End-of-Life Material Waste Quantification and Management for Renewable Energy Capacity Additions in Pakistan

By

Muhammad Ahsan Ashraf

School of Chemical and Materials Engineering

National University of Sciences and Technology

2022

End-of-Life Material Waste Quantification and Management for Renewable Energy Capacity Additions in Pakistan

Muhammad Ahsan Ashraf

Reg.No:00000274388

This thesis is submitted as a partial fulfillment of the requirements for the degree of

MS in Nanoscience and Engineering

Supervisor Name: Dr. Amna Safdar

School of Chemical and Materials Engineering (SCME)

National University of Sciences and Technology (NUST)

H-12 Islamabad, Pakistan

August, 2022

Dedication

To all the creative people who inspire me and keep my level of creativity charged.

Acknowledgement

I dedicate my thesis to my family and friends. I would like to acknowledge and give my warmest thanks to my supervisor, **Dr Amna Safdar**, who made this work possible. I would like to thank my committee members for their brilliant comments and suggestions. A special feeling of gratitude for **Ahmad Jamil** who has never left my side. I also dedicate this thesis to my childhood friends, **Raffeh**, **Usama**, and **Ali** and my flatmates, **Saad bin Azam** and **Saad Mirza,** and to my sister **Saba** for keeping my spirits up.

Abstract

Renewable energy is leading the path to reduce the dependence on fossil fuels. Global warming is a serious threat to the environment and renewable energy can minimize the contribution of the power sector's contribution. Increased capacity of renewables comes with the increased waste of solar panel and wind turbines. There is a limited understanding of the mechanisms and infrastructure needed to ensure the sound disposal of renewable products. End-of-life analysis for renewable energy is important to establish safe and economical waste management practices. End-of- life practices will aid to reduce the environmental impact of renewables. Glass, steel, Al and EVA are the major components of PV module waste while glass, ceramic, steel and iron materials are the major components of wind turbine waste. Pakistan lacks waste disposal policies for renewables as adopted by other developed countries to minimize the harmful impacts. The aim of this thesis is the quantification of end-of-life renewable waste production as a result of capacity addition according to the Indicative Generation Capacity Expansion Plan (IGCEP) 2047 of Pakistan. The total installed capacity for solar energy will reach 1965.5 MW by the end of 2028 for Pakistan. 1 MW of capacity addition will add 17.42 m^3 of end-of-life solar waste. By the end of 2053, the total solar waste will be 34,239.89 m^3. Pakistan will have a total of 3744.3 MW of installed wind energy by the end of 2025. According to the future projection, a total of 463,109.49 tons of wind turbine end-of-life waste will be generated by the end of 2050. Renewable waste materials are quantified, and future projections are made based on capacity addition and installation scenarios for Pakistan. Recommendations for waste management planning and strategies are discussed for recycling technologies used globally for end-of-life renewable energy waste. The most suitable and successful techniques for Pakistan to recycle and recover valuable materials are thermal and mechanical treatments

Table of Content

List of Figures

List of Tables

List of Abbreviations

IPCC	Intergovernmental panel for Climate Chane
GW	Giga Watt
MW	Mega Watt
PV	Photovoltaic
EU	European Union
EVA	Ethylene vinyl acetate
IGCEP	Indicative Generation Capacity Expansion Plan
NEPRA	National Electric and Power Regulatory Authority
CdTe	Cadmium telluride
CIGS	Copper indium gallium diselenide
IoT	Internet of Things
NICE	New Industrial Solar Cell Encapsulation
Pb	Lead
SEIA	Solar Energy Industries Association
IRENA	International Renewable Energy Agency
IEA	International Energy Agency

Chapter: 1

1. Introduction

Renewable energy is leading the path to reduce the dependance on fossil fuel. Global warming is a serious threat to the environment and renewable energy can minimize the harmful effects of climate change and pollution. In the light of Paris Climate Agreement, all countries agreed to a global framework to keep global warming under 2°C. According to the report by Intergovernmental panel for Climate Chane (IPCC), the use of renewable energy sources can reduce the carbon emissions for energy sector by 90% till 2050. Renewable energy can play a vital role in decreasing the average global temperature [1], [2].

Development in renewable energy has increased primarily due to technological advancements and cost reductions. Renewable technologies have gained significant attention since early 2000s. Wind and solar PV energies are considered the most promising technologies for renewables. By the end of 2015, the installed capacity for solar PV reached to 222 GW [3]. Similarly, by the end of 2021 the installed capacity reached to 450 GW [4].

