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WASTE POTENTIAL AND RECYCLING OF PHOTOVOLTAIC PANELS AT THE END OF THEIR ECONOMIC LIFE, A CASE STUDY ON RECYCLING WITH THE GLOBAL SITUATION

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Sultan Büşra ARTAŞ

ABSTRACT

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With the increasing use of photovoltaic (PV) panels, there is a growing concern about the waste they produce at the end of their life. In parallel with the production rates of PV panels, which have an average lifespan of 25-30 years, the potential increase in PV waste in the recent years is also a cause for concern. Projections indicate, global PV waste could reach 60-78 Mt by 2050. Meeting this challenge requires expertise in PV panel structures and waste management strategies. This study aims to make a comprehensive assessment of PV panel waste and the critical role of recycling in reducing environmental impacts, with pros/cons. Waste projections for PV panels on a global scale and specifically in Turkiye are thoroughly analyzed, providing critical insights into the future challenges and opportunities in handling PV waste. Therefore, a detailed case study focusing on the Karapinar Solar Power Plant is conducted in this study, projecting the waste generation and management aspects until 2050. As a result, it has been calculated that 15,662 x 10^6 kg-CO_2 emissions in 2040 and 53,303 x 10^6 kg-CO_2 emissions in 2050 will be prevented through recycling.

Key Words: Solar energy, PV panel, PV panel waste, Recycling of PV panels, Environmental impact.

ÖZET

EKONOMİK ÖMRÜNÜN SONUNDAKİ FOTOVOLTAİK PANELLERİN ATIK POTANSİYELİ VE GERİ DÖNÜŞÜMÜ, MEVCUT KÜRESEL DURUM İLE GERİ DÖNÜŞÜM ÜZERİNE BİR VAKA İNCELEMESİ

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Fotovoltaik (PV) panellerin kullanımının artmasıyla birlikte, ömürlerinin sonunda oluşturacakları atık konusunda endişeler artmaktadır. Ortalama çalışma ömrü 25-30 yıl olan PV panellerin üretim hızlarına paralel olarak, önümüzdeki yıllarda PV atığın artış potansiyeli de endişeleri artırmaktadır. Tahminler, 2050 yılına kadar dünya çapında 60-78 Mt'luk bir PV paneli atığı olacağı göstermektedir. Bu zorluklarla başa çıkmak için PV panel yapılarının ve atık yönetimi stratejilerinin derinlemesine anlaşılması/bilinmesi gerekmektedir. Bu çalışma, PV panel atığı ve çevresel etkilerini azaltmada geri dönüşümün önemini, avantajları ve dezavantajlarıyla birlikte kapsamlı bir değerlendirme yapmayı amaçlamaktadır. Küresel ölçekte ve özellikle Türkiye'de PV paneller için atık tahminleri titizlikle analiz edilmekte ve PV atık yönetimi konusunda gelecekteki zorluklar ve fırsatlar hakkında önemli bilgiler verilmektedir. Ayrıca, Karapınar Güneş Enerjisi Santrali'ne odaklanan, atık üretimi ve yönetimini 2050 yılına kadar öngören ayrıntılı bir vaka çalışması yapılmıştır. Sonuç olarak geri dönüşüm yapıldığında 2040 yılında 15.662 x 10^6 kg-CO_2 , 2050'de ise 53.303 x 10^6 kg-CO_2 emisyon miktarının önleneceği hesaplanmıştır.

Anahtar Kelimeler: Güneş enerjisi, PV panel, PV panel atığı, PV panellerin geri dönüşümü, Çevresel etki

‘’ I would like to thank my dear family, who have always been by my side and provided me with strength through their presence, and my mentors Prof. Dr. Recep YUMRUTAŞ and Assoc. Prof. Dr. Hüseyin YAĞLI.’’

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LIST OF SYMBOLS

E_{ave}	Average amount of CO_2 emission reduction
E_e	Early-loss
E_{ep}	Amount of CO_2 emission reduction for early-loss
E_r	Regular-loss
E_{rp}	Amount of CO_2 emission reduction for regular-loss
T_{ae}	Area covered by early-loss
T_{ar}	Area covered by regular-loss
W_p	Watt peak

LIST OFABBREVIATIONS

AC	Alternative current.
CIGS	Copper Indium Gallium Selenide
DC	Direct current
EOL	End of Life
EPBT	Energy Payback Time
EVA	Ethylene Vinyl Acetate.
GW	Gigawatt
GWP	Global Warming Potential
Gt	Gigaton
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour
µm	Micrometer
Mt	Million Tons
NIOSH	National Institute for Occupational Safety and Health
OECD	Organisation for Economic Co-Operation and Development
PV	Photovoltaic
SPP	Solar Power Plant
TPT	Topotecan Hydrochloride
TW	Terawatt
V	Volt

Al	Aluminium.
Cd	Cadmium
$CdCl_2$	Cadmium chloride
CdS	Cadmium sulfide
CdTe	Cadmium telluride
CO_2	Carbon dioxide
Cu	Copper
Ga	Gallium
HNO_3	Nitric acid
In	Indium
Mo	Molybdenum
NH_3	Ammonia
Pb	Lead
Se	Selenium
SF_6	Sulfur hexafluoride
Si	Silicon
Sn	Tin
Te	Tellurium
Zn	Zinc

CHAPTER 1
INTRODUCTION

There has been a consequential growth in the requisition for energy, as the world's population continues to rise and economic landscapes undergo significant transformations. This increase has been further amplified by the accelerated pace of industrial production and the rapid advancements in technology that our society is witnessing. Energy plays an absolutely pivotal role in this scenario, serving as the bedrock that supports various critical aspects of our modern society.

From powering homes, businesses, and industries to fueling transportation systems and advanced technological infrastructures, energy availability and consumption significantly impact the quality and progression of our lives. It is instrumental in maintaining social welfare by providing basic needs such as lighting, heating, and cooking, as well as more advanced necessities like communication and access to information. Furthermore, energy availability is closely tied to economic growth and development, creating jobs, and driving industrial and technological advancements, hence, playing a fundamental role in enhancing the overall quality of life for individuals around the globe [1]–[3].

Moreover, energy is an essential pillar of social security. A dependable and cost-effective energy supply is necessary for the functioning of critical public systems including health care, emergency services, and utilities. It additionally assumes a pivotal role in ensuring the integrity of various elements of national security[4] Thus, energy is not only fundamental to our daily lives but also a vital component in maintaining societal stability and security, illustrating its growing significance in an increasingly interconnected and complex world.

According to the International Energy Agency, global energy demand stood at 109.3 exajoules (EJ) in 2020 and is projected to surge to 143.1 EJ by 2040. This escalating demand places significant pressure on finite global resources, particularly fossil fuels, which nowadays supply the most of the world's energy and contribute significantly to climate change [5] To counteract these challenges and fulfill the rising demand sustainably, it's crucial to embrace and invest in renewable energy sources like wind power and solar, and implement energy-efficient and energy-saving technologies. These measures not only preserve the quality of energy services but also reduce consumption, allowing for a more optimal utilization of the energy sector's capacity. Moreover, renewable energy sources, being abundant and carbon-neutral, present a vital solution for a sustainable energy future [6]–[9]. Government regulation worldwide, public environmental awareness, efficient use of fossil fuels, widespread adoption of renewable energy, and well-managed population control in developing nations are crucial for safeguarding the Earth's ecosystem, promoting sustainable civilization, and ensuring international stability [10].

Currently, in line with international commitments such as the Paris Agreement, the Kyoto Protocol, and green production accords, there is a important emphasis on minimizing energy use and augmenting the adoption of renewable energy sources. The necessity of transitioning to a low-carbon economy, driven by the critical urgency to mitigate climate change, is a pivotal focus of these international accords [11]. Additionally, such a transition also fosters economic growth by creating green jobs and industries, thus, encapsulating the balance between environmental sustainability and economic development.

Compared to fossil fuels, renewable energy sources like solar, wind, and hydropower provide a sustainable alternative, helping reduce our carbon footprint and move towards a greener and more sustainable future. Furthermore, energy-efficient technologies and practices can significantly cut down on wasted energy, leading to substantial cost savings and a reduction in overall energy demand. Such progress is integral in building resilient energy systems that promote sustainable development, health, and environmental preservation. As a means of reducing the decline of the environment and air pollution, renewable energy is becoming more and more significant. Utilizing the available energy resources effectively is crucial for reducing energy usage. This can be done in a way that is both economically and environmentally beneficial [12]–[15].

There is a steady increase in total renewable energy capacity from 2012 to 2021. It underscores a global transition to renewable energy, starting with 1,443,923 MW in 2012 and reaching 3,063,926 MW in 2021. Despite varying growth rates, the overall trend shows an increasing adoption of renewable energy technologies. Wind, hydropower, bioenergy, geothermal and solar capacities significantly increased, indicating renewable sector expansion. Marine energy capacity also slightly rose. This growth reflects a commitment to mitigating climate change, technological advances, supportive policies and the economic benefits associated with renewable energy [16].

Solar energy is a renewable energy source which harnesses the power of the sun to produce thermal or electrical energy. Solar energy, obtained from the sun, is an unlimited and cost-free energy source. It is abundant, clean, eco-friendly, and well-distributed. This energy source is more available in hot and the majority of the world's population and economic growth will occur in sunny nations in the coming years. Solar energy has been widely accepted as a crucial element of a sustainable energy transformation. Additionally, it is scalable and provides low-carbon resources that can satisfy the increasing global demand for electricity. This energy can be collected and used to power homes, businesses, and other entities. By converting sunlight into usable energy, solar power provides a sustainable alternative to traditional energy sources that rely on fossil fuels. This technology has gained popularity in recent years due to its environmental benefits and decreasing cost, making it an accessible and viable option for many individuals and organizations [17]–[19].

The subject of electricity production from clean energy sources fascinates researchers across the globe. The primary advantage of solar energy lies in its ability to be harnessed directly from sunlight via photovoltaic cells, transforming it into electrical power. There is numerous commercial and residential applications in solar, including solar photovoltaics, large-scale power production, and water heating, have significantly increased. Currently, photovoltaic systems represent the predominant method to use solar. Photovoltaic technology for power production and solar thermal technologies, like solar collectors, are examples of how solar energy is employed to generate electricity [8], [9], [20].

A standard solar power system comprises, a battery or battery pack, a solar controller and a solar panel. If the output power needs to be converted to 220 V (AC) or 110 V

(AC) an inverter is necessary [21]. The semiconductor element of the photovoltaic cell converts sunlight's shortwave irradiance directly into electricity, while also producing heat from the absorption of low-energy waves by the photovoltaic modules [8]. The power and current generated by a photovoltaic cell are affected by various internal and external factors. These factors encompass aspects related to installation, PV system design, costs, and environmental conditions [22]. Multiple solar photovoltaic (PV) technologies exist, each with variations in materials, production techniques, and electrical properties. The most commonly used commercial types include Thin-film, Monocrystalline silicon (Mono-Si) and Polycrystalline (or multi-crystalline) silicon. These technologies offer different characteristics and efficiencies, catering to various applications and market preferences [23].

Crystalline silicon technology dominates the global market for PVs, accounting for more than 90% of it. On the other hand, Cd-Te and CIGS-based PV technologies are not very prominent and occupy only a small fraction of the market share [24].

Solar photovoltaic technologies, which transform sunlight into electricity, have experienced extensive implementation and have become the most affordable source of new power generation in numerous areas. Electricity pricing generated by PV has dropped by 77% from 2010 to 2018, and its capacity surged by a hundred times from 2005 to 2018. These substantial advancements position solar PV as a critical player in the sustainable, low-carbon energy framework needed to realize the objectives of the 2030 Sustainable Development Agenda and the Paris Agreement. The accelerated expansion of solar PV is backed by a global market that frequently exchanges PV components and their manufacturing machinery around the world. This trade, which has seen faster growth than the overall manufacturing sector since 2005, allows access to efficient, competitive, and innovative goods necessary for the transition towards sustainable energy systems. The international deployment of solar PV, led by trade, is vital for fortifying the infrastructure required to tackle COVID-19 and facilitate economic recovery after the pandemic [25].

Solar photovoltaic installations reached an unprecedented level in 2021. Over the last ten years, large-scale production and technological advances have resulted in an 80% reduction in the cost of photovoltaic modules, leading to solar PV becoming the most cost-effective electricity generation method in numerous regions. Nevertheless, in

2021, the cost of modules saw a rise of approximately 20% due to an increase in shipping and raw material expenses. The majority of the material costs for a solar PV module come from silver and polysilicon. Although anticipated further reductions in material usage per unit of output, the rate of these improvements may decelerate in the future [16].

The growing prominence of this industry stimulates competitive dynamics in the global marketplace. This healthy competition not only spurs innovation and efficiency improvements but also drives down prices, making solar technologies for a wider spectrum of customers, is more economical. Moreover, it promotes job creation in the sector and encourages countries to invest in renewable energy infrastructure and research. This increasing competitiveness also underlines the importance of robust policy support and regulatory frameworks to sustain and enhance growth in this critical sector [26].

Despite enduring a second year of the COVID-19 pandemic, early market data indicates a significant growth in the global photovoltaic (PV) market in 2021. Over 175 GW of photovoltaic systems were installed and commissioned globally last year, bringing the total cumulative installed photovoltaic capacity to at least 942 GW by the end of 2021. [27]. Several notable trends have emerged:

• Despite supply chain shortages throughout the year, the Chinese PV market continued to expand in 2021 and remained the largest market regarding the annual installed power. About 54.9 GW of photovoltaic were installed in China in 2021, up from 48.2 GW in 2020 and 30.1 GW in 2019. With 308.5 GW installed, China still leads in cumulative capacity, accounting for almost a third of worldwide photovoltaic installed capacity [27].

• Beyond China, in 2021, the world market for PV also saw substantial growth, jumping Reaching at least 120 GW by 2050 from 97 GW in 2020, representing a 24% year-on-year increase. o The United States market expanded to 26.9 GW, surpassing the EU and making it the second-largest market. Most of the new installations (about 75%) were at the utility scale. The European Union fell to third place globally, installing nearly 26.8 GW in 2021. Outside of the European Union, the rest of Europe added approximately 3 GW. Germany led in Europe with 5.3 GW, followed by France, Spain, the Netherlands, Poland, Greece, Italy, and Belgium. o India and Japan came in fourth and fifth with estimated annual installed capacities of 13 GW and 6.5 GW respectively. o Other key growing markets such as Brazil, Australia, Korea, and Mexico contributed significantly to the new additions in 2021. [27].

• In 2021, the threshold to make it into the top 10 global markets was about 3.0 GW, level that is consistent with 2020 and double the level required in 2019. • The top 10 countries accounted for roughly 74% of the yearly PV market worldwide, a slight decrease from 2020. Several countries, including Spain, Greece, Honduras, the Netherlands, Chile, Germany, and Australia, adequate PV capacity at this time to theoretically cover over 10% of their electricity demand annually. PV provides about 5% of the world's electrical needs. While PV's contribution to energy decarbonization is increasing—potentially offsetting up to 1.1 billion tons of CO_2 equivalent—much work remains. To meet the goals set out in the Paris Agreement during COP21, PV deployment needs to increase substantially [27].

According to data from the Ministry of Energy and Natural Resources, Turkiye has an important owing to its geographic position and abundant sunlight, it has a potential for solar energy.

Although Turkiye may not possess as high solar radiation potential as certain regions, it receives more sunlight than the USA, China, and several European nations, granting it a superior solar energy generation potential per square meter. A look at the top ten G20 countries for per capita solar energy production reveals Turkiye in the tenth position, with all countries on the list, except Australia, having less solar radiation potential. Turkiye's renewable energy installed capacity is projected to increase by more than 26 GW from 2021 to 2026. Around half of this anticipated growth, approximately 12 GW, is expected to be contributed by solar energy [28].

By 2050, the global photovoltaic capacity is predicted to surge to 4,500 GW [29]. As PV technology expands, proper disposal of photovoltaic panel waste is crucial to reduce the environmental impact of e-waste and minimize the need for new raw materials. Photovoltaic panels typically have a lifespan of around 25-30 years, after which they degrade and become less efficient, requiring replacement at the end of their operational period. Addressing the environmental impact of end-of-life waste from renewable energy products is crucial. It presents opportunities for proactive policies and infrastructure development. Accessing insightful information on future waste generation and engaging in discussions about the consequences of improper management is vital for informed decision-making. Utilizing databases for individual and global assessments can provide valuable insights for sustainable waste management practices, helping to comprehensively manage the complex product and move towards more sustainable approaches [30]–[33].

While countries typically manage discarded PV panels within their general waste management framework, specific regulations exist in some jurisdictions. The transboundary movement of waste and scrap has both advantages and disadvantages, as movements into countries lacking robust regulatory frameworks can pose significant environmental risks and additional expenses. Detailed studies have been conducted on policies implemented in OECD countries, with major stakeholders in Korea, Japan, Europe, and the US involved in regulating PV waste management [29], [33], [34].

The transformative potential of solar power in the energy sector should not be underestimated. With the expanding PV panel market, the volume of decommissioned panels is also on the rise [29]. Before until the end of 2019, the cumulative waste from PV panels was estimated to be around 600,000-700,000 tons, and this figure is anticipated to grow substantially in the future. It is concerning considering that solar panels are designed to have a lifespan of 25-30 years before decommissioning is necessary. The absence of sufficient recycling infrastructure for solar panels is a significant factor contributing to this escalating waste stream [33]. Consequently, a significant number of decommissioned panels are disposed of in landfills, occupying valuable space and posing potential environmental risks. In 2019, the global e-waste production became around 53.6 million tonnes, and it is projected to increase to approximately 74.7 million tons by 2030 [33], [35], [36].

If the lifespan of photovoltaic plants, developed during the world PV boom, is reduced, it would lead to a important growth in PV waste generation in the near future [37]. The disposal of end-of-life PVs is predicted to add approximately 5.5-6 million tons of waste annually, while new installations will contribute around 6.7 million tons of waste in the 2050s. These figures highlight the potential future challenges associated with solar panel waste. As the demand for solar panels grows, so will the volume of waste generated from decommissioned panels, exacerbating the global e-waste problem and posing significant environmental concerns. It is crucial to establish sustainable approaches for managing and recycling solar panel waste to address this issue's impact effectively [29].

Upon examining the life cycles of photovoltaic panels, recognized globally as some of the leading sources of clean energy, it becomes evident that both direct and indirect emissions are generated at different stages, including the transportation, electricity generation and production phases. Furthermore, the production of these panels includes using of various chemicals containing harmful toxins. Consequently, certain materials that make up the panels pose a potential risk to environmental health [26]. PV recycling standards encompass environmental, health, and safety provisions and aim to recover metals found in PV modules. It's imperative to reclaim critical and valuable raw materials. This measure, however, will just yield full effectiveness upon the photovoltaic panels reaching their end of life, which is typically in about 25 to 30 years [38]. Despite the material components in PV panels remaining largely unchanged from the past until now, significant saving of materials have been realized owing to improvements in material and resource efficiency [29]. The poisonous elements gallium, arsenic, cadmium, lead, and selenium used in PV technology are only a few examples [39]. The release of these pollutants leak into the land and water systems can give rise to substantial human health and environmental issues with long-term consequences. To mitigate such risks, it is essential to ensure the proper management of these materials once they reach the end of their useful life, thereby preventing any potential harm.

Countries have varying criteria for determining whether certain waste containing harmful components is dangerous or not. For example, the United States considers a PV panel hazardous if it produces leachate with lead concentration of ≥5 mg per liter, while Japan sets a threshold of 0.3 mg lead per liter. Germany's cadmium threshold is 0.1 mg per liter, compared to 0.3 mg per liter in Japan and 1 mg per liter in the USA. As a result, the classification of PV panels as hazardous waste depends on the concentration levels detected, leading to potential variations in different jurisdictions. This is especially crucial in regions where transportation of PV panel waste may occur [40].

Nevertheless, a crucial aspect often overlooked worldwide pertains to the limited lifespan of renewable energy systems. Insufficient research has been conducted regarding the appropriate measures to be taken upon the expiration of these systems, resulting in a lack of necessary precautions. The implementation of PV recycling holds the potential to enhance energy security while yielding positive impacts on the society, economy and environment. Proper management of end-of-life solar PV equipment and the associated toxic materials remains an environmental concern. Recycling offers significant advantages, including the opportunity to reclaim the components needed and establish a dependable secondary raw material supply for the solar industry and other sectors. It ensures resource conservation and sustainability while minimizing waste and environmental impact [32], [41]. In addition, effective PV recycling practices can contribute to reducing the dependence on primary raw material extraction, mitigating environmental pollution caused by improper disposal, and promoting a circular economy in the renewable energy sector. By embracing responsible recycling measures, it can be maximized the value of discarded PV equipment and can be minimized the potential negative consequences associated with their end-of-life management.

Photovoltaic panel recycling provides environmental benefits by reducing the extraction of raw materials such as silicon, silver and rare metals, mitigating habitat destruction and associated environmental impacts. It also significantly reduces the amount of electronic waste thanks to the long lifetime of the PV panels (25 to 30 years) and suitable recycling methods for waste reduction purposes. This recycling process contributes to energy savings because it consumes less energy compared to the production of new panels and contributes to a small carbon footprint by reusing recovered materials. At the same time, the recycling industry creates a closed loop for valuable materials, minimizing the need for freshening and countering resource scarcity, while creating new business opportunities. Therefore, PV panel recycling not only helps to conserve natural resources by providing environmental sustainability, but also offers significant advantages in terms of economic and energy efficiency.

However, recycling of photovoltaic panels faces several challenges and significant environmental impacts. Firstly, solar panels may contain toxic substances like lead, selenium, and cadmium, necessitating proper waste disposal and recycling techniques to avoid damage of the environment. Secondly, the current cost and economic viability of PV panel recycling technologies can be high, particularly in areas with insufficient recycling infrastructure. Technological complexity arises from continuously evolving PV panel designs, with different materials and construction methods used across various panel generations, making recycling more challenging. The lack of standardized recycling processes and regulations globally creates difficulties in establishing an effective and harmonized recycling system. The increasing volume of discarded PV panels contributes to broader electronic waste management challenges, necessitating proper recycling and disposal facilities. Industrial difficulties arise from dealing with complex and large-sized PV panel units, exceeding the capacity of some recycling facilities. Additionally, uncontrolled export of waste PV panels to other countries due to inadequate recycling opportunities in some regions can lead to environmentally and health-hazardous consequences. Uneven distribution of recycling infrastructure among countries complicates the establishment of a globally effective recycling system. The high initial investment costs for setting up and operating PV panel recycling facilities can present short-term obstacles for initiating recycling processes. Furthermore, the lack of awareness and education about PV panel recycling in certain areas hinders proper recycling practices and increases the environmental risk posed by waste panels.

