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Evaluating the Sustainable Lifecycle of solar panels: A Study on Recycling and End-of-Life Management

A sustainable second life

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Abstract

Context and Objective of the Thesis

In recent years in Italy, Europe and beyond, renewable energy sources have taken centre stage economically, socially and politically. The European Union has established, through specific directives, the targets and parameters that Eurozone countries must follow to reduce their heavy dependence on fossil fuels for energy supply. In particular, the strategy goes back to the 20-20-20 initiative, launched in March 2007, the subsequent Climate-Energy Package (2008), continuing with the European Green Deal in 2019 and the **2030 Climate and Energy Framework** in which the EU sets targets to reduce greenhouse gas emissions, increase renewable energy and improve energy efficiency by 2030.

The pursuit of these objectives has fostered the development of a market that has significantly boosted employment and economic growth in countries that have effectively responded to the European directives by encouraging investments. According to the 'Rapporto Statistico 2023 sul Solare Fotovoltaico' published by the Gestore dei Servizi Energetici (GSE), the solar photovoltaic sector has played a particularly important role in Italy, growing exponentially over the past two decades. By the end of 2023, 1,597,447 photovoltaic systems will be installed in Italy, with a total capacity of 30,319 MW. Of these systems, 94% have a capacity of less than 20 kW, mainly in the residential sector. Total electricity production from photovoltaics reached 30,711 GWh in 2023, an increase of 9.2 % compared to the previous year.

However, as the number of installed panels increases, so does the number of outdated panels that need to be either disposed of or repurposed for a second life. This thesis, therefore, focuses on analyzing the potential opportunities within this context, particularly examining ways to recycle or refurbish photovoltaic panels. A key focus of the research is **Keepthesun**, an Italian startup founded in collaboration between **COESA** , an Energy Service Company, and the **Politecnico di Torino**.
This start-up is responding to the growing need to manage the increasing volume of disused photovoltaic panels, with the aim of giving them a second life by reintroducing them to the market, renewing their attractiveness and usefulness.

Thesis Structure

This thesis aims to pursue the mentioned objectives by structuring the text into four main chapters.

The **first chapter** focuses on the history and development of photovoltaic panels. The chapter begins with a detailed overview of the history of solar panels, particularly their evolution in Europe and the regulations that have driven their widespread adoption. It will also highlight key milestones in their technological development, both in Italy and globally, identifying the innovations that have improved both cost-efficiency and productivity.

The **second chapter** will examine the technological advancements that have characterized recent years, distinguishing between well-established technologies and emerging ones that are gaining significant traction in the market. Finally, the chapter will provide a comparative overview of the global solar market, benchmarking Italy's progress with international developments, and exploring future growth strategies in an increasingly global market.

The **third chapter** addresses the end-of-life phase of solar panels and explores potential solutions for the management of obsolete systems. The chapter analyses the growing need for effective strategies for disposal, recycling and reconversion as the number of solar panels reaching the end of their operational life increases. It will analyse the various challenges associated with the management of old panels and discuss innovative approaches to give panels a second life, including current regulatory frameworks and industry practices that support the sustainability of solar infrastructure.

The **fourth chapter** provides an analysis of a case study such as Coesa Energy, an Italian company specialising in energy consultancy, the mother of the aforementioned start-up KeepTheSun, which aims to extend the life of solar panels by reconditioning them and bringing them back to the market. The chapter will focus on strategies and market positioning.

CHAPTER 1

The Power of Solar panels: History and Technological Evolution in Renewable Energy

1.1 Do we really care about solar panels?

The world of **solar panels** and photovoltaic technology is both fascinating and complex.
We frequently see solar[1] panels in our daily lives, on university campuses, rooftops, fields we pass by during car rides, and even on parking structures. But how often do we pause to think about why there are so many? What is their true purpose? And are they really effective?
But the questions don't end there.

Do they generate enough energy to meet our basic needs? Are they truly sustainable, considering both their production and installation processes? And from an economic perspective, are they really worth the investment?
These are the types of questions that prompt deeper exploration into solar technology, urging us to be more mindful of the systems that power our lives.

PV[2] panels harness the power of the sun through the photovoltaic effect, converting sunlight directly into electricity. This process is made possible by semiconductor materials like silicon, that possess unique properties enabling them to generate a great electric current when exposed to light [1]. As time passes, humankind grapple with rising global energy demands and the urgent need to reduce greenhouse gas emissions, solar panels emerge as a critical part of the solution. The potential to convert sunlight, an abundant and inexhaustible resource, into electricity without CO2 emissions, positions solar technology as one of the most promising tools in the fight against climate change[2]. Nevertheless, the implementation of solar energy is not without its challenges. Factors such as **geographic location**, **weather conditions**, and **installation angles** affect the efficiency of solar panels. Moreover, the production of solar panels involves energy-intensive processes that contribute to their overall environmental footprint.

We believed, or at least we used to think, that obtaining energy from renewable sources such as photovoltaics was unquestionably good and right. Although solar energy offers many advantages, the effectiveness of solar panels in achieving a more sustainable future is influenced by a number of variables that deserve continued investigation. Another fundamental question remains:

What will happen to all solar panels once they become obsolete?

By asking critical questions and maintaining a sense of curiosity, we can contribute to the ongoing exploration of the role of renewable energy in our lives and in the broader effort to protect our planet.

We must stay curious to change our future.

---

[1] In everyday language, the terms **solar panel** and **solar thermal panel** are often used interchangeably, leading to confusion regarding their specific functions. However, while both technologies harness energy from the sun, they do so in fundamentally different ways.
[2] Photovoltaic

1.2 The story, evolution and composition of Solar Panels

Solar panels have a long history which dates back to a century with significant scientific discoveries and improvement of solar panel technology. This adventure started in **1839** when French physicist Alexandre-Edmond Becquerel discovered **the photovoltaic effect**; the rudimentary method by which light is transformed to electricity. Nonetheless, it was only in **1954** that Bell telephone laboratory in the United States came up **with the first feasible silicon photovoltaic cell with simply 6% success price**. It was a revolutionary leap for the solar tech field; it provided the chance of using sunlight as a form of energy. In the subsequent decades, the solar technology underwent a rapid development influenced by the demand of reliable **off-grid**[3] power source particularly in space technology whereby the technological invention of the solar cells facilitated the powering of satellites including the "Vanguard I".

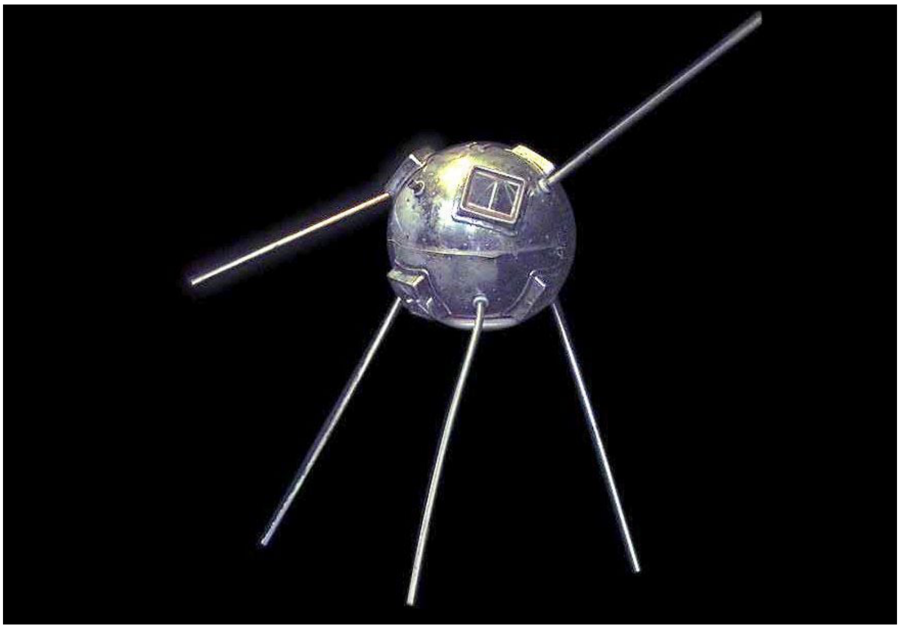

Figure 1.1: *Vanguard I the world's first solar powered satellite*

Source: smithsonian.com

The general construction of today's solar power panels has not changed dramatically since the invention of photovoltaic process. PV systems are mainly based on solar cells; these are mainly from **silicon** [1] , which is a semiconductor material that is relatively cheaper and has the properties of converting sunlight into electricity. They are formed in a matrix structure on the surface of the panel and each of the cell is very important in trapping energy from the sun. Laying on top of them is a layer of encapsulation material, more commonly **EVA- Ethylene-vinyl acetate** act as a barrier to prevent the cells from adverse effects such as moisture or impacts.

Attached to the front side of the panel is a layer of tempered glass which is nicknamed **Low-E Glass** or coated glass developed in a bid to ensure it reflects as little as possible while letting in as much sunlight as can be allowed. This glass is strong and withstands weather

[3] "Off-grid" refers to a system that operates independently of the public electricity grid, using self-generated renewabale energy sources like solar panels or wind turbines

vagaries such as hail and debris and at the same time admits plenty of light. The back sheet is normally produced from a polymer type material and is used to protect other electrical parts, essentially by providing for their isolation from moisture and mechanical stress. At the rear of the panel, a **junction box** houses the electrical connections and diodes that manage the flow of electricity generated by the panel. These diodes are essential for preventing reverse currents, ensuring the system operates efficiently, even under low-light conditions. Over the years, innovations such as **anti-reflective coatings** and **bifacial designs** have been introduced, further enhancing the efficiency and durability of solar panels.
This evolution of design and composition has helped solar panels become a mainstream energy solution, playing a key role in the global shift toward renewable energy. [3]
Here we can have a simplified view of the conversion from solar energy to electrical energy

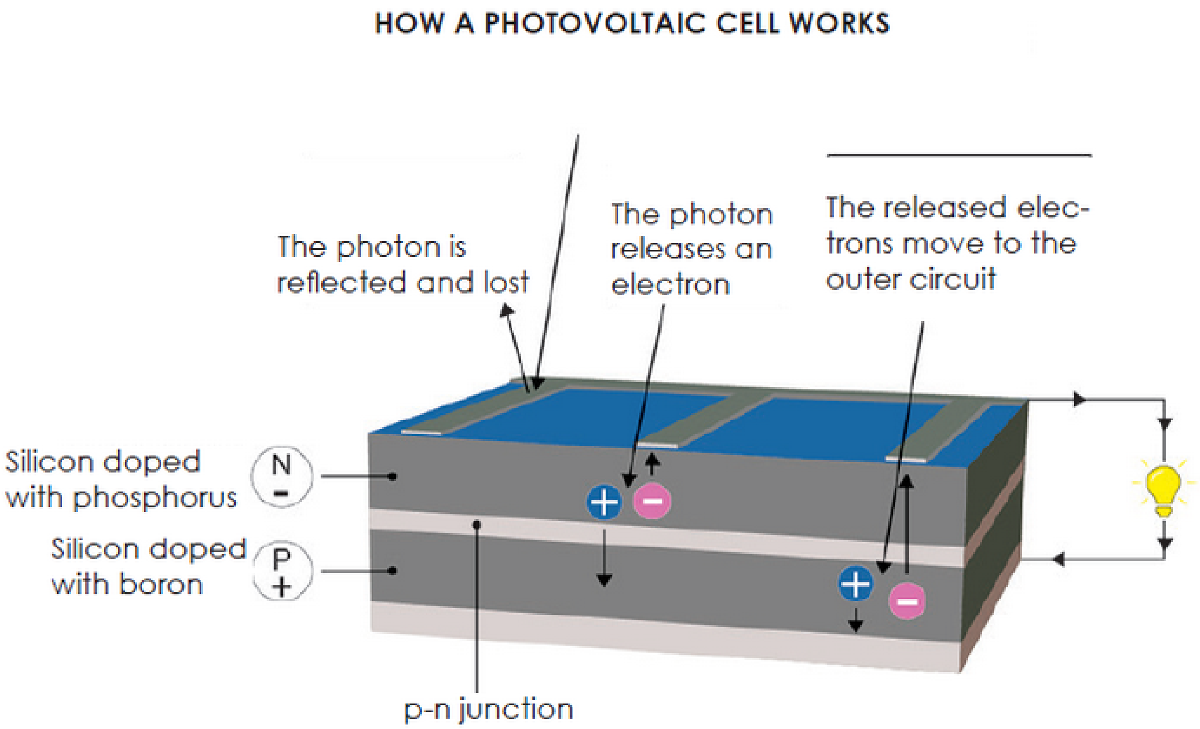

Figure 1.2 *How a photovoltaic cell works [1]*

This diagram shows how a solar panel works; how the sun's light turns into electricity to be used by homes and other buildings. The source of energy in these panels is sunlight which consists of photons that falls on the surface of the panel and which is normally made from semiconductors such as silicon. He signaled when photons impact the panel, they free electrons from the atoms in the silicon layers. This movement of electrons, results in a flow of electric current and this flow of electric current can be used to produce power. In the enlarged section of the diagram, we see how this process works at the microscopic level: the photons represented by yellow arrows establish an electron current (black arrows) in one and hence a corresponding "holes" or the vacancies left behind by the electrons in the other direction (red arrows). These holes are referred to as “lacune.” The solar cell itself has two types of silicon layers: , a p-type silicon with positive charge (positioned at the bottom), and a n-type silicon with negative charge (positioned at the top). In between the p-n junction is to create the required electric field that should force the flow of electrons. When sunlight falls on the surface of this panel, the electric field that is created in the material separates the electron-hole pairs and compels electrons to controllably move to an external load (like a lightbulb in the diagram) to produce electricity.

1.2.1 Material Breakdown of a solar panel

1. Silicon
Out of all semiconductor materials, silicon is widely employed in solar panels since it is effective in utilizing features of photovoltaic work and converting sunlight into electricity. This material is widely used in most of the solar cells available on the market and comes in three types: Monocrystalline, polycrystalline, and amorphous are three types of silicon. Monocrystalline panels are more efficient than other panels, but they can often be quite expensive because of how they are made – by growing large silicon crystals [4]. Polycrystalline panels are cheaper but have relatively low efficiency since they are composed of multiple silicon crystals [5]. The least efficient kind is amorphous silicon, mostly employed in thin-film panels; silicon material is flexible and is not expensive to manufacture[6]. The main factors that explain the current use of silicon are availability, stability, and technological maturity of the processes. Silicon is at the heart of the energy conversion process and determines the efficiency of a panel..

2. Glass
Of particular significance is the use of glass in the construction of solar panels because it safeguards the photovoltaic cells against such factors as precipitation, wind, dust and other conditions of mechanical loads. The glass used is commonly tempered, a process that improves some of its mechanical characteristics in respect to resistance to hail stones or falling objects[7]. Also, the glass used is one that allows the most amount of light to be transmitted to the silicon cells while it allows very little amount of it to the Sun. Sometimes the anti-reflective coating is applied to further enhance the light transmission rates [8]. Through this, glass enables the panel to provide protection as well as act as a long-lasting material that would allow the panel to operate for three or more decades even in harsh weather conditions in accordance with Ref [9].

3. Aluminium
Metallic aluminum is one of the most essential elements in the process of developing frames for the solar panels [10]. Its main function is to provide structural support that helps the solar cells and the protective glass to be placed with no compromise on the structures rigidity or shape [11]. Aluminum is lightweight, strong and offers a high strength to weight ratio meaning that it can easily be transported and assembled into the frames of the pv solar panel systems. Also, the workability of aluminum makes it rarely prone to rust and therefore, a proper coating for the structure of the panel and its components does well in both the outdoor installation we are proposing here and they are weather resistant[12]. This makes sure that aluminum allows the solar panels to bear the loads for winds or other physical impacts or mechanical forces that can negatively affect performance.

4. Polymers

Polymeric materials applied in photovoltaic panels are: ethylene-vinyl acetate (EVA) applied in encapsulation of photovoltaic cells, which provides protection against moisture, mechanical stress, and other conditions which are detrimental for the performance of the solar cell [13]. The EVA layers are put on the top and bottom of the silicon cell, which performs like a lid that sandwiches the cells between the glass and back sheet [14]. This encapsulation is to ensure that the solar panel is not damaged or has faults throughout its lifespan, the cells need to be sealed against water and physical damage [15]. In addition, polymers are found in the back sheet material to protect the cells against more external conditions [16]. Polymers are essential in increasing panel endurance, including electricity conductivity as well as resistance to temperature and ultraviolet radiation [17].

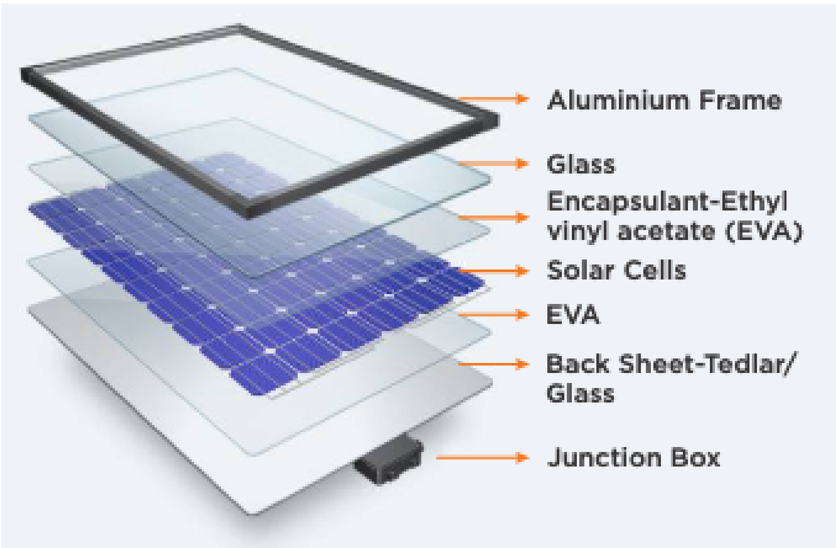

Figure 1.3 *Crystalline Silicon Pv Module Evolution*

Source: Trina Solar

5. Rare Metals
Indium, gallium, selenium, and tellurium which are rare metals are used in small quantities in application such as thin film of technology CIGS and CiteTe [18]. These metals which are rare in the market make the panels to be efficient in low light conditions because they increase the light absorption of the panels[19]. In new cell technologies such as in the perovskite based cells, the metal is necessary for enhanced efficiency and for development of thin films and flexible modules with ability to be transparent [20]. Silicon is the base of the panel and is responsible for converting light energy within sunlight into electrical energy. Sometimes the medals are coated with glass and aluminum to protect and strengthen it to withstand wear and tear. Polymer coating on the cells shields the cells from any mechanical

impact that may act upon them. Although these metals are utilized in small amounts they play a critical role of improving the performance and capabilities of solar systems. The following is a combination of materials to ensure that the solar panels lasts for many decades exposed to weather and at the same time, it produced high energy.

Material	Wt [%]	Absolute weight per module [g]
Glass	74	13,700.0
AL frame	10	1,850.0
EVA encapsulation	6.5	1,210.0
Back cover (PVF)	3.6	660.0
Copper	0.6	110.0
Silicon	3.5	640.0
Zinc + lead (soldering)	0.19	35.2
Silver	0.006	1.1
Silicon glue, etc.	1.16	214.6

Table 1.1 *Material Overview within a Standard Crystalline Silicon Panel [21]*

Approximately 84% of a photovoltaic panel's weight consists of **aluminum** and **glass**, which are both easily recyclable using standard methods like crushing and sorting. However, during the shredding process, the glass often becomes contaminated and is therefore mainly repurposed for construction materials or reflective paint [22]. The most valuable components of the panel, such as **silicon**, **copper**, and **silver**, make up less than 5% of the total weight.

1.3 Available technologies

The following will now list and describe the three main generations of photovoltaic technology, with their various technologies:

1.3.1 First-Generation

The current first generation of PV panels is derived mainly from monocrystalline and polycrystalline silicon cells. Silicon is thus a semi conductor, which is in between the metallic conductor like copper and the non conductor like glass that you can use to change sunlight to electricity.

