emphasizes the significance of considering PV shipments alongside production, with a focus on polycrystalline silicon PVs. The largest production countries, including China, the USA, and Europe, are highlighted, displaying the exponential growth in PV shipments. Manufacturing processes and the use of polysilicon are identified as crucial factors in mitigating negative environmental impacts. The chapter also discusses the greenhouse gas emission intensity of electricity, emphasizing the importance of renewable energy and energy efficiency measures to reduce emissions. The impact of the electricity mixes on the emissions associated with PV module production is examined, emphasizing the need to increase the proportion of renewable energy sources for decarbonization. Furthermore, the chapter addresses the life cycle assessment (LCA) of PV power plants, highlighting their environmental impact throughout their entire life cycle. Ecodesign will be introduced to address waste management and increase the recycling of PV panels. The chapter concludes by setting the stage for the subsequent analysis of emissions during production of multi-Si modules, aiming to assess the environmental sustainability of this energy source.

3.1 Life Cycle Analysis

When evaluating the environmental impact of a photovoltaic power plant, it is essential to conduct a Life Cycle Assessment (LCA) to analyze the emissions that occur during the entire life cycle of the system, including its manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal. Although photovoltaic electricity production does not result in direct greenhouse gas emissions, the production stage of the photovoltaic power plant can result in significant greenhouse gas emissions. For instance, the manufacturing of photovoltaic panels requires enormous amounts of energy, which is often derived from fossil fuels. Additionally, transportation and installation of photovoltaic panels also contribute to the system's environmental impact. By conducting an LCA, it is possible to determine the overall environmental impact of a photovoltaic power plant, including its indirect energy requirements, carbon footprint, and other environmental impacts. This information is crucial in identifying areas where the environmental impact of photovoltaic systems can be reduced, and for assessing their overall sustainability.[48]

Various Life Cycle Assessments (LCAs) have been conducted to analyze the environmental impact of photovoltaic panels. These assessments have identified several impact categories that are particularly relevant, including energy resource depletion, ecotoxicity, global warming, carcinogens, and land use. Among different photovoltaic technologies, crystalline panels tend to have higher values for these impact categories, while thin-film panels have lower values.[49] This is likely due to the manufacturing processes and materials used for each type of panel. In general, it is important to consider the entire life cycle of a photovoltaic panel when assessing its environmental impact, as each stage of the panel's life, from manufacturing to disposal, can contribute to its overall impact. By identifying the most significant impact categories and seeking ways to minimize them, it is possible to develop more sustainable and environmentally friendly photovoltaic panels. [43]

Life cycle assessment (LCA) is a methodology to analyze the environmental impacts of products and processes throughout the life cycle of PV modules. LCA analysis can be divided into three sectors: the manufacturing stage, the use stage, and the end-of-life stage. The manufacturing stage is the process needed to build a PV, including every bill of material needed and the infrastructure which refers to the facilities used for the manufacturing process. The use stage represents the working stage of the panel and end-of-life stage, which is of highest importance, includes the dismantling and transport to a recycling plant or the disposal in a landfill. [50] However, it is important to say that while LCA results can be used to address greenhouse gas emissions and air pollution, other non-combustion emissions or methane leakages from fossil fuel supply, land-use related emissions, Sulphur hexafluoride leakages from electric equipment may also constitute significant sources of greenhouse gas emissions.[43]

Different module types have different impacts on each stage. Regarding multi-crystalline PV modules, the product stage is the most important life cycle stage followed by the use stage. The production of the PV module contributes to 87% of the overall impacts. The impacts are in human toxicity, cancer effects, freshwater ecotoxicity. As to the monocrystalline PVs, the production stage is also the most important stage followed by the use stage. Construction and production of monocrystalline PV contributes to 89% of the total impacts. For thin film modules, the use stage causes 99% of the total impacts with high demand of cumulative energy and end-of-life stage is the second most relevant cycle with high impact on human toxicity, cancer, and non-cancer effects. It is worthwhile to mention the potential effects that may arise from the stages. The first potential consequence could be the depletion of minerals, fossil fuels, silver used as paste for multi- and mono-crystalline modules, as well as copper used for installation. Additionally, the disposal of aluminum may result in human toxicity and cancer effects. The production of copper and zinc, as well as the disposal of ash, could potentially result in non-cancerous effects on human toxicity. [50]

The emissions and in consequence, the impact for the production differ from country to country depending on the electricity mixture, choice of fuel sources, greenhouse gas emission intensity as well as other factors that are not in the scope of this study. In the following sub-chapters, we will analyze those factors.

3.2 Electricity mix

The electricity mix of each country can have a significant impact on the emissions associated with the production of a photovoltaic (PV) module. The production of a PV module requires energy, which can come from a variety of sources, including fossil fuels, nuclear, and renewable energy sources. The carbon intensity of the electricity mix used to produce the PV module can influence the carbon footprint of the module. If a PV module is produced in a country that relies heavily on coal-fired power plants to generate electricity, the carbon footprint of the PV module will be higher than if it were produced in a country that generates a larger share of its electricity from renewable energy sources. This is because coal-fired power plants tend to emit more carbon dioxide than other sources of electricity. [45], [46] In Table 3, Table 4 and Table 5 the share of each material used to produce electricity is shown for U.S.A., China and Europe for years 2015-2020.

U.S.A. **Share of sources (%)**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Coal	33.60%	30.70%	30.30%	28.10%	23.90%	19.70%
Low Carbon	31.90%	33.50%	33.50%	35.80%	36.10%	38.10%
Gas	33.00%	34.40%	32.60%	35.50%	38.60%	40.70%
Renewables	13.10%	14.60%	16.60%	16.50%	17.30%	19.20%

Table 3. Electricity Mix of United States of America for the years 2015-2020.

China **Share of sources (%)**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Coal	72.60%	71.30%	71.00%	69.80%	68.60%	67.20%
Low Carbon	22.4%	23.50%	23.90%	24.90%	26.20%	27.10%
Gas	3.90%	4.10%	4.10%	4.50%	4.40%	4.80%
Renewables	20.00%	20.60%	20.80%	21.40%	22.30%	23.20%

Table 4. Electricity Mix of China for the years 2015-2020.

Europe **Share of sources (%)**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Coal	24.4%	22.40%	21.40%	20.80%	17.00%	14.50%
Low Carbon	52.00%	51.50%	51.30%	53.50%	56.00%	58.30%
Gas	19.20%	21.60%	22.90%	21.60%	22.80%	23.00%
Renewables	31.80%	32.10%	32.40%	34.40%	36.90%	40.70%

Table 5. Electricity Mix of Europe for the years 2015-2020.

A couple of centuries ago, energy mixes were 100% coal. Nowadays, things have changed. Energy production comes by burning of fossil fuels which accounts for ¾ of the global greenhouse emissions. Apart from the environmental cost, air pollution affects human health. To avoid those risks the world needs to shift to an energy mix from low-carbon sources of energy. Photovoltaics take the lead in electricity production regarding renewables, followed by hydropower.

As indicated by the tables presented earlier, the proportion of renewable energy sources in the electricity mix is still relatively low and needs to be increased to achieve the primary sustainability goal of decarbonization. Solar photovoltaics are already playing a significant role in the renewables mix due to their low greenhouse gas emissions. However, to fully decarbonize the electricity grid, a rapid expansion of cleaner energy sources is required. Although Europe has made strides in implementing wind and solar power, the lack of effective management of equipment disposal could lead to a significant increase in waste generation.[47] To address this issue, Ecodesign measures are crucial in managing and reusing old equipment.

In addition, from an LCA (Life Cycle Analysis) standpoint, the electricity supply is an interesting area to explore, which will be examined further in the following chapter to calculate the emissions associated with PV production. Power generation using fossil and biomass fuels exhibit the highest total indirect energy requirements. Among non-biomass renewables, solar photovoltaic has the highest total indirect energy requirements, followed by hydropower. Therefore, to achieve the goal of decarbonization, it is essential to continue to reduce the indirect energy requirements of all electricity sources, including renewables. [43]

3.3 Greenhouse Gas Emission Intensity

In the previous sub-chapter, we examined and assessed the energy mix of the primary PV module manufacturing countries. This is because the carbon footprint of a PV module can be impacted by the carbon intensity of the electricity mix used to manufacture it. Thus, it was crucial to analyze the energy mix of these countries to gain a better understanding of the environmental impact of PV module production.

Electricity generation is a significant contributor to global greenhouse gas emissions. In 2019, the electricity and heat production sector accounted for approximately 42% of global CO2 emissions from fuel combustion, according to the International Energy Agency. The greenhouse gas emission intensity of electricity depends on the fuel mix used in power generation. Power plants that use coal or oil, for example, typically have a higher greenhouse gas emission intensity than those that use natural gas or renewable energy sources.

In addition to emissions from power generation, it is also important to consider the emissions associated with the production and transport of fuels. For instance, extracting and transporting coal and oil can result in significant emissions of carbon dioxide and other greenhouse gases. These upstream emissions can impact the overall greenhouse gas emission intensity of electricity.

In recent years, there has been a growing trend towards transitioning to low-carbon energy sources to reduce greenhouse gas emissions from electricity generation.[42] This occurs through using Renewable energy sources. Many countries have set targets to increase the share of renewable energy in their electricity mix. In addition to renewable energy, energy efficiency measures can also help to reduce energy consumption and lower greenhouse gas emissions.

In Table 6, carbon intensity during 2015-2019 is shown for the leading PV production countries (USA, China, Europe). The global average carbon intensity of electricity worldwide is 463 g (about half the weight of a water bottle) CO2/kWh though for 1kWh produced by PV this number can be 15g depending on the conditions and the type of the PV module. [43] The CO2e impacts vary based on several factors, such as solar potential, efficiency performance ratio, system lifetime and mounting type. Also, the type of fuel used and the efficiency of the power plant where PV is constructed. Different fuels have different carbon intensities, which means that the amount of CO2 emitted per unit of energy produced can vary significantly. For example, coal-fired power plants tend to emit more CO2 than natural gas-fired power plants. More efficient power plants tend to produce less CO2 per unit of energy generated. Modern power plants that use advanced technologies like combined cycle gas turbines (CCGT) tend to be more efficient than older power plants. For this reason, they are impossible to calculate.

gCO2/kWh	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
China	650.20	626.90	622.70	612.80	598	580
USA	455.70	433.20	421.10	411.10	383.20	352.50
Europe	311.50	301.70	299.80	283.40	248.10	215.70

Table 6. Carbon intensity of electricity production during the years 2015-2020 per country. [66]

As deducted from Table 6, the grams of CO2 per kWh are decreasing throughout the years due to the continuous turning to a greener future with more applications of renewable energy sources to our everyday life. The CO2 impacts of production of PV modules, due to numerous factors, cannot be extracted. Given the significant contribution of the electricity sector to global greenhouse gas emissions, it is critical to consider the greenhouse gas emission intensity of electricity and the electricity mix of each manufacturing country to calculate the Greenhouse Gas Emissions of solar module production.

However, several studies have been conducted trying to calculate the C02 impacts during the production of 1kWh of electricity via a PV module. The results were that most of emissions occur during the production of modules, batteries needed and the installation of the photovoltaic. The emissions do not refer only to CO2 but also to methane (CH4), SF6 and others.[44] For example, in China in 2015 the carbon emission during the production of a multi-Si module was 30-45 gC02/kWh. The quantity of carbon dioxide emissions associated with the production of one kilowatt-hour of electricity is subject to significant variation, up to a maximum of 200 grams of CO2 per kilowatt-hour, depending on a variety of factors as previously discussed.