Sections of the study explained. Chapter 2 is literature review. In chapter 3 general information about world energy outlook, solar energy, PV technology and details about the components of photovoltaic panels are given. In chapter 4, The global expansion of the photovoltaic industry is discussed, along with the projected amount of waste in PV capacity until 2050, both on a global scale and specifically in Turkiye. Additionally, it gives an explanation of the mathematical model used to calculate these waste projections.

Chapter 5 is about recycle of PV panels and recycling techniques. This section also includes various aspects related to photovoltaic panels. It discusses their human health and environmental impacts, as well as the potential harm caused by chemicals used in their production. The financial benefits of recycling PV panels are discussed, emphasizing the financial benefits of repairing and recycling the materials used in their manufacturing.

Furthermore, a contrast is drawn between the CO_2 emissions of photovoltaic panels that undergo recycling and those that are manufactured without recycling. The recycling procedures and methods applied to photovoltaic panels are also elucidated. Chapter 6 is the final section includes a case study focusing on the Karapinar Solar Power Plant in Turkiye. It examines the projected waste generation of the PV capacity at this plant until 2050, utilizing mathematical models that were developed for this purpose.

CHAPTER 2
LITERATURE SURVEY

Corcelli et al. [42] examine end-of-life (EoL) PV panels and evaluates the sustainability of PV panel recycling using the emergy analysis method in their research. The results show that PV panel treatment offers significant environmental benefits across various scales and is competitive with fossil energy sources in terms of energy and environmental perspectives. Emergy Accounting (EMA) is suggested as a valuable tool for assessing process efficiency from a global perspective, despite its limitations in addressing waste management. The study emphasizes the need for methodological guidelines integrating EMA with existing waste management evaluation methods to better capture the value of waste recycling.

Xu et al. [21] have a review about the current worldwide status of recycling waste solar panels. which emphasizes the solar panel industry, focusing on production, waste generation, and the challenges of EoL panel management. The increasing global installed capacity of PV panels and their 25 year lifespan make managing waste panels an urgent environmental issue. China lacks a dedicated solar panel recycling system, resulting in resource wastage and environmental risks. Investing in environmental protection equipment can mitigate these issues, while also generating economic benefits. Policymakers and researchers must address the need for effective waste management systems and establish industry standards holding manufacturers accountable. Additionally, the government should ensure transparency, reinforce oversight, and balance stakeholder interests.

Photovoltaic systems are recognized as sustainable and clean energy sources, but their environmental impacts from manufacturing to disposal must be considered. Tawalbeh et al. [43] examines potential environmental challenges, including water pollution, hazardous contaminants, air pollutant emissions, and land use impacts, while presenting novel design proposals to address these issues. A comprehensive analysis was conducted to compare greenhouse gas emissions from various photovoltaic systems with those emitted by fossil fuel energy resources. Results suggest that optimized design, new materials, minimizing hazardous materials use, recycling, and careful site selection can significantly mitigate PV systems' negative environmental impacts, reduce GHG emissions, solid waste accumulation, and protect the water supply. PV systems' carbon footprint ranges from 14–73 g CO_2 -eq/kWh, much lower than that of oil. solar cell recycling materials and new manufacturing materials can further reduce this carbon footprint and GHG emissions. This study provides a management strategy to enhance PV manufacturing sustainability, economic value, and minimize environmental impacts.

The rapid deployment of photovoltaic panels has led to increased discarded panels, posing end-of-life (EoL) management challenges for OECD countries. Mahmoudi et al. [33] projects the PV waste stream from 2001 to 2058, estimating a cumulative waste volume of 25-28.5 million tons, consisting of metals and non-metal waste. Some countries will generate the smallest amount of annual photovoltaic waste threshold for independent treatment businesses, while others will require collaborative programs. The amount that recovered waste materials are worth in total ($36-42 billion) incentivizes stakeholder involvement. Proactive management and policy strategies are needed to support environmental and economic sustainability. Preliminary steps have been taken by the US, Japan, Korea, and the EU, but further actions are required, including robust reverse logistic network design and a united monitoring system. Enhancing public awareness, strengthening local photovoltaic recycling sectors, creating creative financing methods, and creating centralized organizations to oversee multiple management levels are essential for transitioning to sustainable PV waste management in OECD countries.

By 2030, the EU is expected to produce 32% of its energy from renewable sources, according to the Renewable Energy Directive. National Energy and Climate Plans (NECPs) have been created by EU-27 nations for the years 2021–2030, focusing on solar photovoltaic modules. Review of Kastanaki and Giannis [44] assesses future PV waste amounts based on Early Loss, Regular Loss, and EU WEEE Directive scenarios. The projected amount of PV waste by 2050 is 14-18 Mt, with a profit of $21.98-27.36 billion from recovered materials. Efficient management of e-waste supports circular economy principles and sustainability. By 2050, 14–18 Mt of PV trash and $22–27.4

Billion in profit from recovered materials are projected by evaluations of PV waste for all 27 EU nations. The dominant technology will be c-Si technology, followed by CdTe. A plan for EU-27 countries to initiate viable solar panel recycling businesses is proposed, with a core group starting by 2024-2032 and additional countries joining by 2037-2049. Fifteen countries will establish recycling partnerships, utilizing recycled materials in new PVs, closing the material loop, and ensuring a sustainable source of raw materials for low-carbon technologies.

Vellini et al. [45] have a research which is a review and evaluates the environmental effects of a 1 m2 c-Si and CdTe solar system statistically. The analysis reveals that Less energy and material resources are needed using CdTe technology, reducing most consequences of emissions and resource consumption, though human, terrestrial and aquatic toxicity are higher due to toxic materials used in CdTe panels. Recycling at the end of the modules' life is crucial, allowing recovery of raw materials, decreased energy demand, and reduced emissions. The study compares the implementation of procedure of recycling for both CdTe and Si technologies, demonstrating the importance of recycling in reducing potential impacts. Despite lower efficiency, CdTe panels offer energy, environmental and economic benefits, compensating for their reduced energy efficiency. However, managing the high toxicity of CdTe panels is essential; recycling processes at the end of their life are necessary to successfully use this technology in the PV industry.

Savvilotidou et al. [46] discusses the importance of sound and sustainable treatment of End-of-Life photovoltaic modules, specifically the 2nd generation thin-film modules. The paper examines the chemical treatment of two different types of modules, tandem a-Si, c-Si panel and Copper-Indium-Selenide (CIS) panel, and presents experiments for P/V recycling investigation using different acids or acid mixtures. The study shows that in P/V shredded chemical treatment samples is effective and can dissolve the ethylene-vinyl acetate (EVA) resin, allowing for valuable structural material recovery. The information on panels' composition and toxicity characterization is essential prior to any recycling attempt. The study also demonstrates the importance of understanding the practicality of recycling techniques as well as their effects on the economy and environment. Finally, more emphasis is needed to understand the indium and gallium criticality hazards on a worldwide scale.

Overall, the study highlights the need for sound and sustainable treatment of EoL P/V modules and the importance of developing efficient recycling methods.

The increase in solar electricity production brings benefits, but EOL panels also pose environmental challenges. With global installed PV capacity projected to rise significantly, addressing EOL solar panel disposal and recycling becomes crucial. Regulations were pioneered by The European Union, on this issue, and Chowdhury et al. [47] have a review which examines the current state of solar panel waste recycling, technology, policies, and economic aspects. A recycling and recovery strategy must be established by 2040 to address the growing number of EOL solar panels. This study contributes to the literature on sustainable EOL management for solar panels and recommends making recycling commercially necessary, extending producer responsibility, and accelerating R&D to address challenges and develop recycling schemes.

Yıldız et al. [26] explores the environmental impact of solar energy, specifically comparing polycrystalline and cadmium telluride (CdTe) photovoltaic panels. They search emission amounts during the panels' life cycle, encompassing production, recycling, and electricity generation, were compared alongside energy payback times. CdTe panels were found to release fewer emissions than polycrystalline panels, but concerns about their efficiency and potential harm to human health limit their widespread adoption. Energy payback times for both panel types were under one year, highlighting their potential environmental benefits compared to natural gas power plants. The study also emphasizes the importance of solar energy investment, given its immunity to fluctuations in fossil fuel prices and the absence of transportation costs. To meet their carbon reduction commitments under the Kyoto protocol, countries should focus on increasing the incorporation of solar power into their energy plans.

Seo et al. [48] have a study that provides an overview of the capability of renewable energy worldwide and crystalline silicon panel waste generation, and presents recent research on recycling technologies and life cycle assessment of end-of-life c-Si panels an emphasis on resources that can be recovered. Previous LCA studies have often oversimplified or neglected the EoL phase of photovoltaic systems, and differences in methodology have made it difficult for direct comparison of findings. However, recent studies demonstrate that high-rate recovery from EoL photovoltaic panels is possible with recycle methods that help lighten the load on the environment, although improvement in subprocesses with substantial effects on the environment and the proper accounting of avoided impacts from reclaimed resources are needed. Additionally, it remains debatable whether full-scale PV panel recycling is economically feasible. Standardization and the construction of region-specific databases are required to reduce geographic and temporal uncertainty, and effects of transportation need to be fully incorporated into LCA.

Jing Tao and Suiran Yu [49] have a review that investigates the increasing importance of PV module recycling, as production and installation rates rise. The recycling of manufacturing waste, the recycling of discarded PV modules, and the remanufacturing and reuse of PV modules are the three main recycling paths that are looked at. Various methods have been proposed for recycling wafer cutting slurry waste from c-Si modules and recovery of valuable metals in thin-film solar modules. Despite the fact that there are still issues with complexity, energy usage, and chemical use in processes, some recycling technologies are commercially available. The review also highlights wafer recovery and reuse as a more beneficial recycling approach for c-Si modules, with thermal decomposition and solvent dissolution methods being explored. The separation of materials in thin-film modules is more difficult, and several hydrometallurgical techniques have been suggested. Research on PV module remanufacturing and reuse suggests that an ease-to-disassembly design could improve component reusability. Despite environmental benefits, the financial feasibility of photovoltaic module recycling is currently disadvantageous, requiring policy intervention to encourage producer responsibility and an efficient collection network.

Santos and García [37] presents projections for photovoltaic waste mass in Spain until 2050. The study examines the possible effect of the Spanish photovoltaic installation boom in 2007-2008 and uses four degradation scenarios to analyze PV technology reliability's impact on waste generation. The results suggest that the Spanish photovoltaic recycling industry has to start preparing sooner than other European nations to handle huge volumes of waste mass. The study proposes several preventive measures to manage photovoltaic waste at the regional and local levels, including knowledge campaigns, issuing regulations, establishing recycling facilities, and doing a thorough investigation on Jordan's optimal recycling strategy. The study concludes that Long-term revisions should be made to the minimal recycling goals outlined in the Spanish Royal Decree on Wastes of Electric and Electronic Equipment (WEEE).

Maani et al. [50] have a study that is examined employing a life cycle assessment, determine the effects of several recycling processes on the environment for crystalline silicon and CdTe panels. According to the findings, recycling c-Si and CdTe PVs had an influence on the PV lifecycle by 13-25% and 3-4%, respectively. With the exception of pyrolysis, thermal-based recycling techniques have less of an impact on the environment than chemical and mechanical techniques. As nitric acid dissolution has not been tuned for industrial application, it had the greatest effects when used for c-Si PV recycling. The study found that current recycling techniques for PVs produced higher impacts than extracting virgin materials like Si, Al, and glass for CdTe and c-Si. It also identified materials to prioritize for maximum economic and environmental benefits during recycling: Al, Ag, Si, and glass for c-Si modules, and Cu, Te, and glass for CdTe modules.

Gautam et al. [51] highlights the emerging issue of end-of-life disposal of solar photovoltaic electronic waste in India, in their research. The absence of proper recycling infrastructure and guidelines makes India ill-equipped to handle the volume of solar PV waste that is projected to be generated. By using a forecasting model, the study predicts that by 2047, 2.95 billion tonnes of solar photovoltaic and its balance of system (BOS) waste will be generated in India. This waste will contain 21 metals, including gold, aluminium, copper, and silver, at a total cost of US$645 trillion for commodities. However, the study estimates that US$ 452 trillion worth of resources can be recovered through state-of-the-art recycling techniques. The study suggests the need for a commercial model for effective material recovery and process re-engineering and argues for the creation of a specialized circular economy-based reverse supply chain for PV e-waste. The study offers academics and decision-makers insight into this area of study and may be used as a database for future life-cycle analyses, economic feasibility studies, and the creation of closed-loop supply chains.

Japan's rapid introduction of solar modules is accompanied by an inadequate societal method for disposing of used solar panels. Waste generation estimation is required to prepare a recycling system. Typically, lifespan distribution is estimated using the target item's mechanical life. Nevertheless, consumers may think about replacement or disposal before mechanical failure, so a survey of consumer decision-making regarding replacement/disposal was conducted. Murakami et al. [52] have a research which includes a case study for Tokyo found that younger generations are more inclined to think about replacing or discarding panels before they break, leading to earlier waste panel generation. Considering the owners' decision-making could lead to several generations of possibly reusable panels. For the purpose of evaluating the greatest possible waste, waste generated by owners' actions other than mechanical failure should be taken into account. In order to meet the contemporary social environment, which is geared toward a circular economy, policymakers should plan an adequate recycling social system in advance, taking into account the potential reuse of panels. The study suggests that researchers should investigate how customers choose to replace and discard solar panels for circumstances other than mechanical failure, including financial decision-making of owners.

India's fast-paced development has led to an increase in electronic waste (e-waste) generation, amounting to almost 3 million tonnes annually, making it the third-largest e-waste producing country in the world. However, less than 2% of the e-waste generated is recycled, posing serious health and environmental hazards. Given India's commitment to achieving SDGs 2030, particularly goals 3, 6, 8, 11, 12, and 14, efficient e-waste management policies and strategies are essential. Kumar et al. [53] suggests various strategies for effectively managing e-waste to mitigate its negative effects, including promoting investment in waste management infrastructure and adopting a circular economy, formalizing the informal sector, extending the life of products, collaborating with e-commerce platforms, and implementing Corporate Social Responsibility initiatives. These strategies align with UN recommendations for a circular economy that conserves resources and reduces waste. Implementation of these strategies will contribute to achieving SDGs 2030 and provide employment opportunities in the formal sector, while also curbing health and environmental hazards associated with e-waste.

There has been an increase in small-scale solar PV systems in the Australian urban development electricity industry, leading to increased PV waste. Efficient waste management, including collection, transportation, and treatment, is crucial for environmental sustainability. Oteng et al. [54] have a research that also is a case study uses the Weibull distribution model to forecast photovoltaic waste in South Australia and estimates pollutant emissions through various routing scenarios. By 2050, 109,000 tonnes of solar panel waste will be generated, and a routing scenario involving optimized transfer stations and an additional recycling facility can reduce emissions by over 34%. Effective photovoltaic waste management needs government help, regulations, and further research on sustainable end-of-life PV module treatment and recycling facilities.

Al-Zoubi et al. [55] highlights the impending issue of photovoltaic waste in the Kingdom of Jordan as the country adopts clean energy sources like photovoltaic plants. With an estimated global increase in PV capacity to 5000 GW by 2050, between 5% - 15% of total capacity for generating is projected to be PV waste by 2030. This study estimates The anticipated amount of solar panels waste during the following ten years and explores the possible environmental and economic impacts, with a focus on the northern region of Jordan. The management of PV end-of-life is a developing field requiring further research and development. Preventive measures relating to the local and regional management of photovoltaic waste are recommended, including awareness-raising among stakeholders, the issuance of relevant laws and regulations, dedicated areas for waste accumulation, and facilities for treatment, recycling, and reuse of PV waste. There are several ways to look at the significance of PV waste and its management, including legislation, the environment, the economy, social factors, and human health.

Granata et al. [56]assess the long-term viability of PV's economics panel recycling, emphasizing that recycling volumes and silver (Ag) revenues are critical factors in their review. When Ag concentrations remain within 0.1-0.2%, end-of-life photovoltaic panel recycling can be sustainable without additional fees. However, decreasing Ag concentrations in PVs may necessitate PV recycling fees. Sustainability is influenced by Ag concentrations, selling prices, and investment timing. To achieve sustainability in PV recycling, it is essential to maximize material recovery, establish fewer larger recycling centers, promote early investments, and ensure a wise distribution of economic resources among stakeholders.

CHAPTER 3
SOLAR ENERGY

This section is focused on providing general information about projection of world energy outlook and solar energy. The historical development of solar energy is indicated with a timeline, and there is a brief mention of the solar energy technologies used. The main focus of this section is PV technology and types of PV.

3.1 World Energy Outlook

Carbon dioxide levels in the atmosphere rise significantly as a result of the extensive usage of fossil fuels. The dominant use of natural gas, coal and oil for energy production results in the accumulation of carbon dioxide emissions in the atmosphere. This situation intensifies global environmental issues such as the greenhouse effect and climate change. Figure 3.1. shows Country-level CO_2 emissions in the past and forecast.

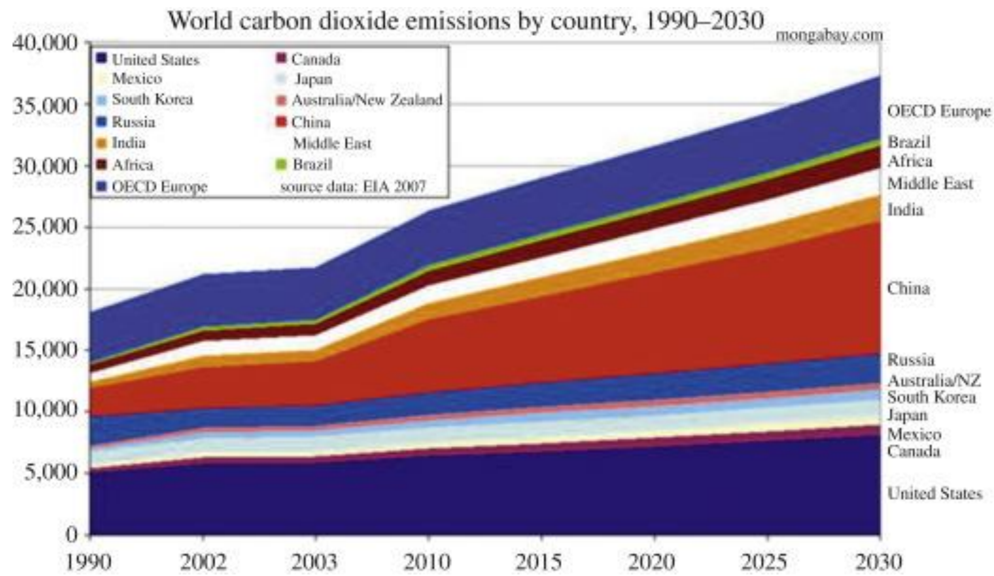


Figure 3.1. Country-level CO_2 emissions in the past and forecast, 1990–2030 [10]

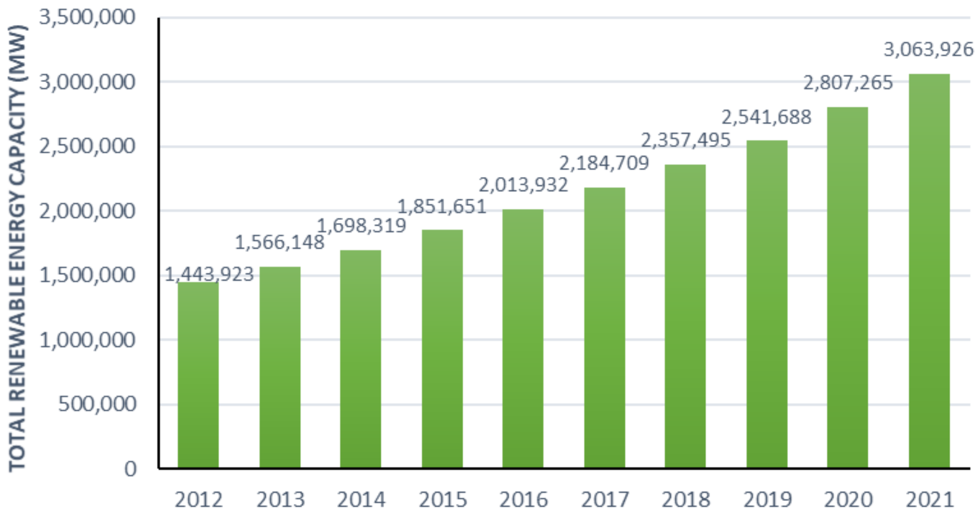
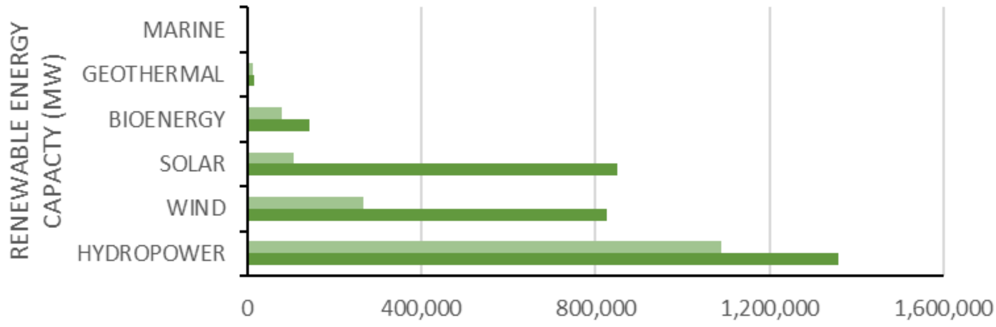


Figure 3.2. The overall capacity for renewable energy from 2012 to 2021 [16]

Figure 3.2. shows the overall capacity for renewable energy from 2012 to 2021, indicating a steady increase. Starting at 1,443,923 MW in 2012, it reached 3,063,926 MW in 2021, highlighting a global shift towards renewable energy. Positive annual capacity additions signify continuous investment and expansion in renewable infrastructure. Despite varying growth rates, the overall trend demonstrates an increasing adoption of renewable energy technologies. This growth reflects a commitment to mitigating climate change, technological advancements, supportive policies, and economic benefits associated with renewable energy.