- **Monocrystalline Silicon**: Built in a single, unbroken crystal both monocrystalline cells are more efficient because the electrons have more space to move without being slowed down or stopped by grain boundaries [4].

- **Polycrystalline Silicon**: Terminating structures may be multiple silicon crystals and the cells in which they incorporated can be of different types. Despite the fact that they are more affordable to manufacture than monocrystalline cells [5] their efficiency is lower because the grain boundaries act as barriers to the flow of electrons.

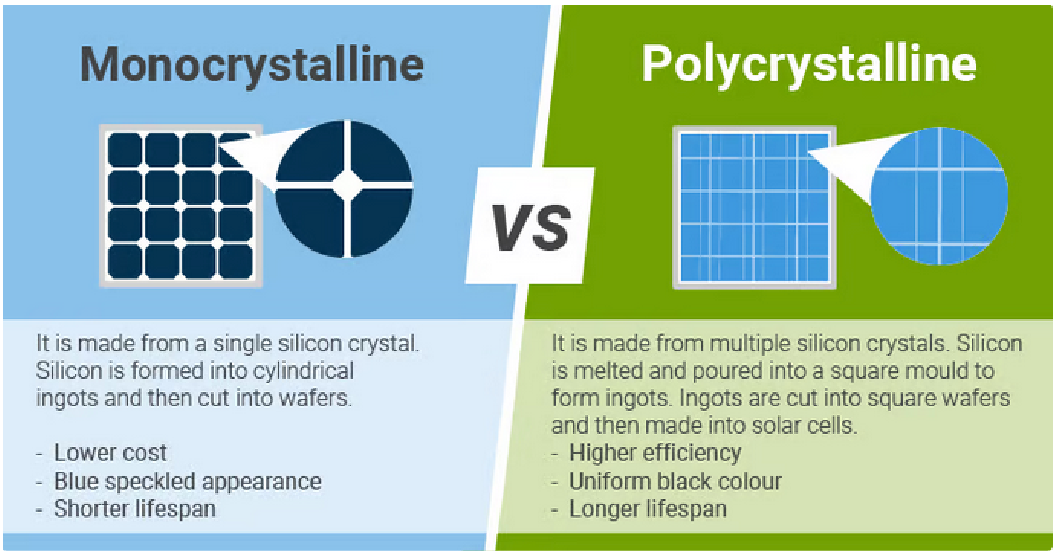

Figure 1.4 *Comparision of a monocrystalline silicon module (left) with polycrystalline silicon module (right)*

Source: Greenmatch.co.uk

The efficiency of first-generation photovoltaic cells is typically in the range of **15% to 20%** for commercially available modules [23]. This efficiency represents the percentage of sunlight that is converted into usable electricity. Silicon's relatively high efficiency and abundant availability have made it the material of choice for PV panels, despite its relatively high production cost and energy intensity [24].

- **Shockley-Queisser Limit**: This is a theoretical limit that defines the maximum efficiency a single-junction solar cell can achieve under standard sunlight conditions. For silicon, this limit is around **33%**, meaning that no matter how advanced the cell becomes, it will not convert more than one-third of the sunlight into electricity due to intrinsic physical constraints [25].

Manufacturing first-generation PV panels requires complex and energy-intensive processes:

- **Wafer production**: Silicon must be purified to a high degree (over 99.999%), which involves melting silicon and forming it into ingots [26].

- **Cutting wafers**: The silicon ingots are sliced into thin wafers, which are then treated and assembled into solar cells [27].

The high costs of manufacturing were initially a significant barrier to widespread adoption. However, continuous improvements in production technology, economies of scale, and government incentives have driven down costs over the decades, making silicon-based PV panels the dominant technology in the global market[28].

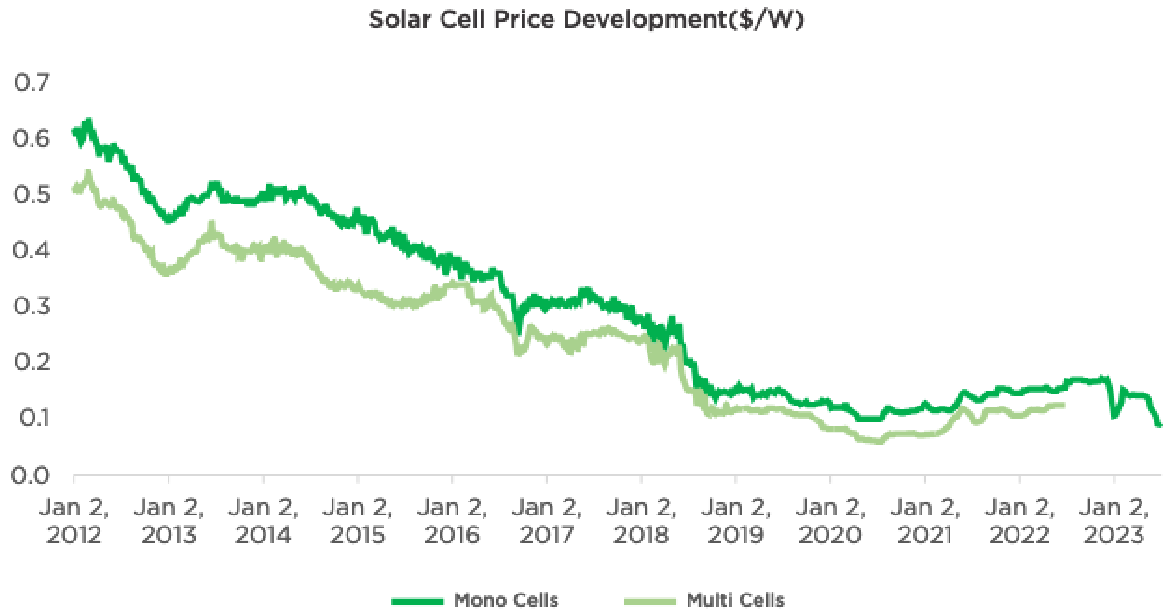

Figure 1.5 *Solar Cell Price Development*

Source: BNEF- Bimonthly PV Index July 2023

As illustrated in the figure, the price of both monocrystalline and polycrystalline cells dropped to \$0.10 per watt in 2020. However, due to the impact of COVID-19, prices increased, reaching \$0.20 per watt. By 2023, prices fell to their lowest point, reaching \$0.09 per watt.Currently, wafer-based crystalline silicon (c-Si) photovoltaic (PV) modules dominate around 95% of the global market, with thin-film PV modules accounting for the remaining share[29].

First-generation PV panels have proven to be highly durable, often with a lifespan of **25 to 30 years**. Over time, they suffer from **degradation**, primarily due to exposure to ultraviolet radiation and temperature fluctuations, which slightly reduces their efficiency[30].

One of the initial challenges in photovoltaic development was the **energy payback time (EPBT)**[4], which refers to the time required for a PV panel to generate an amount of energy equivalent to that used during its manufacturing.. In the 1980s, the EPBT was quite lengthy, often spanning several years. However, advancements in production methods have significantly reduced this period for modern first-generation panels, bringing it down to as little as **1 to 3 years**, depending on installation efficiency and geographic location [31].

[4] EPBT=Annual Energy OutputTotal/ Energy Invested (in production, installation, etc)

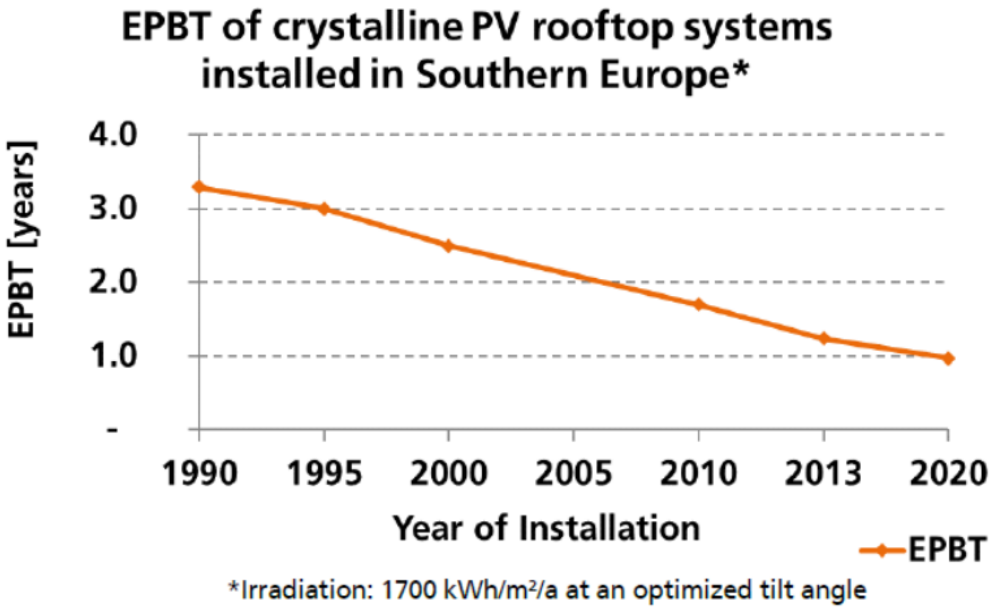

Figure 1.6 *EPBT of crystalline PV during the year*

1.3.2 Second-Generation

The Second-generation PV cells are primarily based on **thin-film technologies**. These cells use a variety of materials that are applied in very thin layers onto substrates like glass, metal, or plastic. The aim is to significantly reduce the amount of material used, which in turn lowers manufacturing costs and allows for more flexible applications.

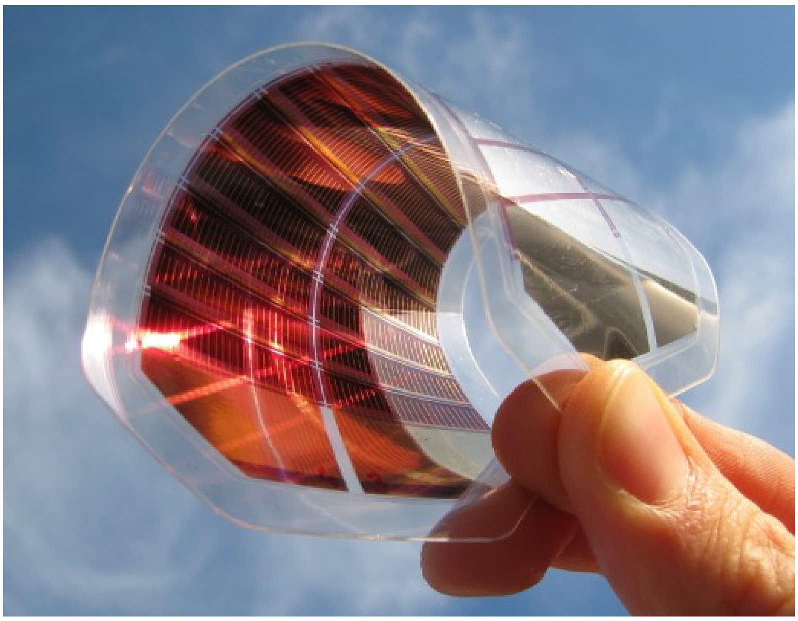

Figure 1.7 *Thin-film solar cell [31]*

The second-generation thin-film solar cells are made using several common materials:

- **Amorphous Silicon (a-Si)**: This non-crystalline form of silicon needs less material and energy for production compared to crystalline silicon. Although flexible, amorphous silicon cells generally have lower efficiency than first-generation siliconcells [32].

- **Cadmium Telluride (CdTe)**: Among the most successful thin-film technologies, CdTe cells offer relatively high efficiency and lower manufacturing costs compared tocrystalline silicon [33].

- **Copper Indium Gallium Selenide (CIGS)**: CIGS cells provide greater efficiency than amorphous silicon and CdTe, and they are also flexible, allowing application on diverse substrates, making them ideal for building-integrated photovoltaics (BIPV) [34].

Thin-film cells, like their first-generation counterparts, use the photovoltaic effect to convert sunlight into electricity. Because these cells are just a few micrometers thick, they interact with sunlight differently. The materials used have varied band gaps, which determine how efficiently they absorb different wavelengths of sunlight.

The **band gap** of a material is the energy difference between the valence band (where electrons are initially located) and the conduction band (where electrons need to go to conduct electricity). Materials like CdTe and CIGS have **optimal band gaps** that make them more efficient at absorbing sunlight, particularly in the visible spectrum [35].

Thin-film solar cells typically have lower efficiency than first-generation panels, with average values between 10% and 15%. However, certain technologies, such as CIGS, have achieved laboratory efficiencies of up to 20%, putting them on par with crystalline silicon in some circumstances [36].

Despite their relatively lower efficiency, thin-film panels are more cost-effective due to their reduced material use and simpler manufacturing processes. Their flexibility, along with their strong performance in low-light and high-temperature environments, makes them particularly advantageous for specific applications [37].

The production of thin-film solar cells is also considerably cheaper compared to crystalline silicon cells. The process generally involves depositing thin-film material onto a substrate using methods like chemical vapor deposition (CVD) or sputtering, both of which are well-suited for large-scale production [38].

- **Amorphous Silicon (a-Si)**: This material can be deposited on substrates at lower temperatures, reducing both production costs and energy consumption [39].

- **Cadmium Telluride (CdTe)**: CdTe panels are suitable for mass production using relatively straightforward methods, which further decreases production costs. However, concerns regarding cadmium toxicity have limited its adoption in certain regions [40].

- **Copper Indium Gallium Selenide (CIGS)**: Though more complex to produce than CdTe, CIGS cells offer higher efficiency and flexibility, which makes them ideal for a wider range of applications, including solar shingles and building-integrated systems [41].

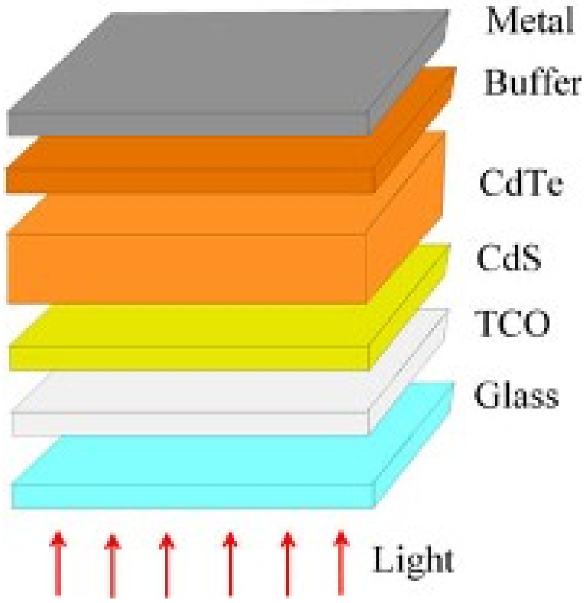

Figure 1.8 *CdTe thin-film schematic*

source: ***www.solar-sse.com***

Flexible modules of the second generation outweigh first-generation analogs especially in aspects of flexibility, weight and price. Some key advantages include:

- **Lower material costs**: The thin film technologies consumes a lot of lesser material compared to the crystalline silicon panel hence its production cost is low [42].
- **Flexibilit**y: In comparison to stiff silicon plates, thin-film solar cells are more easily made flexible to expand applications like bent and BIPV [43].

- **Better performance in low-light**: Thin film panels are effective in cases of indirect sunlight or where the panels are shaded thus; a suitable area for thin-film panels is an area that is not blessed with direct sunlight [44].

- **Temperature resilience**: Thin film panels, in general, lose less output at high temperatures than crystalline silicon, and thus more appropriate in the hot climates [44].

Due to the reduced material use and simpler manufacturing processes, the **energy payback time** for thin-film solar panels is shorter than that of first-generation crystalline silicon panels. In many cases, thin-film panels can generate the amount of energy used in their production within **1 to 2 years** [45].

A recent study from **BNEF Database-ISA Analysis**, shows that most of PV technologies present on earth is Crystalline Silicon followed by Thin Film Si and non Si based

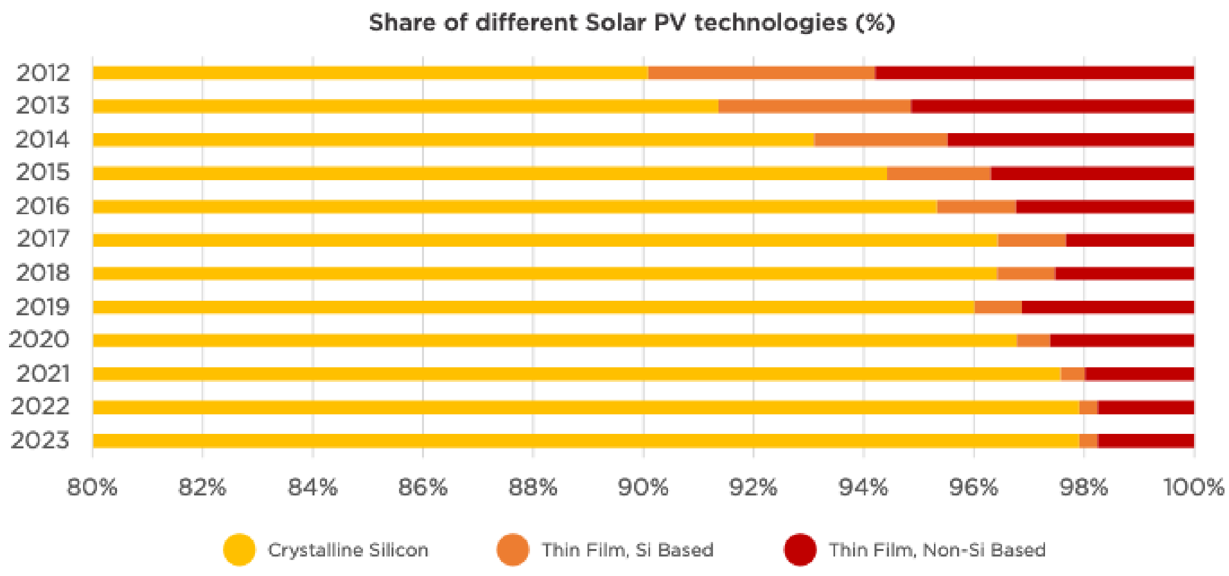

Figure 1.9 *Solar PV technologies*

Source: BNEF Database-ISA Analysis

1.3.3 Third-Generation

Third generation PV systems for the most part concentrates on employing novel materials along with quantum mechanical phenomena to enhance the efficiency of solar energy conversion process. Some of the most promising materials and technologies include:

- **Perovskite Solar Cells**: Perovskites are (ABX3), a class of material that possesses a certain structure that has the property of absorbing sunlight. Power plants based on these technologies are inexpensive to manufacture and have recorded astonishing efficiency enhancement in a short span of time, lab efficiencies in excess of 25% in ten years of their innovation [46].

- **Quantum Dots (QDs)**: Quantum dots are semiconductor particles of a nanometer size which possess unusual fluoroscopic characteristics because of their small size. Due to the size dependence of the quantum confined energy levels the quantum dots can be tuned to capture a range of wavelengths in the solar spectrum and in theory the use of quantum dots could produce PV cells with a larger spectral absorption range than current cells [47].

- **Organic Photovoltaics (OPVs)**: These cells are based on carbon materials to develop solar cells which are portable, portable and perhaps less costly to produce. Compared to silicon or perovskite cells, OPVs are far less efficient, but their relative advantages are applicability to wearable electronics and building-integrated photovoltaics (BIPV) [48].

- **Dye-Sensitized Solar Cells (DSSCs)**: These cells employ the help of an ink to trap photons and produce electrons. DSSCs also have the advantage of being relatively simple to produce at low cost, but typically are less efficient than many other third generation materials [49].