3.4 PV Shipments

Besides PV production, shipments of PVs are also important for this study. To retrieve data about the annual shipments, NATIONAL SURVEY REPORTS from IEA were used, particularly *Chapter 5 production of PV modules*. [41] Subsequently, to focus solely on polycrystalline silicon photovoltaics, a comprehensive investigation was conducted to identify the production plants worldwide that manufacture polycrystalline silicon PV modules. For reference, some of them are Hanwha Solar with plants located in Malaysia, China, Korea. Rene Solar with plants in China, USA, and Europe and Talesun solar with plants located in Europe. Worldwide shipments, shown in the Table 7 are divided in the largest countries of production: China, USA, and Europe.

	Shipments in GW					
Year	2015	2016	2017	2018	2019	2020
Country						
China	6.92	8.54	10.97	16.39	11.10	11.40
USA	0.024	1.11	1.26	0.979	10.75	21.05
Europe	0.77	0.28	0.25	0.30	0.25	0.15

Table 7. Worldwide Shipments.

For USA 2019 and 2020, data regarding the type of PVs that were shipped was not disclosed. Therefore, total shipments were used by U.S. Energy Information. As for Europe, data were collected from each European country that produced and shipped PV multi-Si modules and the summarized shipment is shown in Table 3.

In the NATIONAL SURVEY REPORTS, there are other countries included too, but they are not among the top five manufacturing countries. For geopolitical reasons, in many cases, the PV shipments of these countries remain undisclosed. Upon examining the table, we can observe that some countries have experienced exponential growth in their PV shipments. However, unregulated production of photovoltaics can have a detrimental effect on the environment due to the extensive use of polysilicon, with silicon treatment processes resulting in the most significant Global Warming Potential (GWP) impacts. GWP is a measure of the environmental impact relating to energy use and greenhouse gas emissions. According to the International Energy Agency, approximately 60% of the total energy required to produce each module is necessary to produce silicon wafers. Therefore, it is crucial to consider the impact of GWP and take steps towards regulated manufacturing processes to mitigate negative environmental impacts.

3.5 Ecodesign

Ecodesign aims to minimize environmental impacts during photovoltaic production through different considerations which are then implemented through legislation. The stage of life cycle analysis regarding the 'end of life' is still under investigation. The FRELP project was funded by the European Union with PV Cycle Italia to develop a PV waste treatment process to magnify the recycling of the materials used in panels. In PV waste treatment the main benefit is the recycling of aluminum and the dismantling of PV panels in a decentralized waste management plant. In addition, it is worth noting that photovoltaics has another potential use as secondhand items. Over the past few years, certain industries have been selling used PVs. While some of these PVs may have damage to their diodes and frames that can be repaired, it is important to keep in mind that damage such as cell connection problems or broken glass cannot be fixed. [51]

FRELP project, has researched the disposal treatments for multi-Si photovoltaics and found that there are some discrepancies in the recycling treatment. The reason for that being that construction materials of PV panels are generic and there is significant uncertainty regarding the disposal of PV modules and whether they can be successfully recycled. However, this stage is still in research since panels that are now in recycling stage, were made in a decade that we do not know many things on how they were made.

According to European Commision, Analysis of Material Recovery from Silicon Photovoltaic Panels, there are two potential eco-design measures for PV could focus on:

1. Avoid using halogenated plastics on PV because they must be treated in specialized incineration plants. This can cause higher impacts with the emission of hazardous pollutants and waste in the plant. Otherwise, if halogenated plastics are to be used, this should be labelled in the product.
2. Detailed information provided by manufacturers regarding the composition of the PV panel to help with the recycling stage after each panel's life expectancy. [52]

3.5.1 Regulations regarding end-of-life treatment

The main objective of the EU Ecolabel, established under Regulation EC 66/2010, is to mitigate the adverse impact of products and services on the environment, health, climate, and natural resources. IEC TR 62635 addresses the end-of-life and recyclability of Electrical and Electronic Equipment (EEE), and it outlines the various aspects and stages of the life-cycle assessment that manufacturers should consider during the design of EEE. The document highlights the need for manufacturers and recyclers to share information and collaborate with one another to ensure the entire supply chain is sustainable, effective, and efficient in terms of material usage, energy consumption, and energy recovery.

The commercial recycling process of PV panels began ten years ago following mandatorily the Waste Electrical and Electronic Equipment (WEEE) Directive. [52] The following steps are adhered to by the WEEE directive.

- Transport of waste to the recycling facility
- Unloading of the waste
- Disassembly. In this stage, the frame is separated from the cables, glass, junction box.
- Cable treatment where a huge amount of metal is recovered
- Incineration of cable polymers
- Glass separation from the PV
- Glass refinement
- Cutting of modules

- Incineration of encapsulation and back-sheet layer with energy recovery.
- Sieving which is the treatment of the ashes.
- Acid leaching is to recover silicon metal from the ash
- Filtration
- Electrolysis
- Neutralisation
- Filter press

According to Joint Research's Center Life Cycle Assessment, the highest environmental impact of the treatment of 1000kg of PV waste is in abiotic depletion of fossil fuel followed by freshwater ecotoxicity and climate change.

The WEEE directive involves several steps in the treatment of electronic waste. First, there is a pre-treatment stage where hazardous parts are removed based on information provided by the manufacturers. Dismantling of parts is also done for selective treatment. The next step involves material separation which can be done through mechanical, chemical, or thermal methods. This ensures that materials are properly sorted for efficient recycling. The remaining parts that are not suitable for recycling are considered for energy recovery in appropriate facilities. This ensures that energy is recovered from the waste in an environmentally friendly way. Finally, any residuals that cannot be treated through the above methods are disposed of in appropriate landfills. This helps to ensure that the environment is protected from hazardous materials. [56]

4 Chapter 4: Calculation of Emissions of multi-Si PV module

The significance of ensuring the production of photovoltaic modules aligns with clean energy standards and environmental sustainability has been established in the preceding chapter. Expanding upon this premise, the focus of this chapter is to quantify the emissions and energy requirements associated with the manufacturing process of multicrystalline PV modules and explore potential strategies for reducing these emissions to aid in the development of voluntary industry standards to address these hotspots at a global level. To achieve this, a comprehensive life cycle assessment (LCA) will be employed, incorporating data from diverse PV manufacturers gathered through various datasheets. It is important to note that several assumptions will be made including the production of cells in China but module assembly in Europe.

The study's main objective is to assess the extent of emissions and identify actionable measures for emission reduction. By undertaking this analysis, valuable insights will be gained, providing a roadmap for necessary actions to mitigate the environmental impact of PV module production.

4.1 Emission during production of PV module

During production of PV modules, lots of hazardous gases are emitted and materials used for the production cannot be recycled properly. Therefore, examining how much gas is emitted during the production and how much energy is required to produce a PV module is worth checking. There are many factors to be taken into consideration when it comes to emissions and energy demands for the manufacturing process, some of these being the size of PV panel, the country in which they were produced, the climate, the electricity mix of each country and others as mentioned in the previous chapter. Larger panels require more processing time and energy consumption during fabrication, leading to higher emissions. Where PVs are manufactured is important because carbon intensity emissions differ. [53] The climate where a photovoltaic (PV) panel is manufactured can have an impact on manufacturing emissions due to several factors such as the temperature and water availability in the region. The electricity mix of a country significantly impacts the emissions during photovoltaic (PV) panel production. Countries with a higher proportion of fossil fuel-based electricity generation tend to have a higher carbon intensity, resulting in higher emissions during PV panel manufacturing. Conversely, countries with a larger share of renewable energy sources in their grid have lower emissions during the manufacturing process. The electricity mix affects both the direct emissions from electricity consumption in PV production and the upstream emissions associated with the extraction and processing of raw materials.

In this study different assumptions regarding module efficiency, wafer thickness, cell size, technology etcetera has been made. The results were presented in Preparatory study for solar photovoltaic modules, inverters and systems published in European Commission from *European Commission's Piloting of the Product Environmental Footprint method.* [51] The European Commission's Piloting of the Product Environmental Footprint method is an initiative aimed at developing a standardized methodology for assessing the environmental impact of products throughout their lifecycle. This approach involves gathering data on various stages of a product's lifecycle, including production, use, and disposal, to calculate its environmental footprint. The method considers a range of factors, such as energy use, water consumption, greenhouse gas emissions, and waste generation, among others. The goal of the initiative is to provide a standardized approach for measuring and communicating the environmental performance of products to stakeholders, including consumers, producers, and policymakers, with the aim of promoting more sustainable production and consumption patterns.

To calculate the emissions and energy inputs of PV per kW peak, a detailed study occurred. The PEF study includes 16 indicators that evaluate the impacts on climate, on reducing depletion, air, water, and soil quality.[44]

In Table 8, the results of the above-mentioned study are shown with the manufacturing need of kWh and emissions per m^2.

Input manufacturing	Amount	Unit
European medium voltage electricity	3.7312	kWh
Diesel + emissions from diesel combustion	0.00875	MJ
NMVOC (Non methane volatile organic compounds)	0.0080625	kg
CO2	0.021812	kg

Table 8. Emissions occur during production of PV module (per m2) according to PEF study.

In the context of PV manufacturing, the term "European medium voltage electricity" refers to the electricity required for producing components like silicon wafers and solar cells used in multi-Si modules. The environmental impact of PV manufacturing can vary depending on the electricity mix in Europe. Different countries may generate electricity from various sources such as fossil fuels, nuclear power, or renewable energy. It is important to consider this electricity mix as it directly influences the carbon footprint and emissions associated with PV manufacturing processes.

Diesel engines are commonly used in various applications related to PV manufacturing, such as transportation of raw materials or equipment, as well as for backup power generation. However, the combustion of diesel fuel emits pollutants, including organic compounds and nitrogen oxides (NOx). These emissions can have detrimental effects on human health, contributing to respiratory problems and other adverse health impacts. Additionally, nitrogen oxides can participate in chemical reactions that contribute to the depletion of the ozone layer, which protects us from harmful ultraviolet (UV) radiation.

Non-methane volatile organic compounds (NMVOCs) are a diverse group of organic compounds that have different chemical compositions but exhibit similar behavior in the atmosphere. They include various volatile organic compounds (VOCs) other than methane. NMVOCs are emitted from various sources, including industrial processes, solvents, and the burning of fossil fuels. These compounds can react with other pollutants in the atmosphere, leading to the formation of ground-level ozone and contributing to smog formation. Moreover, certain NMVOCs can also contribute to the depletion of the ozone layer and have adverse effects on human health, including respiratory issues and potential carcinogenic effects.

Carbon dioxide is a well-known greenhouse gas and is primarily responsible for global warming. The burning of fossil fuels, such as coal, oil, and natural gas, releases significant amounts of CO2 into the atmosphere. In the context of PV manufacturing, it is important to consider the carbon emissions associated with the entire lifecycle of the manufacturing process, including the extraction and processing of raw materials, transportation, and energy consumption during manufacturing. Understanding the CO2 emissions helps assess the environmental impact and the potential climate change implications of PV manufacturing processes.

It is worth mentioning that two of the assumptions made, are that solar cells are produced in China, but assembly of the modules is done in Europe. To provide context, in China, fossil fuels account for 78.75% of their electricity mix, while hydro power makes up 18.57%, nuclear energy comprises 2.06%, and renewables represent 0.49%. Meanwhile, in Europe, the electricity mix is composed of 58.3% fossil fuels, 3.40% hydro, 15.9% nuclear, 21.4% renewables, and 1% waste. [57]

Also, the functional units in the context of this study are that 1kWh of electricity is produced by the PV system, the output power of module is 1Wp, the area of module and cell is $1m^2$ and 1 inverter or module is used.