	HYDROPOWER	WIND	SOLAR	BIOENERGY	GEOTHERMAL	MARINE
2012	1,090,111	266,918	104,312	77,198	10,479	509
2021	1,360,054	824,874	849,473	143,371	15,644	524

Figure 3.3. The capacity of renewable energy sources (MW) [16]

Figure 3.3. represents the capacity of different types of renewable energy in megawatts (MW) in the years 2012 and 2021. Comparing to 2012, there has been significant growth in the capacity of most renewable energy sources. Hydropower, wind, solar, bioenergy, and geothermal all experienced substantial increases in capacity, indicating the expansion of these renewable sectors over the years. Marine energy capacity also saw a slight increase.

3.2 Solar Energy

Solar energy is a crucial element in the shift towards sustainable energy, offering scalability and low-carbon resources to meet the global demand for electricity. It can power homes, businesses, and more, providing a sustainable alternative to fossil fuels. With its environmental benefits and decreasing costs, solar power has gained popularity as an accessible and viable option for individuals and organizations. This section is focused on providing general information about solar energy. The historical development of solar energy is outlined with a timeline, briefly touching upon the solar energy technologies in use. The main focus of this section is Photovoltaic technology and types of PV [17]–[19].

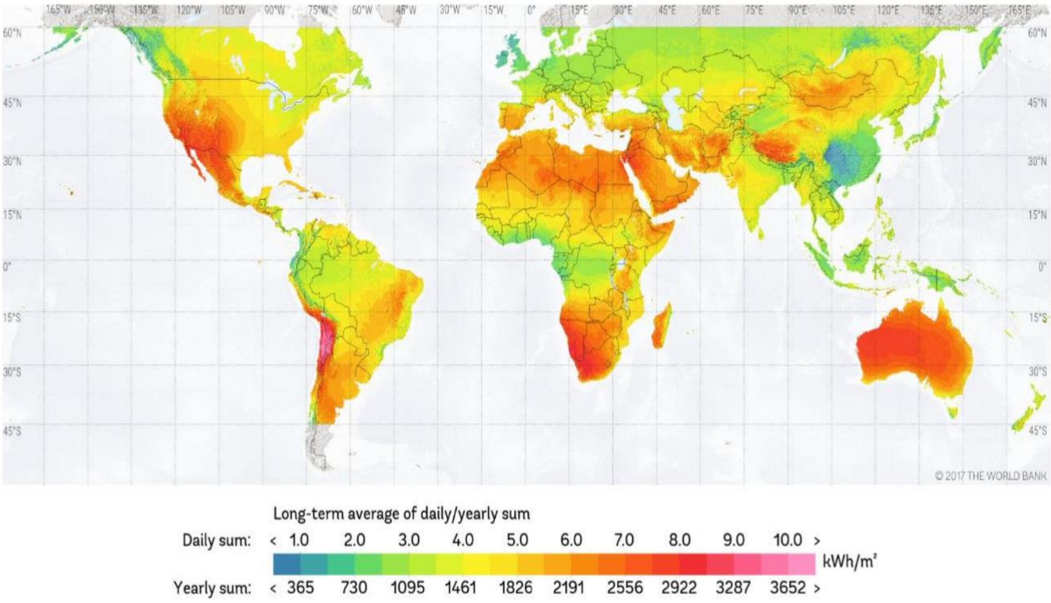


Figure 3.4. Distribution map of direct normal irradiation [57]

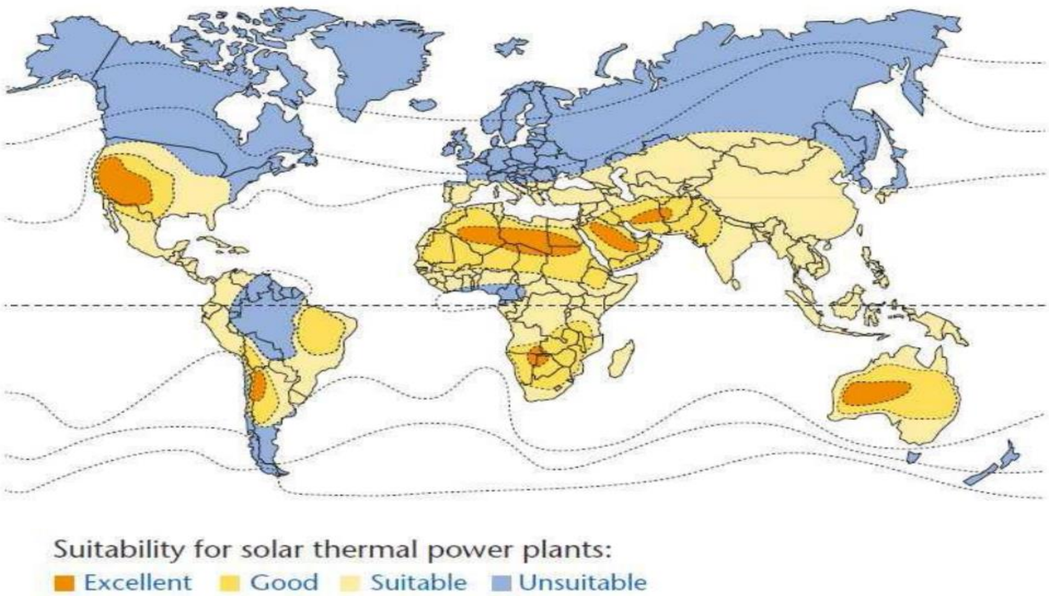


Figure 3.5. Infrastructure for solar thermal power plants [58].

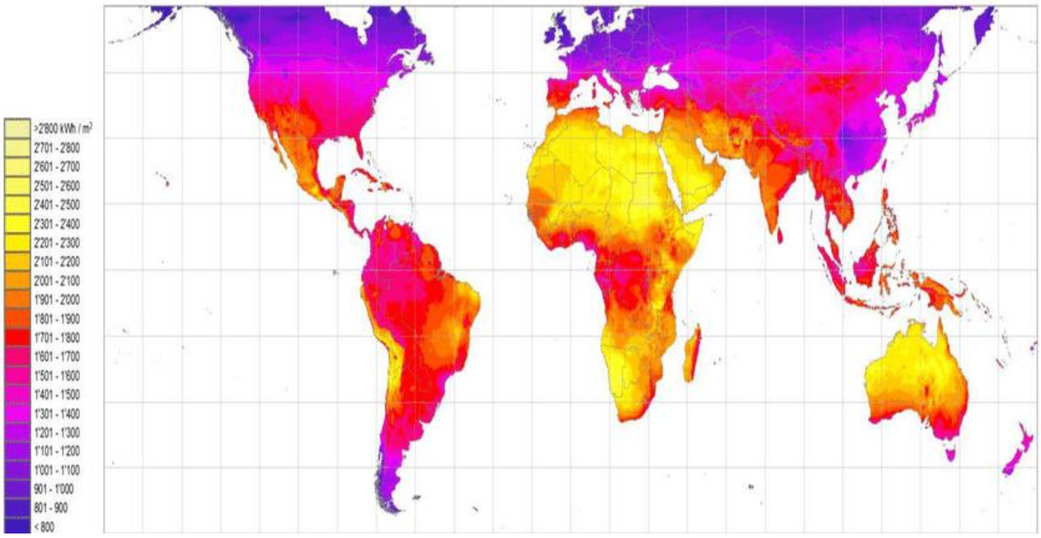


Figure 3.6. Yearly sum of global irradiation [58]

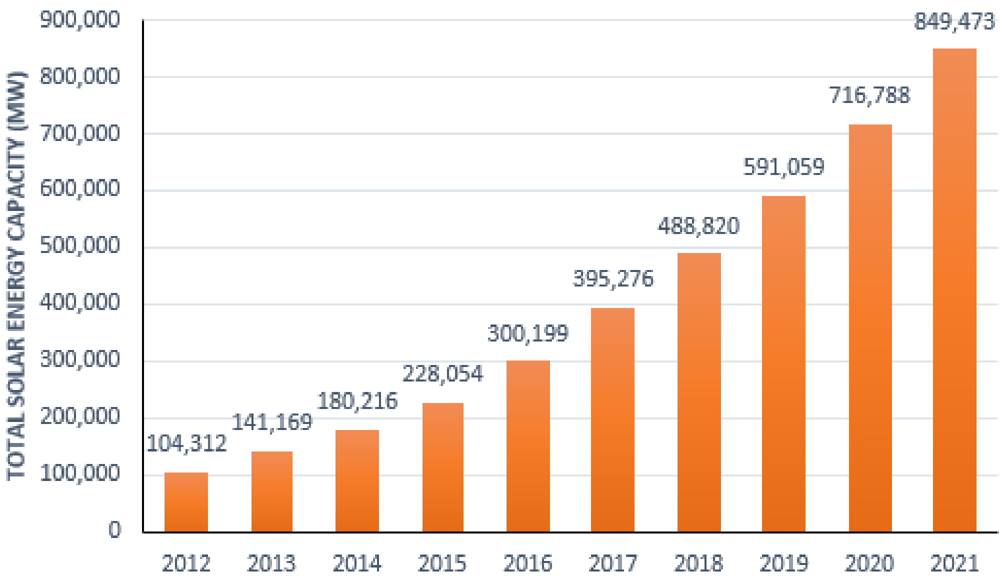


Figure 3.7. The total solar energy capacity from 2012 to 2021 [16]

Figure 3.7. shows the total solar energy capacity from 2012 to 2021, indicating the substantial growth of solar energy capacity. Starting at 104,312 MW in 2012, it reached 849,473 MW in 2021, signifying a substantial increase in solar power installations worldwide. Annual capacity additions have consistently grown, reflecting ongoing investment, technological advancements, and increasing adoption. The expanding solar energy sector reduces emissions, diversifies energy sources, enhances security, and stimulates economic growth.

3.2.1 Solar Energy in Turkiye

Considering Turkiye's geographical location and extensive sunshine duration, its solar energy potential is quite high. According to data from the Ministry of Energy and Natural Resources, Turkiye's technical solar energy potential and some statistics are given as follow.

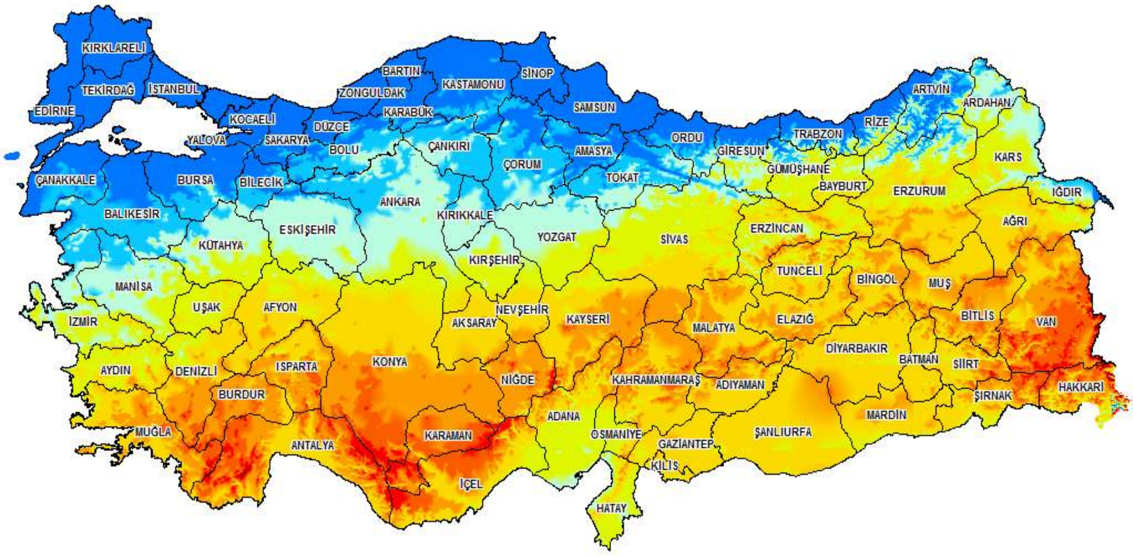


Figure 3.8. Solar Energy Potential of Turkiye [59]

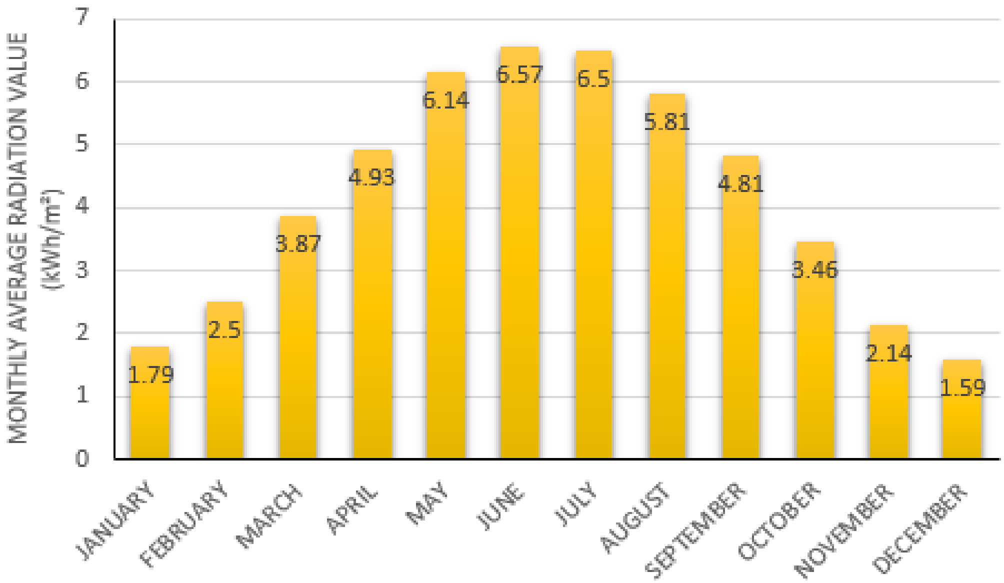


Figure 3.9. Monthly average radiation value of Turkiye (kWh/m²) [59]

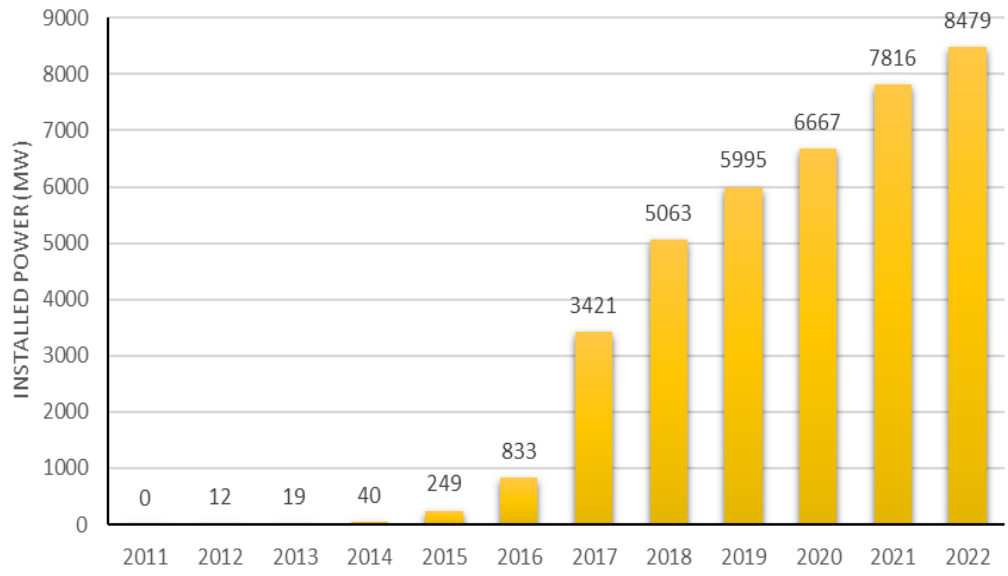


Figure 3.10. Installed solar power of Turkiye [59]

Figure 3.10. Turkiye's solar energy capacity from 2012 to 2022, indicating significant growth from 12 MW to 8479 MW. Annual capacity additions have accelerated since 2015, reflecting increased investment and recognition of solar energy's potential. This expansion aligns with global efforts to combat climate change. However, solar energy capacity alone does not indicate its actual output or share in Turkiye's energy mix. Other renewables must be considered. In conclusion, Turkiye's solar energy capacity has grown substantially due to government support, favorable resources, and energy security, contributing to a cleaner and more sustainable energy future.

3.2.2 Historical Development of Solar Energy

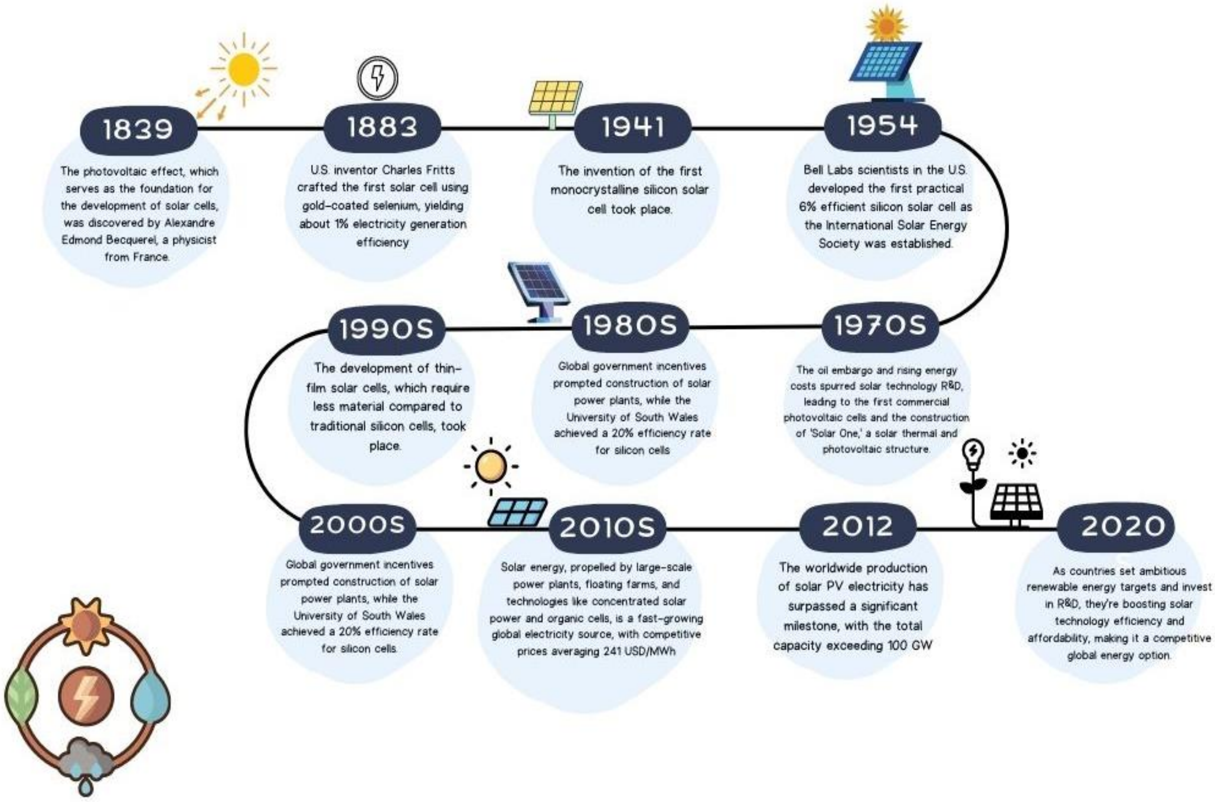


Figure 3.11. Historical development of solar energy [60]

1839: The photovoltaic effect, which serves as the starting point for the creation of solar cells, was discovered by Alexandre Edmond Becquerel, a physicist from France [61].

1883: Charles Fritts, an inventor from the United States, successfully created the first functional solar cell by applying a thin layer of gold onto selenium, achieving an electricity generation efficiency of approximately 1% [61].

1941: The initial monocrystalline silicon solar cell was taken place. [60].

1954: The first practical silicon solar cell, which achieved an efficiency of 6%, was developed by scientists at Bell Labs in the US. Additionally, the International Solar Energy Society was established during this time [60].

1970s: The surge in research and development of solar technology was triggered by the oil embargo and rising energy costs during this period, resulting in the first commercial production of photovoltaic cells. The development of solar technology also prompted the development of the first solar structure, known as "Solar One," which was operational and utilized a combination of solar thermal and solar photovoltaic energy sources [62].

1980s: Incentives were introduced by governments worldwide to encourage the adoption of solar energy, which led to the construction of the first solar power plants. Moreover, the University of South Wales achieved a significant milestone by attaining an efficiency rate of 20% for silicon cells [60], [63].

1990s: Achieving thin-film solar cell technology that require less material compared to traditional silicon cells, took place [64].

2000s: Advancements in technology and economies of scale led to a reduction in the cost of solar panels, making solar energy more accessible to both homeowners and businesses [29].

2010s: Solar energy has been one of the rapidly growing sources of new electricity generation across the globe. This growth is driven by the development of large scale solar power plants, floating solar farms, and the emergence of new technologies like concentrated solar power and organic solar cells. Moreover, the global average solar PV auction price has reached 241 USD/MWh, further highlighting the growing competitiveness of solar energy in the global energy market [29], [60].

2012: The worldwide production of solar photovoltaic electricity has surpassed a significant milestone, with the total capacity exceeding 100 GW [29], [60].

2015: The formation of three significant organizations, Solar Power Europe, the Global Solar Council andthe International Solar Alliance took place during this period [29], [60].

2017: As of recent times, the solar energy sector has created around 4.5 million jobs globally. In addition, the total capacity of solar photovoltaic installations worldwide has reached approximately 400 GW [29], [60].

2020s: The growth of solar energy continues as more countries set ambitious targets for renewable energy and increase investments in research and development. These initiatives are targeted towards enhancing solar energy technologies efficiency and reducing their costs even further, making solar energy an increasingly competitive and attractive option for the global energy market [60], [65].

In the recent decades, solar power has experienced rapid increase, and it is now widely utilized as a significant source of electricity. Initially a small-scale technology, solar power generation has increasingly gained popularity. Following the invention of solar cells in the 1950s, many countries have turned towards solar energy as a viable means of power generation. This shift towards solar power has been driven by advancements in technology, increased investment in research and development, and government incentives to promote the adoption of renewable energy. As a result, solar power has become a major a component of the world's energy mix [23].