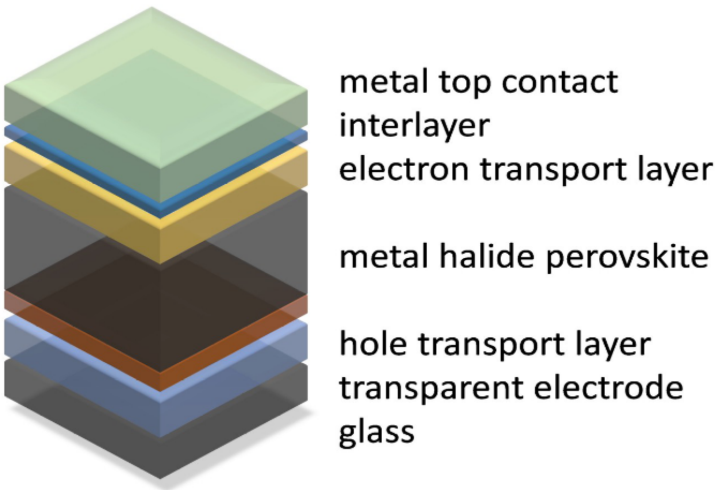

***Figure 1.10** Perovskite Solar cells*

Source:
M2N Research Group Eindhoven

Although the photovoltaic effect is still employed in energy generation in third generation cells, these technologies aim at utilizing solar energy more efficiently either to cover larger area of the solar spectrum or enhance the control of charges carriers[50].

- **Multiple Exciton Generation (MEG)**: Conventional silicon photovoltaics provides one photoexcited electron per photon being received from the sunlight. Third generation technologies however, the likes of quantum dots, strive to attain multiple electron-hole pair generation per photon in order to produce more electricity [51].

- **Hot Carrier Solar Cells**: In traditional photovoltaic devices, the converted energy from the absorbed light is a considerable part dissipated as heat. High-efficiency hot carrier cells want to prevent these thermal losses by collecting “hot” (high-energy) electrons before they relax into lower energy states, thereby theoretically boosting the efficiency of the solar cell[52].

- **Tandem Solar Cells**: Tandem solar cells are designed by incorporating layers of different material thicknesses or by combining layered structures to achieve maximum absorption throughout the solar spectrum. For instance, perovskite-silicon tandem cells are formed from the standard silicon substrate and perovskite layer to achieve a higher efficiency than that of a single material[53].

The third generation of solar technologies have been designed to surpass Shockley Queisser limit mainly designed to provide the theoretical efficiency of only a single-junction solar cell which cannot surpass 33%. It is the hope of these technologies that this barrier will be overcome by new concepts in materials and quantum mechanics. Some notable efficiencies include:

- **Perovskite Solar Cells:** These cells have delivered greater than 25% efficiency in experiments and indicate the possibility of better yields with regard to further improvements in stability and cell lifetime[55].

- **Tandem Cells:** Tandem cells have attained at least 30% efficiency as is apparent from cells where diverse materials such as perovskite and silicon are used [53].

- **Quantum Dot Solar Cells**: Now in the research stage, quantum dot cells can achieve efficiencies that are among the highest, or around 12 percent to 15 percent in a laboratory [56].

The use of third-generation technologies can also be said to be loosely associated with the active reduction of manufacturing costs as well as improving the efficiency of the manufacturing processes. Some of these materials, including perovskite and quantum dots, can be deposited through solution processed techniques which are much cheaper and energy consumable than the conventional Si-wafer processing techniques [57].

- **Perovskite Solar Cells**: Perovskites thin films can be printed using R2R (roll to roll) techniques, and hence reduce the cost of production as compared to the conventional silicon solar cells. Nevertheless, longer writing and stability and degradation concerns are still matters of concern before a commercial breakout is realized [58].

- **Quantum Dot Solar Cells**: These can also be synthesised by chemical processes, but the processes are relatively complex and there is still a major problem regarding up scaling of the process as well as increasing the yield to full commercial scale [57].

- **Organic Photovoltaics**: OPVs can be made by the printing technologies on different flexible structures that provide a good opportunity for applying the devices in different fields. However, due to their lower conversion efficiency and shorter durability, they are not as competitive in utility scale photovoltaic applications[59].

Also third generation solar cells are intended to solve many of the problems of the previous generation such as expensive materials, rigid structures and efficiency maxima [50]. Some key advantages include:

- **High Efficiency Potential**: The third generation of the cells tries to break the efficiency barrier of silicon-based PV systems through incorporation of superior materials, and multiple junctions [53].
- **Flexibility and Versatility**: All the TH-IV materials, including OPVs and quantum dots, can be solution processed on flexible substrates to enable new forms of applications, for instance, wearable solar panels, Windows that generate electricity, and Solar Building Integrated Photovoltaics (BIPV) [60].
- **Lower Production Costs**: Third generation technologies can be manufactured employing low-cost solution based techniques such as printing and coating hence making the solar energy cheap [58].

Decreasing the energy pay-back time is another aim of developing third generation technologies whereby the energy required to build a solar panel is produced by the same through the same system. This can be attributed to the lower materials content and manufacture power of many third-generation technologies [50].

1.3.4 Fourth-Generation

Fourth-generation PV technologies concern with thin film with both organic and inorganic components to produce heavily efficient, flexible photovoltaic solar cells. These hybrids seek to exploit the characters of all classes of materials for the best performance, economics, and environmental impact [61].

- **Organic-Inorganic Hybrid Solar Cells**: Organic-inorganic hybrid cells involve combining of organic materials including conductive polymers, and inorganic materials including perovskites or quantum dots. The concept is to integrate the advantages of low cost, ease of processing, and capability to control properties of the organic materials with the advantages of high efficiency and stability of the inorganic materials[62].

- **Multi-junction Solar Cells**: Whereas, tandem cells with only two sub-cells were typical of the third generation, the fourth generation cells consider use of multi-junction concepts with more than two layers. The performance of these layers is designed to capture different parts of the solar spectrum which can help to go beyond the Shockley-Queisser limit, and thus achieve efficiencies over 40% [63].

New technologies are striving at making changes to the traditional photovoltaic effect by adding other mechanisms that would allow for the capture of more energy than what is required for the photovoltaic effect alone [64].

- **Photonic and Plasmonic Effects**: These technologies aim at improving light trapping by controlling light at the nanoscale, through use of nanostructures. In employed plasmonic solar cells, metal nanoparticles are used to focus the light that falls on the cell's active layer thus enhancing the efficiency without having to use more materials [65].

- **Upconversion and Downconversion**: These processes are meant to confer capabilities on materials of promoting the conversion of low-energy photons in the infrared range to higher energy photons (upconversion) or on the other hand to promote the conversion of high-energy photons to several low-energy photons (downconversion). These technologies enable collection and conversion of a wider range of solar spectrum hence improving the efficiency of the solar cell [66].

Fourth generation solar technologies on the other hand are tools of attaining solar goals beyond what the current conventional and third generation solar cells are capable of delivering. These technologies are still in the research stage, but some of the projected efficiencies include:

- **Multi-junction Solar Cells**: Aim for 40% or higher is now in sight with the integration of several materials with different bandgap values to collect different wavelengths of sun light [63].

- **Quantum Dots**: Fourth generation cells using quantum dots seek to build on the previous generations of quantum dot technologies; efficiencies of 30% or more are possible and even higher by carefully controlling the size and composition of the quantum dots to maximize light capture and charge collection [67].

A major focus of fourth-generation solar technologies is improving **sustainability** by addressing the environmental and resource challenges associated with earlier PV technologies [68]. This involves:

- **Non-toxic and Abundant Materials**: Fourth-generation cells are designed to be free of toxic or hard-to-sourced elements (such as lead in perovskite or cadmium in thinfilm technologies). New approaches emphasize the employment of copper, zinc, or tin for the production of LTCC materials, replacing more dangerous or scarce components [69].

- **Recyclability**: These technologies also research towards the development of solar cells for ease of recycling when they reach the end of their useful life. Fourth generation cells have attempted to decrease toxicity of solar panel by coming up with cells which contain fewer toxic elements and those that are easily separable [70].

- **Self-healing Solar Cells**: Some fourth-generation apexes concerns self-healing concerning unhealed material and which can recover the harm caused by exposure to the environment or mechanical force. This would increase the life span of the cells and help solar panels to be more resilient and less requiring of replacement causes [71].

Fourth-generation panel is expected to marry the efficiency offered by multi-junction or hybrid thin films with the cheap fabrication technique provided by second-generation thin-film technologies [72].

- **Printable Solar Cells**: Most of the Fourth generation or the organic or perovskite solar cells include provide the ability to be manufactured via methods that are printable and hence enabling the construction of a large-area coating system via spray methods. This could result in solar cells that are inexpensive to make and can be affixed to virtually any surface [73].
- **Flexible and Transparent Solar Cells**: Fourth generation of solar cells are flexible and can coupled up with window glasses and wearable devices besides curved in form. This expands new opportunities for urban space, where structures could obtain solar power by integrating the solar cell into windows or the external cladding [75].

The basic novel features of fourth-generation solar cells include flexibility, lightweight and adaptability to a range of practical uses that was not possible with the first to third generation solar cells. Some key areas include:

- **Building-Integrated Photovoltaics (BIPV)**: There are visions of having a clear or slightly colored solar cell incorporated into windows, facades or roofs thereby transforming buildings into power plants [75].
- **Wearable and Portable Solar Devices**: The utility of organic or hybrid solar cells is the flexibility it has for wearable solar technologies for instance clothes or accessories that may be used to power little gadgets for example, phone or sense[76].
- **Space-based Solar Power**: Due to its lightweight and high efficiency, multi-junction cells have been considered for space-based SSPS systems for harvesting and beaming power to earth [77].

1.4 Types of Solar Panel Installations

There are different types of deployment of solar PV systems and they are designed in different structures to serve specific energy requirements as well as location needs. This area defines the major types of solar panel systems, off-grid, or on-grid, and the hybrid one and the features that make them appropriate for usage..

1.4.1 Off-Grid Systems

Off-grid solar systems are also different from the central utility grid in the sense that they have no link with the grid at all. These systems normally include battery storage, in order to store energy that has been generated during the day, for use at night, or during a cloudy day. Off-grid configurations are most advantageous inremote or island locations where physical connections to grid infrastructures cannot be made. They supply local energy security and independence where grid connections are unavailable or expensive to implement. Nonetheless, the capital cost for off-grid systems may vary massively because of the batteries or other power conditioning devices [78][79][80].

1.4.2 On-Grid (Grid-Tied) Systems

On-grid solar systems are connected with the local utility grid developed so as to allow both ways, import and export of energy. During situations that installed PV power exceeds the local consumption, the excess energy is fed to the utility grid and often has appreciable impacts on the economy via net metering [81]. On the other hand, users are allowed to take power from the grid when the amount of solar energy is low. On-grid devices are in most cases cheaper as compared to off-grid devices since they do not require storage systems. Is that these systems are very ideal for residential, commercial as well as industrial uses in the areas that have standard power utility networks[82][83].

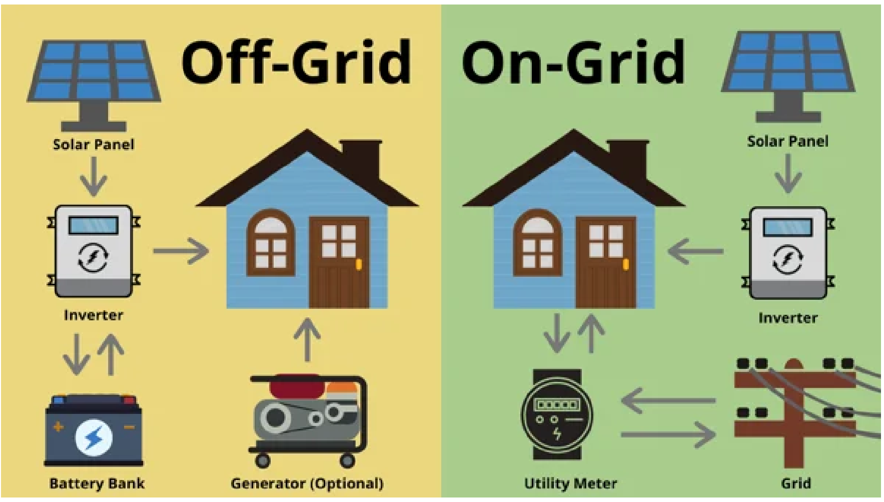

Figure 1.11 *Off-Grid vs On-Grid*

Source: paradisesolarenergy.com

1.4.3 Hybrid Systems

Off-grid and on-grid solar systems are combined in the hybrid systems, but they include elements of energy storage, most commonly in the form of batteries, and they are connected to the utility grid. This configuration lets the consumers utilize the energy reserve when there is a low production of Solar energy for instance at night, or during an outage. In Hybrid systems, flexibility is improved as well as energy security, and therefore, they can be used in areas with fluctuating or weak grid connection or for customers who wish to utilize only limited amounts of energy from the grid [84] [85] [86].

1.4.4 Ground-Mounted Systems

Applications of ground-mounted systems are made on flat landmasses with available structures that enable the tilting of the panels in the best positions to capture the solar radiation. These power systems are employed in relatively large utility applications like solar farms and have the potential of being tuned to reflect the range of seasons [87] [88].

1.4.5 Rooftop Installations

On the other hand, Rooftop systems are installed on the rooftops of residential or commercial buildings, thus, utilizing the roof space of the building for panel mounting. Rooftop systems are especially valuable in networked cities where the access to plot of land is restricted, they are an innovative method to minimize the costs of electrical energy without occupying extra territory [89].

1.4.6 Floating Solar Panels

There is a relatively newer form of deploying solar that involves floating solar panels on water sources like lakes, reservoirs or pond. Unlike the ground mounted PV systems, floating PV systems are practical in areas with little land available for installation of the conventional structures. These systems bring other advantages such as; minimizes evaporation of water and increases the efficiency of the panels by the cold effect of water on the bottom. However, they need additional support infrastructure and installation technique that add to the overall cost expenses on those structures [90] [91] [92].

1.4.7 Agrivoltaics

Agrivoltaics comprise the means of using a piece of land for agricultural production and as a source of solar energy production at the same time. These systems involve placing solar panels in gamers in a way that agriculture can be conducted underneath them, and this offer shade which is important to some crops and at the same time facilitating electricity production. This complementary factor analysis enhances the use of land to produce both energy and food resources, especially in the rural region where the efficient use of resources is of paramount importance [93] [94] [95].

Every kind of installation has its advantages but the choice strongly depends on characteristics of a particular location, energy needs and finances. Off-grid systems ensure the freedom of operation, on-grid bring economic benefits due to the connection to the grid, and hybrid systems are an ideal mix of the two previous systems. Moreover, ground-mounted, rooftop installation, floating and agrivoltaic installation provide viable ways of utilizing the solar power in relative to physical and operation environment.

CHAPTER 2

Market Dynamics and Economic Outlook

2.1 2024 Photovoltaics Report

As the 2024 Photovoltaics Report of Fraunhofer Institute for Solar Energy Systems, ISE with the support of PSE Projects GmbH suggest, the global photovoltaic (PV) market continues its rapid expansion, driven by increasing demand for renewable energy and ongoing cost reductions in solar technologies. The global PV capacity exceeded **1,581 GW** by the end of 2023, with the bulk of installations occurring in **Asia**, particularly China, which accounted for **86%** of the global market. Europe contributed to **20%** of the global PV installations, maintaining its pivotal role in the renewable energy transition.

2.1.2 Price Trends

PV module prices have experienced a sharp decline over the past decade, following a **price learning curve**, where module prices drop approximately **24.4%** over the past 43 years for every doubling of cumulative production. By the end of 2023, the average global selling price of PV modules had reached **$0.20 per watt** (USD/Wp). In Europe, rooftop PV systems (3-10 kWp) in Germany were priced between **1,450 to 2,000 €/kWp**, continuing the long-term trend of decreasing system costs. This ongoing price reduction has been facilitated by improvements in manufacturing processes and economies of scale.

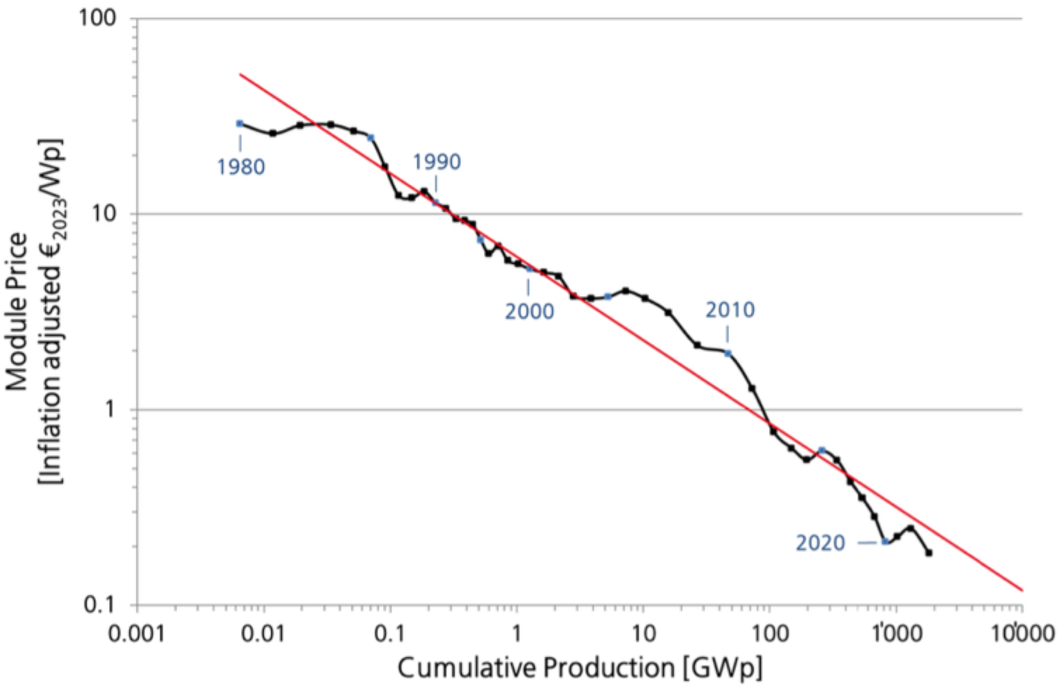

Figure 2.1 *Price learning curve*

Data: *from 1980 to 2010 estimation from different sources: Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS Markit; from 2022: ISE; Graph: PSE Projects GmbH 2024*

2.2 Efficiency Improvements

The technological landscape has evolved significantly, with solar cell efficiency improving rapidly. **Mono-crystalline silicon cells**, which dominate the market, reached a maximum efficiency of **27.3%** in laboratory conditions by 2023. Meanwhile, new technologies like **perovskite** and **tandem cells** continue to push the boundaries of efficiency, with tandem cells aiming for over **30% efficiency**.