4.2 Calculating Emissions per kWp of multi-Si module

In the following sub-chapter, we will explore the environmental impact of multi-silicon (multi-Si) solar panels commonly used in photovoltaic (PV) systems. The calculation of emissions per kWp provides a useful metric for evaluating the environmental performance of multi-Si modules by assessing the amount of greenhouse gas (GHG) emissions generated per unit of energy produced. This sub-chapter will describe the process of calculating emissions per kWp of multi-Si modules, including the data and assumptions used in the calculation, as well as the potential sources of uncertainty and variability. This will help dive into the overall sustainability and environmental performance of PV systems.

The life cycle of PV begins with the extraction of raw materials, followed by processing them, manufacturing them and then ends with the use stage, decommissioning, disposal and or recycling them and LCA contains all the above steps.[54]

Energy payback time is the time needed for the PV to generate the amount of energy needed for the production. There are several factors EPBT depends on with some of them being the technology used, the efficiency of the frame, the irradiation, and the application type. Although the estimated time is around two years. One other metric is the greenhouse gas per kilowatt hour (gCO2) which as explained before varying from each technology, their lifetime, efficiency, and irradiation.[55]

To calculate the emissions per kWp of multi-Si module, the following steps were conducted.

Primarily, different datasheets of multi-Si modules were gathered from different manufactures with plants worldwide. The data needed were the dimensions of the module as well as the output power. The utilization of data from various datasheets is crucial for the forthcoming analysis. The results obtained from the PEF study pertain to a PV module with an area of 1 square meter, which is different from the actual sizes of PV modules applied in the market. Therefore, it is necessary to calculate the conversion factor from 1 square meter to the actual size of PV modules utilized in the field.

The selection of PV module manufacturers has been made randomly, but the deliberate inclusion of both 60-cell and 72-cell modules is intentional and serves a specific purpose in the research. The objective is to obtain a comprehensive understanding of emissions across the entire industry by including both 60-cell and 72-cell modules in the analysis.

Multi-Si is one of the major types of silicon used in the production of photovoltaic (PV) modules. It is widely utilized in the PV industry and represents a significant portion of the global PV market with higher efficiency than other types and this is one of the reasons that multi-Si PVs were selected. Another reason is because crystalline silicon requires a greater quantity of electricity and has higher direct emissions during production of metallurgical grade silicon, polycrystalline silicon wafers and modules.

All the datasheets that have been used are attached in Annex A.

1. First Maker used was Canadian Solar. Datasheet was retrieved from Canadian Solar's website. As seen by Table 9, the photovoltaic module is made up of 60 polycrystalline cells and has a height of 1048mm and a width of 1765mm. The surface area of the module is equivalent to 1.8497 square meters. The maximum output power of the module is 350 watts.

MAKER	Canadian Solar
CELL TYPE	Polycrystalline
NUMBER OF CELLS	60
HEIGHT (mm)	1048
WIDTH (mm)	1765
SURFACE (mm^2)	HxW= 1849720
SURFACE (m^2)	1.8497
MAX. OUTPUT POWER (W)	350

Table 9. Photovoltaic values of Canadian Solar 60-cell module.

2. The second Maker used was Eging PV. The datasheet was retrieved from Eging PV's website and. As seen by Table 10, the photovoltaic module is made up of 60 polycrystalline cells and has a height of 1650mm and a width of 990mm. The surface area of the module is equivalent to 1.6335 square meters. The maximum output power of the module is 290 watts.

MAKER	Eging PV
CELL TYPE	Polycrystalline
NUMBER OF CELLS	60
HEIGHT (mm)	1650
WIDTH (mm)	990
SURFACE (mm2)	HxW= 1633500
SURFACE (m2)	1.6335
MAX. OUTPUT POWER (W)	290

Table 10. Photovoltaic values of Eging PV 60-cell module.

3. Third Maker used was Rosen Solar. The datasheet was retrieved from Rosen Solar's website. As seen by Table 11, the photovoltaic module is made up of 60 polycrystalline cells and has a height of 1640mm and a width of 992mm. The surface area of the module is equivalent to 1.6268 square meters. The maximum output power of the module is 290 watts.

MAKER	Rosen Solar
CELL TYPE	Polycrystalline
NUMBER OF CELLS	60
HEIGHT (mm)	1640
WIDTH (mm)	992
SURFACE (mm2)	HxW= 1626880
SURFACE (m2)	1.6268
MAX. OUTPUT POWER (W)	290

Table 11. Photovoltaic values of Rosen Solar 60-cell module.

4. The fourth Maker used was Akcome. The datasheet was retrieved from Akcome's website. As seen by Table 12, the photovoltaic module is made up of 60 polycrystalline cells and has a height of 1640mm and a width of 992mm. The surface area of the module is equivalent to 1.6268 square meters. The maximum output power of the module is 285 watts.

MAKER	Akcome
CELL TYPE	Polycrystalline
NUMBER OF CELLS	60
HEIGHT (mm)	1640
WIDTH (mm)	992
SURFACE (mm^2)	HxW= 1626880
SURFACE (m^2)	1.6268
MAX. OUTPUT POWER (W)	285

Table 12. Photovoltaic values of Akcome 60-cell module.

5. The fifth Maker used was Yingli Solar. The datasheet was retrieved from Yingli Solar's website. As seen by Table 13, the photovoltaic module is made up of 72 polycrystalline cells and has a height of 1970mm and a width of 990mm. The surface area of the module is equivalent to 1.9503 square meters. The maximum output power of the module is 285 watts.

MAKER	Yingli Solar
CELL TYPE	Polycrystalline
NUMBER OF CELLS	72
HEIGHT (mm)	1970
WIDTH (mm)	990
SURFACE (mm2)	HxW= 1950300
SURFACE (m2)	1.9503
MAX. OUTPUT POWER (W)	285

Table 13. Photovoltaic values of Yingli Soalr 72-cell module.

6. The sixth Maker used was Hanwha Solar. The datasheet was retrieved from Hanwha Solar's website. As seen by Table 14, the photovoltaic module is made up of 72 polycrystalline cells and has a height of 1960mm and a width of 991mm. The surface area of the module is equivalent to 1.9423 square meters. The maximum output power of the module is 335 watts.

MAKER	Hanwha Solar
CELL TYPE	Polycrystalline
NUMBER OF CELLS	72
HEIGHT (mm)	1960
WIDTH (mm)	991
SURFACE (mm2)	HxW= 1942360
SURFACE (m2)	1.9423
MAX. OUTPUT POWER (W)	335

Table 14. Photovoltaic values of Hanwha Soalr 72-cell module.

7. The seventh Maker used was Jinergy. The datasheet was retrieved from Jinergy's website. As seen by Table 15, the photovoltaic module is made up of 72 polycrystalline cells and has a height of 1960mm and a width of 991mm. The surface area of the module is equivalent to 1.9423 square meters. The maximum output power of the module is 395 watts.

MAKER	Jinergy
CELL TYPE	Polycrystalline
NUMBER OF CELLS	72
HEIGHT (mm)	1960
WIDTH (mm)	991
SURFACE (mm2)	HxW= 1942360
SURFACE (m2)	1.9423
MAX. OUTPUT POWER (W)	395

Table 15. Photovoltaic values of Jinergy 72-cell module.

Upon analyzing the datasheets provided by PV distributors worldwide, it is necessary to calculate the average surface area to determine the emissions-to-industry values. This calculation is based on the number of cells, which can either be 60 or 72, and involves dividing the surface area calculated in square meters by three. The same process is applied to determine the maximum power output under standard test conditions. The outcome of these calculations is presented in Table 16.

60 cells:	Area (m2)	/Wp
EGING PV	1.6335	290
ROSEN SOLAR	1.6268	290
AKCOME	1.6268	285
Average:	1.62903	288.33
72 cells:	**Area (m2)**	**/Wp**
YINGLI SOLAR	1.9503	285
HANWA SOLAR	1.9423	335
JINERGY	1.971	395
Average:	1.9545	338.33

Table 16. Average area and corresponding Watt peak according to PV datasheets.

After reviewing Table 8, which displays the results of the PEF screening study, we calculated the emissions and energy requirements for the average area of a PV module. For this calculation, we utilized an area of 1.9545m2, which represents the worst-case scenario with the highest expected emissions and requirements. The updated values are presented in Table 17, which provides details on the emissions and energy requirements for a multi-Si PV module with an area of 1.9545m2.

Input manufacturing	Amount	Unit
European medium voltage electricity	7.2926	kWh
Diesel + emissions from diesel combustion	0.1710	MJ
NMVOC (Non methane volatile organic compounds)	0.0158	kg
CO2	0.0426	kg

Table 17. Corresponding values of emissions during production according to 1.9545m^2 module.

The subsequent step involves calculating the emissions and energy requirements per kWp (kilowatt peak) of PV, which enables us to determine the actual emissions based on PV shipments in each country, as shipments are typically measured in kWp rather than the area of each PV module. As per Table 16, we are aware that 1.9545m2 of PV corresponds to a power output of 338.33Wp. By utilizing a simple rule of three, we can deduce that for 1m2 of PV, the theoretical power output would be 173.10Wp. Subsequently, applying the same rule of three, we can infer that since 173.10Wp corresponds to the values in Table 8, the values for 1000Wp (1 kWp) would correspond to those in Table 18. This calculation allows us to scale up the emissions and energy requirements data to reflect the larger scale of PV installations and obtain a more comprehensive understanding of the overall environmental impact associated with PV deployments.

Input manufacturing	Amount	Unit
European medium voltage electricity	21.554	kWh
Diesel + emissions from diesel combustion	0.5054	MJ
NMVOC (Non methane volatile organic compounds)	0.0466	kg
CO2	0.1260	kg

Table 18. Emissions and energy requirements per kWp of multi-Si PV.

The calculation of the numbers should consider the production of photovoltaic shipments in each country. By utilizing the known shipments of multi-Si modules for each country, from Table 3, it is possible to derive conclusive data for emissions and energy requirements in the following tables (Table 19, Table 20, Table 21), which are based on the annual shipments of each major manufacturing country.

China	*2015*	*2016*	*2017*	*2018*	*2019*	*2020*	
European medium voltage electricity	1491e+5	1840e+5	2364e+5	3532e+5	2392e+5	2457e+5	*kWh*
Diesel and emissions from diesel combustion	3497e+3	4316e+3	5544e+3	8283e+3	5609e+3	5761e+3	*MJ*
NMVOC	3222e+2	3977e+2	5108e+2	7632e+2	5169e+2	5308e+2	*kg*
CO2	8719e+2	1076e+3	1382e+3	2065e+3	1398e+3	14036e+3	*kg*

Table 19. Annual emissions for shipments from China during years 2015 to 2020.

USA	2015	2016	2017	2018	2019	2020	
European medium voltage electricity	51e+4	2392e+4	2715e+4	2110e+4	2317e+5	4537e+5	kWh
Diesel and emissions from diesel combustion	12129	5609e+2	6368e+2	4947e+2	5433e+3	1063e+4	MJ
NMVOC	1117	51692	58678	45592	5006e+2	9802e+2	kg
CO2	3024	1398e+2	1587e+2	1233e+2	1354e+3	2652e+3	kg

Table 20. Annual emissions for shipments from the USA during the years 2015 to 2020.