3.3 Solar Energy Technologies

Recent years have seen a considerable increase in interest in solar energy technology as a result of their ability to produce clean and sustainable energy. The two primary forms of solar energy technologies are Photovoltaic and Concentrated Solar Power (CSP) systems. Solar cells are used in PV systems that transform sunlight direct to energy, while in CSP systems, sunlight is focused onto a receiver using mirrors or lenses that converts the energy into heat, and then into electricity. Both PV and CSP technologies have unique advantages and limitations, making them suitable for different applications. PV technology is widely used for small-scale applications such as residential rooftop solar panels, while CSP technology is more suitable for large-scale utility applications due to its ability to provide continuous power with thermal storage. Despite their differences, both PV and CSP technologies have the potential to play a crucial role in the transition towards a future with sustainable energy [29], [66].

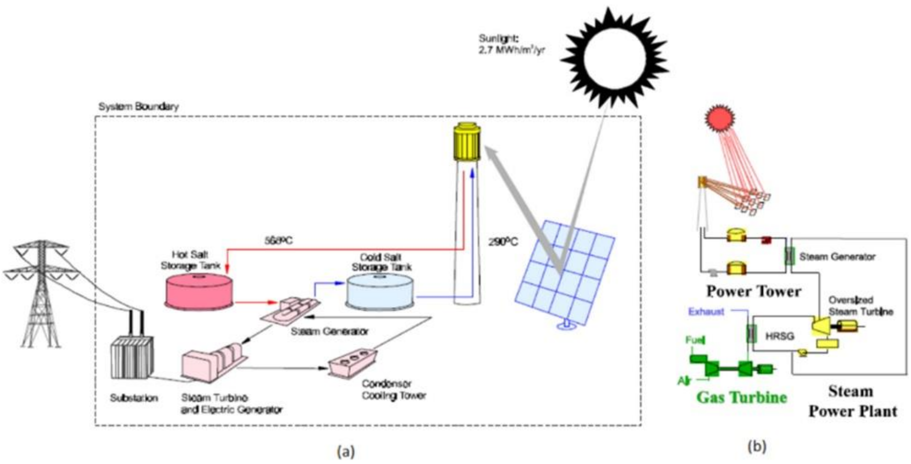


Figure 3.12. Concentrated Solar Power systems [67], [68]

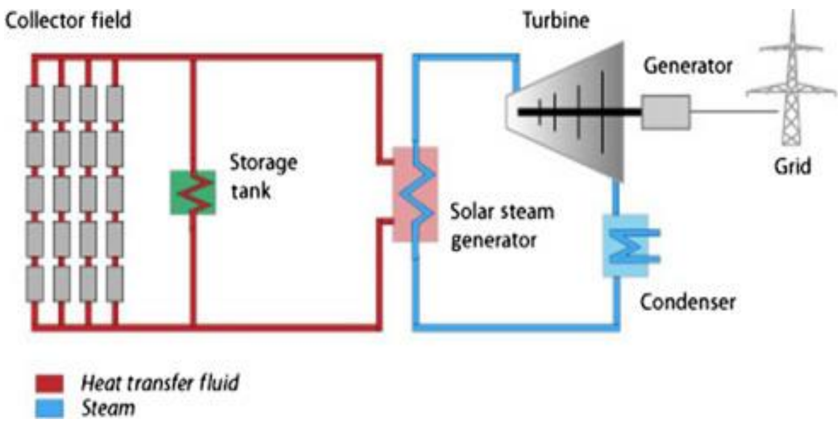


Figure 3.13. Components of concentrated solar power system [69].

Solar Thermal Electricity (STE) is a promising technology that enables the production of solar power during peak and mid-peak hours, and can operate continuously with thermal energy storage. This technology is based on Concentrated Solar Power (CSP) and is particularly suitable for regions with high solar radiation and clear skies. STE can be used in conjunction with other energy sources to provide cost-effective solar energy solutions. Long-distance transmission lines can be used to transport clean energy from favorable areas to other high-consumption regions. STE technology is well-suited for utility-scale power plants, as it complements Photovoltaic technology. In addition, it can be used in niche markets such as remote or weak grid applications. STE, along with PV technology, has the potential to transform the lives of people in developing countries by providing access to electricity. Solar thermal applications such as solar cooking and water heating can also significantly improve living standards. STE technology represents a reliable and sustainable energy source that offers enhanced energy security, particularly in countries with well-developed energy systems. STE technology has significant potential to contribute to a transition towards a low-carbon energy system [70].

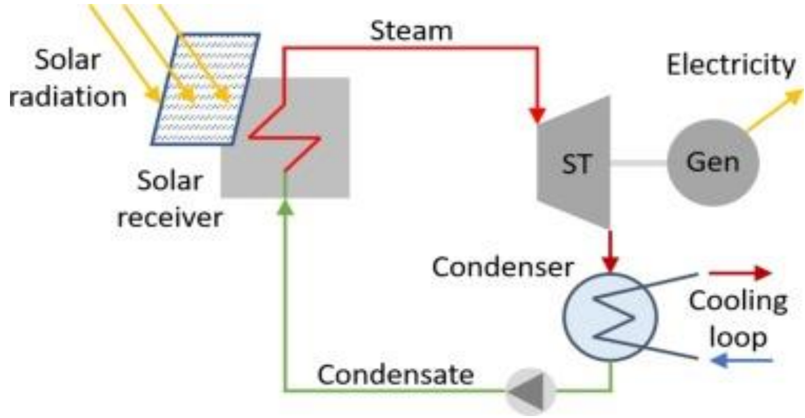


Figure 3.14. Simplified process diagram of a solar thermal power plant [71] .

3.3.1 Photovoltaic Technology

Solar panels are utilized to generate electricity from sunlight in solar photovoltaic systems. Solar photovoltaic technology has been at the forefront of renewable energy for many years. This source is a critical component of clean energy transitions globally, supporting efforts to achieve international energy and climate objectives. As the world continues to shift towards more sustainable energy sources, it is important to recognize the role that solar PV has played and will continue to play in our energy future. In the past ten years, solar PV usage has grown significantly, while costs have decreased dramatically. Solar photovoltaic technologies have emerged as a vital element in sustainable energy systems, contributing to the attainment of the Paris Agreement and the 2030 Sustainable Development Goals. The substantial reduction in solar PV costs has made it increasingly accessible worldwide. International standards, along with technical support and capacity-building, are essential for promoting the universal adoption and implementation of solar PV standards, leading to regulatory consistency and ensuring the availability of high-quality solar PV products. Achieving a net-zero emissions pathway for the world necessitates the global expansion of solar PV on a larger scale, leading to worries about the security of production supply to meet such high levels of growth. However, this also provides new prospects for diversification. The deployment of photovoltaic systems has been an incredible accomplishment in the field of renewable energy. This success has been largely due to incentives like feed-in tariffs that have encouraged the growth of PV installations around the world. PV technology is particularly attractive because it is modular, easy to accessible to the general public and install. With policies which are established, mature markets, and appropriate financing, Photovoltaic projects can be deployed quickly. With the significant increase in deployment, In the past few years, the price of PV has dropped significantly. The learning rate of PV refers to the rate at which the cost of PV systems decreases as the cumulative capacity of installed photovoltaic systems increases. This phenomenon has been observed globally and has made PV systems even more competitive with other forms of energy. The overall progress in PV deployment is a significant achievement in the transitioning to renewable energy, and it is anticipated that PV costs will continue to decrease as deployment increases further [25], [41], [60], [70].

The solar photovoltaic industry is undergoing rapid changes with innovations taking place at every stage of the process. As the market grows and diversifies, it also faces several challenges. One of the main drivers for innovation in recent years has been the need for higher efficiency. Improving the efficiency of solar cells is crucial for producing modules that are competitive, as it decreases the costs associated with processing cells by reducing the amount required to achieve a certain output. As solar PV demand rises, module and inverter prices have dropped, benefiting project developers but challenging manufacturers' profits. Local manufacturing of solar modules, trackers, inverters, electrical components and mounting structures requires skilled workers and supportive factors like government policies, raw material availability, and related industries. However, local production may not be ideal in highly competitive situations [60].

3.3.1.1 The Development of Annual PV Installations

In 2021, the global PV market saw significant growth despite the COVID-19 pandemic, with a minimum of 175 GW of installed and operational photovoltaic systems worldwide, raising the total cumulative installed capacity to a minimum of 942 GW with China, the European Union, the US, Japan, India, Australia, and Korea as significant contributors. Asia dominates the global PV market, led by China and followed by India, Japan, Korea, and Vietnam. The US and Brazil contributed significantly in the America. Germany, Spain, and France contributed in Europe. Africa and The Middle East represented a small portion of the market, with Israel and Turkiye making the most significant contributions. Off-grid and rooftop PV markets are rapidly growing in many countries [5], [27].

The top 10 countries in the PV market made up about 74% of the global annual PV market, with several countries having adequate photovoltaic capacity to potentially produce over 10% of their yearly power needs. However, a tenfold increase in PV deployment may be necessary to meet COP21 targets. The PV market is becoming more diversified, with increasing contributions from various countries, making it less dependent on a few major players [27].

Decommissioning and repowering of PV plants is a growing concern, but many countries are not tracking these processes accurately. Real decommissioning is rare due to the relatively recent installation of PV systems. Recycling schemes are not widespread, and data availability needs improvement [27], [29].

Measuring PV electricity production for an entire country is challenging due to variations in solar irradiation, weather conditions, and installation factors [27].

3.3.1.2 Components of PV Panels

A solar panel, a solar controller and a battery or battery pack normally make up a solar power system. An inverter is required whether the output power is 220 V (AC) or 110 V [21]. Shortwave irradiance from the sun is immediately converted into electricity by the semiconductor component of the solar cell. generating heat from the low energy waves captured by the PV modules [8]. The power and current output of a solar cell is influenced by a variety of internal and external factors. These include environmental conditions and installation, solar power system, and financial factors [22]. The global expansion of solar PV value chains, combined with favorable policies and technological advancements, led to a remarkable capacity of installed solar photovoltaic (PV) panels growing between 2005 and 2018 [25]. Various solar PV technologies exist, with differences in materials, production techniques, and electrical properties. The most prevalent commercial kinds are thin-film, polycrystalline (or multicrystalline) silicon, and monocrystalline silicon (Mono-Si) [23].

The efficiency of these systems can be influenced by different installation methods, which depend on the specific site conditions. Amorphous silicon, cadmium telluride, and copper indium gallium selenide are just a few of the materials used to create thin-film-based panels. They tend to be less efficient than crystalline silicon panels, but they are cheaper to produce. Crystalline silicon panels, on the other hand, are made from a single crystal or a polycrystalline material. Compared to thin-film-based panels, they are more effective, but they also tend to be more expensive. Both types of panels have their own advantages and disadvantages. The global solar module market is diversified, with the majority held by crystalline silicon module producers. Asia-Pacific dominated the solar module market in 2017, followed by the America and Europe. Innovations along the entire value chain have driven the solar PV industry, with efficiency improvements being a major focus. For competitive module manufacture, increasing cell efficiency is essential since it lowers the cost of processing. At the system stage, effectiveness is also crucial, as it reduces transportation, land, and wiring requirements. The solar PV industry is experiencing rapid innovation in module manufacturing, materials, end-of-life management, operation and maintenance and applications, [41], [60], [70].

However, the most widely employed materials to produce PV panels are monocrystalline and polycrystalline silicon. These materials are widely preferred because they are efficient and have a high power output. Solar panels made from these materials are capable of generating electricity even in low light conditions. Solar arrays use crystalline silicon panels which can be recycled easily. Thin film solar panels are designed to be cost-effective, but they have a uniform appearance and low efficiency. Utilizing the photovoltaic effect of the semiconductor material inside the solar panel, electricity is produced. The main part of the panel is made up of a few solar cells connected in series. The battery group stores the energy produced once the panel is exposed to sunlight, which can be utilized by the load at any given time. The controller's primary function is to stop the battery from being overcharged. The inverter converts direct current to alternating current. The basic power-generating components of a solar power system are PV panels. [21].

The figure 3.15. shows the typical components of a PV panel as listed below [72].

- ✓ Solar cells
- ✓ Tempered glass,
- ✓ Backsheet (TPT, Topotecan Hydrochloride)
- ✓ Aluminium (Al) frame,
- ✓ Junction box,
- ✓ EVA Film (ethylene/vinyl acetate copolymer)

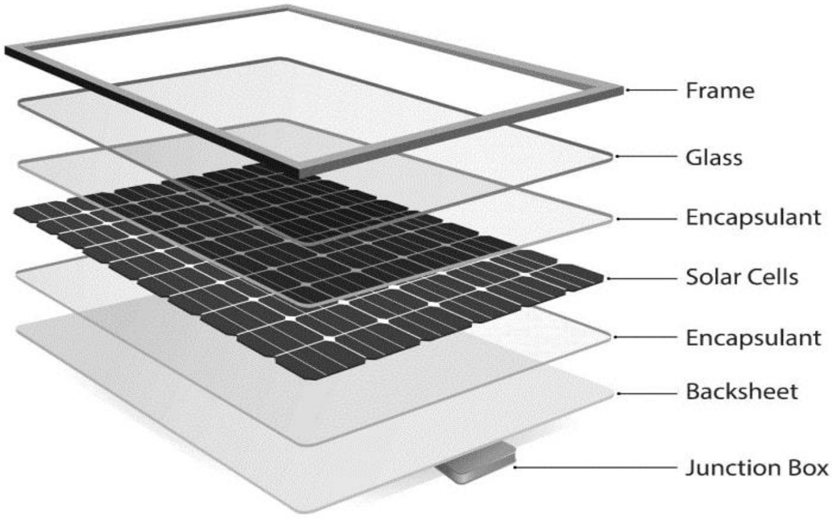


Figure 3.15. Components of a photovoltaic panel [73], [74].

Photovoltaic panels are categorized based on the materials that are utilized in their production. The solar cell materials can vary in their band gaps, crystallinity, absorption potential and how difficult they are to produce [36].

Over the years, the competitive nature of the industry has driven the developing of novel and improved technologies, which have contributed to the evolution of panels. As a result, they have become increasingly stronger and lighter, enhancing their overall performance and durability. In addition, the use of innovative materials and production techniques has allowed for greater customization and flexibility in terms of design, enabling panels to fulfill the particular demands and preferences of different customers. Overall, the evolution of panels is a reflection of the ever-changing demands of the industry, and the ongoing pursuit of excellence and innovation. PV panels have become lighter and more efficient by using glass layers, and sheets, thinner frames, and improving the designs of cells and panels. While the materials used in solar panels have not significantly changed, the PV value chain has enabled the production of more products with less resource and material input. This focus on resource and material efficiency allows us to use the earth's limited resources in a sustainable way thereby reducing the effects on the environment. Figure 3.16. from IRENA [29] demonstrates how the improvement in solar cell efficiency and material savings in PV panels have led to a steady decrease in the mass/power ratio over time.

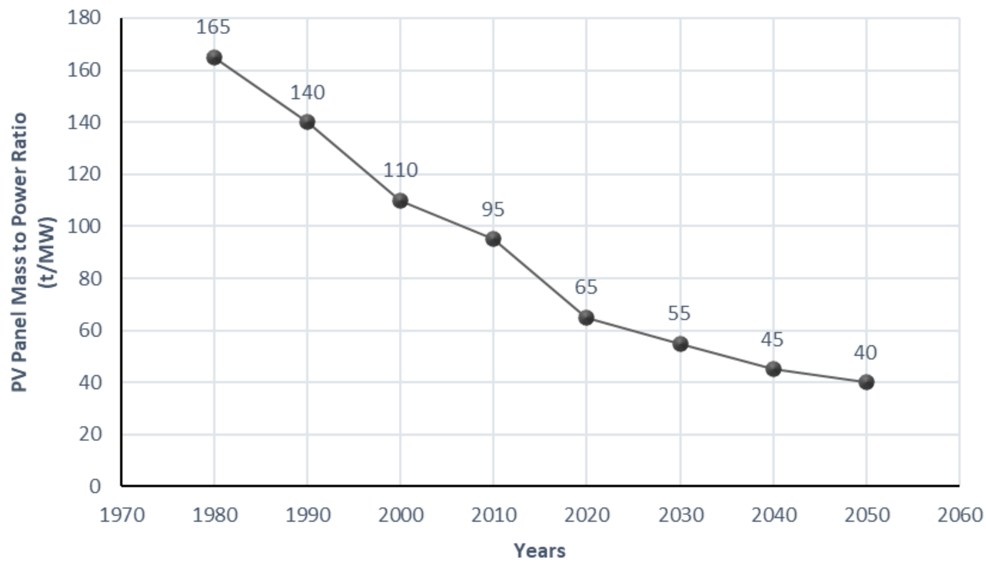


Figure 3.16. A declining mass/power ratio throughout the years (t/MW) [29]

In 2021, solar PV generated over 3% of all power produced worldwide, adding a record 150 GW of capacity. Crystalline silicon modules accounted for 95% of this capacity. Prices of PV modules have decreased by 80% over the past decade, making solar photovoltaic is often the most cost-effective form of power generation in many regions. However, in 2021, module prices increased by about 20% due to higher freight and commodity costs. Raw materials, such as silver and polysilicon, make up a significant portion of the module costs. While these materials constitute 5% or less of the module's weight, they show almost two-thirds of the cost of materials. Material efficiency has improved in the past, but further advancements are expected at a slower pace [16].

Under the Near-Zero Emissions (NZE) Scenario, yearly increases in photovoltaic (PV) capacity are projected to increase more than fourfold from 150 GW in 2021 to 650 GW by 2030. This growth mirrors past trends, as PV capacity quadrupled from 37 GW in 2013 to 150 GW in 2021 over an eight-year period. China currently dominates the global solar PV market, with an 80% share in the supply chain. There is potential for this dominance to expand further, reaching a share of 95% in polysilicon, ingot, and wafer production. Manufacturing capacity varies across different stages of the PV supply chain, with excess capacity in wafer and cell manufacturing but tighter conditions in polysilicon production, which ultimately determines overall manufacturing capacity [16].

With the anticipated 150 GW increase in manufacturing capacity, the world's ability to produce polysilicon might reach 400 GW by the end of 2022, or almost half of what is needed by 2030 under the NZE Scenario. Substantial capacity expansions are necessary in the years leading up to 2030 to meet the anticipated deployment levels. Although announced expansion plans indicate the potential to meet the NZE Scenario's deployment levels, there is uncertainty surrounding these plans. Material supplies must also expand to meet the growing demand. In 2021, PV contributed for 6% of silicon with a metallurgical grade and 11% of the world's silver output, and more than 40% of refined tellurium. Need for critical materials is expected to increase by 200-300% by 2030 compared to 2021 levels, in the NZE Scenario, For example, the demand for silver in solar PV manufacturing is projected to triple by 2030, equating to 35% of the world's silver production in 2021, in spite an anticipated 25% decline in silver intensity [16]. Figure 3.17. below demonstrates the expansion of PV capacity and the corresponding mineral demand within the context of the Net Zero Emissions Scenario, observed for both 2021 and projected for 2030.

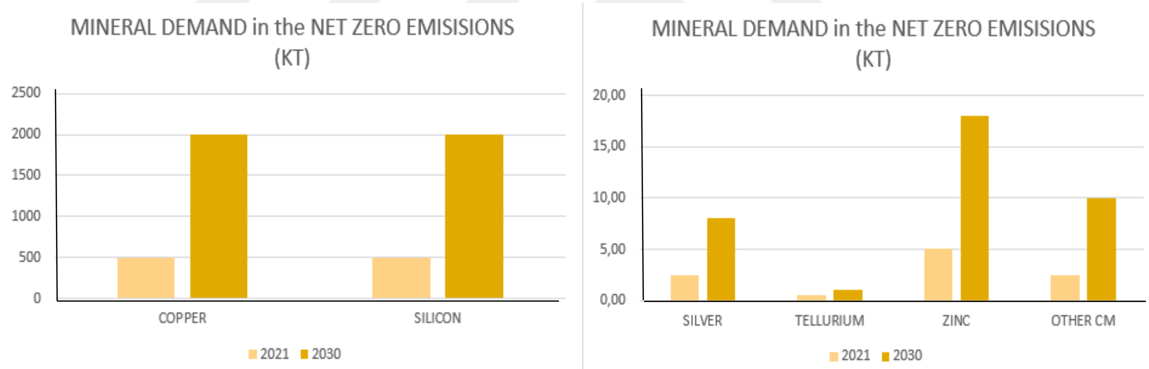


Figure 3.17. The expansion of Solar PV capacity and the corresponding mineral demand within the context of the Net Zero Emissions Scenario, observed for both 2021 and projected for 2030 [16]

3.3.2 Crystal Silicon PV Panel

The first solar technology are crystalline silicon panels and currently have the largest market share, accounting for approximately 92%. (When looking at the global market, polycrystalline technologies make up 51% and monocrystalline technologies make up 41%.) These panels have proven to be reliable and efficient in converting solar energy into electricity. However, there are other photovoltaic technologies that are emerging and gaining attention due to their unique properties and potential to compete with crystalline silicon PV panels. For example, thin-film solar cells are suited for uses like building-integrated photovoltaics and portable electronics because they are lightweight and flexible. Additionally, organic solar cells offer low-cost production and the ability to be produced in different shapes and colors. While crystalline silicon PV panels continue to be the dominant technology, it is important to keep an eye on the emerging technologies and their potential impact on the market. In the market for crystalline silicon technology, polycrystalline silicon PV panels are dominant with a 55% market share while monocrystalline silicon PV panels hold a 45% market share. Due to poor productivity rates, a-Si product production has ceased, and it currently has a very small market share [23], [29], [41], [70], [75]

c-Si PV module production was dominated by Asian manufacturers who accounted for 93% of the total. China was the top producer with a 70% share in 2021 [76].