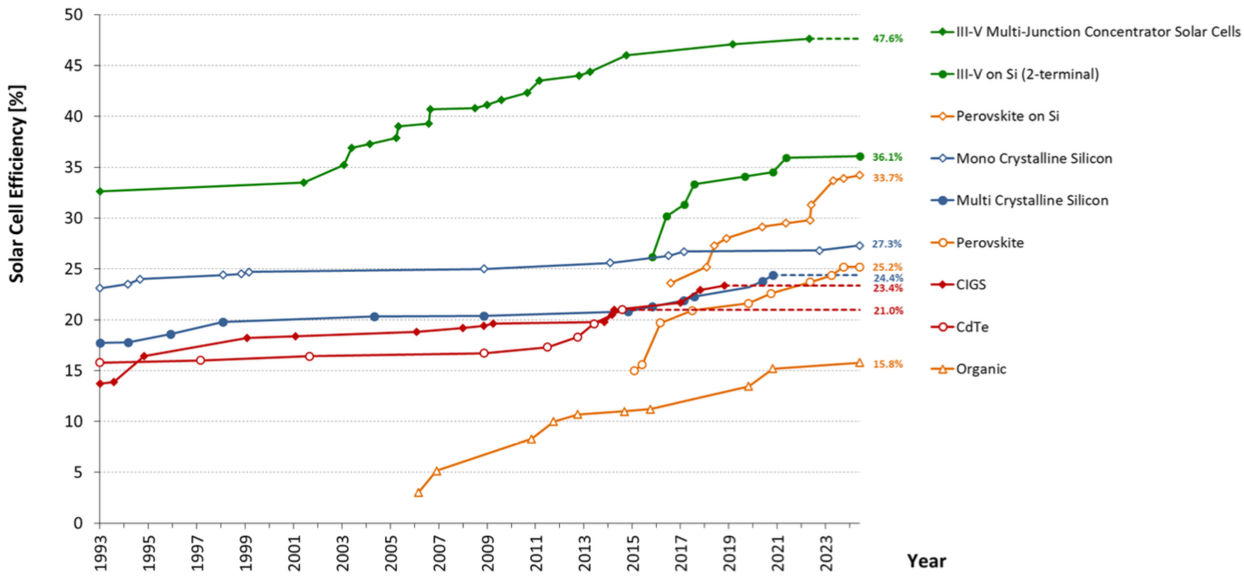

Figure 2.2 *Development of Laboratory Solar Cell Efficiencies*

Data: Solar Cell Efficiency Tables (Versions 1 to 64), Progress in Photovoltaics: Research and Applications, 1993-2024. Graph: Fraunhofer ISE 2024. Date of data: 06/2024

Observing the year 2023, 15GWp of new PV power addition in Germany took place and reached a new capacity installation of 82.7GWp.p. Wind and solar power supported 12.5% of the electricity demand of the country and clearly signifies renewable energy leadership of the country. In the PV market of Europe, there is a transition for programmes that are highly subsidized and expensive to Power Purchase Agreements PPAs, which again are costcompetitive.

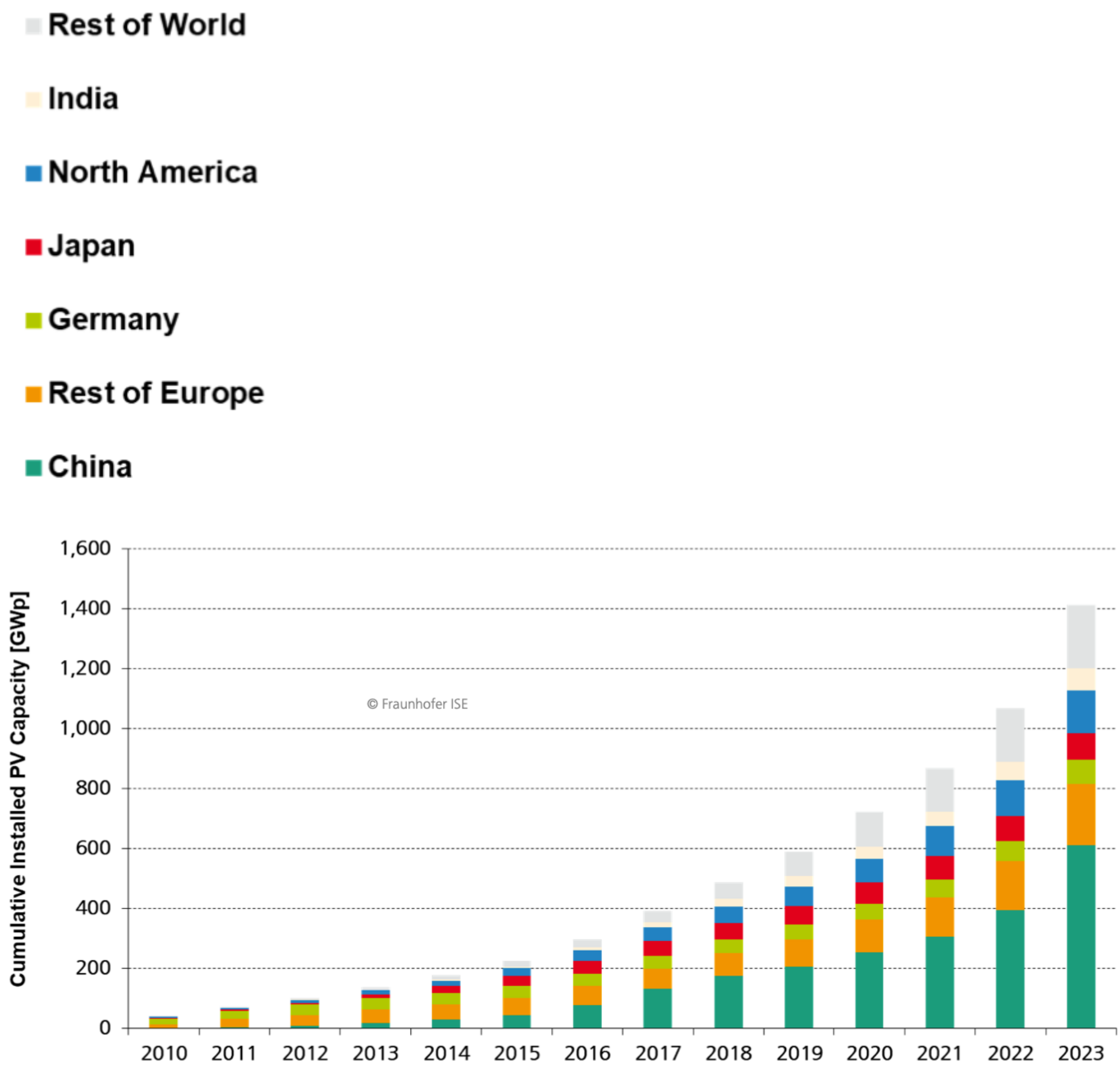

Figure 2.3 *Global Cumulative PV Installation by Region*

Data: Fraunhofer ISE

Further, the market will experience a higher growth rate with the introduction of new forms of solar including floating PV, agri solar (solar on agriculture), and BIPV building-integrated photovoltaics. Moreover, the integration of PV systems in vehicle ports and wearable products also has potential to revolutionise the application of solar. This authenticates a trend that solar energy will occupy a more prominent place in the global energy mix in future given the fact that cost of energy continues to reduce and efficiency increases.

2.3 Italy's Renewable Energy Landscape: Recent Market Insights and Economic Trends

Italy has become one of the leading countries in Europe in the adoption of solar energy, specifically through photovoltaic (PV) technology. Over recent years, the installed PV capacity has grown significantly, despite some setbacks due to reductions in state incentives such as the Superbonus[5]. Despite this, italy remains one of the countries in the european community that invests the most in ecological transition, as of **2023**, Italy had installed **1,597,447 photovoltaic systems**, contributing to a total installed capacity of **30,319 MW**. This represents a **21% increase** in installed capacity compared to the previous year. The energy production from PV systems in 2023 amounted to **30,711 GWh**, marking a **9.2% growth** compared to 2022 [96]

Figure 2.4 *Connected power per year*

fonte: Italia Solare

However, the distribution of solar panels on the peninsula is not homogeneous and is not done on a large scale indeed the majority of installed PV systems in Italy are small-scale. In fact, **94%** of the PV systems have a capacity of **20 kW or less**, reflecting the prevalence of residential installations. However, these small systems contribute only **29%** of the total installed capacity. Larger systems, particularly those with a capacity greater than 1 MW, account for **21%** of the national installed capacity [97]

Solar power in Italy is distributed in opposite poles and a lot of investments are being made in southern Italy still at the regional level, **Lombardy** leads with an installed PV capacity of **4.05 GW**, representing **13.4%** of the national total, followed by **Puglia** with **3.31 GW**. Together, these regions contribute significantly to Italy's solar energy production. A pie chart

[5] The **Superbonus** is a 110% tax incentive introduced in Italy in 2020 for energy efficiency and seismic risk reduction renovations.

or regional map visualizing the distribution of installed capacity across key regions would effectively illustrate these statistics [98]

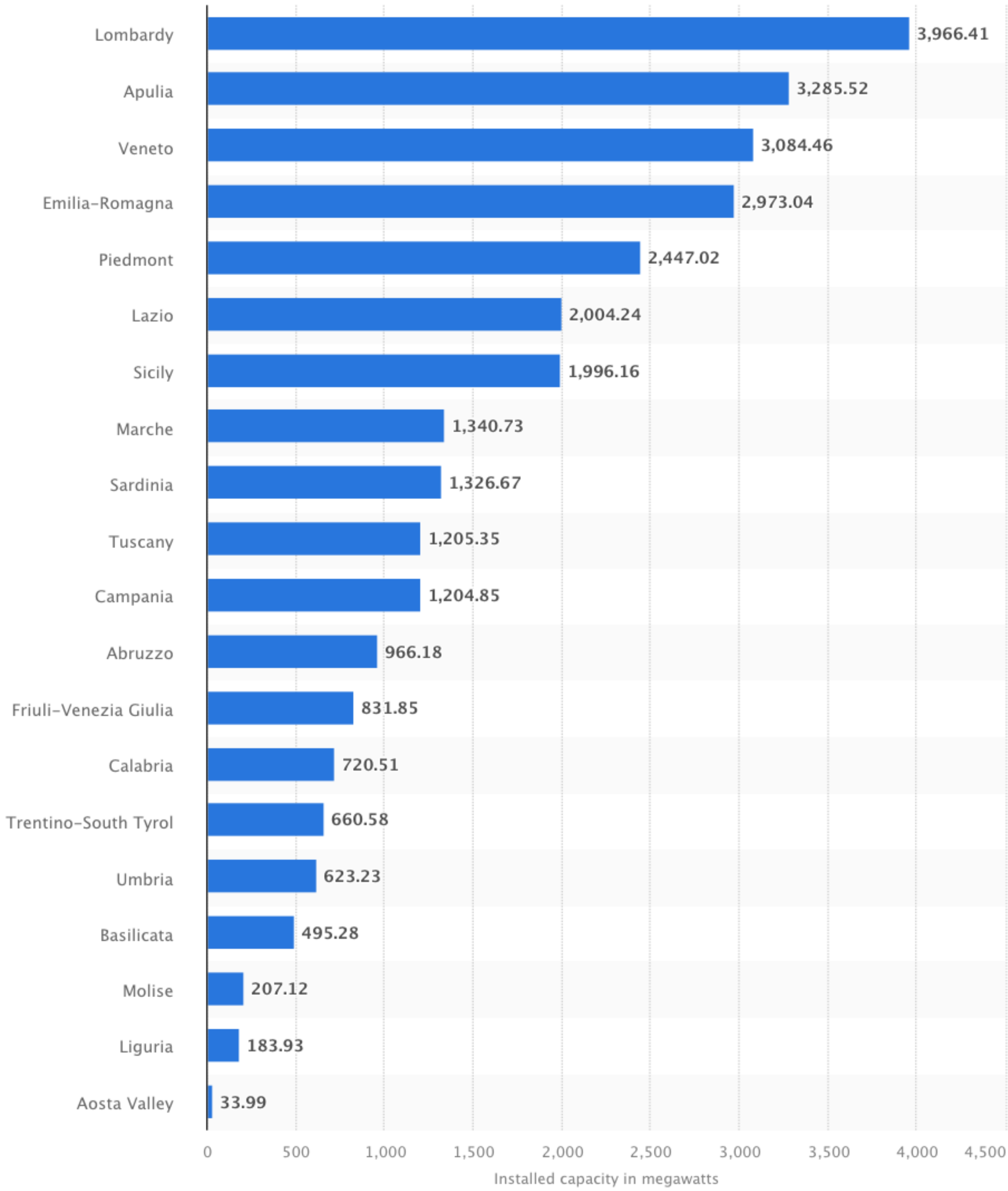

Figure 2.5 Installed Capacity of Solar Panel per region in Italy
Published by Statista Research Department

The future looks bright in italy, according to **IRENA** [6]and the **GSE**[7], Italy has a high potential for expanding its PV capacity. The country aims to install an additional **8-10 GW** of capacity by the end of **2024**, which aligns with Italy's broader goals for energy transition and decarbonization. However, the future expansion of solar power faces challenges, particularly uncertainties related to regulatory changes like the "areas eligible" decree, which could impact large-scale land-based PV installations. Despite these hurdles, the rising cost of energy and growing corporate awareness around sustainability have driven an increase in PV adoption, particularly within the commercial and industrial sectors[99].

[6] IRENA: International Renewable Energy Agency
[7] GSE: Gestore dei Servizi Energetici

CHAPTER 3

Solar Waste

3.1 Introduction to the Concept of Second Life for Solar Panels

As the solar energy industry continues to grow rapidly, the number of **solar panels reaching the end of their useful life** is also increasing. While the operational lifespan of a typical solar panel is around **25 to 30 years** [22], the question of what happens to these panels after they are no longer efficient enough for energy production is becoming more pressing.

Despite the recent surge in photovoltaic (PV) installations in both residential and large-scale environments, the deployment of solar panels is anticipated to further accelerate in the near future, driven by multiple factors. These include the declining cost of panels due to advancements in technology, as well as improvements in manufacturing and economies of scale, government incentives and subsidies supporting initial installations, the increasing conversion efficiency of solar panels, and, in some cases, rising power costs as low-cost, high-emission power generation methods are phased out. [22]

According to IRENA the waste generated by PV technologies is projected to be around 60 milion tons. However, with the rapid advancement of new PV technologies and their widespread implementations, the outcome could be far worse than anticipated.

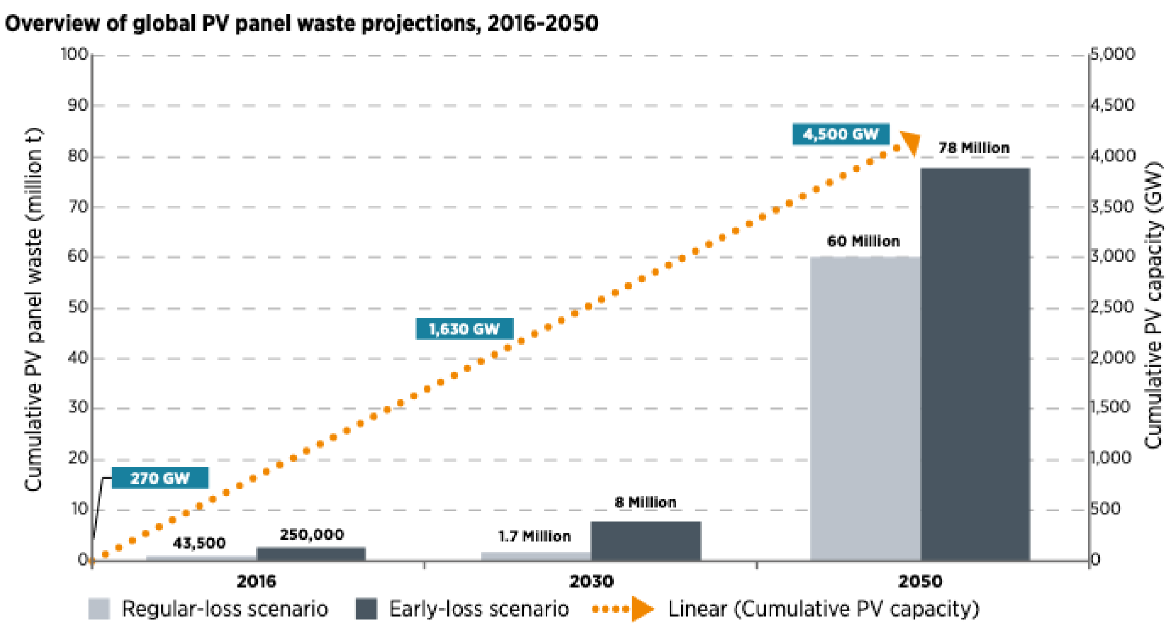

Figure 3.1 *PV panel waste projections 2016-2050*

Source: IRENA

Based on the findings from a study presented in the paper [22], replacing existing photovoltaic (PV) panels with modern, more efficient ones can become financially advantageous within just 10 years of their initial installation. This means that many panels, even those currently in use, may be replaced much sooner than originally anticipated. As a result, the projected amount of PV panels reaching end-of-life, as depicted in **Figure 2.1**, could be significantly **underestimated**. The accelerated rate of replacements could lead to an even **larger volume** of decommissioned panels, necessitating enhanced recycling strategies and end-of-life management solutions to address the growing influx of retired solar modules.

This is where the concept of a **second life** for solar panels comes into play a critical idea within the broader framework of the **circular economy**. The second life of solar panels refers to the various strategies used to **extend their utility** beyond their initial phase of operation.

Rather than treating solar panels as waste once they reach the end of their designed lifespan, the goal of second-life strategies is to **recover valuable materials**, **reuse components**, or even **refurbish panels** to give them new functionality. These strategies not only reduce the environmental impact associated with the disposal of solar panels but also open up economic opportunities for creating a more sustainable solar industry.

The concept of second life represents a shift from the traditional linear economic model of "take, make, dispose" to a more **circular approach** in which products are kept in use for as long as possible, and materials are continuously reused. This shift is particularly important in the solar industry, where the growth in installed capacity over the past two decades means that the volume of decommissioned solar panels is expected to increase substantially in the coming years [28].

If not properly managed, however, decommissioned panels can contribute to the growing problem of **electronic waste (e-waste)**, posing risks to human health and the environment due to the presence of potentially hazardous materials.

Figure 3.2 *Solar Panel Waste*

Source: ISA solar tech report

On the economic level, the second-life use of the PV panels suggests great potential for cost reduction and the development of new applications. For instance, almost functional panels, those with slightly reduced efficiency can be sold in second hand markets at a cheaper price and this makes solar energy useful in areas where there is no power such as the third world or off grid. Second life application also help towards the long term vision of conserving as many materials as possible and less reliance on the virgin feed stock and thus; further reducing or minimizing the environmental foot print of the solar industry.

3.1.2 Possible end-of-life solutions

Although photovoltaic technologies are relatively recent and the waste from the latter is relatively small, the numbers are beginning to rise dramatically by 2050 reaching tens of thousands of tons annually, with significant impacts on waste management and the environment.
This scenario highlights the urgent need to develop sustainable recycling and disposal strategies to effectively manage the growing volume of PV waste and minimize its environmental impact.

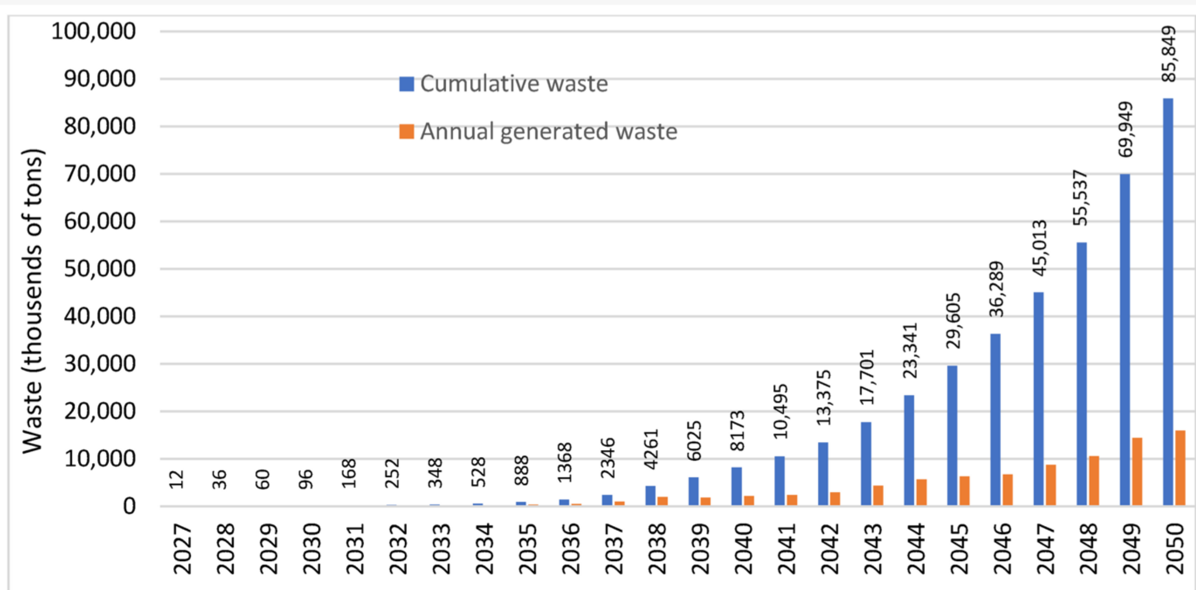

Figure 3.3 *Estimated amount of global PV waste [101]*

Starting from just **12,000 tons** in 2027, the cumulative waste is expected to skyrocket to approximately **85,849 thousand tons** by 2050. This staggering growth can be attributed to the long lifespan of solar panels (typically 20-30 years), which means that many of the panels installed in the early 2000s will begin to reach the end of their life around 2040.