Europe	2015	2016	2017	2018	2019	2020	
European medium voltage electricity	1659e+4	6035e+3	5388e+3	6466e+3	5388e+3	3233e+3	kWh
Diesel and emissions from diesel combustion	3891e+2	1415e+2	1263e+2	1516e+2	1263e+2	75810	MJ
NMVOC	35858	13039	11642	13971	11642	6985	kg
CO2	97020	35280	31500	37800	31500	18900	kg

Table 21. Annual emissions for shipments from Europe during the years 2015 to 2020.

The calculations performed for determining emissions and energy requirements per kWp of PV are founded on the disclosed shipments data obtained from various markets in different countries. It is evident that China has the most substantial impact due to being the leading country in both PV module production and shipments. On the other hand, Europe exhibits the least impact, although its shipments are also comparatively minimal.

By analyzing the data presented in the above tables, we can draw conclusions and make recommendations aimed at reducing the environmental impacts associated with PV module production and fostering sustainability for the future.

4.3 Interpretation of results

Although photovoltaic (PV) modules are often viewed as a source of clean, renewable energy, it is important to note that the production process of these modules has a significant impact on the environment. When we consider the various aspects of module production, such as the amount of electricity used, the release of CO2 emissions, diesel emissions, and NMVOC, the environmental cost becomes apparent.

To mitigate this impact and truly characterize PV modules as clean energy sources, several actions must be taken. For instance, innovative module-level designs can be implemented to provide a range of benefits throughout their life cycle and operational use. For example, using alternative framing materials, such as carbon fiber, could lead to a reduction in CO2 emissions and a simplified manufacturing process. This is because aluminum, which is currently used for framing PV modules, contributes to the highest share of CO2 emissions during production. [58] An alternative solution regarding the module design is the use of frameless modules that can better protect the solar cells from damage and increase the life expectancy of each module. By eliminating the need for a frame, manufacturers can reduce the amount of material used in the production process, which can decrease the overall environmental impact of the module. In addition to frameless designs, anti-soiling coatings can be applied to the module glass to reduce the accumulation of dust and dirt on the module surface. This can lead to higher efficiencies and a longer lifespan for the modules. These coatings act as a barrier to prevent the accumulation of dirt and dust on the surface of the modules, which can cause a decrease in efficiency over time.

There are other strategies that can be employed to achieve a specific level of reduction in primary energy use and CO2 emissions during the manufacture of PV modules. One such strategy involves utilizing energy from renewable sources to supply a portion of the energy needed for module production. By doing so, the environmental impact of module production can be reduced, while also supporting the growth of the renewable energy sector. As previously discussed, the current leading PV production country, China, has an electricity mix that relies heavily on coal. Shifting production to countries with more renewable-based electricity mixes could help to significantly reduce CO2 emissions associated with module production.

Another consideration is to evaluate the transportation emissions associated with shipping PV modules from the production location to their destination. Manufacturing modules closer to their point of use could reduce transportation emissions and further contribute to the overall reduction in CO2 emissions associated with PV module production. [58]

An even more effective approach is to substitute the consumption of energy during the manufacture of PV modules with a specific grade of energy that is sourced on-site. This approach can be particularly beneficial in locations where renewable energy sources are abundant, such as areas with significant solar or wind resources. By sourcing energy on-site, the need for external energy sources can be reduced or eliminated altogether, leading to a significant reduction in both primary energy use and CO2 emissions.

Increasing the efficiency of PV modules can help reduce emissions during production by decreasing the amount of material and energy needed to produce a given amount of electricity. When PV modules have higher conversion efficiencies, less material is required to produce a given amount of electricity. This means that the manufacturing process will require less energy and fewer resources, leading to lower emissions. Higher module efficiencies can also reduce the environmental impact of the transportation and installation of PV systems, as fewer modules are needed to generate a given amount of electricity. This can result in lower transportation emissions and reduced land use requirements for solar installations. To increase the efficiency of PV modules, manufacturers can focus on optimizing the materials used in module production, improving the design and engineering of the modules, and investing in research and development of innovative technologies.

Lat but not least, improvements in our knowledge of GHG emissions from end-of-life processes can help reduce emissions from PV module production by enabling manufacturers to make informed decisions about the end-of-life management of modules and develop strategies for reducing emissions associated with module disposal. Understanding the emissions associated with end-of-life processes can help manufacturers design modules that are easier to recycle or dispose of, reducing emissions associated with module disposal. By developing modules that use fewer toxic materials and are designed for easy disassembly and recycling, manufacturers can reduce the emissions associated with module disposal and promote more sustainable end-of-life management practices.

These strategies can play a key role in reducing the environmental impact of PV module production, while also promoting the use of renewable energy sources. By adopting these approaches, manufacturers can create a more sustainable and environmentally friendly product, while also supporting the transition towards a cleaner and more sustainable energy system.

5 Chapter 5: Conclusions

In summary, we first addressed the different renewable energy sources that exist and the possible environmental damage that can be caused by human exploitation. Renewable sources such as geothermal, hydropower, bioenergy, wind, and solar power offer potential solutions. Geothermal harnesses the Earth's natural heat, but it poses risks such as harmful gas emissions and the potential for earthquakes. Hydropower utilizes kinetic water movement but can harm aquatic life and be costly. Bioenergy derived from biomass reduces waste and is carbon neutral, though the conversion process produces only ethanol. Wind and solar power show promise, with wind turbines converting wind energy into electricity and solar power relying on PV modules fueled by the sun. However, wind turbines generate noise and can impact animal reproductive cycles, necessitating careful location selection. Additionally, emerging renewables like marine and enhanced geothermal face challenges such as the uncertainty of oceans and the need for precise drilling for geothermal energy. Furthermore, the manufacturing phase of PV modules is a notable drawback due to emissions generated and is the main objective of this thesis.

Next, we discussed the photovoltaic effect, an innovative discovery of the nineteenth century, that marked the beginning of harnessing the sun's abundant renewable energy. Photovoltaic cells, including mono-crystalline, poly-crystalline, and thin film modules, have been developed. However, the prevailing technology is crystalline cells due to their higher efficiency and simplified manufacturing process. PV modules consist of multiple connected cells, typically sixty or seventy-two, complemented by inverters for current transformation and cabling. These modules are further interconnected to form PV arrays. Photovoltaic arrays offer an alternative to coal-based electricity generation and are produced in various proportions globally. Major producing countries include China, Korea, the USA, and certain European nations. We emphasized careful consideration that must be given to crystalline PV production and end-of-life stages due to the high emissions.

Consequently, a comprehensive analysis of relevant factors was then presented. With data obtained from National Survey Reports and identification of production facilities, China, the USA, and Europe were found to be the largest production countries. With China experiencing exponential growth in shipments throughout the years 2015-2020. It is essential to regulate manufacturing processes to mitigate negative environmental impacts resulting from the extensive use of polysilicon, particularly as electricity generation is a significant contributor to global greenhouse gas emissions, accounting for about 42% of global CO2 emissions from fuel combustion.

The greenhouse gas emission intensity of electricity was also analyzed, with emissions depending on the fuel mix used in power generation, with coal and oil having higher emissions than natural gas or renewable sources. Upstream emissions associated with the production and transport of fuels also impact the overall greenhouse gas emission intensity of electricity, which renewable energy and energy efficiency measures are being increasingly used to reduce. The impact of the electricity mix of each country on the emissions associated with the production of a photovoltaic (PV) module was also discussed. The carbon intensity of the electricity mix used to produce the PV module can influence the carbon footprint of the module. If a PV module is produced in a country that relies heavily on coal-fired power plants to generate electricity, the carbon footprint of the PV module will be higher than if it were produced in a country that generates a larger share of its electricity from renewable energy sources.

The environmental impact of a photovoltaic during its entire life cycle, including manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal, was also analyzed, with conducting a Life Cycle Assessment (LCA) deemed essential to analyze the emissions and overall environmental impact of a photovoltaic, including its indirect energy requirements, carbon footprint, and other environmental impacts.

The subject of Ecodesign was also addressed, highlighting the importance of implementing eco-design measures to avoid negative impacts that waste management of panels obtains in the end-of-life process. The FRELP project aims to develop a process for treating PV waste to increase the recycling of materials used in panels, but the recycling treatment of PV panels is still uncertain due to generic construction materials. Avoiding the use of halogenated plastics and providing detailed information regarding the composition of PV panels could help with the recycling stage.

The highest environmental impact of treating PV waste was found to be in abiotic depletion of fossil fuel, followed by freshwater ecotoxicity and climate change, according to the Joint Research Center Life Cycle Assessment.

The main objective of the study aims to identify the environmental effects associated with photovoltaic (PV) cells made up of multi crystalline silicon (multi-Si) by life cycle assessment. Results showed that multi-crystal solar PV technology provided significant contributions to respiratory inorganics, global warming, and non-renewable energy. The emissions generated by aluminum, coal-based electricity, and multi-Si wafer production processes play a significant role in the overall environmental burden. Using the findings from *European Commission's Piloting of the Product Environmental Footprint method* and data retrieved from IEA regarding the shipments, we conducted a calculation on the emissions that each country produces during PV production. China, being the lead country in PV shipments has the most environmental impact.

To mitigate the potential environmental impacts associated with the production of multi-Si PV cells, a range of measures must be implemented.

The current market situation for photovoltaic products highlights several areas that require attention and improvement. Firstly, there is a need to establish a higher performance of the PV and minimize the environmental impact during production. Moreover, the manufacturing and design of modules and inverters often present challenges in terms of repairability and recyclability. Selling PV modules second hand, for example, aligns with sustainability goals and commitments, such as reducing carbon emissions and promoting resource conservation. By extending the lifespan of modules and maximizing their utilization, it contributes to a more sustainable energy infrastructure and supports the reduction of greenhouse gas emissions. Due to the growing shortage, critical raw materials should be recovered from components. This poses a significant obstacle to the sustainable management of these products. Incorporating better design practices that consider site-specific conditions, implementing best installation practices, and reducing losses through the selection of appropriate equipment, cabling, and maintenance protocols can also promote and reduce the emissions. It is also imperative to enhance the share of renewable energy in the country's overall electricity production and enhance the efficiency of energy and raw material consumption. This is crucial because the analysis reveals that most energy consumption and greenhouse gas emissions occur during these stages. The production of photovoltaic cells constitutes the most energy-intensive and carbon-intensive phase in the life cycle of silicon-based technologies. Furthermore, the disclosure of all materials used in photovoltaic (PV) production is crucial for reducing emissions associated with PV manufacturing. It allows producers to identify emission sources, conduct comprehensive lifecycle assessments, explore material substitutions and innovations, ensure transparency in the supply chain, and establish industry benchmarks and regulations. By understanding the environmental impact of specific materials and components, producers can implement targeted measures to reduce emissions and drive sustainability in the PV industry. Material disclosure promotes accountability, informs decision-making, and supports the adoption of cleaner production practices, ultimately contributing to the goal of reducing PV production emissions.

Even though the study conducted gives a perspective regarding the emissions occurring during PV module production, it is worth mentioning some limitations and challenges that exist. First, there are data gaps for PV shipments and specific processes of materials. Second, PV modules can vary in terms of materials used, manufacturing processes, and technologies. This variability makes it challenging to develop a standardized LCA methodology that can be applied uniformly across different module designs. Results can also be influenced by regional variations in factors such as energy mixes, transportation distances, waste management practices, and environmental regulations. Also, the environmental impacts associated with electricity generation, used in different life cycle stages of PV modules, can change over time due to shifts in energy mixes. Finally, the rapid evolution of PV technology introduces challenges in conducting LCAs. The environmental performance of PV modules can change with advancements in manufacturing techniques, new materials, and increased energy efficiency. Keeping up with these technological developments can be demanding.