3.3.2.1 Monocrystalline Silicon PV Panel

The initial monocrystalline silicon is cultivated into ingots using the Czochralski method, which necessitates the use of silicon in a liquid state obtained by heating it to 1400ºC. Although these cells offer high efficiency and long life, they necessitate a substantial energy input compared to alternative technologies and have the most expensive among all solar cells [77]. The foundation of PV cells lies in semiconductor materials, with monocrystalline silicon cells being made from an extremely pure form of silicon that enhances their photoelectric conversion efficiency. These cells boast an efficiency of over 20%, outperforming other types. Additionally, they have a longer lifespan, with manufacturers often providing warranties of up to 25-30 years for such systems. Consequently, from an investment standpoint, polycrystalline panels are often the preferred initial choice for consumers [78]

3.3.2.2 Polycrystalline Silicon PV Panel

Polycrystalline have a crucial role in the fabrication of solar panels. Due to its simpler production process, polycrystalline silicon solar cells are more affordable, leading to their increasing prominence over single-crystal silicon cells. Commercial polycrystalline silicon cells typically have an efficiency of 13-19% [79] Comprised of cells containing numerous tiny silicon crystals, polycrystalline modules exhibit an ice-like appearance [80].

Despite these advantages, there are still some drawbacks to using polycrystalline silicon solar cells. One of the main issues is that they are less efficient than single-crystal silicon solar cells, which means that they do not convert as much sunlight into electricity [41], [70].

3.3.3 Thin-film PV Panel

7% of the market for solar panels are thin-film panels [81]. Technology-wise, thin-film panels are more advanced than silicon-based ones. They require an intricate manufacturing process that involves multiple thin layers of semiconductor material coated on large materials such as polymer, metal or glass. Despite being more complex, they offer several advantages over silicon-based panels. For example, since thin-film panels are often lighter and more flexible, they are also simpler to carry and install. Additionally, they are less prone to damage from environmental factors such as hail or wind. The use of thin-film panels is becoming increasingly popular in both residential and commercial settings as a result of their many benefits. Thin-film technologies can be classified into two main types: CdTe (Cadmium Telluride) and CIGS (Copper indium gallium selenide) [29]. Thin-film technology has the highest cell efficiency, with CIGS cells having a laboratory efficiency of 23.4% and CdTe cells having an efficiency of 21.0%. The efficiency of CdTe modules has recently increased from 9% to 19% [76].

3.3.3.1 CIGS (Copper-Indium-Gallium-Selenide)

Due to its many benefits, including increased efficiency at both the module and cell levels and simple manufacturing processes, CIGS-based solar cells are among the most promising thin-film solar cells. Additionally, CIGS solar cells are attractive options for thin-film cell production because they offer consumers features like flexibility and lightweight. Lately, alkali element post-deposition processes, primarily involving heavy alkali elements, have played a substantial role in enhancing the performance of CIGS cells [82], [83].

3.3.3.2 CdTe (Cadmium Telluride)

Both substrate and top sheet configurations of CdTe panels may be created, with the top sheet configuration chosen for obtaining above 17% efficiency. A key component of thin-film cells is CdTe. According to reports, CIGS panels cost around 30% more than CdTe technology. Thus, utilizing CdTe-based thin-film cells can result in a favorable efficiency-to-cost ratio [84].

3.3.4 Selected Materials in Solar PV Manufacturing

It is demonstrated how certain materials are used in the production of c-Si and CdTe solar PV in Table 3.1. and Table 3.2. as follows.

Table 3.1. The employment of certain materials in the production of c-Si PV [41]

Material	Main uses
Aluminium	Module frame; mounting structure; connectors; back contact; inverters
Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
Copper	Cables, wires, ribbons, inverters
Glass	Module cover
Indium	Transparent conducting layer (indium tin oxide [ITO]) in silicon heterojunction (SHJ)
Lead	Soldering paste and ribbon coating in c-Si modules
Silicon	c-Si wafers; in the form of high-purity quartz (HPQ), for crucibles to grow monocrystalline silicone ingots via the Czochralski process
Silver	Electronic contacts: silver paste, busbars and soldering
Tin	Solder, ribbon coating in c-Si modules
Zinc	Galvanized steel in mounting structures

Table 3.2. The employment of certain materials in the production of CdTe PV [41]

Material	Main uses
Aluminium	Module frame; mounting structure; connectors; back contact; inverters
Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
Cadmium	Absorber layer
Copper	Cables, wires, ribbons, inverters
Glass	Module cover
Indium	Transparent conducting layer (indium tin oxide [ITO])
Molybdenum	Back contact layer
Selenium	Absorber layer in some CdTe cells
Silver	Electronic contacts: silver paste and soldering
Tellurium	Absorber layer (CdTe) and back contact (ZnTe)
Tin	Solder; transparent conducting oxide (indium tin oxide)
Zinc	Galvanized steel in mounting structures; back contact (ZnTe)

Notably, in addition to aluminium, copper, indium, and the like, CIGS, GaAs, and a-Si thin-film technologies also have unique material needs. These materials include gallium and arsenic. However, these technologies only make up a small portion of the overall demand for these materials at the moment.

Other raw materials that do not end up in a solar PV module's final composition are also employed throughout the production process in addition to the constituent components that make up solar PV modules. For instance, the carbothermic reduction of quartz into metallurgical-grade silicon uses carbonated feedstock materials (coal, woodchips, and charcoal), and the high-purity quartz (HPQ) crucibles used in the Czochralski process to produce monocrystalline silicon ingots must be changed every six to eight ingot cycles. The need for these materials will increase along with the volume of solar PV module manufacturing. Tables 3.3 and 3.4 display the weighted average material composition ratio of crystalline silicon and CdTe thin-film solar PV modules.

Table 3.3. Comparison of c-Si modules: weight, value, and material proportion [41]

Material	**weigh based**	**value based**
Glass (containing antimony 0.1-0.3%)	68-72%	11-15%
Aluminium	12-14%	9-12%
Polymers	8-10%	7-10%
Silicon	3-4%	35-45%
Copper	2-4%	5-12%
Silver	0.03-0.08%	9-23%
Zinc	0.03-0.1%	0.03-0.1%
Lead	0.01-0.05%	0.05%
Tin	0.01-0.05%	<0.5%
Other	0.20%	<0.5%

Table 3.4. Comparison of CdTe modules:weight, value, and material proportion [41]

Material	**weigh based**	**value based**
Glass (containing antimony 0.1-0.3%)	80-85%	47-54%
Aluminium	11-14%	28-37%
Polymers	2-4%	5-12%
Copper	0.03-0.4%	0.3-4%
Tellurium	0.05-0.07%	3-6%
Cadmium	0.04-0.07%	0.1-0.2%
Other	0.02-0.8%	0.05-3%

Notes: The value-based composition calculations are derived from the average market prices of materials in 2021. Figure 3.18. shows mineral demand of PV industry's as a percentage of global production; projected 2030 values in IEA Net Zero by 2050 Scenario in 2021.

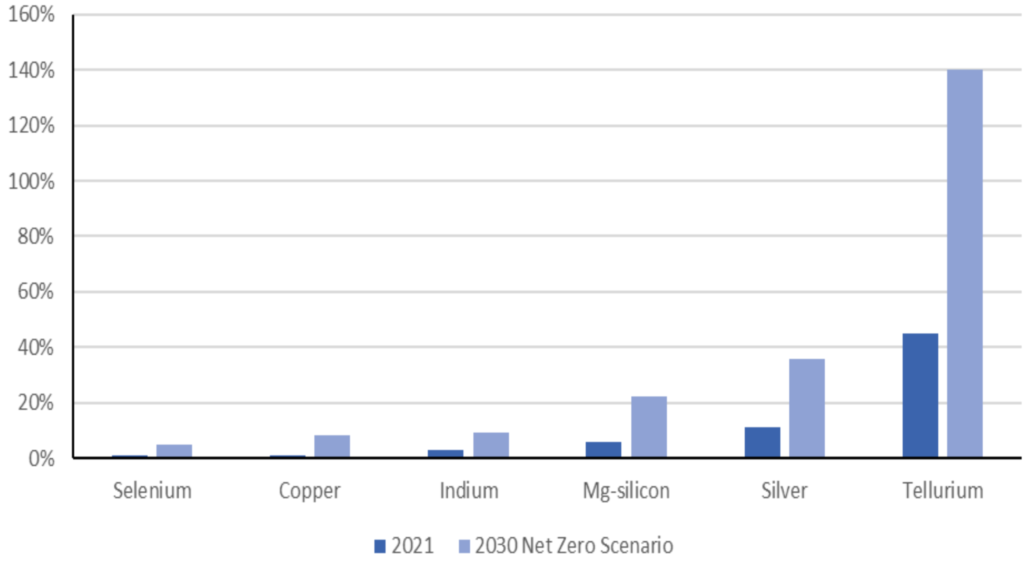


Figure 3.18. In 2021, PV industry's mineral demand as a percentage of global production; projected 2030 values in IEA Net Zero by 2050 Scenario [41]

CHAPTER 4
WASTE PROJECTION OF PHOTOVOLTAIC PANELS

This section is about the waste projection of solar energy. There are two sections to this chapter. The first section presents the global projection of solar energy waste over the years, while the second part shows the projection of waste for Turkiye over the years. In determining the amount of waste to be generated over the years, a conversion from GW to tons has been made.

As the availability of fossil fuels decrease, their costs increase, and they are vulnerable to potential conflicts. In contrast, solar energy is not impacted by these factors, making it a smart investment [45]. The utilization of photovoltaic technology for solar energy generation is becoming increasingly popular due to its potential in the production of clean energy [25]. Solar power has experienced explosive growth from 1992 to 2020, transforming from a niche application to a major source of electricity. After solar cells were developed in the 1950s, many countries have turned to solar energy generation [23]. However, as the use of PV technology remains to grow, it is significant to consider the disposal and waste management of PV panels at the end of their life cycle. Appropriate disposal of PV panel waste is necessary to decrease the environmental impact of e-waste and lessen the demand for new raw materials [30]–[32].

Although the lifespan of panels is about 25-30 years, they degrade over time, and their efficiency decreases, necessitating replacement at the end of their service life [85], [86].

It is crucial to address the potential environmental impact of end-of-life waste from renewable energy products, also called green energy. However, this presents opportunities for proactive policies and infrastructure development. To make informed decisions, it is important to gather insightful information on future waste generation and engage in discussions about the consequences of improper management. This approach will ensure a holistic management of this complex product. Individual and global assessments are databases that can provide valuable information for sustainable waste management practices. By using these databases, the waste generated by PV systems can be better comprehended and take steps towards more sustainable practices [33].

Most countries handle discarded PV panels under their general waste management framework, but some have specific regulations. Transboundary movements of waste and scrap can have advantages and disadvantages, with movements into countries without sound regulatory frameworks posing high environmental risks and extra costs. In-depth studies have been done on policies implemented in OECD countries, with Europe, Korea, Japan, and the United States having major parties involved in regulating PV waste management [29], [33], [34].

IRENA reports project that the global cumulative installed capacity of photovoltaic systems will experience a substantial shift towards renewable energy, reaching 4,500 GW by 2050 [29]. This is due to the increasing competitiveness of solar power with traditional energy sources, resulting in greater accessibility and affordability. By lowering greenhouse gas emissions, such technologies can aid in minimizing the effects of climate change. Government policies and falling costs are driving the shift towards renewable energy sources, with solar power expected to become the fastest-growing source of electricity in the next decade. The potential of solar power to revolutionize the energy sector cannot be underestimated [29], [87].

As the photovoltaic panel market grows, the capacity of decommissioned panels will also increase. At the end of 2019, cumulative solar panel waste streams were estimated to be in the range of about 600,000-700,000 tons. This amount of waste is anticipated growth significantly in the coming years. This number is staggering, considering that solar panels are designed to last for 25-30 years before they need to be decommissioned. One of the main reasons for this increasing waste stream is the lack of proper recycling facilities for solar panels [33], [53].

As a result, many decommissioned panels end up in landfills, where they can take up valuable space and potentially harm the environment. About 53 million tons of e-waste were reported to have been produced globally in 2019. Furthermore, it has been estimated that by 2030, 74.7 million tons of e-waste will be generated globally [33], [35], [36]. End-of-life panels will result in an annual waste increase of 5.5–6 million tons and an increase in the volume of new installations of nearly 6.7 million tons in the 2050s. These statistics indicate that solar panel waste could become a significant issue in the future. As the demand for solar panels increases, the amount of waste generated by decommissioned panels will also increase. This waste will contribute to the growing global e-waste problem, which is a significant environmental concern. It is necessary to develop sustainable methods of managing and recycling solar panel waste to mitigate the impact of this issue [29]. Figure 4.1. below represents projected 2050 cumulative EoL PV panel waste volumes for top five countries, categorized by early loss and regular loss scenarios.

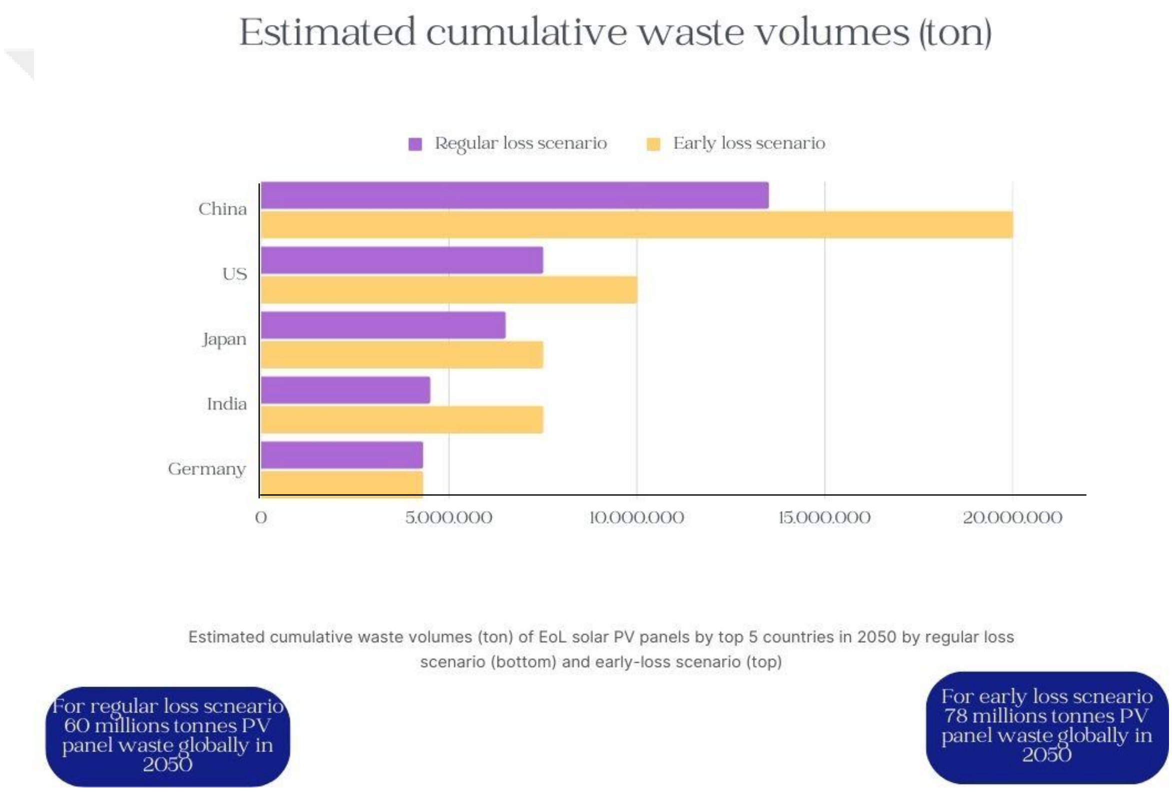


Figure 4.1. Projected 2050 cumulative EoL PV panel waste volumes for top five countries, categorized by early loss and regular loss scenarios [29]

4.1 Progressive Mass/Power Ratio Reduction Over Time (t/MW): A Trend Analysis

PV panels have experienced a reduction in weight and an increase in strength due to various reasons. One of the primary factors is the rise in competition in the market, which has forced manufacturers to develop more efficient and economical technologies. Furthermore, advancements in technology have resulted in a decrease in mass in PV panels by enhancing cell and panel designs. This has led to the creation of thinner frames, glass layers, and sheets that have significantly contributed to the improvement of the panels. [29]

While the materials utilized in the panels have not changed significantly, every step of the PV value chain has played a vital role in generating products that use fewer resources and materials. This is essential since it enables people to utilize the earth's finite resources responsibly while reducing the effects on the environment [20], [29], [41]. By consuming fewer resources, the carbon footprint of the production process can be reduced, which is a significant move towards achieving a more eco-friendly future [88].

4.2 Projection of The Solar Panel Capacity, Installed or to Be Installed

The first statement illustrates a visual representation of the predicted growth in global photovoltaic capacity from the present until 2050. The second statement showcases a global analysis of the total PV installations from the past until now, separately for International Energy Agency (IEA) member countries and non-IEA countries, up until 2021. Finally, the third statement displays a visual representation of the top ten countries with the highest annual installed PV capacity in the year 2021. Figure 4.2. below indicated the estimation of global cumulative growing in photovoltaic capacity until 2050 and Figure 4.3. represents Worldwide development of cumulative PV installations over time

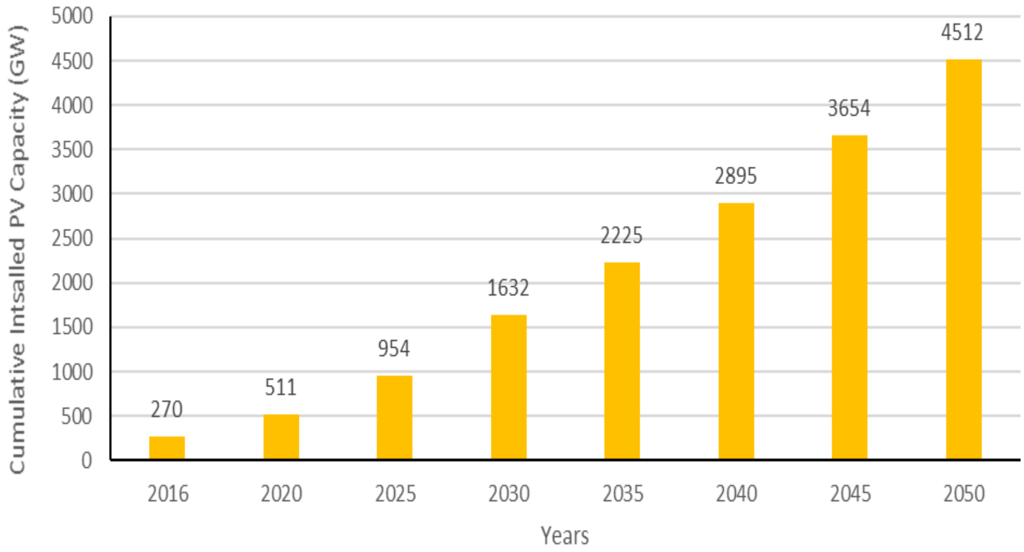


Figure 4.2. The estimated global cumulative increase in PV capacity until 2050 [29]

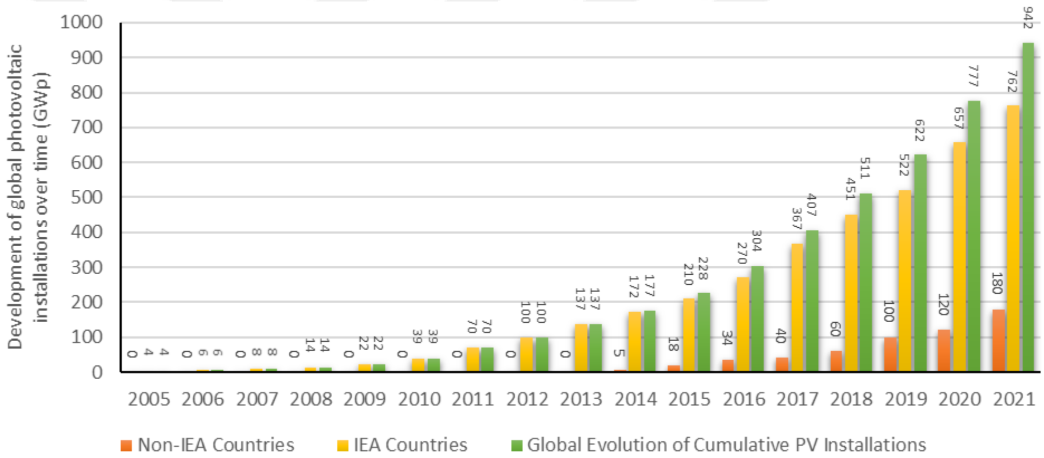
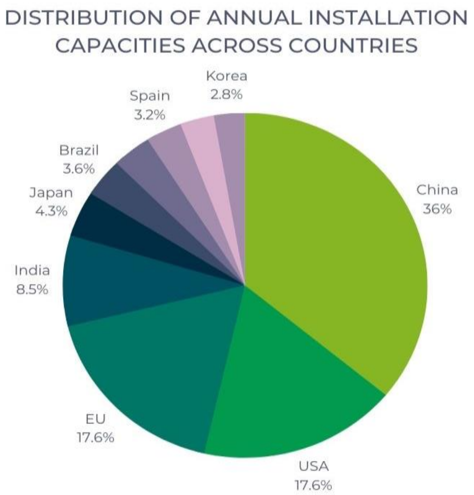


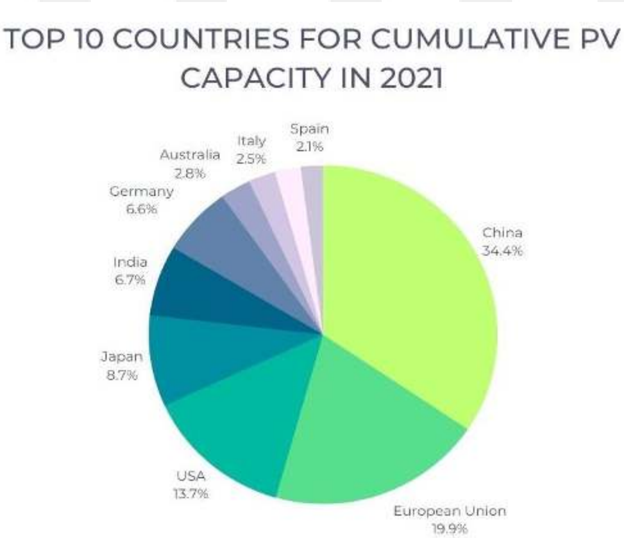
Figure 4.3. Worldwide development of cumulative PV installations over time [27]

According to Figures 4.2. and 4.3., there is a difference in the values for 2016 and 2020. This is because the installed capacity of PV plants exceeded the initial estimates. For that reason, the values for 2016 and 2020 in the tables were taken from Figure 4.3., while the values for other years were taken from Figure 4.2. Figure 4.4. Annual PV Installations and Total Annual Installed Capacity in the Top 10 Countries in 2021 and Figure 4.5. Cumulative PV Installations and Total Cumulative Capacity in the Top 10 Countries in 2021.