The **annual generated waste**, represented by the orange bars, shows a similar upward trajectory. Although the annual waste generation remains relatively low in the early years, it begins to increase significantly after 2035. By 2050, it is expected to reach over **7,000 thousand tons per year**. This growth reflects the mass decommissioning of PV systems installed during the solar energy boom of the 2010s and 2020s.

Among the solutions to the end of life of solar panels at the moment are **reuse**, **recycling** and **landfilling**. For obvious reasons, landfilling, which consists of burying the panels and then disposing of them in this way, is not among the optimal or even the most sustainable or technological solutions.

3.2 Recycling

According to the discussion made in chapter 1, solar panels consist of silicon, aluminum, glass, polymers and some silver and cadmium though they are in small proportions [21]. These panels, if discarded in the right bin for landfilling, present several risks; For instance, although glass and aluminum are chemically stable, cadmium, lead, and other heavy metals that can contaminate the earth, water and air, which is dangerous to the health of both ecosystems and humans. Furthermore, stamina of the panel market can be maintained due to the large volume of panels available that are at the end of their lifecycle and which can become a huge threat as electronic waste or e-waste which is among the fastest-growing waste streams in the world. To the environmental risks, one can add the following fact: solar panels are created to be long lasting, and therefore are almost impossible to destruct. While other types of e-waste like the consumer electronics, PV panels require other techniques of disassembling and recycling of the materials. If the structure is not available, these panels may end up in dumpsites where they take decades to degrade[100].

Mechanical Recycling Processes

The most common process of recycling solar panels is mechanical recycling in which the panel is mechanically recycled through processes such as shredding crushing and separation to reclaim the constituent material. This method mainly focuses on the identification and collection of the glass, aluminum and plastics, which costlier panel accounts for 60-70% of the overall weight. The most of a typical solar panel is glass, which accounts for 75% [21], and the glass can be recycled from the other materials and used in the production of new glass products. Likewise, the aluminum frames used in the production process can be easily recycled for use in the production line other products. However, when it comes to recycling, mechanical recycling systems are deficient in reclaiming valuable matters such as silicon, silver, and other hard metals which form 5% of the total components [21] of photovoltaic cells. Some of these materials are embedded within the layers of the panel meaning that it is almost impossible to remove them mechanically. In this regard, recycling can end up with a high percentage of the high value material being wasted, thus the process becomes uneconomical. And thus bringing the opportunity of the developmenet of the recycling processes very slow! Nevertheless, mechanical recycling is still dominant in the process of solar panel recycling, mostly because of lower costs and existent structures for the method. Furthermore, the current research and development are aimed at refining the mechanical recycling sequences, especially for the purposes of recovering valuable materials such silicon and silver. Future developments of the mechanical recycling could be attributed through robotics-assisted disassembly and additional sorting techniques.

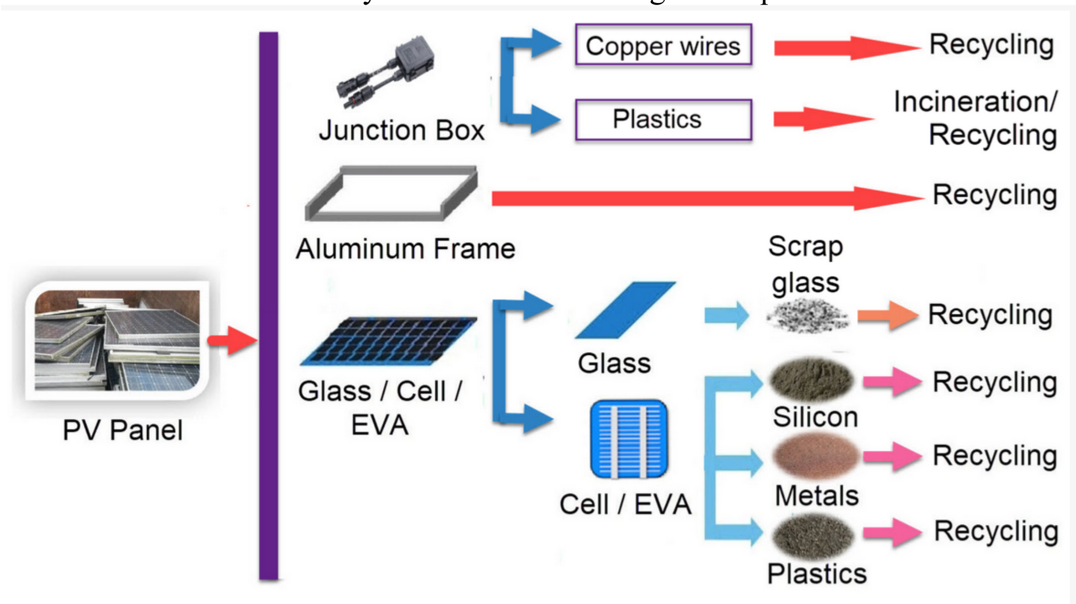

Figure 3.4 *Mechanical Recycling Processes [101]*

Thermal Recycling Processes

Thermal recycling is another approach that is increasingly being explored for solar panel recycling. This method involves the use of high temperatures to break down the solar panel components and separate the valuable materials from the non-recyclable ones. In thermal recycling, the panels are subjected to **pyrolysis** or **incineration** [101], which burns off the plastic encapsulants and other organic materials, leaving behind the metal and glass components. The **silicon** from the photovoltaic cells can also be recovered in this process, although its quality may be degraded by the high temperatures.

One of the key advantages of thermal recycling is that it allows for the **recovery of metals** that are difficult to extract through mechanical methods. For instance, **silver, copper, and other rare metals** used in the cells and electrical components can be more effectively separated through thermal processes. These metals are often present in small quantities but have significant economic value, making their recovery important for the overall viability of recycling operations.

However, thermal recycling is not without its drawbacks. The high temperatures required for the process consume a substantial amount of energy, which can offset some of the environmental benefits of recycling. Additionally, the burning of certain materials can release harmful emissions, necessitating the use of **emission control technologies** to minimize the environmental impact. As such, while thermal recycling has potential, it is typically combined with other methods to maximize efficiency and reduce negative side effects.

Chemical Recycling Processes

Chemical recycling represents a more advanced method for recovering high-value materials from solar panels. This process involves the use of chemical solvents or acids to break down the panel's layers and dissolve specific components for recovery. For example, chemical recycling can be used to dissolve the **polymeric encapsulants** that bind the silicon cells to the glass and other materials, allowing the silicon to be extracted in a relatively pure form. In addition, chemical processes can target the recovery of **silver, indium, gallium, and other rare metals**, which are often difficult to extract through mechanical or thermal methods [101].

The key benefit of chemical recycling is its ability to recover materials at a higher purity level, which makes them more suitable for reuse in the production of new solar panels or other high-tech applications. This method is particularly valuable for **next-generation solar technologies**, such as **thin-film solar cells**, which rely on rare and expensive materials like **cadmium telluride (CdTe)** and **copper indium gallium selenide (CIGS)**. Chemical recycling can also contribute to the recovery of these critical materials, reducing the need for virgin resource extraction and enhancing the sustainability of the solar industry.

However, chemical recycling presents several challenges. The process often requires the use of toxic or corrosive chemicals, which can pose health and environmental risks if not properly managed. Additionally, chemical recycling can be expensive, as the solvents and acids used in the process must be carefully controlled and disposed of to avoid contamination. While the technology holds great promise for improving the sustainability of solar panel recycling, further innovation is needed to make chemical recycling more cost-effective and environmentally friendly on a large scale.

3.2.1 Regulatory Framework and Compliance

Due to the dangers posed by the disposal of solar panels, the same governments and bodies across the globe have started coming up with policies and mechanisms to properly deal with fate of panels when they are no longer of use. The European Union's Waste Electrical and Electronic Equipment (WEEE) Directive also contains special provisions for the recycling and recovery of PV panels. According to this directive, manufacturers are expected to bear the cost of collecting, treating, and recycling of the retired panels that falls under the category of electronic waste. That is, while such regulations are relevant, their compliance raises myriad issues. The solar industry is also very dispersed meaning the manufacturing companies, the installation companies, and even the recycling companies are normally different. It can therefore be a challenge to ensure there is centralization in the collection and recycling of the panels. Further, although the WEEE Directive and literature from other parts of the world offer a guideline to the best way to address the disposal of solar panels, its execution is largely inconsistent across borders. Sometimes these structures and resources are completely lacking, which means that recycling can be ineffective, and many panels are uncollected at the end of their lifespan.

3.2.2 Logistical and Economic Barriers

The process of accumulating and transporting the end utilisation solar panels to their recycling facilities is also another robust hindrance to end-of-life solutions. They are commonly installed in areas that are hard to access or spread over a wide geographical area, therefore it is expensive and inconvenient to reclaim the solar panels after they have become obsolete. Additionally and most importantly, given the future influx of panels that will require processing in the next few decades, increased solar panel recycling and refurbishment capacity is needed today, despite many facilities are not yet ready for a hike in solar panel recycling amounts.

However, from an economic viewpoint, recycling and reusing or repurposing solar panels is not always easy and can get expensive. Of all that can be used, some like aluminum and glass are somewhat easier to be recycled and still maintain its worth while others like silicon and polymers are quite difficult and costly to be processed. This often has an effect of making the cost of recycling higher than the benefits and therefore companies are discouraged from opting for end of life management solutions. More so, the market for the second life of solar panels, those that can be recycled, is also relatively undeveloped, which reduces the amount of economic incentive for recycling as well.

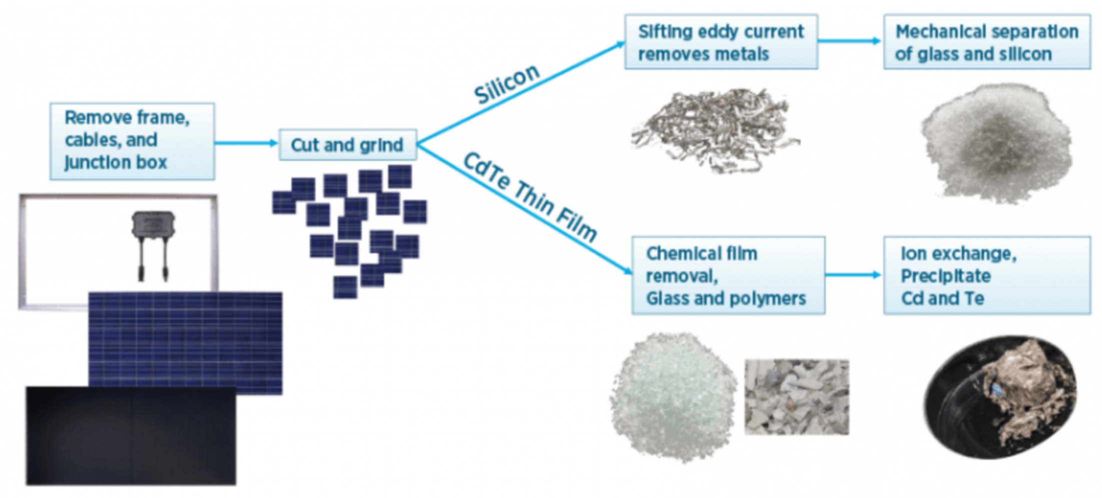

***Figure 3.5** Commercial module recylying process*

***Source:** [Office of Energy Efficiency & Renewable Energy]*

3.2.3 Challenges in Recycling Photovoltaic (PV) Modules

1. **Lack of Standardized Collection Systems**: Currently there is no standard global PV modules collection and no legislation or bonuses that push for recycling. Thus, recycling rates remain low, while there are prospects for the irregular disposal of waste.

2. **Limited Recycling Infrastructure**: Currently there is lack of proper methods and equipment to recycle PV modules.

3. **Low Market Demand for Recycled PV Modules**: There is very little market for recycled or used PV modules and thus little incentive for recycling.

4. **Lack of Awareness**: The public and other major stakeholders are unaware of the difficulties and possible advantages of recycling photovoltaic modules.

5. **Complexity of Materials**: PV modules are made from many materials the use of which is elaborate in the process of manufacturing and these materials call for unique methods of recycling. It also becomes difficult to ease the separation and recovery of the other useful parts from the plastics.

6. **High Costs**: The recycling of PV modules is a process that remains highly manual, expensive, and not always profitable. It was also found that often the costs of recycling are higher than the benefits that can be drawn from the recovered commodities.

7. **Obstacles to Reuse**: This is due to differences in new standards, warranties, and the general problems of finding compatible modules for large installations for reusing PV modules.

8. **Risk of Landfilling**: For various economic considerations, PV waste is normally buried in landfills in spite of the fact that they can be recycled across many countries [101].

3.4 Reusing, A secod life for solar panel

The fact that the number of **installed solar panels** is now coming to the end of their **useful life** is both a problem and a potential for the solar industry. Through repurposing and renovating solar panels, one is able to decrease on waste, demand new materials and catalyze economic activities as well as provide affordable energy where it is scarce in the world. To realize the full potential of circular economy in the context of the solar industry, reuse and refurbishment will be presented in this section as viable strategies for integrating them into the solar value chain from the technological aspect while discussing their economic and environmental impact.

3.4.1 The Process of Refurbishment

Panels that have been retired are not wholly non-functional; the capability of the panels could have drastically reduced due the accumulation of micro cracks, the degradation of the materials or inefficient wiring. Faults present in panels are then corrected and after this process, they can have a considerable amount of the **initial efficiency** so that they maybe used in new installations.
The process of refurbishing is possible where the degradation is partial, in that it will only require overhaul to be effected in order to regain functionality.

For instance, faulty diodes repair or correction of delamination problems means that a panel can be fixed without disassembly. **New ones** are bought into the market, the pre-owned ones which are then refurbished are exercised to quality checks to ensure that they can perform as desired before they are sold or **reinstalled.**
Of all the changes that happen during refurbishment, they are specifically more advantageous in solving aspects concerning the economy as well as the environment. Refurbishment and revamping decreases the rate at which panels are manufactured and used hence decrease the amount of raw material consumed and the energy used in the production of these new panels.

3.4.2 The Market for Second-Life Solar Panels

The second-life market is a term used for referring to the market for second hand solar panels, these are normally renovated solar panels and they are cheaper than new ones. Today, this market became quite popular especially in those areas where the initial investment in new solar installations is still high. Off-grid and developing countries are the most significant beneficiaries of the second-life solar panels since it affords an opportunity to get serviceable panels cheaper than the new ones. [102]

Lighting remains a challenge for many developing regions' populations, including those residing in the rural or remote areas where the conventional electricity grid is unavailable. Second-life solar panels are therefore very vital in such areas as they provide cheaper energy solutions for improving the standards of living. For instance, reconditioned panels can help several applications like off-grid solar home systems, rural electrification, and community mini-grids that support the cause of extending energy access to everybody. [103]

Apart from deploying in the inaccessible regions of developing countries, second life PV panels are being adopted in industrial segments where the high performer pv panels may not be considered optimal. For instance, second-life panels can be used in agriculture, in warehouses, or in places where low levels of electricity are needed because even at **8-10 percent efficiency level EL** [104] panels can supply sufficient power for the tasks to be accomplished. This also creates new business prospects for such companies as the solar sector looks to circular economy by refurbishing and reselling panels.

Numbers and key players

Globally, the market for used and refurbished solar panels is estimated to involve **millions of panels**, with some brokers handling up to **10 million used panels** annually. In Europe, **45 GW** of solar panels were stockpiled in warehouses by 2023, nearly equivalent to the total installed in the region that year, creating a buyer's market with declining prices [105] [106]
Key players in the global solar market, including **Trina Solar** and **Canadian Solar or Second Solar**, are actively involved in strategies to manage end-of-life solar equipment, with a focus on recycling and refurbishment. Companies like **RecyclePV** have pioneered processes to recover up to 98% of materials from decommissioned panels, facilitating their reuse at lower prices for markets in developing countries [107]
This second-life market is particularly important for off-grid applications, where refurbished panels are used in areas without access to conventional electricity grids. In Africa, for example, second-hand panels are commonly used for water pumping and community electrification projects. In terms of numbers, it's estimated that this market could potentially supply millions of people with affordable energy solutions in underserved areas by extending the lifecycle of PV panels. [108]

3.4.3 Challenges in Reuse and Refurbishment

Reuse and **refurbishment** have their advantages; however, there are several **issues** that need to be resolved to make reuse and refurbishment more effective. Among them, the most crucial one is the **quality** and the **credibility** of the refurbished panels. While new panels are accompanied by **manufacturer warranties** and **performance warranties**, refurbished panels have a high level of **quality fluctuation** and performance because they have undergone different levels of **degradation**. For refurbished panels to be declared **safe** for use, and to function optimally like new ones for a specified period, they require time to undergo the relevant **tests** and **certification** to achieve these standards, which also makes the total **cost of refurbishment** steep.
The last issue is related to **collection** and **transportation**. This can be viewed as one of the main challenges, as it may not be easy to determine the best way to collect all the necessary materials and transport them to the needed place. **Solar panels refurbishment** involves a system for the collection of the deconstructed panels, which may be scattered across different locations, to the refurbishing centers. It can prove to be **expensive** and **resource demanding**, especially if panels are located in rather **remote locations** or areas not easily accessible.

However, there are no well-defined **procedures** on how to refurbish panels, leading to **inefficiency** and uneven quality of the refurbished products.
Further, **regulatory challenges**, which are among the prominent constraints of the **solar panel industry**, also act as a restraint in the development of the **second-life solar panel market**. To control the importation of used equipment, some countries only allow it if the solar energy equipment meets certain **performance standards** and **safety requirements**. Managing this **legislation** poses challenges, especially in regions where **laws on electronic waste** and **second-hand equipment legislation** are not very developed. Efforts to rationalize **regulation** within one and several markets and to establish definite guidelines for the further **refurbishment** and **reselling** of solar panels will be vital to unlocking this market's potential.

3.4.4 Environmental and Economic Benefits

However, there are a number of benefits that come with **reuse** and **refurbishment**, especially if it's done in a bid to **save the environment** and **cut down costs**. In this way, reuse and refurbishment save the amount of **electronic waste** that originates from the **solar industry**; As projected by IRENA in figure 3.1, this sector is expected to produce **78 million tons of waste** by **2050** . According to this **production method**, we can cut down on the **waste** that usually ends up in the dustbin, as well as the **materials** and **energy** that would be required to manufacture new panels.
Economically, the **second-life market** is useful because it **generates demand** that fosters the creation of **jobs** and **businesses** in the solar industry. **Organizations** dealing in the **reuse** and sale of the solar panels might benefit from the increased need for **cost-effective renewable energy products** in the **developing marketplace**. Also, the increase in the use of the **second-life concept** undoubtedly can lead to a **decrease in the overall cost** of using **solar energy**, as well as open up additional **opportunities** for using **renewable energy technologies** for as many **consumers** as possible.

3.4.5 Future Prospects for Reuse and Refurbishment

Turning to the **future perspectives**, it is possible to state that options for reuse and refurbishment in solar industry have a **great potential**. With solar panel installations progressing across the globe, the number of panels which are likely to end up in the second-life market is set to rise thus meaning that there is untapped chances of growth in terms of invention and business opportunities. Improved efficiency and effectiveness in testing and certification procedures will go a long way in explaining and availing evidence that products in the second life of panel product are as safe as new products hence enhancing confidence of consumers.

Moreover, it is expected that this market will call for policy support that will help to boost the growth of second-life applications of solar panels. Governments also may propose the possibility of refurbishment through financial measures such as subsidies or tax rebates to companies that get involved in refurbishment. Another area, where PPPs could help, is organization of collection and distribution of second-life panels, as this would help to minimize the logistics' costs, which are important in making refurbishment a more cost-effective undertaking.