It is crucial for production countries to acknowledge and address these key issues, while also establishing a shared policy framework for photovoltaic (PV) production. By adopting a unified approach, the PV industry can make significant strides towards achieving multiple objectives.

Firstly, a common policy framework would facilitate efforts to improve and reduce emissions throughout the PV production process. By implementing standardized guidelines and regulations, production countries can effectively mitigate the environmental impact of PV manufacturing, such as reducing energy consumption and greenhouse gas emissions. This collective effort would contribute to a more sustainable and environmentally responsible PV industry.

Furthermore, a collective policy framework promotes greater efficiency in energy generation and consumption. By encouraging the adoption of advanced technologies, best practices, and innovative solutions, production countries can optimize the energy output of PV systems. This includes optimizing site-specific conditions, implementing efficient installation practices, and improving equipment selection, cabling, and maintenance protocols. The result is improved energy yield and reduced losses, thereby maximizing the overall efficiency of PV systems.

By addressing these key issues and fostering a collaborative policy approach, production countries can contribute to the advancement of the PV industry, aligning it with sustainable development goals. This collective effort lays the foundation for improved environmental performance, product quality, and energy efficiency, leading to a more sustainable and prosperous future for the PV sector.

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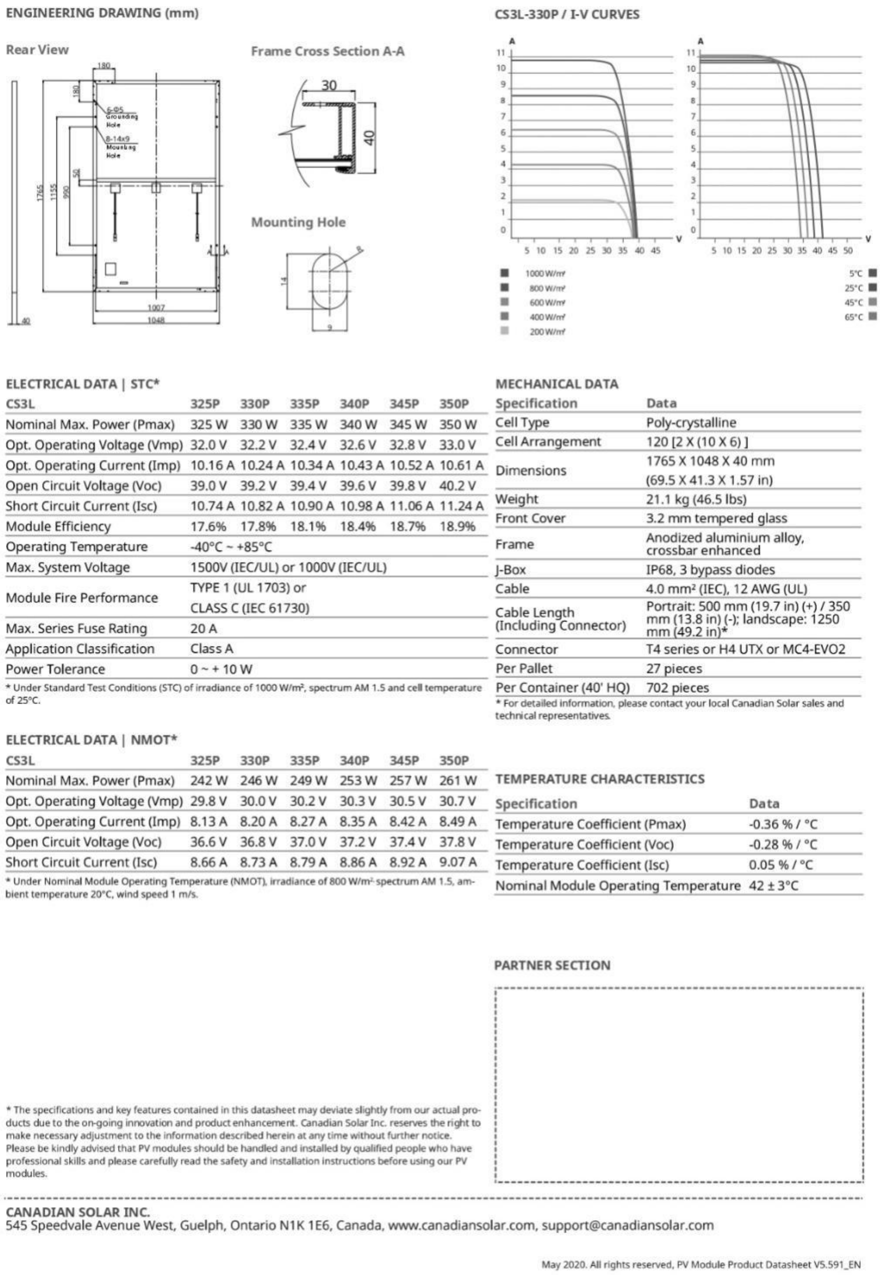
ANNEX A

I) CANADIAN SOLAR PV DATASHEET



ENGINEERING DRAWING (mm)

CS3L-330P / I-V CURVES

ELECTRICAL DATA | STC*

CS3L	325P	330P	335P	340P	345P	350P
Nominal Max. Power (Pmax)	325 W	330 W	335 W	340 W	345 W	350 W
Opt. Operating Voltage (Vmp)	32.0 V	32.2 V	32.4 V	32.6 V	32.8 V	33.0 V
Opt. Operating Current (Imp)	10.16 A	10.24 A	10.34 A	10.43 A	10.52 A	10.61 A
Open Circuit Voltage (Voc)	39.0 V	39.2 V	39.4 V	39.6 V	39.8 V	40.2 V
Short Circuit Current (Isc)	10.74 A	10.82 A	10.90 A	10.98 A	11.06 A	11.24 A
Module Efficiency	17.6%	17.8%	18.1%	18.4%	18.7%	18.9%
Operating Temperature	-40°C ~ +85°C					
Max. System Voltage	1500V (IEC/UL) or 1000V (IEC/UL)					
Module Fire Performance	TYPE 1 (UL 1703) or CLASS C (IEC 61730)					
Max. Series Fuse Rating	20 A					
Application Classification	Class A					
Power Tolerance	0 ~ + 10 W					

* Under Standard Test Conditions (STC) of irradiance of 1000 W/m², spectrum AM 1.5 and cell temperature of 25°C.

MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline
Cell Arrangement	120 [2 X (10 X 6)]
Dimensions	1765 X 1048 X 40 mm (69.5 X 41.3 X 1.57 in)
Weight	21.1 kg (46.5 lbs)
Front Cover	3.2 mm tempered glass
Frame	Anodized aluminium alloy, crossbar enhanced
J-Box	IP68, 3 bypass diodes
Cable	4.0 mm² (IEC), 12 AWG (UL)
Cable Length (Including Connector)	Portrait: 500 mm (19.7 in) (+) / 350 mm (13.8 in) (-); landscape: 1250 mm (49.2 in)*
Connector	T4 series or H4 UTX or MC4-EVO2
Per Pallet	27 pieces
Per Container (40' HQ)	702 pieces

* For detailed information, please contact your local Canadian Solar sales and technical representatives.

ELECTRICAL DATA | NMOT*

CS3L	325P	330P	335P	340P	345P	350P
Nominal Max. Power (Pmax)	242 W	246 W	249 W	253 W	257 W	261 W
Opt. Operating Voltage (Vmp)	29.8 V	30.0 V	30.2 V	30.3 V	30.5 V	30.7 V
Opt. Operating Current (Imp)	8.13 A	8.20 A	8.27 A	8.35 A	8.42 A	8.49 A
Open Circuit Voltage (Voc)	36.6 V	36.8 V	37.0 V	37.2 V	37.4 V	37.8 V
Short Circuit Current (Isc)	8.66 A	8.73 A	8.79 A	8.86 A	8.92 A	9.07 A

* Under Nominal Module Operating Temperature (NMOT), irradiance of 800 W/m² spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s.

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.36 % / °C
Temperature Coefficient (Voc)	-0.28 % / °C
Temperature Coefficient (Isc)	0.05 % / °C
Nominal Module Operating Temperature	42 ± 3°C

PARTNER SECTION

* The specifications and key features contained in this datasheet may deviate slightly from our actual products due to the on-going innovation and product enhancement. Canadian Solar Inc. reserves the right to make necessary adjustment to the information described herein at any time without further notice. Please be kindly advised that PV modules should be handled and installed by qualified people who have professional skills and please carefully read the safety and installation instructions before using our PV modules.

CANADIAN SOLAR INC.
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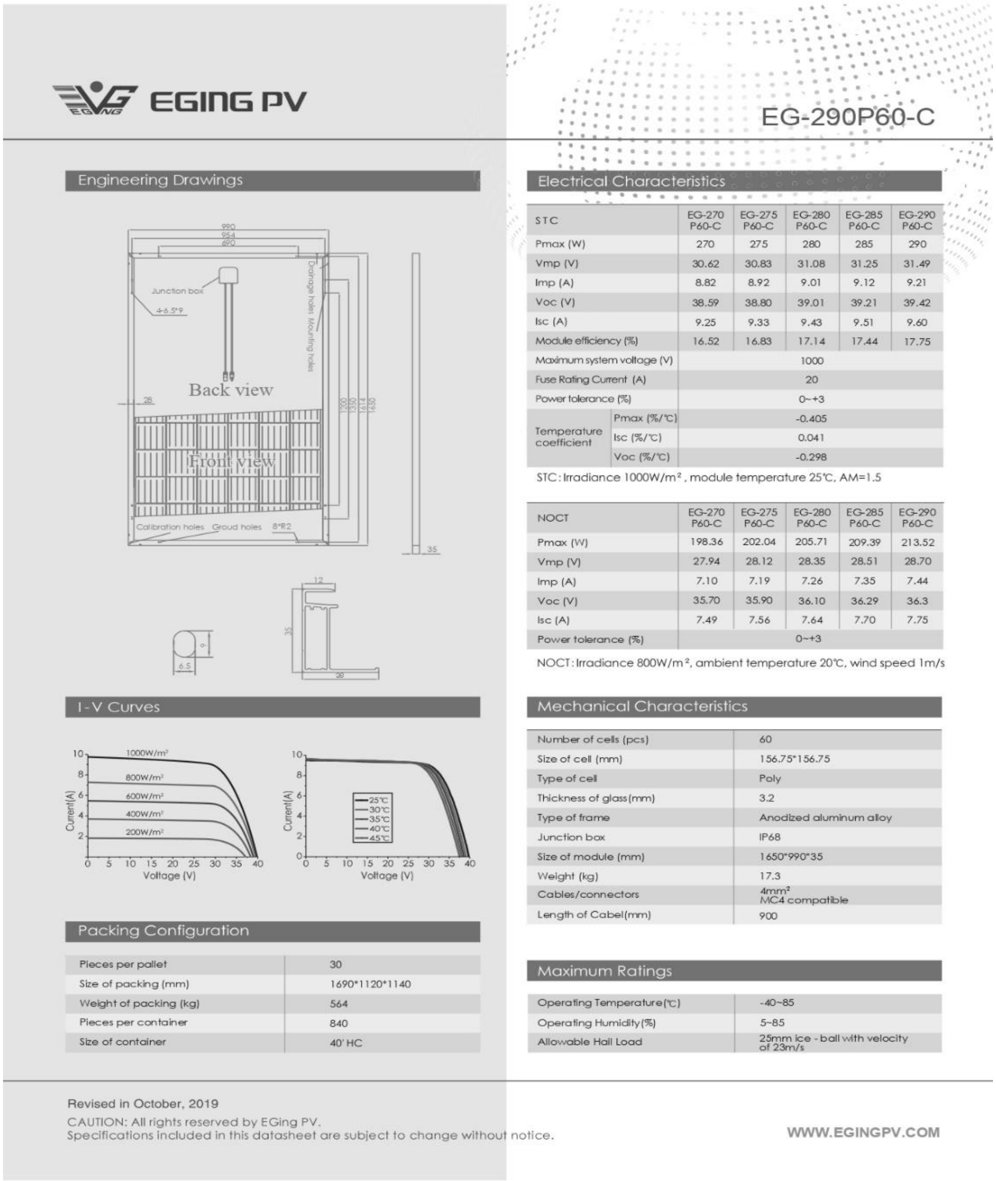
II) EGING PV DATASHEET