COUNTRIES	FOR ANNUAL INSTALLED CAPACITY
China	54,9 GW
USA	26,9 GW
European Union	26,8 GW
India	13 GW
Japan	6,5 GW
Brazil	5,5 GW
Germany	5,3 GW
Spain	4,9 GW
Australia	4,6 GW
Korea	4,2 GW

Figure 4.4. 2021 Annual PV Installations and Total Annual Installed Capacity in the Top 10 Countries [27]



COUNTRIES	FOR CUMULATIVE CAPACITY
China	308,5 GW
European Union	178,7 GW
USA	123 GW
Japan	78,2 GW
India	60,4 GW
Germany	59,2 GW
Australia	25,4 GW
Italy	22,6 GW
Korea	21,5 GW
Spain	18,5 GW

Figure 4.5. 2021 Cumulative PV Installations and Total Cumulative Capacity in the Top 10 Countries [27]

In 2021, the EU included 27 European countries, Italy, Germany, the Netherlands and France with Spain being among them. These five countries also appear in the top 10 countries for either the installed capacity or annual installations of photovoltaic systems.

4.3 The Waste Problem with Increasing PV Panel Capacity

4.3.1 World PV Projection

Photovoltaic deployment has increased more than predicted in the early 2010s, leading to a higher-than-expected rise in end-of-life waste flows [89].

This research analyzes the potential growth of photovoltaic capacity from 2016 to 2050 in both Turkiye and worldwide, and estimates the amount of waste that may result from this expansion under two various scenarios: regular-loss and early-loss. The data used for this study is based on reports from IRENA in 2016 and IEA in 2014. The Karapinar Solar Power Plant, located in the Konya province of Turkiye, serves as a case study for this research. To convert gigawatts (GW) to tons, Equation 4.2 was used for the analysis. During the conversion process, Table 4.1. was referenced for the technical specifications of the panels used and calculations were made for specific periods. The early-loss and regular-loss scenarios take into account a correction factor that considers the increased durability and reduced weight of panels resulting from design improvements for panels and cells, as well as the use of frames, thinner glass layers and sheets. Both scenarios assume that the average lifespan of a panel is between 25-30 years and there is a 99.99% chance of loss after 40 years. The use of a 25-30 year panel lifespan is a common practice in analyzing the environmental impact of photovoltaic systems over their lifetime. According to the model, PV panels are assumed to be dismantled for refurbishment and modernization within 40 years at the latest. The probability of losses during the photovoltaic panel lifecycle is determined by the shape factor α, which differs between the early-loss and regular-loss scenarios. The alpha shape factor of 2.4928 is assumed and directly used for the early-loss scenario, while the alpha shape factor of 5.3759 is assumed and directly used for the regular-loss scenario [29] The formula is:

$$F(t) = 1 - e^{-(t/T)^{\alpha}} \tag{4.1}$$

where α is the shape factor that determines the characteristic S-shape of the Weibull curve, t represents time in years and T refers to the average lifespan.

There are various methods described in literature to convert gigawatts (GW) to tons.

Gautam et al. [51] used three distinct photovoltaic technologies. The rated power outputs for Silicon-based, CIGs and CdTe solar panels are 224 watts, 80 watts, and 65 watts respectively. According to these values, mass (tonne)/GW values are for c-Si 102,678.5, for CIGs 157,500 and for CdTe 184,615.4 respectively.

Santos and Alonso-García [37] developed a mathematical model and used graph that to convert gigawatts (GW) to tons.

The formula presented below was utilized by Domínguez and Geyer [75] in their work:

$$\text{Material content (kg)} = \frac{\text{Ins.Capacity (W)} \times \text{Material composition(kg/m}^2\text{)} \times \text{Market Share(\%)}}{\text{Module Nominal Power (Wp /m}^2\text{)}} \quad (4.2)$$

The above equation is used for three distinct types of photovoltaic panels that are typically c-Si, CIGS and CdTe for this study. The mechanical information of these panels is sourced from IRENA's 2016 data.

Table 4.1. Panel's Mechanical Specifications [29]

PV Technology	*Nominal Power (Wp)*	*Mass (kg)*	*Market Share (%)**
Crystalline*	270	18.6	92
CdTe**	110	12	5.5*
CIGS***	160	20	2.5*

* Trina Solar TSM-DC05A.08 **First Solar FS-4100 ***Solar Frontier SF160-S

** For Crystalline, CdTe and CIGS, market share rates are 92%, %5 and %2, respectively. For other technologies, the rate is 1% but this rate is ignored and added into CdTe and CIGS as 0.5%

Table 4.2. presents estimates of the expected growth in photovoltaic capacity from 2016 to 2050, as projected by the International Energy Agency in 2014 and the International Renewable Energy Agency in 2016. The table also shows the amount of waste that is expected to be generated globally as a result of this increase, under two different scenarios: early-loss and regular-loss. In addition, the table provides data on the amount of waste that will be generated per gigawatt (GW) of PV capacity by year.

Table 4.2. The projected growth increase in PV capacity (GW and ton) worldwide and the waste forecast that will occur worldwide resulting from this increase(t) [29]

World	Unit	2016	2020	2030	2040	2050
Total PV capacity	GW	304	777	1632	2895	4512
Total PV capacity*	$x10^3$ ton	22,040	56,334	89,760	130,275	180,480
Total waste regular loss	ton	43,500	100,000	1,700,000	15,000,000	60,000,000
Total waste early loss	ton	250,000	850,000	8,000,000	32,000,000	78,000,000
Regular loss	ton waste/GW	143.09	128.7	1,041.67	5,181.35	13,297.87
Early loss	ton waste/GW	822.36	1,093.95	4,901.96	11,053.54	17,287.23
Regular loss	ton waste/ ton capacity	0.002	0.0018	0.0189	0.1151	0.3324
Early loss	ton waste/ ton capacity	0.011	0.015	0.0891	0.2456	0.4322

* The values of PV Capacity (ton) based on equation 4.2.

**The values for 2016 and 2020 based on Figure 4.3. and other values taken from Figure 4.2.

To enhance the accuracy of annual photovoltaic capacity predictions from 2016 to 2030, an average yearly rate of growth of 8.92% was computed. The growth rates for certain countries were found to be lower or higher based on their level of development. In contrast, more cautious growth predictions have been made for the period between 2030 and 2050, assuming an annual growth rate of approximately 2.5%. [29]

4.3.2 PV Projection in Turkiye

An assessment of Turkiye's photovoltaic panel projections suggests that the country is likely to achieve a PV installed capacity of 18.9 GW through the year 2030 [29], [35].

According to the projections, the most substantial waste streams from photovoltaic panels in Turkiye are estimated to generate between 1,500 to 11,000 tons of waste per year under the early-loss and regular-loss scenarios, respectively. Table 4.3. provides information on the expected growth (in GW) of Turkiye's photovoltaic capacity between 2016 and 2050, as well as waste projections (in tons) resulting from this expansion, under both the early-loss and regular-loss scenarios. Additionally, the table includes data on the amount of waste that will be produced per GW of PV capacity by year.

Table 4.3. The projected growth in Turkiye's PV capacity (GW and ton) and waste forecast that will occur throughout Turkiye resulting from this increase (t) [29], [35]

Turkiye	Unit	2016	2020	2030	2040	2050
Total PV capacity	GW	0.83	7	19	30	45
Total PV capacity*	ton	60,175	507,513	1,045,000	1,350,000	1,800,000
Total waste regular loss	ton	30	100	1,500	20,000	200,000
Total waste early loss	ton	70	350	11,000	100,000	400,000
Regular loss	ton waste/GW	36.0144	14.4928	79.3651	657.8947	4,484.3049
Early loss	ton waste/GW	84.0336	50.7246	582.0106	3,289.4737	8,968.6099
Regular loss	ton waste/ ton capacity	0.0005	0.0002	0.0014	0.0146	0.1121
Early loss	ton waste/ ton capacity	0.0012	0.0007	0.0106	0.0731	0.2242

* The values of PV Capacity (ton) based on equation 4.2

CHAPTER 5
RECYCLING OF PHOTOVOLTAIC PANELS

Photovoltaic systems are becoming increasingly popular as a way to solve energy problems in an environmentally-friendly manner.

Over a 17-year period, the emission amount of a PV panel is 201.4 kg- CO_2, which is much lower compared to the 1918 kg- CO_2 emitted to generate the same amount of electricity in a natural gas power plant. This indicates the environmental friendliness of PV panels compared to other energy sources. PV panels can save up to 1.72 tons-CO_2 emission compared to thermal power plants in the same period [26].

However, at the end of their useful life, solar panels need to be decommissioned and disposed or re-used in a way that does not contribute to untreated waste. While The projected lifespan of PV panels is 30 years, the problem of their decommissioning has not yet been adequately addressed. Given the PV market's explosive expansion and the associated environmental problems that arise at the end of their useful life, the European Union is calling for the long-term sustainability of the photovoltaic industry [42].

As the average lifetime of photovoltaic panels is 25-30 years, the global amount of photovoltaic waste is expected to increase from 43,500-250,000 metric tons in 2016 to over 70 million tons by 2050. Recycling these end-of-life photovoltaic panels is essential for the long-term sustainability of the solar energy sector, both economically and environmentally. The European Union has formally recognized this need by listing EOL-PV panels as waste of electric and electronic equipment (WEEE) and setting specific minimum goals for their recovery, recycling, and collection. These targets require at least 65%, 80%, and 85% of the panels to be collected, recycled, and recovered, respectively, starting from August 2018. Therefore, it is strongly predicted that effective and sustainable recycling techniques would be developed and implemented [29], [42], [56], [90].

Nowadays, electricity production with PV panels are thought environmentally friendly compared to other sources due to its lower carbon emissions. However, emissions arising from the energy consumed in the supply of and processing of chemicals required in industry, among other operations can directly or indirectly impact the environment. Additionally, emissions can also be released when panels are integrated into solar power plants. Therefore, environmental harms may occur when producing electricity with photovoltaic panels [91].

The impact on the environment during the usage of a PV system is typically considered to be minimal. However, it is crucial to note that the replacement of electronic components, particularly the inverter, is a significant consideration after a period of 15 years of operation [45].

Due to fears that clean energy technologies may face raw material constraints despite efforts to reduce material usage, recycling these technologies at the end of their lifecycle has received significant attention under the circular economy concept. However, photovoltaic technology was not initially designed with end-of-life recycling in mind, and this poses challenges for reusing its raw materials in new products [89].

Implementing regulations for recycling and applying correct policies could alleviate the impending scarcity of resources, reduce the hurdles and expenses associated with PV recycling, and facilitate the transition to a circular economy in the energy sector.

The conventional economy operates on a linear model where resources are extracted, used to manufacture goods, and discarded after use. An alternative model, the circular economy, could help address resource and environmental challenges by encouraging the recovery and reuse of products and materials. However, the photovoltaic circular economy faces challenges such as low material recovery rates, low recycling rates and profits due to non-specialized PV recycling, difficulty in separating module components, and limited product reuse due to lack of awareness of consumer and negative attitudes about used goods and present policies [92].

In a traditional linear economy, products are discarded in landfills at the end of their useful life, and new products are made from raw materials to replace them. On the other hand, a circular economy aims to maximize the use of energy and materials throughout the entire life cycle of a product by reusing, repairing, refurbishing, remanufacturing, and recycling discarded products. This approach extends the lifespan of products and reduces waste. However, recycling complex products can be challenging because they often contain a mix of materials that are difficult to separate and recover. One way to make circular economy products is to design them with recycling in mind from the beginning. Design for recycling (DfR) aims to increase the speed and ease of dismantling, as well as improve purity of recovered materials and the recycling rate. DfR focuses on developing goods that can be recycled safely and affordably utilizing current technology and procedures. Additionally, it aims to replace materials to create safer products for the environment and people. Nevertheless, in some cases, it may not be possible to replace certain dangerous or rare components. In these instances, cooperation between manufacturers and recyclers is critical to ensure proper recycling and control of environmental risks [89].

Since the early 1990s, electronic equipment has been designed with recycling in mind (DfR) procedures. Recycling helps minimize trash while also lowering emissions and the energy required to obtain and process raw materials. Recycling typically involves multiple processing stages, but DfR can allow for the direct reuse of intact components, minimizing overall recycling energy use and intermediate losses. Reusing components often needs fewer life-cycle routes than recycling, which might result in a superior economic value, especially since current PV recycling techniques do not produce enough income to cover the expenses of transport and processing [89], [90], [93].

Globally, manufacturers are required to use waste management methods or seek the assistance of waste management consultants or non-profit organizations to handle the disposal of EoL PV panels.

The European Union updated the waste electrical and electronic equipment (WEEE) directive to incorporate PV components as discarded electronic devices, resulting in their inclusion under the ten categories of WEEE in July 2012. As a result, solar PV components are now part of the electronic waste management system and must be recovered and disposed of properly [21].

The Directive, which became effective on February 14, 2014, aims for the improvement of old electronic device collecting, reuse, and recycling in order to reduce waste and make efficient use of resources. A major concern with the treatment and disposal of photovoltaic EoL products is the release of hazardous metals like lead and chromium, and toxic gases such as hydrofluoric acid, which could negatively impact the environment if not disposed of appropriately. A sustainable solution to resource availability, economic viability, and EoL-related environmental issues may be found with proper EoL management of PVs. In order to do this, the European PV industry founded the PV CYCLE association in July 2007. This organization advocates for an optional take-back and recycling scheme for EoL panels and is in charge of PV modules' whole life cycle. Recycling has benefits in terms of the environment, market acceptance and support, environmental regulations, and resource availability. Recycling items typically results in cost savings in terms of landfill space, energy, emissions, and raw resources. These benefits are particularly important for strategic materials such as rare earths and precious metals, because the methods used to extract raw materials can involve large energy and ancillary demands as well as accompanying emissions. Therefore, the treatment of waste electrical and electronic equipment (WEEE), or the conversion of it into materials still usable by humans or nature, remains critical in the face of worldwide energy and resource scarcity. It is crucial to keep in mind that resources originate from both sources of renewable energy and from the storage of materials and energy from previous biosphere production [42], [94], [95].

5.1 Economic Benefits of Materials Gained From Recycling PV Panels

Considering the efficiency of recycling, a majority of the metals present in photovoltaic panels are both environmentally beneficial and economically significant to recycle. The key metals that offer environmental and economic advantages upon recycling are outlined in this segment. Investigations have been conducted on metrics like the per-unit volume of recycled materials and the per-unit area of the photovoltaic panel. Silver is the most valuable and efficient metal for c-Si PV panels. As such, the recycling strategy for c-Si solar panels should predominantly focus on the recovery of silver metal [96]. Hence, the environmental repercussions can be minimized and the reproduction cost might be notably cut by reducing the dependence on raw silver metals. Metals such as silicon, tin and titanium and carry relatively high prices and substantial impacts. In the case of CdTe panels, Tellurium and Manganese are the priciest metals. Silver continues to be costly due to its substantial Global Warming

Potential (GWP) effects for c-Si panels. The production of silver is associated with high GWP impacts. Even though aluminium is moderately priced, it is expensive in terms of its environmental impact. This elevated impact is attributable to the high unit mass to unit area ratio of aluminium in c-Si panels. Analogous trends are observed for other elements, including silicon and glass. Therefore, the prices and impacts of raw materials hinge on the unit mass to unit area ratio utilized in photovoltaic panels. The most efficacious elements are silicon, aluminium, glass and silver. In the context of CdTe panels, tellurium and copper are the costliest elements, whereas glass is the most efficacious, given it makes up around 94% of the CdTe panel. Zinc, with the lowest GWP, is the least expensive. Consequently, the goal of recycling photovoltaic panels should be geared towards the retrieval of high-cost and efficacious metals such as copper, silver, silicon, aluminium, tellurium and glass [50].

Table 5.1. Materials used in PV Panels*,** [97]

Materials	Al	Cd	Cu	Ga	In	Mo	Pla	Se	Si	Sn	Te	Glass	Zn
x-Si (%)	17.5	-	1.0	-	-	-	12.8	-	2.9	-	-	65.8	-
CdTE (%)	-	0.08	0.03	-	-	-	3.0	-	-	0.02	0.07	96.8	-
CIGS (%)	-	-	0.01	0.01	0.01	0.12	3.0	0.01	-	-	-	96.9	0.04
Recycling rate (%)	100	98	78	99	75	99	-	80	85	99	80	97	90
Market prices* ($/kg)	2.30	1.68	8.4	285	212	46.5	0.09	57.3	2.07	24.8	81.6	0.1	3.01

* Al:Aluminium, Cd:Cadmium, Cu:Copper, Ga:Gallium, In:Indium, Mo:Molybdenum, Pla:Plastic Se:Selenium, Si:Silicon, Te:Tellurium, Zn:Zinc, Sn:Tin

** Values are taken from LME The London Metal Exchange (LME). https://www.lme.com/ (accessed 20 January 2023) [98]

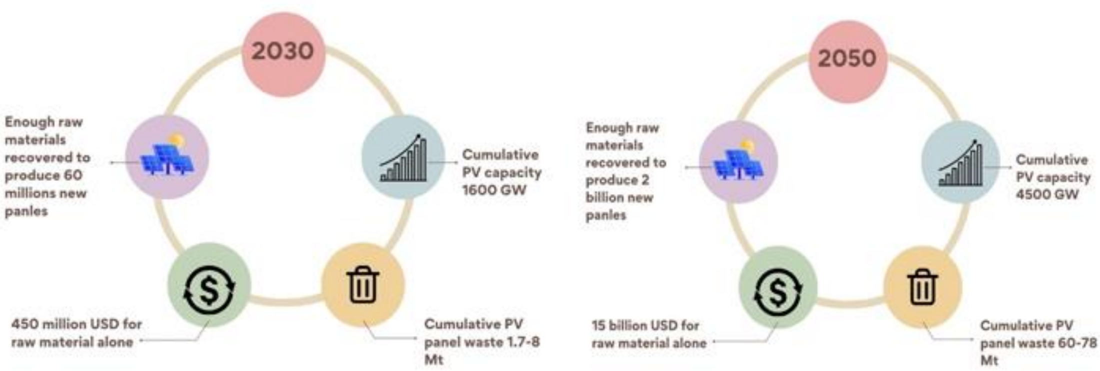


Figure 5.1. The possible value that can be generated by effective manage PV-EoL [29]

Table 5.1. presents the constituents used in PV panels. It also provides the percentage of recycling for each material, their market prices, and the types of panels in which they are used. Moreover, it examines the value and significance of recycling each of

these materials. Glass and aluminium and have an approximate recycling rate of 100%. The environmental and economic implications of recycling the materials listed in this table are tremendously substantial. Given that glass accounts for more than 80% of the mass of solar panels, irrespective of the panel technology used, it follows that the largest quantity of recycled material originates from glass. The quantity of recycled glass is projected to reach around 960,000 tonnes by 2030 [29]. Figure 5.1. illustrates the potential values that could be generated through end-of-life management of photovoltaic panels between the years 2030-2050. The overall estimated value of the material that could be recuperated through the processing and recycling of solar panels is projected to be about US$450 million by 2030. This is equivalent to the raw materials necessary for the production of 60 million new panels, or 18 GW. To put it in perspective, In 2015, a total of 180 million new panels were manufactured. Assuming the same regular loss rate, the potential value of the raw materials is anticipated to surpass US$15 billion by 2050. This corresponds to the raw materials required to manufacture two billion new panels, or generate 630 GW. Therefore, as PV waste capacity expand quickly, a market for secondary raw materials from end-of-life panels will emerge [29]. Energy Payback Time (EPBT) is the most commonly used metric for evaluating the efficiency of photovoltaic systems, as it calculates the primary energy consumed during the production phase and the power generated by the system [99]. By using recycled modules instead of standard ones, the Energy Payback Time could potentially be reduced from 2.5 years to 0.6 years in regions with high sunlight, and from 4.3 years to 1.14 years in continental climates [100]. Lowering the Energy Payback Time (EPBT) of photovoltaic cells requires a significant decrease in material and production costs, a considerable increase in PV cell efficiency, or a blend of both strategies. Such measures serve in order to lower the expense of generated electricity by PV cells, thereby enhancing the commercial competitiveness of this technology [29].

5.2 Comparison of The Amount OF CO_2 Emissions Occurring in Photovoltaic Panel Production and Recycling

In this section, the focus is on examining the emissions produced throughout the manufacturing and recycling of CdTe and Polycrystalline panels, as well as the variance in the quantities of these CO_2 emissions. At this stage of the research, the focus is on CdTe and Polycrystalline panels. Polycrystalline is used more common in the crystalline silicon panel technology, while CdTe panel is used more common in the thin-film technology category.

The use of photovoltaic panels for electricity generation is often considered environmentally friendly due to their lower carbon emissions compared to other energy generation methods. However, the environmental effects extends beyond just energy use, as it also includes the effects of various processes like procuring and processing raw materials, along with the utilization of certain chemicals during manufacturing. Moreover, the integration of these panels into solar power plants, while generating electricity, also contributes to some CO_2 emissions, negatively impacting the environment. The growing focus on PV technology is driving its gradual advancement, with numerous panels being designed to boost performance. As we continue to refine these technologies, it's crucial to also consider ways to mitigate their environmental impacts. For instance, developing more efficient recycling methods for EoL PV panels could be a significant step towards more sustainable solar power. Ultimately, the goal should be not only to enhance the effectiveness and capabilities of photovoltaic panels but also to ensure that their entire lifecycle, from production to disposal, is as environmentally friendly as possible [26]. The quantity of CO_2 emissions can differ based on the model of the solar panel, influenced by variables such as variations in the production process and the types of raw materials used.

Harnessing over 8,500 GW of solar energy could potentially meet more than 25% of the total electricity requirements projected for 2050, and this could result in a significant reduction of CO_2 emissions (4.9 Gt CO_2). This represents a 21% decrease in potential total CO_2 emissions through renewable energy sources and energy efficiency measures. Among all low-carbon technologies, photovoltaics hold a substantial potential for CO_2 emission reduction up to 2050. The primary reason for this is the substantial growth of solar energy, which is replacing conventional power generation sources. This transition is made possible by leveraging advanced technological solutions and ensuring sufficient availability of resources, especially in more favorable locations with abundant resources [60].