Summing up, it is seen that reuse and refurbishment are the useful approach to improve the management of the end-of-life phase of solar panels with regard to sustainability and cost-effectiveness. In that way, a continuous dialogue on which the solar industry can build and learn from, helps gain a better understanding of the current and probable limitations of the system and thus helps to advance towards a more circular and sustainable energy solution.

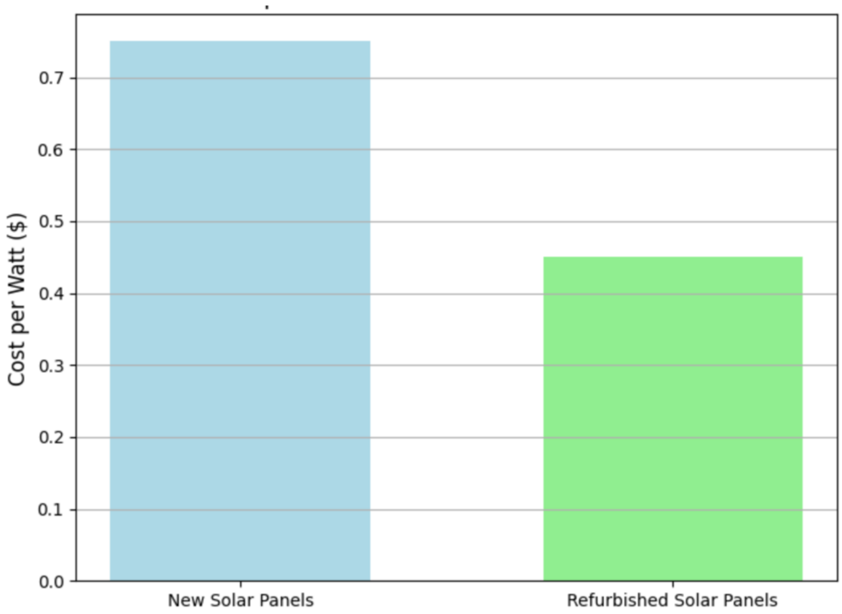

Figure 3.6 *Cost comparison: New vs Refurbished Solar Panels*

Data Sorce: energysage.com, adapted by the author

3.5 Economic and Environmental Benefits of Second-Life Solutions

The inclusion of **second-life** solutions including the re-use, refurbishment and recycling of the solar panels gives economic and environmental benefits that are key to the sustenance of the solar energy industry. In the context of the growing global demand for renewable energy, second-life strategies can be used to enhance the reuse of valuable resources to a larger extent as well as to minimize the costs while generating new sources of income at the same time. In this section, it is necessary to discuss how second-life practices create the basis of the circular economy and contribute to the profitability of solar systems as well as environmental protection.

3.5.1 Economic Benefits of Second-Life Solar Panels

A clear economic benefit of second-life solutions includes the opportunities for cost-saving that has the solar industry holding dear. Through rejuvenation and reuse of the solar panels, the industry can reduce the requirement of manufacturing new panels which in return reduce the consumption of silicon, aluminum, and metals, etc. This, in a way, cuts on expenses involved in the extraction and processing of these materials which are most times demands a lot of energy and have unpredictable prices in the market.
For example, recall that refurbishing involves the reuse of decommission panels and the option enables manufacturers to offer panels which have been refurbished and cheaper than those manufactured afresh. This makes the use of solar power cheaper than possibly developing an all new solar installation which may not be feasible in certain markets. In developing countries, where one of the biggest obstacles is to provide affordable energy, second-life solar panels serve the purpose of extending the energy access at relatively low

cost. Thus, through increasing the access to affordable solar technology, second-life panels can contribute to the ongoing development of the specified regions' economies and the improvement of people's quality of life.

Further, the second-life market of solar panels may bring new opportunities for generating new working business along with fulfilling the goals of the industry of generating solar energy. There is an opportunity in refurbishing companies, reselling second-life panels and distribution services as more companies come up to meet the energy needs especially in developing nations. The specialised companies can also utilise different state initiatives and programs that address circular economy, and thus increase its profitability and development factors.

Besides generating new economic activities, second-life solutions could also decline the LCOE of solar energy. Since refurbishment of the panels enhances the durability of panels, the cost of installation of solar systems can be made to accrue over a longer period and thus leading to decrease cost per **kilowatt-hour (kWh)** of electricity generated. This has placed the cost of solar energy at a more competitive level as compared to the conventional sources of energy such as the fossil fuels thus ushering the rest of the globe into the renewable energy era.

3.5.2 Environmental Benefits of Second-Life Solutions

It obvious that second-life solar solutions are equally effective in terms of the environmental impact, especially in the fight against climate change and the promotion of green energy. Second-life practices thus offer an economic as well as an environmental benefit because it decreases the demand for the regular production of new solar panels hence saving on the energies and hazards linked with mining, material processing and manufacturing. This reduction in resource demand is specially beneficial in areas where there is a lack of resources such as scarce metals which are indifficult areas to extraction.

The application of second-life solutions has probably the greatest environmental impact, as it eradicates e-waste. Second-life strategies also assist in this challenge by taking panels from the dumpsites and recycling them, making them useful again thus reducing impound. This is in line with the principles of circular economy which aim at lengthening the amount of time that materials are in use by the consumers.

Furthermore, the second-life solutions play a significant role in decreasing the solar industry's effect on the environment. Globally, new production of solar panels entails high levels of emissions of greenhouse gases especially resulting from the refining of silicon and producing photovoltaic cells. Second-life solutions do not require new production therefore minimising the emission of greenhouse gasses resulting from the manufacturing process of new panels. This is especially valuable given the solar industry's effort to promote itself as a driving force behind the worldwide effort to transition to carbon-free energy.
In addition to this, there are other gains that second-life solutions offer in terms of environmental conservation, including the conservation of scarce resources such as water, minimization of pollutions and better management of available natural resources such as vegetation otherwise used to manage waste. Most of the materials that are mined include copper, silver, and rare earth elements are found in sensitive environment which leads to environmental degradation through habitat loss, water pollution and social issues affecting the communities. Second-life solutions therefore alleviate these negative environmental and

social impacts by demanding lesser virgin material inputs, thereby promoting conservation of scarce resources.

3.5.3 The Role of Government Policies in Supporting Second-Life Solutions

It can, therefore, be stressed that the level of second-life solar solutions' implementation also depends on governmental policies and regulations to a significant extent. Another very important stakeholder involved in the reuse, refurbishment and recycling is the government as it sets policies that support the implementation of use of reuse, refurbishment and recycling policies and or methods, and offers finance for such projects through partnerships with private firms. Where solar panel wastes are now emerging as an issue, there are policies put in place that make manufacturers liable for the post-use phase of their products.

For instance, **EU's Waste Electrical and Electronic Equipment (WEEE**) Directive ensures that the solar panels producers take financial responsibility for dismantling, treating and recycling the panels once they are no longer in use. It has also led to advancement in technologies that are used in recycling as well as enhancing the take up of second life causes by firms. Such policies are being formulated in other parts of the world especially in North America and Asia where the solar industry is expanding.

Other ways may include offering tax credits, subsidies and grants in order to prompt companies to invest in second life solutions. Such incentives are useful in ensuring that costs such as those incurred through the collection, renovation and sale of solar panels are manageable making these practices more feasible. Moreover, second life arrangements rely on government-backed funding for take-back centers, reverse logistics, and compliance standards for remanufactured photovoltaic panels.

3.5.4 Future Prospects for Second-Life Solutions

With the current trends followed in the solar business across developed and the developing nations, there is room for increased development of second-life solutions. There is a trend in the expanding volumes of decommissioned panels and that fuels desire for technologies of recycling and refurbishment. New technologies available in robotics, for instance, in the disassembly process, and AI applications that may be deployed in the quality check of products for second life imply increased efficiency of solutions, which contributes to economic and environmental gains.

Third, the increase of second-life markets in developing countries as the opportunity to solve the global energy divide. Refurbished and affordable, second-life solutions also guarantee a solution to the energy-deficient areas that hardly have functional and stable electricity grid networks. The outcomes contribute to the **United Nations Sustainable Development Goals-SDGs** [102], particularly the energy, climate change, and economic dimensions of sustainable development.

In conclusion, the second-life solar solutions present the prospects of embracing solar infrastructure as a bridge towards attaining a sustainable and an equitable solar market. In other words, creating an emphasis on 'green' materials also fuels the growth of the industry while also reducing its negative environmental impact – the concept of a 'circular' economy. If supported by influential policy, financing, and important technological developments, the second-life solutions can really become the part of renewable energy framework and contribute to the decarbonization of the global economy.

3.6 The Potential for a Circular Economy in the Solar Industry

Circular economy has been popular in the recent past as industries and organizations across the globe seek for effective ways of managing waste, conserving resources, and thus lowering the effects on the environment. In the case of the solar industry, circular economy means shifting from the current ‘take-make-dispose’ model where the solar panels and their components are used, thrown away and replaced to the closed-loop system where the components are used, remanufactured and recycled. This change offers a big opportunity not only to increase the sustainability of the solar industry but also to create new business and to minimize the negative impacts on the environment. This section aims at analysing the possibility of implementing the circular economy in the solar industry with regards to design, material recycling and policies.

3.6.1 Circular Economy Model in Relation to Solar Panels

In its simplest form, a circular economy seeks to reduce the pool of waste by understanding the need to repurpose, refurbish or recycle products, components, and materials. In the solar industry, these principles entail that solar panels are made in a way that can be uninstalled, fixed, and disposed of in a better way hence improving their lifecycle.
This vision can only be realised if the solar panel manufacturers embrace circular design principles. This means selecting materials and components which can be readily disassembled and removed at the end of the panel life. For instance, if the concept of modularity was to be employed in the production of solar panels, then it would be possible to replace parts of the panels including the cells or the frames without having to dispose of the entire panel. Also, there is a possibility to use bio-based polymers and other eco-friendly materials in the production of panels to decrease the negative influence on the environment and improve the efficiency of recycling.
The following are the advantages of this approach: Through reuse of materials, the solar industry can lessen its dependency on virgin resources such as silicon, aluminum and rare metals, which are costly, and hazardous to the environment due to their extraction and refinement. This in turn can lead to the reduction of the cost of the solar panels and therefore increase the market for companies that deal with the refurbishing or recycling of the solar panels.

3.6.2 Opportunities for Material Recovery and Reuse

Perhaps the most promising of these areas for the solar industry is the recycling and re-use of materials. The element which comprises the solar panels include glass, aluminum, copper, and silicon plus other small amounts of metals like silver and indium which can be retrieved and used again in the creation of other solar panels or other products. Solar manufacturers can thus ensure that these materials are reclaimed and fed back into the supply chain of manufacturing in the event of technological advancements in recycling thus reducing the demand for new raw materials from the environment.

The process of recovery starts with dismantling the used panels where it is possible to take out the glass and aluminum frames and recycle them. Third, silicon and metals from the photovoltaic cells can be recovered by applying more developed recycling methods, for

instance, chemical processing or pyrolysis. They can then be purified and reused in the manufacturing of new solar panels or other state-of-the-art products including semiconductors and electronics.
But it has been identified that there is a lot of potential in material recovery and there are a number of challenges that have to be met in order to realize this potential. One of the main issues that hinder the process is the fact that solar panels have different designs and there is no clear cut way of how to recycle them. Each producer may apply different materials and ways of construction, which makes the process of recycling even more difficult. For this reason, there is a need to ensure that there are attempts made towards the standardization of design within the industry. If manufacturers use standardized materials and assembly methods then the recycling processes can be made easier and efficient for material recovery.
One of the vital aspects of material recovery is the profitability of recycling processes that are in place. At the moment, the expenses required to extract some of the rare metals and materials may be higher than their worth especially when they are in low concentrations. Some of the ways through which governments and other industry stakeholders can enhance the economic viability of recycling include providing incentives in form of subsidies or tax exemptions to firms that spend resources on recycling systems and technologies.

3.6.3 Policy Frameworks Supporting the Circular Economy

Policies and regulations set by the government has been identified as one of the key drivers that influence the circular economy practice in the solar industry. Such regulatory mechanisms as Extended Producer Responsibility (EPR) presuppose that manufacturers are to be held accountable for their products throughout the entire life cycle of the product, including disposal. This encourages the firms to produce products that are easily recyclable and also promotes the need for the establishment of reverse logistics network that is used in recovering the used panels.
The European Union has done much in this regard through the **Waste Electrical and Electronic Equipment (WEEE)** Directive that has some provisions for solar panels. As provided for under the WEEE Directive, manufacturers are obliged to finance the collection, treatment and recycling of panels at their end-of-life, which means that valuable material is reclaimed for reuse and hazardous material handled appropriately. This policy framework has thus led to the development of a market for solar panel recycling in Europe and innovation of recycling technologies.
In the United States, the same approaches are starting to be developed at the state level. For instance, Washington State followed through to become the first state in the United States of America to enact law that requires recycling of solar panels through making the manufacturers come up with recycling programs. Following the suit by other states, circular economy practices in the U. S. solar industry will likely increase in the future.
In the international level, policy coherence and cooperation are important for expansion of circular economy principles in the solar industry. Non-governmental organizations, including the **United Nations Environment Programme (UNEP**), are encouraging the application of circular economy concepts in RE as a part of the general efforts to support sustainable development and accomplish the **Sustainable Development Goals (SDGs).**

3.6.4 Economic and Environmental Benefits of a Circular Economy

The shift toward circular economy model in the solar industry brings a lot of economic and environmental benefits. In economic approach, circular practices will help to minimize the procurement of raw materials hence reduce the costs of resources. New revenue streams can be created for companies that focus on refurbishing, recycling and recovering materials whereas consumers can get solar technology at a cheaper cost due to reduced production costs.
Socially, the circular economy minimises the environmental impact of producing and disposing off solar panels. Thus, the reuse of materials for a longer period will help to minimize the contribution of the solar industry to e-waste, and the detrimental effects of mining and resource extraction. Furthermore, by recycling and reuse of materials, the industry will be able to cut down the energy use and the emission of greenhouse gases and thus make solar energy even more environmentally friendly.

3.6.5 Possibilities of the circular economy in the solar power sector

Therefore, it is possible to note that the potential for circular economy in the solar industry is huge. In the future as the solar technology keeps on advancing, the manufacturers will come up with new materials and designs of the panels that can be easily recycled and reused. States are expected to step up the efforts in supporting the circular economy through policies, measures and cooperation between public and private sectors.
But this is where the crux of challenge lies; it is imperative that the manufacturers, policymakers and the consumers come together to make the circular economy a success. The current section focuses on the need for manufacturers to adopt circular design principles and for material recovery while policymakers must develop policies that support the same. There is also a part of the consumers which also needs to act in a responsible manner by demanding eco-friendly products and advocating for second life products.
Finally, the circular economy can be considered as a highly effective approach that can help promote the further sustainability and resilience of the solar industry. With circular economy principles, the solar industry can sustain its growth and achieve it without compromising the environment and the supply of resources. The change from the prevailing linear model to a circular economy is not only critical for the sustainable future of the solar industry but also for attaining other Sustainable Development Goals.

3.7 Critical Challenges in Implementing Second-Life Solar Solutions

While the potential benefits of second-life solutions for solar panels are substantial, these strategies also face several critical challenges that must be addressed to achieve their full potential. The economic viability, logistical complexities, and infrastructural limitations present significant barriers to the widespread adoption of second-life practices in the solar industry. In this section, we will critically engage with these challenges, offering a nuanced analysis of the obstacles that currently hinder the implementation of second-life solutions and proposing avenues for overcoming them.

Tab 3.1 Challenges and Solutions for Second-Life Solar Panels

Challenge	Description	Strategic Solution
Economic Viability	Recycling processes are often more expensive than the value of recovered materials.	Investment in **innovative recycling technologies** and **public-private partnerships**.
Logistical Complexities	Retrieval of panels from remote locations is costly and logistically challenging.	Development of **reverse logistics networks**, including **regional collection hubs**.
Infrastructural Limitations	Lack of specialized recycling facilities and inconsistent panel designs hinder recycling scalability.	Promotion of **standardized panel designs** and investment in **regional infrastructure**.

3.7.1 Economic Viability of Recycling Processes

Perhaps the biggest problem in the second-life market is the profitability of recycling solar panels. Despite the fact that recycling makes it possible to reclaim valuable materials like silicon, aluminum and rare metals, the costs of disassembling and separating materials, as well as purifying them are frequently higher than the price of the materials retrieved from the recycling process. This is especially so in case of older panel models that were not developed with the recycling element in mind and this leads to low recovery rates and high costs of operation.

The mechanical separation techniques that are in wide use in the field do not always produce high recovery rates, particularly when the material to be separated is as difficult to recover as rare metals, for example, and this makes the whole process uneconomical. Chemical recycling can improve material recovery but it requires a high amount of energy and is quite costly; this is an added challenge to the overall feasibility of such operations. This paper however lacks sufficient information on the current state of recycling technology to support the economic viability of recycling decommissioned panels.

To this end, the industry needs to adopt new recycling technologies that can enhance the recovery of materials and at the same time, cut on the costs of operation. This could be best achieved through public private partnership whereby the government offers subsidies or tax incentives to the companies in order to ease the costs of recycling and make it more plausible. Also, the adoption of uniform recycling systems across the various companies in the industry could make the processes more efficient and cheaper.

3.7.2 Logistical Complexities of Panel Retrieval

Another challenge that arises with the decommissioned panels is the difficulty in the process of recovery of the panels. Solar panels are mainly placed in locations that are hard to access or in sites that do not have access to power such as solar farms. It is also a daunting task to get these panels to recycling or refurbishing centres owing to their size and weight and this requires a lot of funding.

Both the authors noted that there is no clear and well-organized reverse logistics systems in the solar industry that addresses the disposal and transportation of the end of life panels. Many a time, the cost of retrieving these panels from remote regions becomes expensive, and in such a scenario, such panels end up being disposed of in wrong ways or simply abandoned. This not only cancels out the environmental gains of second-life applications but also passes on extra expenses to the sector.

In order to overcome these barriers there is a call for huge investment in the reverse logistics networks. This can help in identification of regional centres where all the decommissioned panels can be collected at one place thus reducing on the transportation costs and ease the recycling process. Moreover, the use of new technologies, for instance, drones or self-driven vehicles to pickup panels from areas which would have been difficult to access could be of great assistance in enhancing efficiency and reducing costs.

There are however some key challenges that have been observed in the application of second-life solutions and one of them is the infrastructural constraints. Although the recycling and refurbishment of solar panels are increasingly in demand, few regions have the required specialized infrastructure to properly dispose of large numbers of solar panels at their end of life. This has the effect of making there be more emphasis on exporting the solar waste to areas that have better recycling facilities which in turn leads to increased environmental effects and costs.

However, the fact that there is no uniformity in the design of panels between the different manufacturers, poses an additional problem for recycling. Different panels from different brands come in different forms and materials, not to mention different ways of assembling them, which in turn makes recycling of such products a complicated task. This variability also exacerbates the challenge of recycling and also negates the potential for large-scale second-life applications.

This paper considers the following challenges in the current design and manufacturing of solar panels to address these infrastructural challenges. Thus, the use of standard materials and technologies in the production of products and in their assembly can help to facilitate the recycling process and decrease the cost and increase the effectiveness of the second life applications. Further, the growth of recycling facilities and other infrastructures in the regions as well as the support of government policies for investments is essential for enhancing the ability to recycle the decommissioned panels in a proper manner.