EG-290P60-C

Engineering Drawings

Electrical Characteristics

STC		EG-270 P60-C	EG-275 P60-C	EG-280 P60-C	EG-285 P60-C	EG-290 P60-C
Pmax (W)		270	275	280	285	290
Vmp (V)		30.62	30.83	31.08	31.25	31.49
Imp (A)		8.82	8.92	9.01	9.12	9.21
Voc (V)		38.59	38.80	39.01	39.21	39.42
Isc (A)		9.25	9.33	9.43	9.51	9.60
Module efficiency (%)		16.52	16.83	17.14	17.44	17.75
Maximum system voltage (V)		1000				
Fuse Rating Current (A)		20				
Power tolerance (%)		0~+3				
Temperature coefficient	Pmax (%/℃)	-0.405				
	Isc (%/℃)	0.041				
	Voc (%/℃)	-0.298				

STC: Irradiance 1000W/m², module temperature 25℃, AM=1.5

NOCT	EG-270 P60-C	EG-275 P60-C	EG-280 P60-C	EG-285 P60-C	EG-290 P60-C
Pmax (W)	198.36	202.04	205.71	209.39	213.52
Vmp (V)	27.94	28.12	28.35	28.51	28.70
Imp (A)	7.10	7.19	7.26	7.35	7.44
Voc (V)	35.70	35.90	36.10	36.29	36.3
Isc (A)	7.49	7.56	7.64	7.70	7.75
Power tolerance (%)	0~+3				

NOCT: Irradiance 800W/m², ambient temperature 20℃, wind speed 1m/s

I-V Curves

Mechanical Characteristics

Number of cells (pcs)	60
Size of cell (mm)	156.75*156.75
Type of cell	Poly
Thickness of glass(mm)	3.2
Type of frame	Anodized aluminum alloy
Junction box	IP68
Size of module (mm)	1650*990*35
Weight (kg)	17.3
Cables/connectors	4mm² MC4 compatible
Length of Cabel(mm)	900

Packing Configuration

Pieces per pallet	30
Size of packing (mm)	1690*1120*1140
Weight of packing (kg)	564
Pieces per container	840
Size of container	40' HC

Maximum Ratings

Operating Temperature(℃)	-40~85
Operating Humidity(%)	5~85
Allowable Hail Load	25mm ice - ball with velocity of 23m/s

Revised in October, 2019

CAUTION: All rights reserved by EGing PV.
Specifications included in this datasheet are subject to change without notice.

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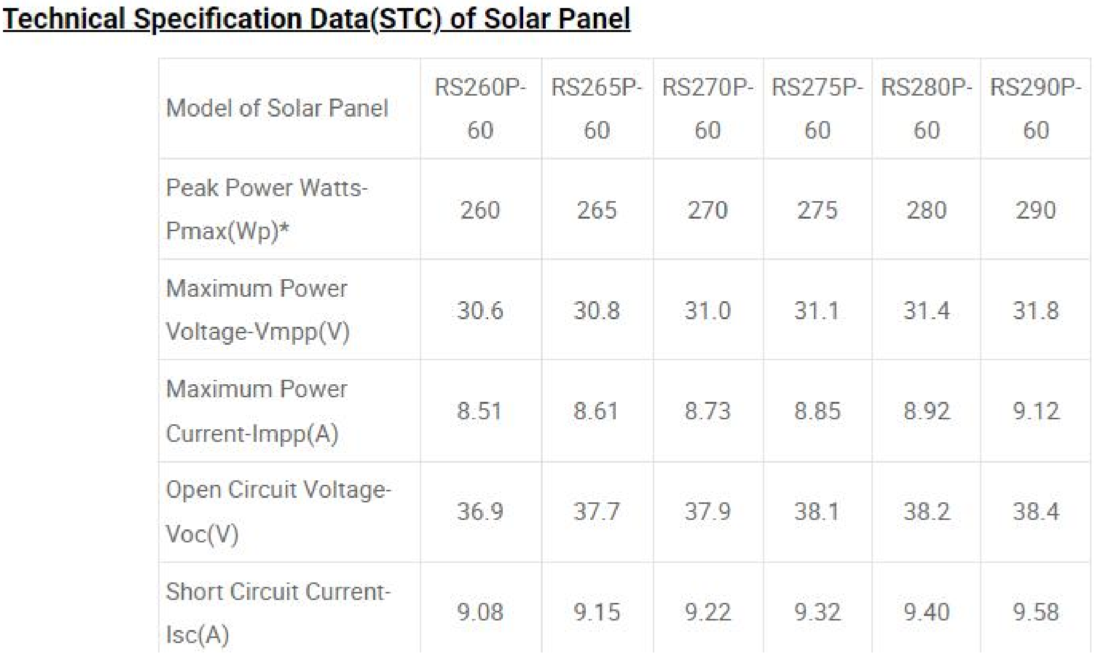
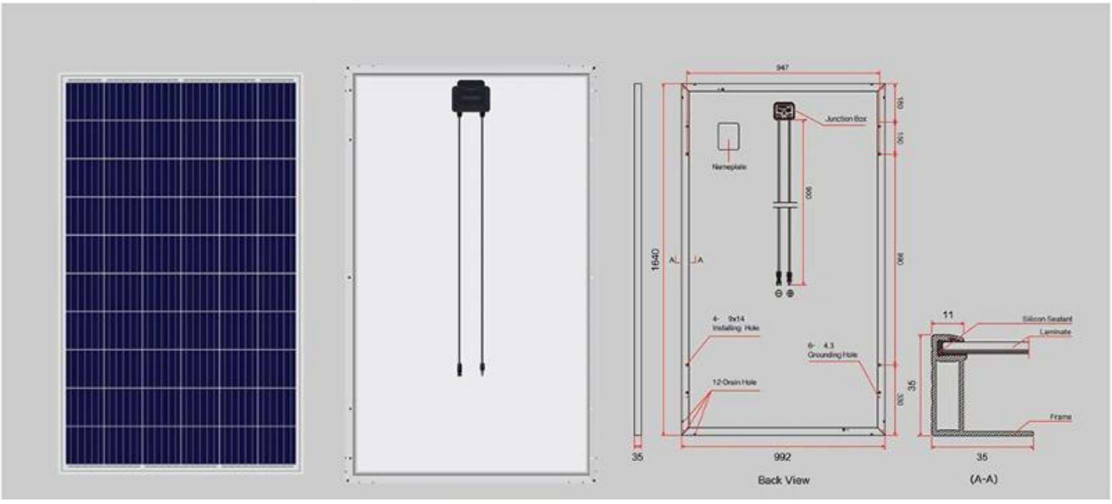
III) ROSEL SOLAR PV DATASHEET



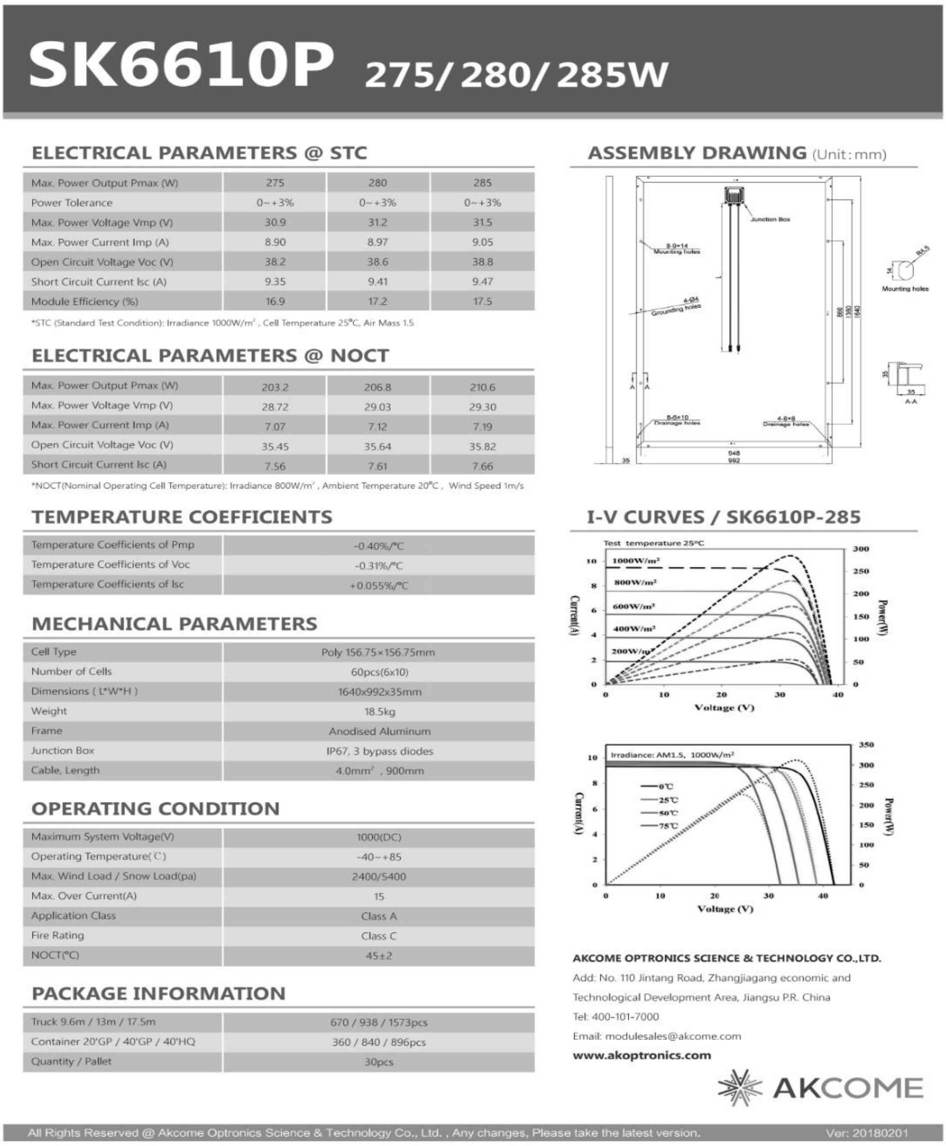
Technical Specification Data(STC) of Solar Panel

Model of Solar Panel	RS260P-60	RS265P-60	RS270P-60	RS275P-60	RS280P-60	RS290P-60
Peak Power Watts-Pmax(Wp)*	260	265	270	275	280	290
Maximum Power Voltage-Vmpp(V)	30.6	30.8	31.0	31.1	31.4	31.8
Maximum Power Current-Impp(A)	8.51	8.61	8.73	8.85	8.92	9.12
Open Circuit Voltage-Voc(V)	36.9	37.7	37.9	38.1	38.2	38.4
Short Circuit Current-Isc(A)	9.08	9.15	9.22	9.32	9.40	9.58