Worldwide, CO_2 emissions from the manufacture of PV panels have nearly increased fourfold to 51,900 kilotonnes of carbon dioxide, fueled by advancements in the photovoltaic industry and a surge in demand, accounting for approximately 0.15% of total global energy-related emissions in 2021. However, the rise in CO_2 emissions has been offset by advancements in material and energy efficiency, along with a decrease in the emissions intensity of electricity generation in many countries [41].

5.2.1 Average Amount of CO_2 Emissions in Polycrystalline PV Panel Production

CO_2 emissions are a direct or indirect result of the specific amount of energy consumed during each phase of solar panel production. The quantity of CO_2 emissions released in the process of manufacturing a 1 m^2 polycrystalline panel has been roughly estimated in countries where photovoltaic panels are produced. Notably, different levels of CO_2 emissions have been observed in the production of a 1 m^2 polycrystalline panel across various countries. Figure 5.2. shows that the projected CO_2 emissions for countries [26].

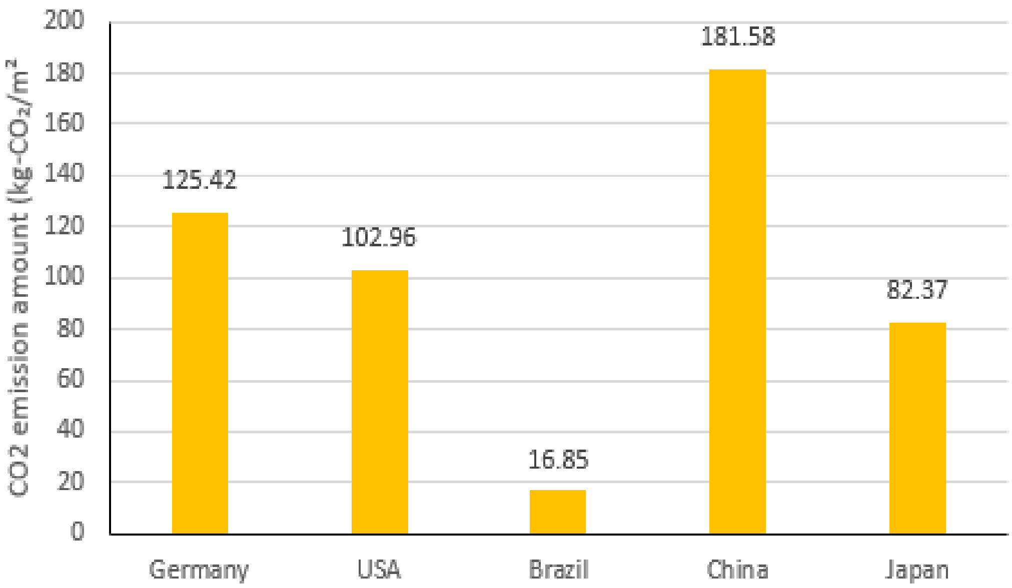


Figure 5.2. The quantity of CO_2 emission throughout the producing of the polycrystalline panel [26].

5.2.2 Average CO_2 Emission Amount During Recycling of Polycrystalline PV Panel

Solar panels designated for recycling significantly contribute to the production of new panels. This is largely due to many of the processes involved in recycling panels requiring less raw materials [101]. The recycling process, from silicon sourcing to sheet production, utilizes significantly fewer raw materials compared to the standard manufacturing process.

The recycling process, from sourcing silicon to producing sheets, requires substantially reduced usage of raw materials and energy compared to the traditional manufacturing method, leading to a reduction in CO_2 emissions [102]. In the process of producing the backsheet, the raw material is primarily sourced from the panel that is being recycled.

Assuming the 1 m^2 polycrystalline panel is recycled, this method allows for the production of approximately, 0.888 m^2 of polycrystalline panels, consuming 21.1 kWh of energy in the process. Given that the energy consumed consequences in indirect CO_2 emissions, it varies among countries in the range of 2-20.47 kg- CO_2. Figure 5.3. depicts the CO_2 emissions amounts for different countries.

The calculation's outcome highlights that there is a considerable difference in CO_2 emissions between the production of recycled panels and non-recyclable panels. These results show how important of PV recycling is.

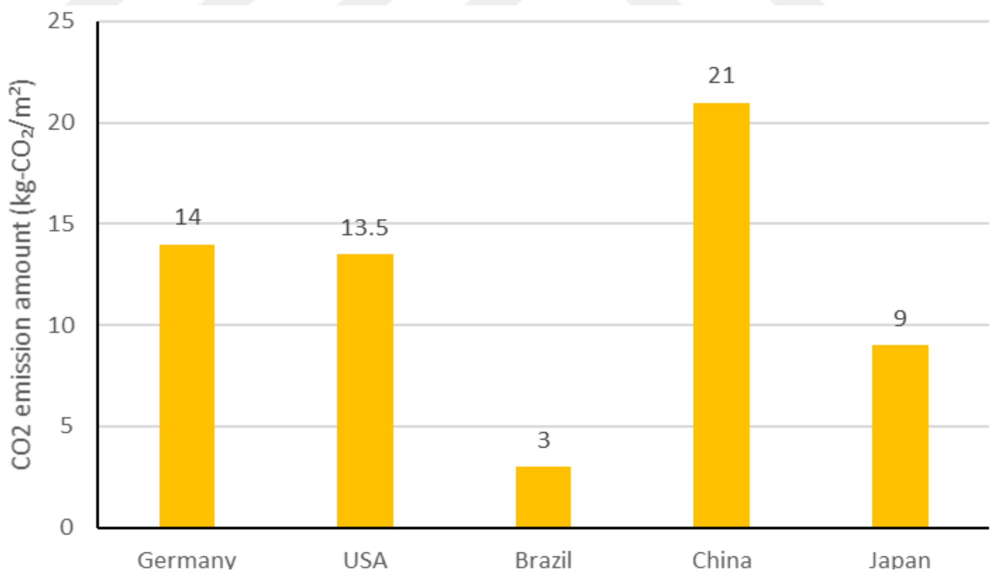


Figure 5.3. The quantity of CO_2 emission throughout the recycling of the polycrystalline panel [26]

5.2.3 Average Amount of CO_2 Emissions in CdTe PV Panel Production

The process of purifying cadmium for the production of 1 kilogram uses 1.25 kWh of power. As a consequence of these procedures, CO_2 emissions in the ranging from 0.11–

1.21 kg-CO_2 occur, when five countries are compared. Following the purification stage, the manufacturing process for semiconductor-grade cadmium requires an energy input of 3.86 kWh. CO_2 emissions of between 0.35 and 3.74 kg-CO_2 are emitted into the air in this process. The production of 1 kg of $CdCl_2$ requires 0.0425 kWh of energy through the reaction of 0.646 kg of semiconductor cadmium with 0.419 kg of hydrochloric acid. This process leads in low CO_2 emissions of approximately 0.3–41.23 g-CO_2. After this step, the production of CdS requires an energy input of 0.004 kWh, and the associated CO_2 emissions are negligible, ranging from 0.00036 to 0.00388 g−CO_2 [42]. During the procurement of tellurium for the manufacturing of PV panels, approximately 0.043 kWh of electricity is utilized, resulting in a small quantity of CO_2 emissions, approximately ranging from 3.87 to 41.71 g -CO_2. Throughout the manufacturing process of semiconductor-grade tellurium from raw tellurium, CO_2 emissions in the range of 0.98 to 10.56 kg- CO_2 are generated. Figure 5.4. illustrates the country-specific environmental CO_2 emissions resulting from the production of CdTe panels. The CO_2 emission quantities associated with manufacturing 1 m² of CdTe PV panels were calculated for five countries, revealing varying levels of emissions for each country. Additionally, when comparing the production of 1 m² CdTe panels to that of 1 m2 polycrystalline PV panels, it is evident that CdTe PV panels exhibit lower CO_2 emissions [26] .

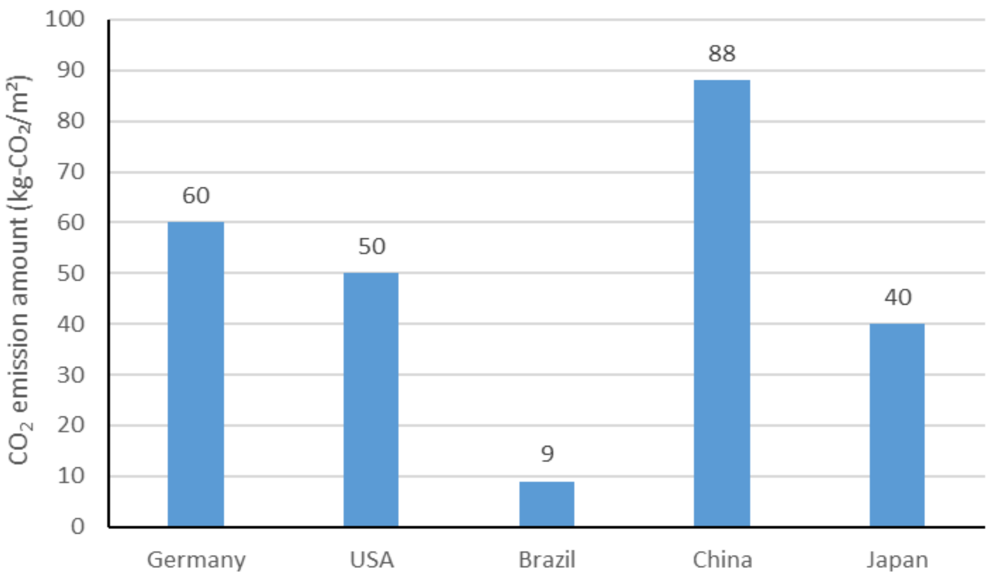


Figure 5.4. The quantity of CO_2 emissions throughout the producing of CdTe [26]

5.2.4 Average CO_2 Emission Amount During Recycling of CdTe PV Panel

Approximately 90% of CdTe PV panels that are recycled can be recovered. This recycling practice is highly advantageous as it leads to significant savings in raw materials. Once analyzing the recycling of a 1 m^2 CdTe PV panel, it is observed that approximately 0.0412 kg of CdTe PV panel is obtained through this method. The process consumes 4.4 kWh of energy and indirectly results in CO_2 emissions ranging from 0.4 to 4.27 kg- CO_2 [45]. Figure 5.5. illustrates the contribution of each country to CO_2 emissions in the environment through the recycling of CdTe panels. It is evident that the production of recycled panels and CdTe panels leads to considerably varied levels of CO_2 emissions compared to non-recyclable panels. The findings demonstrate that each type of photovoltaic panel offers substantial energy savings during manufacturing, consequently resulting in significant reductions in CO_2 emissions through the recycling process [26].

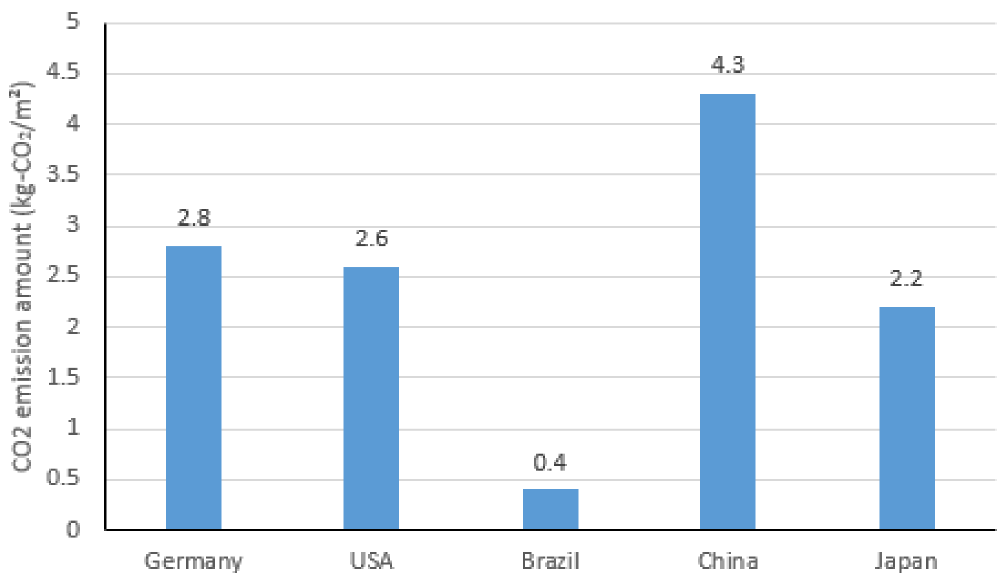


Figure 5.5. The quantity of CO_2 emissions throughout the recycling of CdTe [26]

Cadmium, which is known as one of the most poisonous substances to humans, is the highly toxic nature the recycling method employed for CdTe panels brings about several benefits. This includes a reduction in primary energy consumption, EPBT, and other impact potentials, as it ensures a significant supply of CdTe semiconductor material for panel fabrication. In comparison to silicon panels, the production process for CdTe panels is simpler. The findings indicate that while CdTe cells may have lower energy efficiency compared to Si cells, CdTe cells offer advantages in terms of the environment, economy, and energy that can compensate for this drawback [45].

The graphs clearly demonstrate a significant contrast in CO_2 emissions between Brazil and China. Brazil stands out with remarkably lower carbon emissions compared to other countries. This can be attributed to the fact that in 2021, around 80% of Brazil's power generation was derived from renewable energy sources. In contrast, China's power generation relied on renewable energy sources for approximately 30% of its energy production [103].

Table 5.2. Impact of 1 kWh electricity generation on environment across PV tech [104]

	unit	mono-si	multi-si	CIS	CdTe
Greenhouse gas emissions	g CO_2 -eq	42.5	42.3	36.3	26.5
Resource use fossil fuels	MJ	0.54	0.54	0.54	0.38
Module efficiency	%	19.5	18	16	18
Data	Years	2017-2019		2010	2018-2019

5.3 Recycling Techniques

Recycling of PV modules is a better option than simply throwing them away. Photovoltaic module recycling is now a key topic, and many governments, organizations, and companies around the world are developing recycling programs to preserve PV's status as a clean energy technology [105].

The deployment of PV has been increasing at a faster pace than anticipated since the beginning of the 2010s. To achieve a state of zero emissions by 2050, it is necessary to develop regulatory and technological strategies that can optimize end-of-life PV management plans that are adapted to each country or region's specific conditions [29], [106].

Establishing feasible PV recycling systems requires not only technological availability, but also consideration of the advantages for the environment and the economic feasibility. While recycling waste from photovoltaic module production and EoL modules can reduce environmental impact by decreasing the need for scarce resources, chemicals and energy required for new modules, currently, the economic incentive to recycle most PV modules is not favorable. To address this issue, policies should be implemented to promote producer responsibility, not only within the PV manufacturing sector but also across the entire energy industry. Additionally, an efficient collection network is crucial for the economic feasibility of photovoltaic module recycling businesses [90].

Various types of waste, including electronic waste, are viewed as the responsibility of product manufacturers to manage. Holding manufacturers accountable for the EoL management of photovoltaic panels can encourage sustainable PV material management. Furthermore, it would be beneficial to encourage manufacturers to adopt eco-friendly designs by implementing relevant regulations. This measure can help mitigate the environmental impact of PV products. The conservation of resources through the recycling of end-of-life products and the production of new solar panels with recycled materials can also significantly contribute. The implementation of strict laws regarding the collection and recycling process can help establish a logistics network that promotes sustainable technology and creates connections within a sustainable and eco-friendly supply chain [29], [47], [107], [108] .

A study evaluated the environmental impact of polycrystalline silicon and CdTe photovoltaic panels throughout their life cycle using the LCA methodology. The study found that implementing a recycling process at the end of the operation phase resulted in significant reductions of environmental impacts for polycrystalline silicon technology. However, implementing a recycling process for CdTe technology resulted in small enhances of the Global Warming Potential and reductions of other environmental impacts. Comparison of the two technologies showed that CdTe panels had lower impacts due to their smaller total energy consumption for production and lower environmental impacts associated with resource depletion. The recycling of CdTe panels played a crucial role in significantly reducing all toxicity-related impacts. Si-panel production technology, when coupled with end-of-life recycling, showed minimal toxicity potential and is regarded as the most favorable technology. The EPBT was calculated to be around 2.6 years for silicon panels and about 1.30 years for CdTe panels, which could be decreased to around 1.6 years for silicon panels through the incorporation of the recycling process. The analysis showed that the recycling phase of end-of-life panels holds significant importance in mitigating the environmental impact throughout the life cycle of both panels and in achieving a low Energy Payback Time (EPBT). Despite CdTe cells having a lower efficiency than Si cells, they have energy, economic, and environmental benefits which can compensate for low energy efficiency. However, CdTe panel production is associated with high toxicity, so Incorporating a recycling process at the end of the product life cycle is essential to ensure the success of this technology in the photovoltaic market [45].

Currently, solar module recycling is a major focus of research and development in Japan, Europe and the US. The majority of these efforts are centered on Si panels, with the goal of recovering and recycling the most essential components. Currently, three primary recycling methods are employed for solar PV panels: physical, thermal, and chemical processes [47].

Recycling PV modules to reduce waste presents various difficulties. Although researchers are trying to recover specialty, valuable, hazardous materials and bulk, the process is still mainly in the research and development and pilot stages. Photovoltaic modules are built to last for decades in harsh environmental conditions, without considering how to disassemble them and recover materials at the end of their life. Consequently, high-recovery PV recycling necessitates substantial energy and material consumption, resulting in potential losses. Additionally, it leads to air pollutant and greenhouse gas emissions, as well as the utilization of chemicals. The wide array of c-Si PV modules, characterized by differences in silicon cell thickness, cell area, module size, and chemical composition, further impacts recycling approaches and the efficacy of material recovery. Currently, there are thousands of module designs in use, and even if these modules are recycled, employing recycled silicon in high-value applications poses challenges concerning attainable purity and form factor [109]–[111].

In a perfect closed-loop life cycle, materials are maximized and waste leaving the cycle is minimized. However, the reality of the life cycle for PV modules is not ideal. There is a significant reliance on natural resources for metal supply, and there are substantial losses of metal during the production of raw materials. While scrap recycling is available, the extent of recycling depends heavily on the type of waste. Obtaining materials from consumer goods is difficult owing to the technical and economic challenges of recycling products at the end of their useful life [90].

Numerous companies are engaged in managing PV module waste and implementing effective end-of-life (EOL) management and recycling solutions in the market, irrespective of any restrictions associated with PV waste. However, because of low volumes, recycling technologies, logistical challenges, and underdeveloped markets for recovered materials, the recycling of PV modules is currently costly and generates low revenue. In order to meet future demands and achieve high-value, cost-effective recycling of photovoltaic modules, improvements in the end-of-life process are necessary. PV modules undergo processing to recover nonferrous metals and glass at different plants. Additionally, PV cell materials and plastics are also retrieved. However, certain facilities handle c-Si PV modules by recycling Si PV cells along with plastics as a mixed material. During this process, glass is sent to the next processing plant for recycling, while ferrous and nonferrous metals are directed to smelters, the next processing plant, or secondary markets. The metals used in c-Si cells, including Si, Ag, and Cu, are also sent to smelters, the next processing plant, or secondary markets. However, these metals are often not separated and are treated together with Si cells. In some cases, recovery may be less preferable than landfilling due to treatment costs and the value of the recovered metals. Plastics or polymers are handled differently, and sometimes they are treated together with c-Si PV cells without separation. This approach may pose potential challenges in terms of material recovery or recycling, including low value, high transportation costs, lack of proper destinations, limited recovered amounts, and no suitable destination for Si. Nonetheless, heat recovery is an effective and promising approach to recycling plastics/polymers [105].

5.3.1 Physical Separation

In the dismantling process, panels are primarily taken apart by removing the surrounding aluminum frame, junction boxes, and embedded cables. The individual parts of the PV modules (panels, junction boxes, and cables) are shredded and crushed to assess the individual toxicity of each part as well as the total toxicity of the module for disposal. The frame is the final component to be removed from the module. It serves as a bonding component, isolates the module edges from the exterior (to prevent water infiltration, for instance), and provides mechanical strength while keeping the overall structure lightweight. Once the frame component is separated from the module, it can undergo secondary metallurgy for recovery. Other elements like iron, silicon, and nickel, which are present in small quantities, are typical components of aluminum alloys. However, the replacement of elements in solar cells to repair systems is limited to the replacement of electrical components and does not involve material separation or cell treatment. There are two widely used processes for detecting and repairing junction box faults. This approach can effectively boost the output power of older solar panels. However, it is worth noting that this method is applicable only for external junction boxes situated outside the main body of the solar panel [47].

5.3.2 Thermal and Chemical Treatment

Several different methods have been tried in the literature related to thermal and chemical methods.

Pagnanelli et al. [112] used mechanical crushing to break down glass into smaller pieces and tested different solvents, temperatures, and ultrasonic power to dissolve the EVA layer. Lead was noted as a hazardous by-product. Fiandra et al. [88] used high temperature treatment to recover polycrystalline silicon from PV modules. Samples were obtained by cutting a 10x10 cm piece with a diamond blade, then heated in a furnace with different gas mixtures. Marwede et al. [113] reviewed different means of treating EOL PV materials and found that the pH value changed during metal recovery with sodium hydroxide. First Solar and a German company recycle solar panels commercially. Physical or mechanical processes generate dust and noise pollution, while inorganic solvents produce harmful gases. Silicon wafer reuse requires frame removal and disposal of remaining liquid. The EVA layer can be dissolved more quickly using ultrasound, but the process generates a large amount of waste that is difficult to treat. Thermal and chemical methods are advanced, but produce toxic gases and consume high amounts of energy [47]. Table 5.3. and Table 5.4. are represent descriptions of recycling processes for c-Si and thin-film, respectively.