3.7.4 Strategic Solutions and Future Outlook

The next level of second-life solutions in the solar industry can only be achieved by addressing the economic viability, logistical issues and infrastructural constraints. The challenges include: the lack of public-private partnerships; insufficient investment in

technology; and the absence of adequate reverse logistics systems; all of which can be solved by the following measures. In addition, the role of international cooperation and policy in the shift towards a more sustainable and **circular PV system** is also examined in detail. Thus, by integrating the industry practices with the global sustainability goals and promoting cooperation among the stakeholders the solar industry can overcome these challenges and unleash the full potential of second-life applications.
Thus, it is possible to conclude that despite the numerous difficulties that are likely to be encountered on the way to the widespread use of second-life solutions, the carefully thought-out approach to the use of innovation, collaboration, and investment can pave the way to a better future for the solar industry. Through analysing these challenges, the industry can create solutions which not only work to overcome them but further promote the circular economy in the solar energy sector.

As we can see from this **flow chart**:

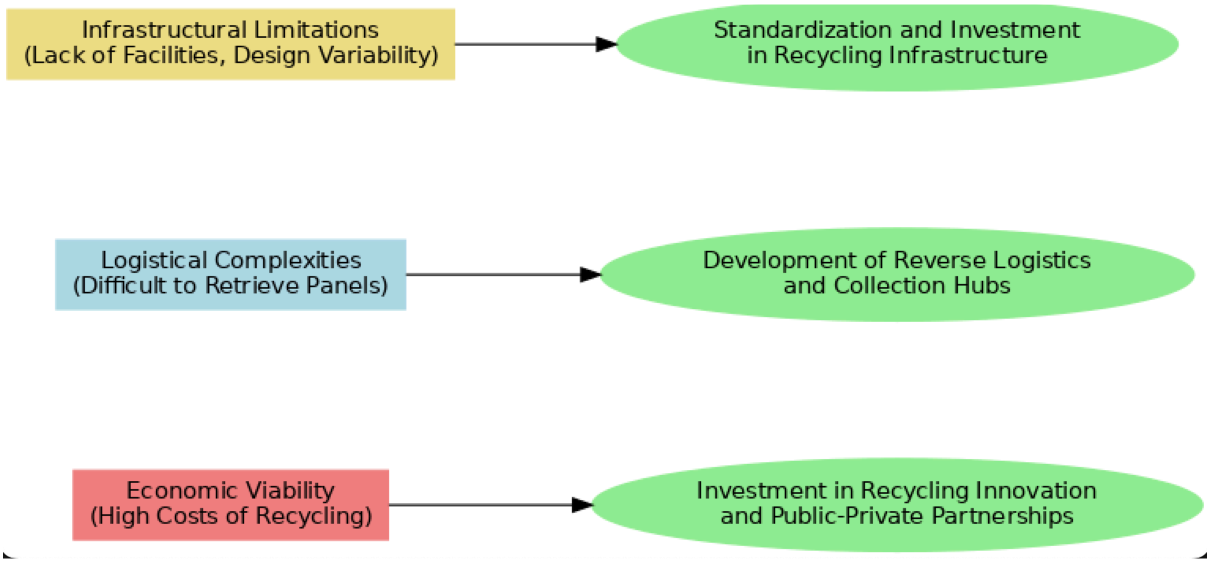

Figure 3.7 *Limitation of Second Life for Solar Panel*

adapted by the author

CHAPTER 4

4.1 Introduction to KeepTheSun

KeepTheSun is an innovative startup born in 2023 through a collaboration between three students from the **Politecnico di Torino**, **Coesa Energy**, a Turin-based Energy Service Company (ESCo), and the Cottino Social Impact Campus. The initiative wants to create the first European e-commerce platform dedicated only to the sale of used photovoltaic panels, providing a certified and transparent marketplace for second-hand solar modules [103]. The idea is born from the desire to develop an innovation project with a high social impact that met the ESG criteria of innovation and renewability. The realisation of this project was made possible thanks to the '**Impact Prototypes Labs**' course at the Politecnico di Torino. The course is a project-based training programme developed by the **Cottino Social Impact Campus** in cooperation with the **Politecnico di Torino** and local companies like, in this case Coesa. The focus of the course is to create **social impact prototypes** to address the challenges posed by partner companies, with the aim of providing innovative solutions that improve business models, organisational processes, governance and services, with a particular focus on sustainability.

4.1.2 Key players

Cottino Social Impact Campus

The **Cottino Social Impact Campus** is Italy's first educational hub exclusively dedicated to **social impact** learning and innovation[104]. Founded with the goal of driving positive change, the campus offers a range of educational programs that integrate social, environmental, and economic sustainability principles. It partners with universities, businesses, and organizations to nurture **impact-driven entrepreneurship**, helping participants develop solutions for real-world challenges. Through its **interdisciplinary** and **experiential** approach, the campus aims to empower future leaders and professionals to act with a strong focus on **social responsibility** and **sustainable development**.

The campus emphasizes **active learning**, blending theory with hands-on experiences, mentoring, and collaborative work with businesses and communities. Its programs target a broad range of learners, from students to professionals, helping them **acquire practical skills** and a **purpose-driven mindset**. By focusing on **impact entrepreneurship** and **sustainable innovation**, the Cottino Social Impact Campus provides an ideal environment for cultivating the competencies needed to drive **social change** in today's complex world.

Coesa Energy

Coesa Energy is a specialized **Energy Service Company (ESCo)** based in Turin, focusing on energy efficiency, sustainability, and renewable energy solutions. The company provides **turn-key projects** aimed at optimizing energy consumption for both public and private sectors. Their services include **energy audits**, **design and installation** of photovoltaic systems, and **attraction of financial incentives** such as the Superbonus. By integrating cutting-edge technologies and environmental standards, Coesa helps clients reduce energy costs, improve sustainability, and increase overall energy efficiency in line with **EU climate goals**.

Coesa Energy is structured to deliver a comprehensive range of services focused on **energy efficiency and renewable solutions**. The company is organized into key divisions that address specific aspects of the energy service process:

1. **Energy Audits and Consulting**: This division performs assessments of energy consumption, identifies inefficiencies, and recommends strategies for optimization.
2. **Project Development and Installation**: The team designs and implements **turn-key photovoltaic systems** and other energy solutions tailored to client needs.
3. **Incentive Management**: Coesa navigates **regulatory frameworks** and secures financial incentives, such as **Superbonus**, for clients, facilitating investments in energy-efficient projects.
4. **Maintenance and Monitoring**: This division ensures that all energy systems are regularly maintained and monitored for optimal performance, providing long-term value.

Coesa's growth is driven by its ability to integrate **economic sustainability** with **innovative energy solutions**, enabling clients to reduce operational costs while adhering to **environmental standards**.

From an economic perspective, Coesa's business model aligns with the increasing demand for **energy-efficient solutions** in a rapidly transitioning market towards renewable energy. Their expertise in navigating **regulatory frameworks** and **incentive programs** positions them as a key player in Italy's energy sector, fostering growth in both **residential** and **industrial** energy solutions. Coesa also addresses energy efficiency challenges through **photovoltaic installations**, helping to meet rising demand for green energy. Their strategic partnerships with companies and startups enable them to continuously innovate and expand their service offerings.

In 2022, Coesa saw a significant boost in its revenue, reporting **€24.7 million**, reflecting a **140% growth** compared to the previous year, a testament to their effective market strategy and the increasing demand for sustainable energy services[105]. This growth underscores the company's ability to navigate the dynamic landscape of **renewable energy**, leveraging both market needs and legislative frameworks to provide **economically viable** and **environmentally sustainable** energy solutions.

4.2 KeepTheSun

KeepTheSun is one of the first marketplace in Europe dedicated to second-hand photovoltaic panels, providing a reliable platform where you can buy and sell tested and certified panels.

The emergence of second-life solar markets is especially relevant in the current economic landscape, where **declining prices for new solar modules** create both opportunities and challenges for the resale of used panels. On the one hand, lower prices for new panels may reduce the financial appeal of second-hand options, still a good use panel can be way more efficient . On the other hand, there remains a significant demand for **affordable renewable energy solutions**, particularly in off-grid installations and regions where access to government incentives is limited. In this context, KeepTheSun wants to position itself as a key player, offering **cost-effective alternatives** that meet the needs of price-sensitive consumers who wants also have an environmental impact, while contributing to the circular economy by fostering the reuse of solar panels in Italy and beyond. Indeed, KeepTheSun aims to position itself not only as an Italian, but also a European and global benchmark. In fact, very often reused panels have more appeal in those rural and remote areas of the world where there is more need for off-grid installations, i.e. (as mentioned in chapter 3) all those installations not connected to the national electricity grids.

Moreover, recent studies indicate that the **global trade in solar waste** is on the rise, with many European countries exporting decommissioned solar panels to other regions where they are refurbished and reintroduced into the energy market. This highlights the **global potential** for second-life solutions, as companies like KeepTheSun tap into this growing supply of used panels and contribute to their reintegration into the energy system. KeepTheSun’s business model is built on **sustainability principles**, emphasizing the importance of **resource recovery** and **waste reduction** while providing economic value to both consumers and the broader energy market.

This represents an opportunity, but also a warning: instead of fostering a sustainable market, it could become a way for Western countries to shift waste to less developed countries, transferring the problem rather than solving it.

The role of **European policies** in shaping this market is also critical. Regulations such as the **Waste Electrical and Electronic Equipment (WEEE) Directive** have placed responsibility on manufacturers for the disposal and recycling of solar modules, creating a regulatory framework that supports the growth of second-life solutions.
As policy initiatives continue to evolve, companies like KeepTheSun are uniquely positioned to benefit from the increased focus on **sustainable waste management** and **resource efficiency** across the European Union.
In this chapter, we will explore KeepTheSun's business model, focusing on how the company capitalises on key economic, regulatory and environmental developments. The analysis will highlight KeepTheSun's approach in dealing with logistical obstacles in acquiring, testing and reselling second-hand solar panels, while ensuring that strict quality and performance standards are met. In addition, we will explore the company's potential for international expansion, benchmarking itself against other companies operating in the growing second-hand solar market. The discussion will offer an assessment of the opportunities and challenges facing the second-hand solar industry, highlighting the market prospects and environmental benefits of initiatives such as the start-up KeepTheSun.

4.2.1 Business Model

The business model of **KeepTheSun** is centered around the creation of a **digital marketplace** for second-life solar panels, designed to address both environmental challenges and market demand for affordable renewable energy solutions.
As one of the first platform of its kind in Europe, KeepTheSun provides a secure and reliable space for the **buying and selling of refurbished solar panels**, offering a sustainable alternative to the traditional solar industry. This model leverages the principles of the **circular economy**, where products are reused, refurbished, and resold, extending their lifecycle and reducing waste.

Business Model scheme

1. Platform-Based Business Model
- **Function**: A platform that facilitates transactions between buyers and sellers.
- **Key Feature**: Operates within a **regulated and transparent framework**.

2. Sellers
- **Who**: Owners of solar installations that are being **revamped** or **decommissioned**.
- **Action**: Sellers list their **used solar panels** on the platform.

3. Testing & Certification Process
- **Partnership**: Testing is conducted in collaboration with **Coesa Energy**.
- **Process**: Each panel undergoes **rigorous testing** to ensure:
  - **Performance standards** are met.
  - Panels are reliable and efficient.
- **Outcome**: This process is essential for **quality assurance**, a critical concern in the second-life solar market.

4. Buyers
- Engage on the platform, confident in the **certified quality** of the refurbished panels.

KeepTheSun operates on a **platform-based business model**, which allows both buyers and sellers to engage in transactions within a regulated and transparent framework. Sellers, often owners of solar installations undergoing **revamping** or decommissioning, list their used panels on the platform. Each panel undergoes a **rigorous testing and certification process**, carried out in collaboration with **Coesa Energy**, to ensure that it meets the required performance standards. This testing phase is crucial, as it guarantees the reliability and efficiency of the refurbished panels, addressing a key concern in the second-life solar market: **quality assurance**.

The business model is structured around multiple revenue streams. First, KeepTheSun charges **listing fees** to sellers who wish to post their solar panels on the marketplace. These fees can be adjusted based on the service level selected by the seller, such as **basic listing services** or **premium testing and certification services**. Additionally, KeepTheSun could generates income from **advertising** and **sponsorship deals** with companies looking to gain visibility in the renewable energy space. By offering both basic and premium services, the company ensures that it can cater to different market segments, from small-scale sellers to larger corporate players.

A significant **value proposition** of KeepTheSun is its ability to offer **affordable solar energy solutions** to underserved markets. In particular, refurbished panels sold through the platform are often purchased by entities in **developing regions**, where access to new solar installations may be cost-prohibitive. This aspect of the business model aligns with global trends in **solar waste management** and the **expansion of off-grid energy solutions**. Recent reports indicate that the **secondary market for PV modules** offers significant cost advantages, particularly in the U.S. and other regions where the price of new solar modules has dropped.

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4.3 Market Potential and Opportunities

The market potential for second-life solar panels is expanding significantly as both **economic pressures** and **environmental concerns** drive demand for affordable and sustainable energy solutions. According to recent studies, the global push towards a **circular economy** has opened new opportunities for companies like **KeepTheSun**, which capitalize on the reuse and refurbishment of photovoltaic modules. This business model addresses the increasing volumes of decommissioned solar panels expected to reach between **60 to78 million tons by 2050**, while providing cost-effective alternatives for consumers in both developed and developing regions.

As reported in "End-of-Life Management: Best Practice Guidelines" a report by solar power europe investigating best practices for managing the end-of-life of solar panels, the report indicates that **more than 50% of photovoltaic panels** deemed as waste are still functional and could be reused. For calculation purposes, let's assume **50%** as the lower bound. As said in chapter 3, the projected waste volume is **60 million tons** globally by 2050 and if **50%** of these panels can be reused, then:

Reusable Waste

Volume: *60 million tons×50%= 30 million tons*

Market Potential for Reusable Panels:

The estimated **market potential** for second-hand panels globally is **€20 billion annually**.

If **50%** of the panels are reusable, the **market value** of reusable panels could potentially be **€10 billion annually**.

Italian Market Share:

As calculated previously, the **Italian market share** of the global PV capacity is approximately **1.92%**. Applying this percentage to the **€10 billion** market potential:

10 billion euros×1.92%≈192 million euros annually

With the new assumption that **50% of the PV panels deemed as waste are reusable**, the estimated **market size for the second-hand photovoltaic panels in Italy** could be **approximately €192 million annually**. This value represents a significant opportunity for the circular economy, assuming that reuse can be conducted under safe and environmentally sound conditions.

There is not much competition on a global or European level because the topic of solar EoL is still a very young topic. Although KeepTheSun endeavours to find customers worldwide, its competition is European specifically in Germany, namely SecondSol GmbH an online platform that sells both new panels and spare parts and has recently also opened up for second-hand sales.

Unlike KeepTheSun, SecondSol operates a 10,000 square metre warehouse in central Germany, but this is mostly used for storing spare parts, and therefore like KeepTheSun does not directly handle the storage of used panels advertised online on their site. The type of business of both players is very similar. The seller places the ad on the site free of charge, after which he will be contacted by a buyer. Logistics are not handled by the players but are the responsibility of the seller, while the buyer pays a commission to the platform for the purchase of the panels. If, on the other hand, Coesa, through collaborations or partnerships, undertakes to assess the condition of the panels or to recycle them if they cannot be reused, SecondSol merely acts as a third party partner in the buying and selling of these used goods.

A major driver of **second-life market** is the reduction in the cost of the fresh solar modules which has been established in the report by PV Magazine. While lower prices seem to reduce the appeal of second-hand panels, they have increased the growth of demand for secondary market panels, especially for the USA and European countries where second-hand panels are considerably cheaper than new ones, for example, for distributed off-grid installations and small PV plants. KeepTheSun is correct placed to capitalise on this trend as it sources and provides tested, accredited second-life panels in its marketplace. Another factor is that company's products and services are relatively cheap, thus fitting lower demand categories as well as areas of the world where access to rebates is limited. It also important to note that the exportation of solar waste has now assumed the role of a market mover especially in Europe. From a study on the dumping of solar waste, prevalent across Europe, many nations are exporting old panels to nations where they can be fixed and returned to the power system. This trend shows that second-life solar is global in nature and that there are entities like KeepTheSun ready to organize effective supply chains for the recycling and trading of such panels. As such, KeepTheSun has connected with recyclers and logistic firms to guarantee that its approach to handling second-life panels is both environmentally friendly and expandable, to meet the increasing market demand.

In **Europe**, the market for second-life panels is primarily driven by **revamping projects**. Many of the region's early solar installations are approaching the end of their peak efficiency periods, leading to a surge in demand for replacement panels. The European **WEEE Directive** has played a crucial role in shaping this market by mandating that manufacturers are responsible for the disposal and recycling of PV modules. This regulation has fostered the growth of solar panel recycling industries across Europe and has created a favorable environment for businesses like KeepTheSun to thrive. By aligning its business model with these regulations, KeepTheSun not only complies with **legal standards** but also positions itself as a leader in **sustainable waste management** and resource recovery.
The **U.S. secondary market** also presents new opportunities for KeepTheSun. As recent reports have shown, the declining prices of new solar modules in the U.S. have opened a window for the resale of used panels, offering buyers significant cost savings while contributing to the **expansion of solar energy** in off-grid and low-income regions. KeepTheSun's robust testing and certification processes ensure that the second-life panels sold on its platform meet high standards of quality and reliability, making them a competitive option in a market where affordability is paramount.

Second-life solar markets are developed on the basis of **circular economy** which is the main factor of their growth worldwide. KeepTheSun, for instance, ensures that it offers affordable and renewable solar panel solutions by emphasizing on reuse, revamping and recycling, refurbishing of solar panels. It has, however, noted such models in its efforts to protect the solar industry and minimize the generation of wastage. This change towards sustainability alongside the increasing awareness of the benefits of repurposing panels makes KeepTheSun well-placed for future expansion. Since KeepTheSun continues to improve the quality of its solar products as it aims for growth, the company's focus on customer satisfaction will help it meet the needs of the growing market for affordable solar products in emerging markets such as **Africa, Asia, and Latin America**.

In sum, the market prospects have not yet been exhausted by second life solar panels owing to ever increasing demand of cheap energy, increasing problem of waste management and emergence of circular economy business models. KeepTheSun is in a rather favorable to capture these trends as the company would address the problems posed by solar waste while generating value for consumers and the economy. Through its simple yet effective business model of supporting the provision of used, yet fully verified, panels, **KeepTheSun** is paving the way not only for the future of global solar markets but also for a sustainable future of those markets that will not sacrifice revenue to be environmentally friendly.

According to market news from Solar Power Union the second-life module market is growing with the amount of decommissioned modules rising and will rise dramatically with time. Such growth is economical as well as environmental because many of them are looking for second life application to avoid e-waste and bring affordable power to people. Notably, used panels tend to cost **30-50%** less than new ones and this comes with a huge advantage for markets which struggle to make large upfront investments or markets that consider initial costs as prohibitive. For instance a **250 watt** second hand solar panel costs between **$70 and $150**, while a new one cost between $150 and $300. This price advantage promotes the deployment of refurbished panels in developing areas; such devices help to achieve a sustainable development outlook in application areas such as off-grid solar home systems and community mini-grids (SolarReviews, 2024).