Dimension of PV Module(mm)



IV) AKCOME PV DATASHEET



SK6610P 275/280/285W

ELECTRICAL PARAMETERS @ STC

Max. Power Output Pmax (W)	275	280	285
Power Tolerance	0~+3%	0~+3%	0~+3%
Max. Power Voltage Vmp (V)	30.9	31.2	31.5
Max. Power Current Imp (A)	8.90	8.97	9.05
Open Circuit Voltage Voc (V)	38.2	38.6	38.8
Short Circuit Current Isc (A)	9.35	9.41	9.47
Module Efficiency (%)	16.9	17.2	17.5

*STC (Standard Test Condition): Irradiance 1000W/m², Cell Temperature 25°C, Air Mass 1.5

ELECTRICAL PARAMETERS @ NOCT

Max. Power Output Pmax (W)	203.2	206.8	210.6
Max. Power Voltage Vmp (V)	28.72	29.03	29.30
Max. Power Current Imp (A)	7.07	7.12	7.19
Open Circuit Voltage Voc (V)	35.45	35.64	35.82
Short Circuit Current Isc (A)	7.56	7.61	7.66

*NOCT(Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s

TEMPERATURE COEFFICIENTS

Temperature Coefficients of Pmp	-0.40%/°C
Temperature Coefficients of Voc	-0.31%/°C
Temperature Coefficients of Isc	+0.055%/°C

MECHANICAL PARAMETERS

Cell Type	Poly 156.75×156.75mm
Number of Cells	60pcs(6x10)
Dimensions (L*W*H)	1640x992x35mm
Weight	18.5kg
Frame	Anodised Aluminum
Junction Box	IP67, 3 bypass diodes
Cable, Length	4.0mm², 900mm

OPERATING CONDITION

Maximum System Voltage(V)	1000(DC)
Operating Temperature(℃)	-40~+85
Max. Wind Load / Snow Load(pa)	2400/5400
Max. Over Current(A)	15
Application Class	Class A
Fire Rating	Class C
NOCT(°C)	45±2

PACKAGE INFORMATION

Truck 9.6m / 13m / 17.5m	670 / 938 / 1573pcs
Container 20'GP / 40'GP / 40'HQ	360 / 840 / 896pcs
Quantity / Pallet	30pcs

ASSEMBLY DRAWING (Unit: mm)

I-V CURVES / SK6610P-285

AKCOME OPTRONICS SCIENCE & TECHNOLOGY CO.,LTD.
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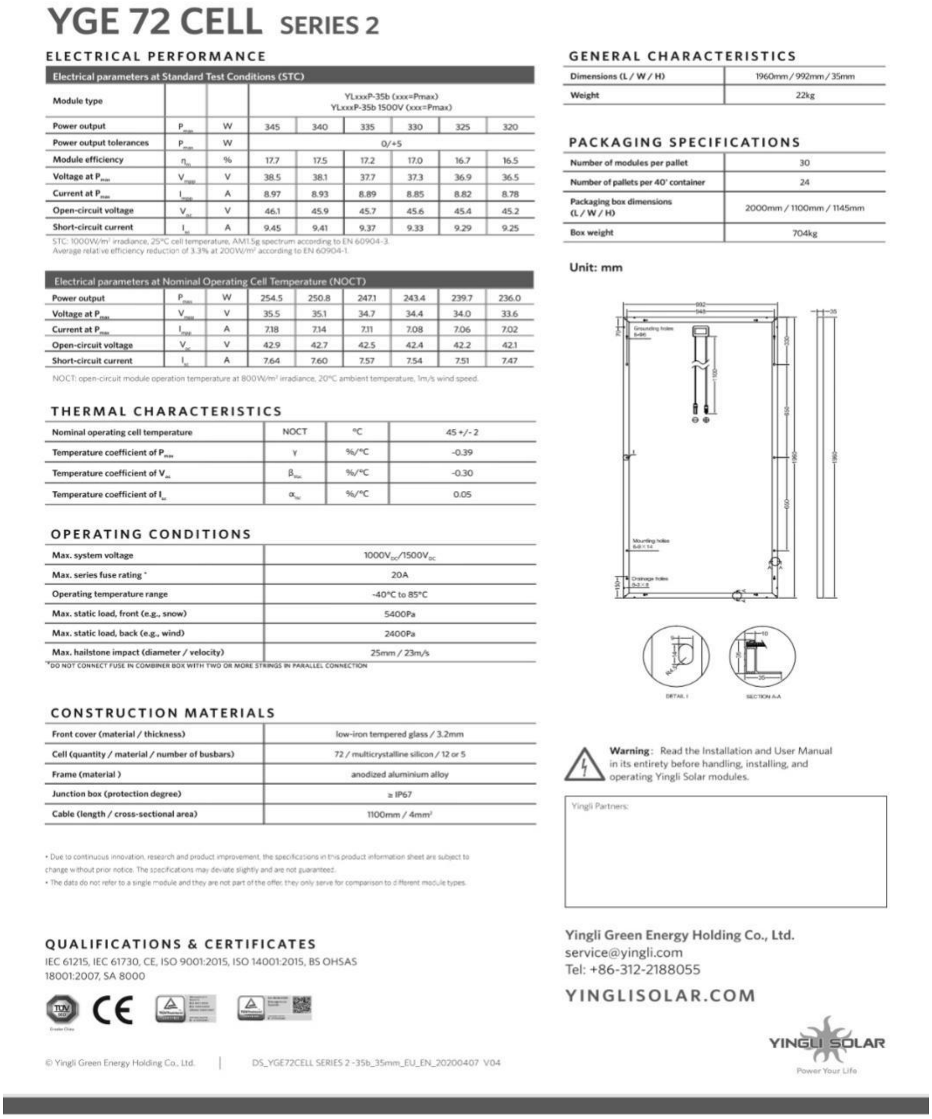
AKCOME

Ver: 20180201

V) YINGLI SOLAR PV DATASHEET



YGE 72 CELL SERIES 2

ELECTRICAL PERFORMANCE

Electrical parameters at Standard Test Conditions (STC)

Module type			YLxxxP-35b (xxx=Pmax) YLxxxP-35b 1500V (xxx=Pmax)					
Power output	P_{max}	W	345	340	335	330	325	320
Power output tolerances	P_{max}	W	0/+5					
Module efficiency	η_m	%	17.7	17.5	17.2	17.0	16.7	16.5
Voltage at P_{max}	V_{mpp}	V	38.5	38.1	37.7	37.3	36.9	36.5
Current at P_{max}	I_{mpp}	A	8.97	8.93	8.89	8.85	8.82	8.78
Open-circuit voltage	V_{oc}	V	46.1	45.9	45.7	45.6	45.4	45.2
Short-circuit current	I_{sc}	A	9.45	9.41	9.37	9.33	9.29	9.25

STC: 1000W/m² irradiance, 25°C cell temperature, AM1.5g spectrum according to EN 60904-3.
Average relative efficiency reduction of 3.3% at 200W/m² according to EN 60904-1.

Electrical parameters at Nominal Operating Cell Temperature (NOCT)

Power output	P_{max}	W	254.5	250.8	247.1	243.4	239.7	236.0
Voltage at P_{max}	V_{mpp}	V	35.5	35.1	34.7	34.4	34.0	33.6
Current at P_{max}	I_{mpp}	A	7.18	7.14	7.11	7.08	7.06	7.02
Open-circuit voltage	V_{oc}	V	42.9	42.7	42.5	42.4	42.2	42.1
Short-circuit current	I_{sc}	A	7.64	7.60	7.57	7.54	7.51	7.47

NOCT: open-circuit module operation temperature at 800W/m² irradiance, 20°C ambient temperature, 1m/s wind speed.

THERMAL CHARACTERISTICS

Nominal operating cell temperature	NOCT	°C	45 +/- 2
Temperature coefficient of P_{max}	γ	%/°C	-0.39
Temperature coefficient of V_{oc}	β_{Voc}	%/°C	-0.30
Temperature coefficient of I_{sc}	α_{Isc}	%/°C	0.05

OPERATING CONDITIONS

Max. system voltage	$1000V_{DC}/1500V_{DC}$
Max. series fuse rating *	20A
Operating temperature range	-40°C to 85°C
Max. static load, front (e.g., snow)	5400Pa
Max. static load, back (e.g., wind)	2400Pa
Max. hailstone impact (diameter / velocity)	25mm / 23m/s

*DO NOT CONNECT FUSE IN COMBINER BOX WITH TWO OR MORE STRINGS IN PARALLEL CONNECTION

CONSTRUCTION MATERIALS

Front cover (material / thickness)	low-iron tempered glass / 3.2mm
Cell (quantity / material / number of busbars)	72 / multicrystalline silicon / 12 or 5
Frame (material)	anodized aluminium alloy
Junction box (protection degree)	≥ IP67
Cable (length / cross-sectional area)	1100mm / 4mm²

- Due to continuous innovation, research and product improvement, the specifications in this product information sheet are subject to change without prior notice. The specifications may deviate slightly and are not guaranteed.
- The data do not refer to a single module and they are not part of the offer, they only serve for comparison to different module types.

GENERAL CHARACTERISTICS

Dimensions (L / W / H)	1960mm / 992mm / 35mm
Weight	22kg

PACKAGING SPECIFICATIONS

Number of modules per pallet	30
Number of pallets per 40' container	24
Packaging box dimensions (L / W / H)	2000mm / 1100mm / 1145mm
Box weight	704kg

Unit: mm

Warning: Read the Installation and User Manual in its entirety before handling, installing, and operating Yingli Solar modules.

Yingli Partners:

QUALIFICATIONS & CERTIFICATES

IEC 61215, IEC 61730, CE, ISO 9001:2015, ISO 14001:2015, BS OHSAS 18001:2007, SA 8000

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YINGLI SOLAR
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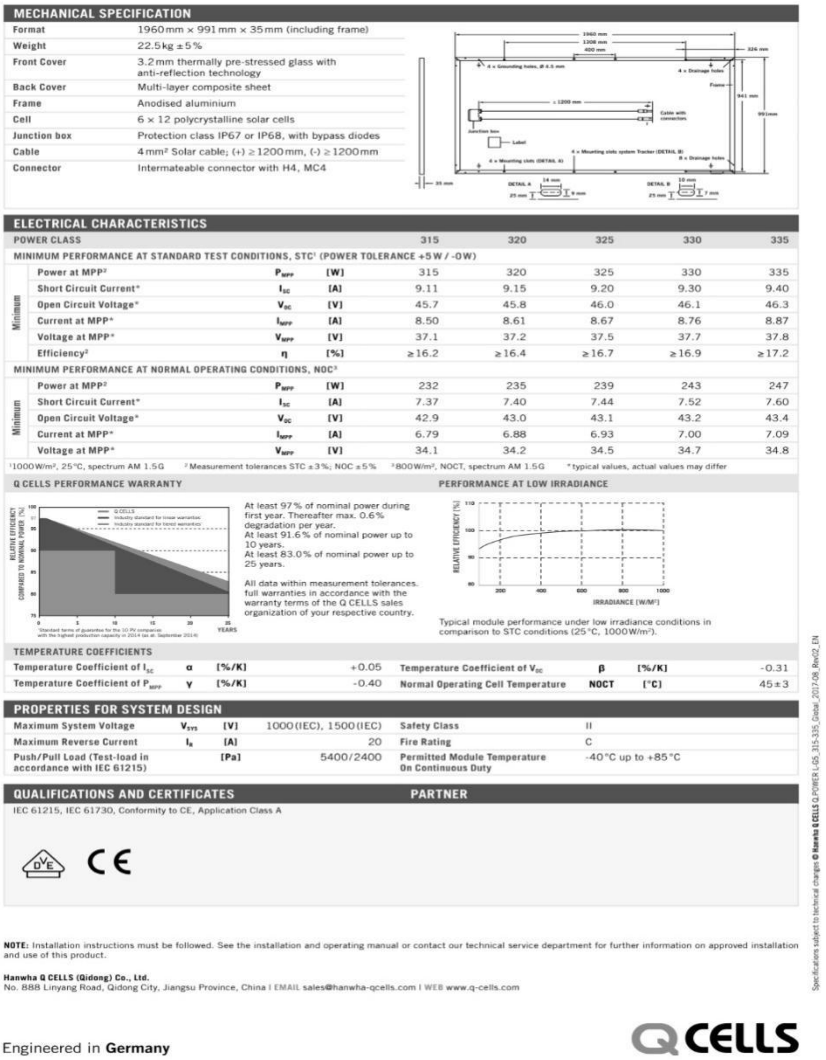
VI) HANWHA SOLAR PV DATASHEET