Table 5.3. Descriptions of Three Existing c-Si PV Recycling Processes [89]

Process	Separation type	Resulting products	Status
Veolia	Mechanical only	Al frame, junction box, external cables, two grades of glass cullet products, two particle sizes of a mixed plastic product, two grades/particle sizes of Si product, and a Cu-bearing metals fraction	Commercial scale, France
Hot knife	Mechanical + thermal (Cu smelter)	Aluminium (Al) frame, glass pane or cullet (to market) backsheet + cell + ethylene-vinyl acetate (EVA) sandwich (sold to Cu smelter) Cu, silver (Ag), and potentially Pb/tin (Sn) (post smelting)	Pilot scale, Japan
Full Recovery End of Life Photovoltaic	Mechanical, thermal, hydrometallurgical	Al frame, glass cullet, Ag, Cu, metallurgical-grade Si	Pilot scale, Italy

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Table 5.4. Thin-film Recycling Processes [89]

Process	Advantages	Disadvantages	Status
Hotwire cutting	✓ Low cell damage ✓ Recovery of glass	✓ Other separation processes required for encapsulant	Research
Physical disintegration	✓ Capable of treating waste	✓ Other processes required ✓ Dusts containing heavy metals ✓ Breakage of PV cells ✓ Equipment corrosion	Commercia l
Irradiation by laser	✓ Easy access to encapsulant	✓ Slow process ✓ Very expensive equipment	Research
Organic solvent dissolution	✓Easy access to encapsulant ✓ Less cell damage ✓ Recovery of glass	✓ Time for delamination depends on area ✓ Harmful emissions and wastes	Research
Thermal treatment	✓ Full removal of encapsulant ✓ Recovery of intact cell ✓ Simple and economical	✓ Harmful emissions ✓ High energy requirements ✓ Cell defects and degradation	Commercia l
Vacuum blasting	✓ Removal of semiconductor layers without chemicals ✓ Recovery of clean glass	✓ Relatively slow process ✓ Emission of metals ✓ Further treatments needed	Research (pilot)
Chemical etching	✓ High-purity materials ✓ Simple and efficient process	✓ Use of chemicals	Commercia l
Flotation	✓ Relatively simple process ✓ Low use of chemicals	✓ High losses of valuables ✓ Flotation process required	Research (pilot)
Dry and wet mechanical process	✓ No process chemicals ✓ Equipment widely available ✓ Low energy requirements	✓ No removal of dissolved solids	Commercia l
Attrition	✓ No use of chemicals ✓ Recovery of clean glass	✓ Further chemical or mechanical treatments needed	Research (pilot)
Leaching	✓ Complete removal of metals	✓ High use of chemicals ✓ Generation of acidic fumes	Commercia l

Table 5.5. Recyclability and techniques of the materials composing the PV panels [112]

Treatment	Al	Cd	Cu	Ga	In	Mo	Pla	Se	Si	Sn	Te	Ge	Pb	Ag	Glass	Zn
Physical	X	-	-	-	X	-	-	-	X	-	X	-	-	-	X	-
Chemical	-	X	X	X	X	X	-	X	X	X	-	X	X	X	X	X
Thermal	-	-	-	-	-	-		-	X	-	-	-	-	-	X	-
More than one type combined	X	X	X	-	-	-	-	-	X	-	X	-	-	X	X	-
Availability	RN	RN	RN	RN	RN	RN	NU	RN	RN	RN	RN	RN	RN	RN	RN	RN

* Al:Aluminium, Cd:Cadmium, Cu:Copper, Ga:Gallium, In:Indium, Mo:Molybdenum, Pla:Plastic Se:Selenium, Si:Silicon, Te:Tellurium, Zn:Zinc, Sn:Tin

** RN: recycle needed *** NU: not usable

CHAPTER 6
CASE STUDY

This research delves into an in-depth examination of the Karapinar Solar Power Plant, strategically located in the Karapinar district of the Konya province in Turkiye. The solar plant is of significant interest due to its considerable size and potential for renewable energy production, specifically its capacity to generate solar power. The study takes into account the solar power plant's installed capacity at the close of 2021, which was reported to be approximately 600 MW. This level of installed capacity represents the maximum power that can be output by the plant at any given moment, a considerable achievement for a renewable energy source. The plant, when fully operational, is projected to have an impressive installed capacity of 1,000 MW. Achieving this milestone will mark a major step forward in renewable energy generation in Turkiye, significantly bolstering the nation's solar energy capacity. To make these determinations, the study employs a methodology similar to that used in global and Turkish contexts to calculate installed capacity and potential waste production. The plant's potential waste output upon reaching maximum capacity is another focus of the study. This aspect is crucial, as the management of waste, especially in renewable energy production, is an important factor in maintaining environmental sustainability [114]–[117]. The figure 6.1. represents the Karapinar Solar Power Plant on the map.

Figure 6.1. Karapinar Solar Power Plant on the map

Table 6.1. represents the projected growth in photovoltaic capacity (in both GW and tons) for the Karapinar Solar Power Plant from 2021 to 2050. It also displays the anticipated waste (in tons) from panels that have reached the end of their lifespan, under two different scenarios: early-loss and regular-loss.

The total PV capacity in tonnage was determined by reviewing various technical reports. The crystalline silicon (c-Si) panels used at the Karapinar Solar Power Plant exhibit technical properties very similar to those of the c-Si panels listed in Table 4.1. Consequently, the values from Table 4.1. were utilized in these calculations. Moreover, because there is no expected increase in capacity over the years, the weights for all years are assumed to be constant. The steps for these calculations are elaborated upon in the sections that follow:

P symbolizes the capacity of a single solar panel, W stands for the weight of a solar panel, and A signifies the surface area covered by a single panel. Tw represents the total weight of panels required to achieve a capacity of 1 GW, while Ta indicates the total area these panels would occupy for a 1 GW capacity.

$$P = 270 \times 10^{-9} \text{GW} \tag{6.1}$$

$$W = 18.6 \times 10^{-3} \text{ton} \tag{6.2}$$

$$A = 1.639 \times 10^{-6}\ km^2 \quad (6.3)$$

Utilizing the unit values defined above, the total mass (T_w) associated with a 1 GW capacity panel was calculated. Similarly, for the area, the total area (T_A) covered by a panel capable of producing 1 GW was determined. The obtained (T_w) and (T_A) values were then multiplied by the respective GW values given in the table for each year to carry out the annual calculations.

$$T_w = \frac{W}{P} = 68{,}888.88\ ton/GW \quad (6.4)$$

$$T_A = \frac{A}{P} = 6.0703\ km^2/GW \quad (6.5)$$

Table 6.1. Estimated increase (GW and ton) PV capacity and projection of waste that will occur at the facility depending on this increase in Karapinar SPP [114]

Karapinar SPP	Unit	2020	2030	2040	2050
Total PV capacity	GW	0.60	1.00	1.00	1.00
Total PV capacity*	ton	41,333	68,888.88	68,888.88	68,888.88
Total waste regular loss	ton	0.00	0.00	657.89	4,484.30
Total waste early loss	ton	0.00	0.00	3,289.47	8,968.60
Regular loss	ton waste/GW	0.00	0.00	657.89	4,484.30
Early loss	ton waste/GW	0.00	0.00	3,289.47	8,968.60

*A typical crystalline PV panel with 270 Watt peak capacity (W_P), an aluminium frame and 60 cells, mass 18.6 kg, and module dimensions 1650x992x35 mm (Trina Solar TSM-DC05A.08)

When converting GW to tons, the values from Figure 3.16. were utilized for the years 2030, 2040, and 2050 for both the world and Turkiye, showing a declining trend over time. However, for Karapinar, this value was held constant because the installation was recently completed, and no additional panels will be added, meaning the mass will remain unchanged. Equation 6.4 was used to calculate total PV capacities (in tons).

To compute the total waste regular loss and total waste early loss figures shown in Table 6.1., the overall value for Turkiye was taken into account. The values for the Karapinar plant were determined by proportionally scaling down the total capacity of Turkiye to match that of Karapinar, using reference data. Table 6.2. then presents the estimated quantities of raw materials expected to accumulate under two scenarios - regular losses and early losses - in 2040 and 2050, as well as the economic value of recycling these materials in Karapinar [98] .

Table 6.2. The amount of raw materials and the economic values of their recycling

	2040 regular loss	2040 early loss	2050 regular loss	2050 early loss	2040 value	2050 value
Unit	ton	ton	ton	ton	USD	USD
Glass	460.523	2,302.629	3,139.010	6,278.020	84,000	210,000
Aluminium	85.525	427.631	582.959	1,165.918	66,000	165,000
Polymers	65.789	328.947	448.430	896.860	51,480	128,700
Silicon	23.815	119.078	162.331	324.663	240,000	600,000
Copper	19.736	98.684	134.529	269.058	51,000	127,500
Silver	0.361	1.809	2.466	4.932	102,000	255,000
Zinc	0.427	2.138	2.914	5.829	420	1,050
Lead	0.197	0.986	1.345	2.690	300	750
Tin	0.197	0.986	1.345	2.690	1800	4,500
Other	1.315	6.578	8.968	17.937	3000	7,500

6.1 Mathematical Calculation Model of Case Study

This study computed two distinct CO_2 emission values for the years 2040 and 2050 under two different scenarios: the amount of CO_2 emissions that would occur if no recycling took place (E_1) and the amount of indirect CO_2 emissions resulting from the recycling process (E_2). These CO_2 emission values were calculated by averaging the quantity of CO_2 emissions generated during the production of 1 m² of polycrystalline panels across five countries that manufacture these panels.

$$\mathrm{E_1} = 101.8\ (\mathrm{kg} - \mathrm{CO_2})/\mathrm{m}^2 \tag{6.6}$$

where 101.8 kg-CO_2/m^2 is the average value from the five countries showcased in Figure 5.2.

$$\mathrm{E_2} = 12.1\ (\mathrm{kg} - \mathrm{CO_2})/\mathrm{m}^2 \tag{6.7}$$

where 12.1 kg-CO_2/m^2 is the average value from the five countries showcased in Figure 5.3.

- To ascertain the amount of CO_2 emissions produced in 2040 without any recycling under the regular-loss ($\mathrm{E_{r_1}}$) and early-loss ($\mathrm{E_{e_1}}$) scenarios:

In the regular-loss scenario for Karapinar, there will be a production of 660 tons of waste. The area that this volume of waste will occupy is denoted as T_{ar_1}.

$$T_{ar_1} = \frac{A}{W} \times 660 \tag{6.8}$$

where W and A are taken from equations 6.2 and 6.3, respectively. In the early-loss scenario, there will be a generation of 3300 tons of waste. The area this volume of waste would cover is denoted as T_{ae_1}.

$$T_{ae_1} = \frac{A}{W} \times 3{,}300 \tag{6.9}$$

$$E_{r_1} = E_1 \times T_{ar_1} \tag{6.10}$$

$$E_{e_1} = E_1 \times T_{ae_1} \tag{6.11}$$

- To calculate the amount of CO_2 emissions produced through the recycling process in 2040 under the regular-loss (E_{r_2}) and early-loss (E_{e_2}) scenarios:

$$E_{r_2} = E_2 \times T_{ar_1} \tag{6.12}$$

$$E_{e_2} = E_2 \times T_{ae_1} \tag{6.13}$$

Quantifying the reduction in CO_2 emissions:

For regular-loss;

$$E_{rp_1} = E_{r_1} - E_{r_2} \tag{6.14}$$

For early-loss;

$$E_{ep_1} = E_{e_1} - E_{e_2} \tag{6.15}$$

The average of the two scenarios;

$$E_{ave_1} = 15.662 \times 10^6 \text{kg} - CO_2 \tag{6.16}$$

- The same computations are carried out for the year 2050. This involves determining the amounts of CO_2 emissions in the absence of recycling under both the regular-loss (E_{r_3}) and early-loss (E_{e_3}) scenarios:

In the regular-loss scenario at Karapinar, it's expected that 4500 tons of waste will be produced. The area that this quantity of waste will occupy is represented as T_{ar_2}.

$$T_{ar_2} = \frac{A}{W} \times 4500 \tag{6.17}$$

Under the early-loss scenario, a substantial 9000 tons of waste is projected to be generated. The area this amount of waste will cover is denoted as T_{ae_2}.

$$T_{ae_2} = \frac{A}{W} \times 9000 \quad (6.18)$$

$$E_{r_3} = E_1 \times T_{ar_2} \quad (6.19)$$

$$E_{e_3} = E_1 \times T_{ae_2} \quad (6.20)$$

- To calculate the amount of CO_2 emissions produced through the recycling process in 2050 under the regular-loss (E_{r_4}) and early-loss (E_{e_4}) scenarios:

$$E_{r_4} = E_2 \times T_{ar_2} \quad (6.21)$$

$$E_{e_4} = E_2 \times T_{ae_2} \quad (6.22)$$

Calculating the reduction in CO_2 emissions:

For regular-loss;

$$E_{rp_2} = E_{r_3} - E_{r_4} \quad (6.23)$$

For early-loss;

$$E_{ep_2} = E_{e_3} - E_{e_4} \quad (6.24)$$

Average of the two scenarios;

$$= 53.303 \times 10^6 \text{kg} - CO_2 \quad (6.25)$$

The quantities of materials and energy that can be reclaimed from PV panels for 1 GW of energy production are computed for the year 2040 and depicted in Figure 6.2. Projections for 2050 are also provided in Figure 6.3. The results illustrated in these figures show that the volume of material to be recycled experiences a sharp increase every decade.

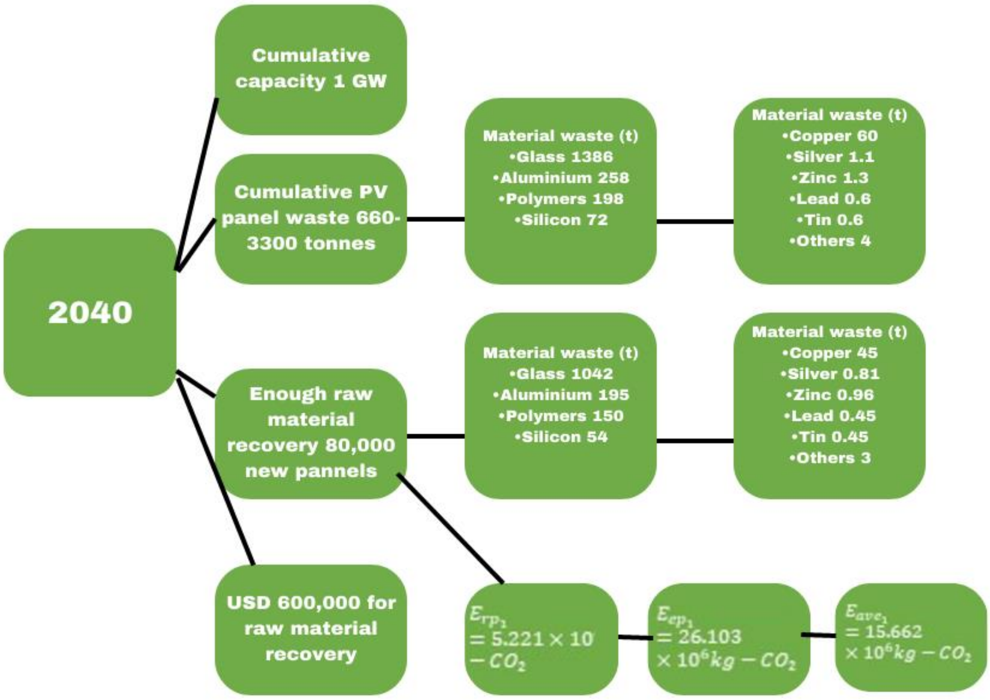

Figure 6.2. The recycling of PV panels used in generating 1 GW of energy in 2040 will yield specific quantities of materials and energy.

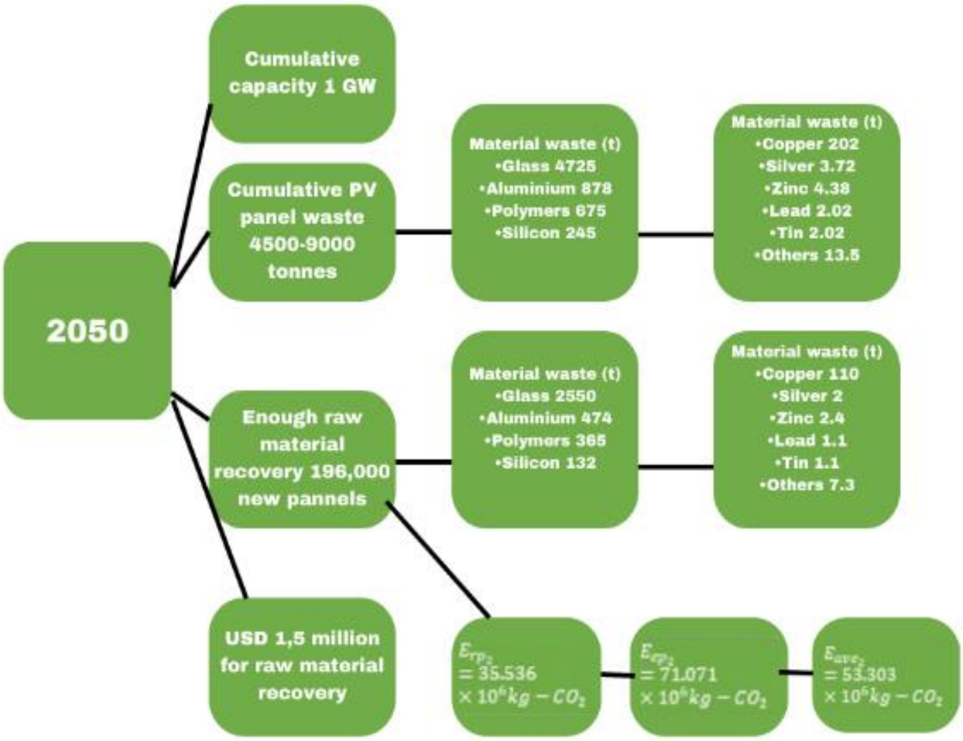

Figure 6.3. The recycling of PV panels used in generating 1 GW of energy in 2050 will yield specific quantities of materials and energy.

CHAPTER 7
CONCLUSION

While the world is turning to renewable energy sources, solar energy is a clean, sustainable and renewable energy source that has increased in importance in recent years in meeting the energy needs of humanity. Capturing the energy from the sun by humans with various technologies and converting it into electrical energy is a critical step in reducing dependence on fossil fuels, preventing greenhouse gas emissions and minimizing negative effects on the environment. Photovoltaic panels have gained significant popularity as a clean and sustainable energy solution.

Solar energy technologies were not efficient and cheap when they first started gaining popularity. As technology advanced and the market grew, the competitive environment intensified. Significant breakthroughs, however, occurred mainly after the 2010s. Nowadays, solar energy technology is developing much faster compared to its early days of popularity. Artificial intelligence models, machine learning, and deep learning will continue to permeate every aspect of the energy sector.

Despite the growing adoption of PV panels, there is a rising concern regarding the waste they produce at the end of their operational life.

The waste potential of solar energy is an important factor to be considered in the formulation of future energy strategies and environmental policies. With continuous advances in science and technology, solutions are being researched and implemented to produce and recycle solar panels in a more environmentally friendly and efficient way. This will be an important step towards reducing the waste potential of solar energy and for a cleaner energy future.

In the near future, everyone, especially developed countries, must take action to control the emerging waste threat. The waste projections in this study clearly demonstrate this. According to calculations, by 2050, there will be approximately 60,000,000 to 78,000,000 tons of PV panel waste worldwide.

One of the important results of this study is that: China dominates other countries both in annual installation and cumulative capacity. In parallel with this amount of investment, in 2050 it will be the country that generates the most waste for regular-loss and early-loss scenarios. Estimated cumulative waste volume of China is about 14-20 million tons.

It is predicted that the amount of PV waste that will be generated in Turkiye in 2050 will be around 200,000-400,000. Considering the amount of waste to be generated per GW, Turkiye will generate approximately 4500 tons (regular-loss) and 9000 tons (early-loss) waste in 2050. Consequently, compared to the world, these rates are about one third for regular-loss and about half for early-loss.

To minimize the amount of generated waste, more emphasis should be placed on the relatively new field of recycling. Current figures and efforts are expected to improve over time. A comprehensive approach is necessary to save the planet, and efforts to maximize efficiency from every sector should continue to accelerate.

Recycling panels at the end of their life is an important issue when environmental and economic factors are taken into account. One of the results of this study shows that recycling solar panels reduces the amount of waste, prevents the depletion of natural resources and reduces environmental pollution. Solar panels contain some toxic substances. If they are not recycled with the right methods, leakage of these substances into the environment or accumulation in landfills can cause environmental hazards.

As a result, the recycling process allows the materials used in the panels to be reused. This encourages longer-term use of raw materials and reduces the consumption of resources required for the production of new panels. Recycling rare and precious metals used in solar panels strengthens the supply chain of these metals and provides economic returns.

The amount of raw materials to be accumulated for regular losses and early losses in 2040 and 2050 and the economic values of their recycling are given for the case study (Karapinar SPP).

As a result of this study, the highest recycling amount by weight is glass. The weight of silver is very low compared to glass and aluminum which are in the first two rows.

However, despite this low weight, it has the highest economic value compared to others.

Another important result is that: Recycling currently has low values, similar to the early years of solar energy. Nevertheless, there are promising and positive developments. In this study, the carbon footprint of two different PV panel models was examined when recycled and when new panels were produced without recycling. The results clearly indicate that the panels produced through recycling have a significantly lower carbon footprint. Based on these findings, the CdTe panel emits fewer emissions into the environment compared to the polycrystalline panel. However, CdTe panels are not widely preferred due to their lower efficiency and the presence of harmful substances that can affect human health.

According to another study, it has been determined that recycling PV panels can result in energy savings of up to 58%. Additionally, the use of recycled panels contributes to a 42% reduction in greenhouse gas emissions. These findings highlight the significant environmental benefits of recycling PV panels, making it an important step towards a more sustainable and eco-friendly energy sector.

The recycling process of solar panels can be energy intensive. Therefore, the environmental benefit of recycling may decrease depending on the amount of energy expended in the production of recycled materials. Also, recycling solar panels can be a costly process, meaning that recycling infrastructure is inadequate in some countries. The absence of standardized recycling processes and regulations around the world creates challenges in creating an effective and cohesive recycling system. In conclusion, recycling of solar panels is an important step in terms of sustainability and environmental protection. Correct recycling methods and infrastructure must be developed to minimize environmental impacts and maximize economic benefits. It is also important to adopt more environmentally friendly and recyclable design approaches from the production stage.

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PUBLICATIONS

A. International Journals

[1] Artaş, S. B., Kocaman, E., Bilgiç, H. H., Tutumlu, H., Yağlı, H., & Yumrutaş, R. (2023). Why PV panels must be recycled at the end of their economic life span? A case study on recycling together with the global situation. Process Safety and Environmental Protection, 174, 63-78.

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B. National Conference

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