Table 4.1 Comparison of New vs. Used Solar Panels

Panel Condition	Price Range (USD)	Typical Efficiency	Best Use Cases
New	$150 - $300	100%	High-demand installations requiring maximum efficiency
Used (250-watt)	$70 - $150	80-90%	Budget-conscious projects, off-grid installations, developing regions

Data: SolarReviews - All About Used Solar Panels, IRENA, End-of-Life Management: Solar Photovoltaic Panels, 2016, IRENA, End-of-Life Management: Solar Photovoltaic Panels, 2016

4.4 Regulatory Landscape and Policy Framework

The governing framework, and policies influencing second-life solar panels are instrumental in determining the formation and advancement of this market. It has been appreciated globally and at regional levels that sustainable waste management and circular economy have become a major concern, especially given the increasing use of renewable energy. In Europe such policy known as Waste Electrical and Electronic Equipment (WEEE) Directive has been used in guiding the disposal, recycling, and even refurbishment of photovoltaic (PV) modules. This directive makes manufacturers take accountability of the management of solar panels at their end of their life cycle ensuring sustainability within the industry. The business model of the KeepTheSun is in compliance with these regulations and enables the company to function in accordance with the described rules of the European Union. Since second-life panels have the potential to be sold in the market, it is equally important for KeepTheSun to alert consumers and buyers that all its second-life panels meet the legal requirements of environmental and safety standards, thereby setting itself up as an ecological benchmark for other solar industries. EU renewable energy legislation has also been especially favorable to firms advocating resource conservation and waste minimization, which will strengthen the market for second-life modules for solar panels. Other parts of the world are also following the same trend where they put measures that ensure that the solar panels are recycled or reused. For instance, in the United States, there are gradually rising state-level policies governing the problem of solar panel waste. These policies are encouraging the formation of secondary markets for solar modules allowing for growth of players such as KeepTheSun. Likewise, the developing nations are slowly waking up to the realisation that second-life solar panels actually make great economic and environmental sense and that some of the developing nation governments are actually encouraging investors to take up the refurbished solar technologies. Second-life solar markets are also on the rise which are aligned with circular economy policies as regulators around the worldwide are passing new policies to come up with means that could give a second life to the panels. It can be assumed that those enterprises that orient their activities through compliance with such frameworks will receive additional stimuli and opportunities, as policymakers improve the regulatory environment.

KeepTheSun is well-positioned to take advantage of these developments, leveraging its compliance with environmental standards to expand its market presence and build **strong partnerships** with stakeholders who are committed to sustainability.

In conclusion, the regulatory landscape is a driving force behind the expansion of the second-life solar panel market. Policies that promote the reuse and recycling of PV modules are creating new avenues for growth and ensuring that companies like KeepTheSun can thrive while adhering to strict environmental guidelines. As the global focus on sustainability continues to intensify, the regulatory support for second-life solar solutions will likely increase, providing a solid foundation for future market expansion.

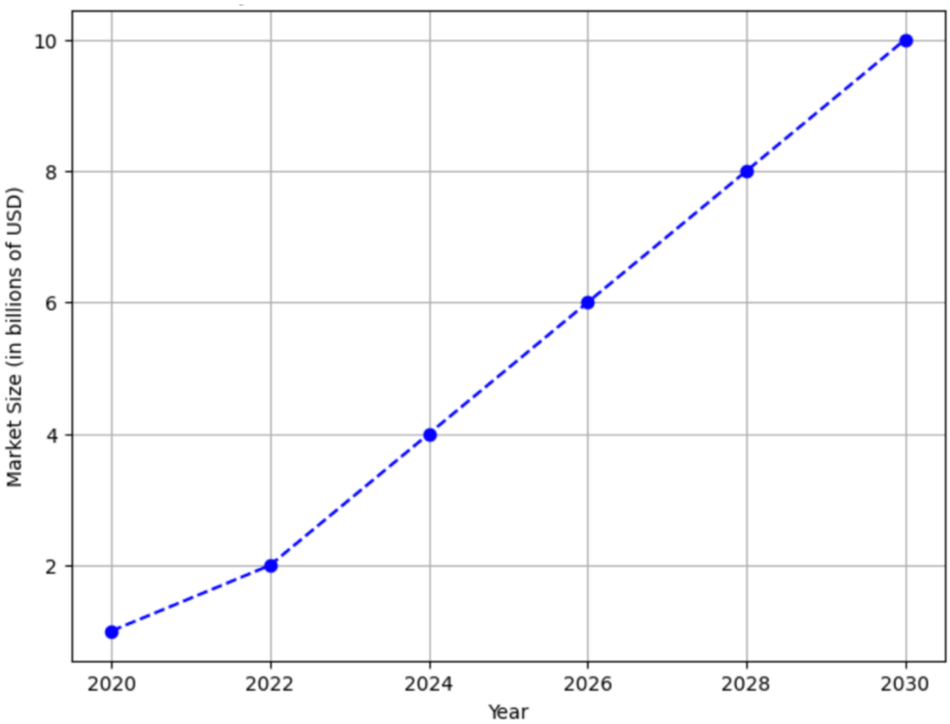


Figure 4.1 *Projected growth of Global Second-Life Solar Market*

Data: European Commission, Study on the EU Solar PV Panel Market & Circular Economy, 2023, EA, Global PV Market Trends, annual reports. RENA, Renewable Energy Statistics, updated annually, Adapted by the author

4.6 The Potential for a Circular Economy in the Solar Industry

The idea of circular economy has recently emerged as an important principle in the context of solar energy, especially in regard to commonplace problems encountered when dealing with end of life photovoltaic (PV) panels.

Circular economy is defined as a closed economy where owners and users of products find ways to reuse, refurb and recycle these products on their last stage. Alternatively, within the solar sector, this approach is based on the concepts of increasing the solar panels' service life and reducing the adverse effects they have on the environment. The shift to circular economy system in the solar industry has its following advantages. The first is the environmental improvement through the reduction of raw material since the utilization and renewal of solar panels are key to cutting the usage of silicon, silver, and aluminum.

These materials are difficult and energy-consuming to mine and purify and therefore if their utilization in solar panels manufacturing is decreased this their energy impact would be reduced. This is in line with broader sustainability goals going forward as well as the

European Green Deal that focuses on issues to do with efficient use of resources and managing wastes. Apart from generating revenue through the resale and reuse of these panels, KeepTheSun has a noble responsibility of minimizing solar waste. It serves as the example of how economic feasibility can be derived at the benefits of sustainable strategies while providing a baseline for both ecological and economical needs. Furthermore, the factor of implementing the circular economy in the solar industry has fueled innovation.

While corporations spend money to invent and innovate, innovations for the ability of disposed of and longer durability of the solar panels are being developed. Technological advancements like the improved design of panels that facilitate disassembly, developments in material recovery processes that will likely lower costs of recycling, and improvement of processes enhancing material recovery are some of the numerous indications supporting the economic benefit of circular economy initiatives. In general, it can be concluded that KeepTheSun has identified all necessary factors of the circular economy and applies them while creating a successful and efficient environment for a sustainable business.

Since the company provides an opportunity to buy and sell refurbished solar panels, the company contributes to reducing solar waste and the shift towards a cleaner energy source. Integrating KeepTheSun's operations into the global trends in sustainability places the firm in a strategic vantage point in the incipient market for repurposed solar panels.

In conclusion, the potential for a circular economy in the solar industry is substantial, offering significant environmental and economic advantages. Companies like KeepTheSun are at the forefront of this shift, demonstrating that it is possible to build a successful and sustainable business by embracing circular economy principles. As the solar industry continues to evolve, the adoption of these practices will likely become more widespread, driven by technological advancements, regulatory support, and growing consumer demand for sustainable energy solutions.

4.7 Social and Ethical Considerations in the Second-Life Solar Market

As the market of second-life solar applications grows, the social and ethical implications regarding the reuse and refurbishment of photovoltaic (PV) panels should be further discussed. Albeit, there are numerous economic and environmental advantages of increasing the efficiency of the usage of solar panels but other social realities of practice including community impacts, labor relations, and equality in access to energy, have to taken under consideration. On of the more significant ethical issues in second-life solar market is about exporting solar waste to the third world countries. According to recent research, there are rising cases in which old solar panels are shipped from Europe and the United States to other parts where they can be reconditioned and resold. On a positive note this can make energy accessible to relevant communities but can also feed cheap substandard panels to new markets and cause serious environmental and health impacts if they are not competently refurbished or recycled. This means that exports are transferred with environmental burdens when the panels are produced in developed countries while they meet safety and performance standards before exportation to developing nations. Nevertheless, the existence of the second-life solar market can influence labor practices in the industry. When firms such as KeepTheSun grow their business they must guarantee that the work of people involved in the renovation and resale of solar panels meets fair labor practices. These are to cover matters such as working conditions, wages, non-exploitation in areas that lack robust labor laws with specific reference to various countries that are target markets. It should be noted that ethical labor practices are not only highly desirable from ethical perspective but are also profitable for business and execute a sustainable model of organizational management. Another social issue is equal usage rights for energy. The second-life solar market in particular is a perfect commodity to introduce cost effective solutions for energy-starved areas that do not have reliable electricity. However, there is potential of this market developing in a fashion that can increase injustice since while the refurbished panels will be used by the well off areas and the energy poor areas remain neglected. To this end, it is critical for firms in the second-life solar market to ensure that they distribute their products in a manner that enhances energy democracy where all groups of people in society will get to enjoy clean and affordable energy.

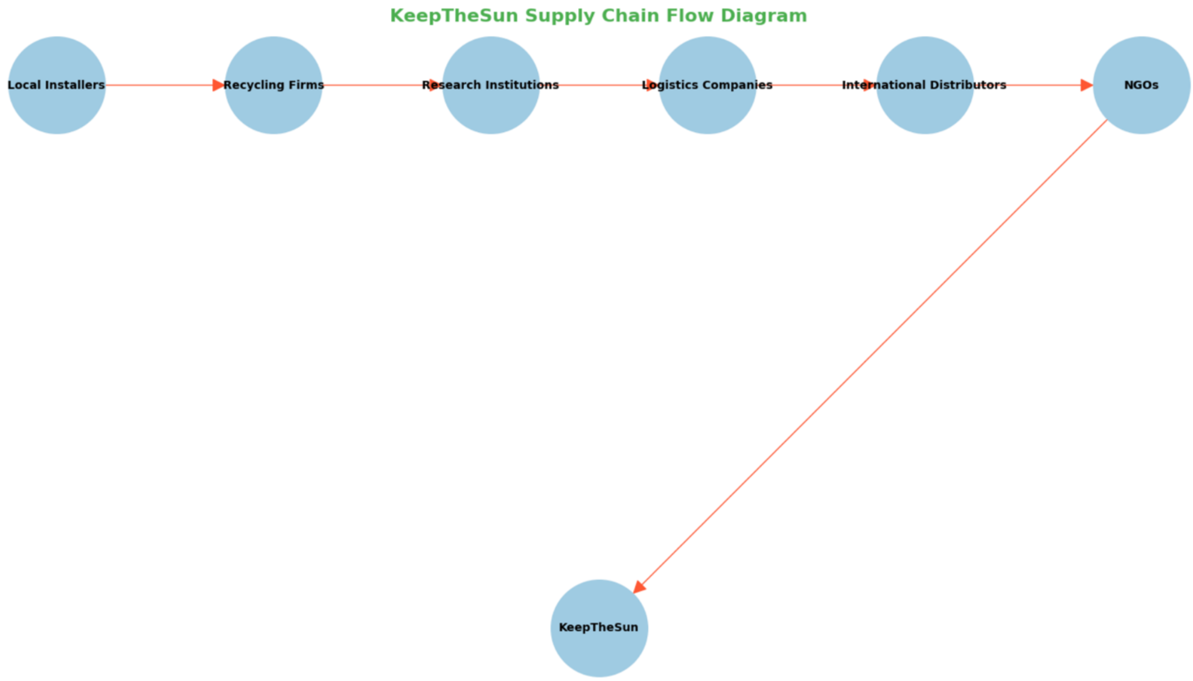
KeepTheSun is ready to consider and solve these social and ethical issues in order to implement its mission of making second-life solar panels' market sustainable and integrated. Some of the policies developed in the company's business model cover the testing and certification of all refurbished panels to justify their safety and performance on the market. Moreover, KeepTheSun collaborates with organisations that advances appropriate labour relations and energy justice to ensure the company's actions benefit the societies it serves. Summing up it can be stated that the second-life solar market is also positive for the environment and in terms of its economical contribution, it is also remarkable but nevertheless important to recognize such a market's social and ethical impact. Being a business, KeepTheSun has a social responsibility to call for special attention so that its operations and profits are got without infringing the rights of the society. In doing so the second-life solar market has the potential to foster greater sustainability outcomes worldwide and enhance social justice endeavors.

4.8 Strategic Partnerships and Collaborations in the Second-Life Solar Market

As the second-life solar market contiuously develops, defining key success factors have surface with partnership and collaboration as key drivers. With the growth of the use of refurbished photovoltaic (PV) panels, supply chain management, product quality assurance, and market access need to be coordinated and aligned with participants with complementary capabilities. To elaborate, strategic partnerships help the firms like KeepTheSun to reach the intended goals and pick up new opportunities that may not be feasible to unlock individually. For example, working with companies involved in recycling and research organizations helps KeepTheSun to remain on the cutting edge of new developments in panel restoration and recycling processes. These entities must be supportive of KeepTheSun to improve the company's business model adoption of advanced technologies suitable for running efficient and sustainable business models. These partnerships are useful for countering the technological issues discussed in previous sections including enhancing rates of material recovery and ideally presenting less costly recycling technologies. Further, strategic supply relationships with logistics service providers, and local installation companies are necessary for co-coordinating the complex value chains in the second-life solar market. The proper flows of flows, collection, transportation and distribution of the used panels are very important especially in the areas where the infrastructure is relatively not developed. To implement efficient transportation of its refurbished panels to clients all across the world, KeepTheSun needs the support of local partners who understand the logistics of the local markets adequately. The third important function is in market access and growth of operations, which is a cornerstone of strategic partnership. With partnerships with global distributors and energy companies, KeepTheSun can reach out to new customers in these areas where the need for affordable solar systems is anticipated to increase. These affiliations are also useful for entering new markets, but give the company valuable information about the local market that it can then use in marketing its service, which KeepTheSun has done by creating packages that address localized needs. Coordination with such authorities and other policymakers is further necessary to effectively address the second-life solar market's complex compliance structure. Communicating with regulators is beneficial for KeepTheSun to know about new standards that needs to be complied and be able to push for beneficial policies towards circular economy. Despite being in its infancy, KeepTheSun can engage policy-makers and industry organisations to influence policy environments of second-life solar products to support sustainability outcomes without stifling innovation.

Furthermore, **partnerships with NGOs and community organizations** play an important role in addressing the social and ethical considerations of the second-life solar market. By collaborating with organizations that promote **energy access and equity**, KeepTheSun can help ensure that the benefits of refurbished solar panels are distributed fairly and reach underserved communities. These partnerships enhance the company's social impact, aligning its business objectives with broader societal goals such as reducing energy poverty and promoting sustainable development.
In conclusion, strategic partnerships and collaborations are fundamental to the success of companies operating in the second-life solar market. For KeepTheSun, these alliances enable technological innovation, logistical efficiency, market expansion, regulatory compliance, and social responsibility. By leveraging the strengths of its partners, KeepTheSun is well-positioned to lead in the growing market for second-life solar panels, ensuring that its operations are both profitable and sustainable.

KeepTheSun Supply Chain Flow Diagram



The diagram highlights the importance of **strategic partnerships** in the successful operation of KeepTheSun's business model. Each node represents a key partner or a critical phase in the process:

1. **Local Installers**: Responsible for collecting used solar panels from installation sites.
2. **Recycling Firms**: Manage the refurbishment and recycling process, preparing the panels for reuse.
3. **Research Institutions**: Collaborate to develop advanced technologies that improve the efficiency of recycling and material recovery.
4. **Logistics Companies**: Ensure the efficient transportation of refurbished panels to their destination markets.
5. **International Distributors**: Facilitate access to global markets, enabling KeepTheSun to expand its international presence.
6. **NGOs**: Support the distribution of panels to underserved communities, promoting equitable access to energy.

Final Considerations

The primary research question of this thesis is to reveal the nature of solar waste. Currently, only a few know about the this growing problem, however, by 2050 a total-solar waste production is expected to reach 70 million tons. This is the case of solar panels, where the production process has a number of environmental benefits in the short term provided that the products do not emit pollutants during electricity generation but this presents a problem when the panels get old and are replaced by newer models. The new panels are now optimized and cost-effective that gives a new impetus to replacing the older ones but can this frame work become sustainable as well is another question. The world we live in is not a product today for the West to consume endlessly without facing bitter consequences; it is time for the folks of the future. Projects like KeepTheSun are imbued with regard to sustainable values and disrupt the logic of purchase and discard that dominate the modern economy, offering the circulation and longevity of items. Despite the fact that the proliferation of such initiatives takes time and the concept of sustainability is in its infancy, projects like KeepTheSun are a move in the right direction to a world where business and the environment complement each other. Coesa's KeepTheSun in conjunction with Politecnico di Torino's project has dedicated itself into the recycling of the panels instead of recycling the solar waste that is accumulating around the world. To ensure the longevity of photovoltaic panels, and to address the issue of the end-of-life management of such technologies, the project aims to introduced the principles of circular economy to the solar industry. The photovoltaic market surpassed a cumulative capacity of 1,581 GW by the end of the year 2023 across the global with phenomenal growth in China and Europe region. Photovoltaic systems with a total capacity in Italy of 30,319 MW, are dominated by small-scale residential systems ~3,141 MW, or 10.42%, that is 21% more than in the previous year. As with any waste generation activity, with this growing solar energy capacity also comes the need for handling decommissioned solar panels – hence efforts like KeepTheSun that aims at repurposing these panels. Solar waste is expected to increase to 60 million tons by 2050 and this is influenced by increase in replacement frequency

KeepTheSun aims to intercept these decommissioned panels and refurbish them, making affordable solar technology available, especially in off-grid markets and developing regions where energy access is limited and costs for new installations are prohibitive. Market analysis shows significant potential for second-life panels in these contexts. KeepTheSun's focus is on refurbishing decommissioned panels to reintroduce them into the market. This involves addressing common defects such as delamination or faulty diodes. However, variability in quality presents a major challenge, as consumers may be hesitant to adopt panels with inconsistent performance. Recycling, while not the primary goal of KeepTheSun, is also discussed as a context for comparison. Methods such as mechanical, thermal, and chemical recycling often have limitations related to efficiency, cost, and environmental impact. Refurbishment, by contrast, offers a more sustainable and practical option, preserving much of the value embedded in the original panels while avoiding the challenges of traditional recycling. The reuse of photovoltaic panels offers clear economic and environmental advantages. Economically, reducing the need for virgin materials lowers production costs and provides price stability for raw materials. Reusing panels also helps lower the levelized cost of energy (LCOE), making solar energy more accessible in emerging markets. Environmentally, extending the life of panels reduces electronic waste and minimizes the need for extracting and processing rare materials, thus limiting environmental impact. Government incentives play a crucial role in the feasibility of such projects. Policies that support the circular economy, such as tax credits or subsidies for companies investing in panel reuse, could significantly enhance the project's viability. The European WEEE directive, which mandates manufacturers to finance the collection and treatment of decommissioned panels, serves as an example of the kind of regulatory support needed. KeepTheSun's strengths lie in its alignment with sustainability goals and its ability to provide cost-effective solutions for energy access in underprivileged areas. The project has substantial environmental benefits by reducing waste and minimizing the demand for new raw materials. However, challenges such as variability in the quality of refurbished panels, consumer trust, and logistical complexities remain significant hurdles. The long-term feasibility of the project will heavily depend on external support, particularly from government policies and incentives.

KeepTheSun started with a small enthusiastic team as a young startup; it is their primary target to obtain consumer trust and to work on quality of their products, which was reached through the effective refurbishment. Proper backing could make KeepTheSun a key driver for enhancing the circular economy of solar panels and the outlook of the solar industry. But more advancement and affirmative patronage are needed since it stands as still the nascent work. On the strengths, weakness, opportunities and threats of reselling refurbished solar panel, the factors include the following; The reselling of refurbished solar panel has the following strengths; Cost of production is low because these types of panels are recycled, they are efficient in some ways since they do not produce any waste by products, and they address a rising market need for cheap sources of energy in the developing countries. Some problems include; the level of quality of the refreshed panels that can be obtained; the customers themselves have no confidence in second life products; there are questions on how to get them to refresh the panels. The risks of the project: The promise of government grants for circular economy schemes, the idea that such panels are currently unused in similarly developed countries where affordability heavily dictates its application of renewable energy schemes, the potential that such newer engineering breakthroughs add to the value of second-life panels. Threats are notably: competitors through new developing technologies which could provide more cheap new solar panels, legal barriers affecting the market for second hand panels, and economic challenges through volatile economies of the refurbishing methods though no steady market support. At the present we can enable a new future in which the innovative impulse and sustainable line intertwine and such a future is possible to build at the present time with joint forces.

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