MECHANICAL SPECIFICATION

Format	1960 mm × 991 mm × 35 mm (including frame)
Weight	22.5 kg ± 5 %
Front Cover	3.2 mm thermally pre-stressed glass with anti-reflection technology
Back Cover	Multi-layer composite sheet
Frame	Anodised aluminium
Cell	6 × 12 polycrystalline solar cells
Junction box	Protection class IP67 or IP68, with bypass diodes
Cable	4 mm² Solar cable; (+) ≥ 1200 mm, (-) ≥ 1200 mm
Connector	Intermateable connector with H4, MC4

ELECTRICAL CHARACTERISTICS

POWER CLASS				315	320	325	330	335
MINIMUM PERFORMANCE AT STANDARD TEST CONDITIONS, STC[1] (POWER TOLERANCE +5 W / -0 W)								
Minimum	Power at MPP[2]	P_{MPP}	[W]	315	320	325	330	335
	Short Circuit Current*	I_{SC}	[A]	9.11	9.15	9.20	9.30	9.40
	Open Circuit Voltage*	V_{OC}	[V]	45.7	45.8	46.0	46.1	46.3
	Current at MPP*	I_{MPP}	[A]	8.50	8.61	8.67	8.76	8.87
	Voltage at MPP*	V_{MPP}	[V]	37.1	37.2	37.5	37.7	37.8
	Efficiency[2]	η	[%]	≥ 16.2	≥ 16.4	≥ 16.7	≥ 16.9	≥ 17.2
MINIMUM PERFORMANCE AT NORMAL OPERATING CONDITIONS, NOC[3]								
Minimum	Power at MPP[2]	P_{MPP}	[W]	232	235	239	243	247
	Short Circuit Current*	I_{SC}	[A]	7.37	7.40	7.44	7.52	7.60
	Open Circuit Voltage*	V_{OC}	[V]	42.9	43.0	43.1	43.2	43.4
	Current at MPP*	I_{MPP}	[A]	6.79	6.88	6.93	7.00	7.09
	Voltage at MPP*	V_{MPP}	[V]	34.1	34.2	34.5	34.7	34.8

[1] 1000 W/m², 25 °C, spectrum AM 1.5G [2] Measurement tolerances STC ± 3 %; NOC ± 5 % [3] 800 W/m², NOCT, spectrum AM 1.5G * typical values, actual values may differ

Q CELLS PERFORMANCE WARRANTY

At least 97 % of nominal power during first year. Thereafter max. 0.6 % degradation per year.
At least 91.6 % of nominal power up to 10 years.
At least 83.0 % of nominal power up to 25 years.

All data within measurement tolerances. full warranties in accordance with the warranty terms of the Q CELLS sales organization of your respective country.

*Standard terms of guarantee for the 10 PV companies with the highest production capacity in 2014 (as at: September 2014)

PERFORMANCE AT LOW IRRADIANCE

Typical module performance under low irradiance conditions in comparison to STC conditions (25 °C, 1000 W/m²).

TEMPERATURE COEFFICIENTS

Temperature Coefficient of I_{SC}	α	[%/K]	+0.05	Temperature Coefficient of V_{OC}	β	[%/K]	-0.31
Temperature Coefficient of P_{MPP}	γ	[%/K]	-0.40	Normal Operating Cell Temperature	NOCT	[°C]	45 ± 3

PROPERTIES FOR SYSTEM DESIGN

Maximum System Voltage	V_{SYS}	[V]	1000 (IEC), 1500 (IEC)	Safety Class	II
Maximum Reverse Current	I_R	[A]	20	Fire Rating	C
Push/Pull Load (Test-load in accordance with IEC 61215)		[Pa]	5400/2400	Permitted Module Temperature On Continuous Duty	-40 °C up to +85 °C

QUALIFICATIONS AND CERTIFICATES

IEC 61215, IEC 61730, Conformity to CE, Application Class A

PARTNER

NOTE: Installation instructions must be followed. See the installation and operating manual or contact our technical service department for further information on approved installation and use of this product.

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No. 888 Linyang Road, Qidong City, Jiangsu Province, China I EMAIL sales@hanwha-qcells.com I WEB www.q-cells.com

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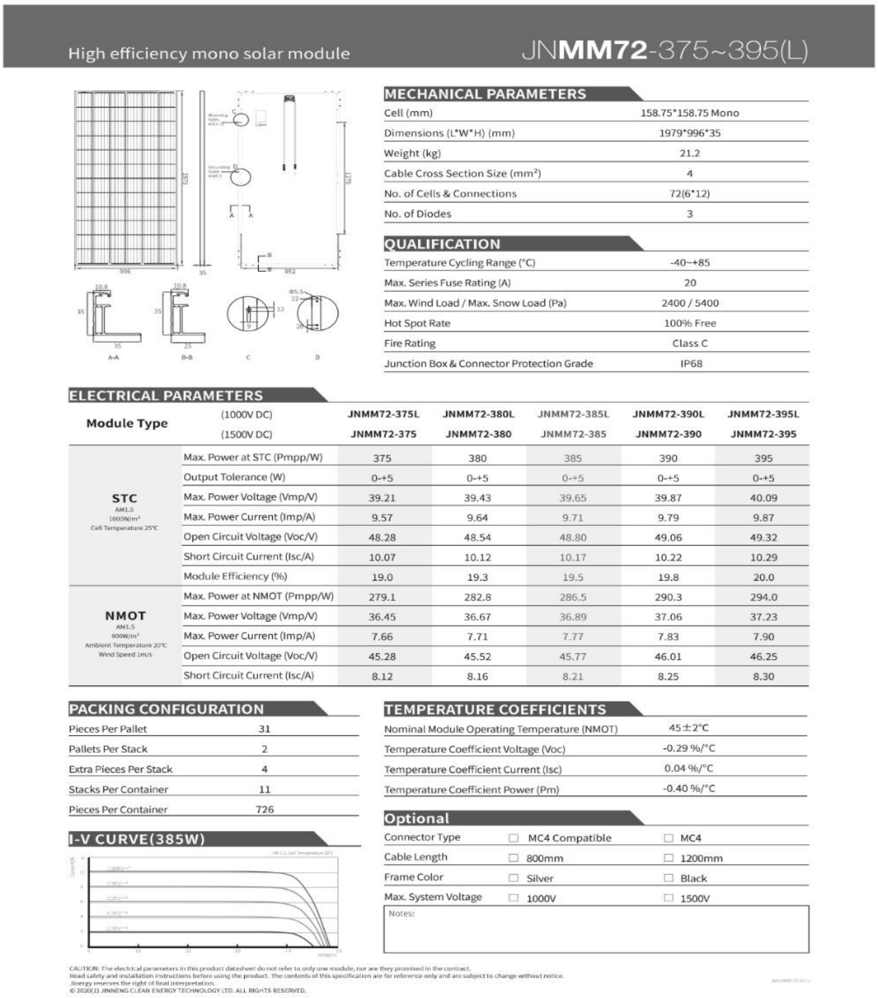
Engineered in **Germany**

VII) JINERGY PV DATASHEET



High efficiency mono solar module

JNMM72-375~395(L)

MECHANICAL PARAMETERS

Cell (mm)	158.75*158.75 Mono
Dimensions (L*W*H) (mm)	1979*996*35
Weight (kg)	21.2
Cable Cross Section Size (mm²)	4
No. of Cells & Connections	72(6*12)
No. of Diodes	3

QUALIFICATION

Temperature Cycling Range (°C)	-40~+85
Max. Series Fuse Rating (A)	20
Max. Wind Load / Max. Snow Load (Pa)	2400 / 5400
Hot Spot Rate	100% Free
Fire Rating	Class C
Junction Box & Connector Protection Grade	IP68

ELECTRICAL PARAMETERS

Module Type	(1000V DC)	JNMM72-375L	JNMM72-380L	JNMM72-385L	JNMM72-390L	JNMM72-395L
	(1500V DC)	JNMM72-375	JNMM72-380	JNMM72-385	JNMM72-390	JNMM72-395
STC AM1.5 1000W/m² Cell Temperature 25°C	Max. Power at STC (Pmpp/W)	375	380	385	390	395
	Output Tolerance (W)	0-+5	0-+5	0-+5	0-+5	0-+5
	Max. Power Voltage (Vmp/V)	39.21	39.43	39.65	39.87	40.09
	Max. Power Current (Imp/A)	9.57	9.64	9.71	9.79	9.87
	Open Circuit Voltage (Voc/V)	48.28	48.54	48.80	49.06	49.32
	Short Circuit Current (Isc/A)	10.07	10.12	10.17	10.22	10.29
	Module Efficiency (%)	19.0	19.3	19.5	19.8	20.0
NMOT AM1.5 800W/m² Ambient Temperature 20°C Wind Speed 1m/s	Max. Power at NMOT (Pmpp/W)	279.1	282.8	286.5	290.3	294.0
	Max. Power Voltage (Vmp/V)	36.45	36.67	36.89	37.06	37.23
	Max. Power Current (Imp/A)	7.66	7.71	7.77	7.83	7.90
	Open Circuit Voltage (Voc/V)	45.28	45.52	45.77	46.01	46.25
	Short Circuit Current (Isc/A)	8.12	8.16	8.21	8.25	8.30

PACKING CONFIGURATION

Pieces Per Pallet	31
Pallets Per Stack	2
Extra Pieces Per Stack	4
Stacks Per Container	11
Pieces Per Container	726

TEMPERATURE COEFFICIENTS

Nominal Module Operating Temperature (NMOT)	45±2°C
Temperature Coefficient Voltage (Voc)	-0.29 %/°C
Temperature Coefficient Current (Isc)	0.04 %/°C
Temperature Coefficient Power (Pm)	-0.40 %/°C

I-V CURVE(385W)

Optional

Connector Type	☐ MC4 Compatible	☐ MC4
Cable Length	☐ 800mm	☐ 1200mm
Frame Color	☐ Silver	☐ Black
Max. System Voltage	☐ 1000V	☐ 1500V

Notes:

CAUTION: The electrical parameters in this product datasheet do not refer to only one module, nor are they promised in the contract.
Read safety and installation instructions before using the product. The contents of this specification are for reference only and are subject to change without notice.
Jinergy reserves the right of final interpretation.