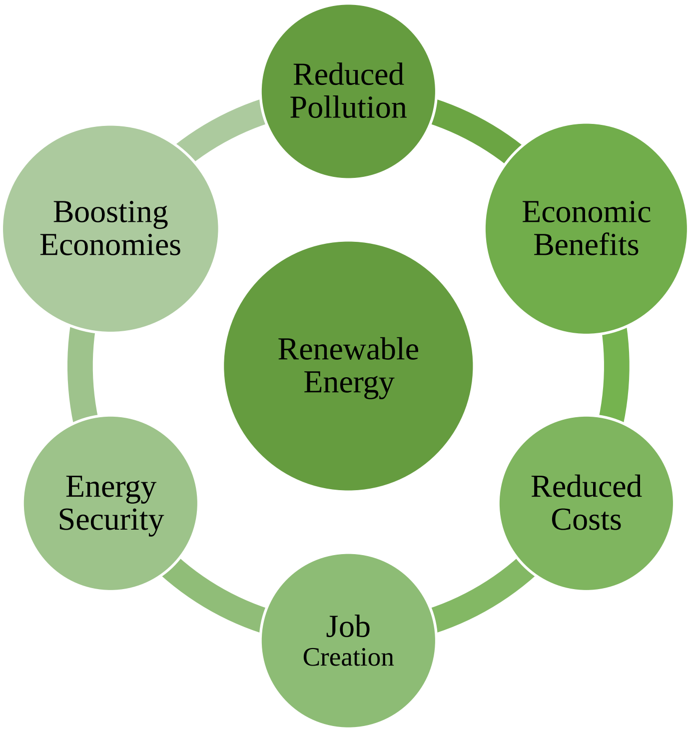


Figure 1: Benefits of renewable energy.

The installed capacity for solar PV is expected to reach 4500 GW by the end of 2050 [5]. Installed capacity

of wind energy stands at 837 GW by the end of 2021 [6]. The installed capacity of wind energy is expected to reach 6000 GW by the end of 2050 [7]. Main factors influencing the use of renewable energy are decrease in renewable energy cost, reduction in air pollution and carbon emissions [8]. Benefits of renewable energy are shown in figure 1. Production of renewable energy is free of any harmful emissions in comparison with fossil fuels. But as the demand for renewable energy is increasing across the globe, the need for raw materials to manufacture solar PV modules and wind turbines will increase. Moreover, wind turbines and solar PV modules reaching end-of-life pose severe challenges for generated waste disposal. To ensure the sustainability of renewable energy, the overall impact of waste generation must be minimized through recycling and reusing of the materials. The waste management processes must ensure the safe recovery of various materials to reduce the burden on raw materials [9], [10].

Increased capacity of renewables comes with increased waste of solar panel and wind turbines. Average life for solar panel and wind turbines is 20 to 30 years. End-of-life analysis for renewable energy is important to establish safe and economical waste management practices. These measures are vital for value addition in renewables. Furthermore, end-of-life practices will aid to reduce the environmental impact of renewables. EU has pioneered the legislations and regulations for PV and wind turbine waste recycling and disposal mechanisms. The framework laid by EU is helping other countries to follow similar footsteps [11]. Solar PV modules can generate renewable and clean energy over time span of 25 year. The increase in PV installation comes with the increase in end-of-life solar waste. Figure 2 depicts the production of solar waste as the cumulative installed capacity of solar PV module is increased [12]. Cumulative capacity for solar PV started to grow drastically after 2007, and it is estimated that every 1 MW new installation will lead to the production of 80 metric tons of waste. From 2023 and onward, large amount of solar waste will start to accumulate. The cumulative waste will reach 3.6 million tons in coming 10 years. The life cycle of solar PV module is determined by durability and reliability. Reliability tells about the probability of premature failures in solar PVs while the durability reveals the degradation rate. The degradation rate of solar panels determines the reliability and durability. Main degradation factors for solar PVs are humidity, irradiation, temperature, and mechanical damages [13]. Degradation of solar modules includes discoloration, corrosion, breakages, and delamination. Degradation leads to reduced efficiency and output of solar module [14]. Figure 3 shows various degradation mechanisms of solar PV modules [15].

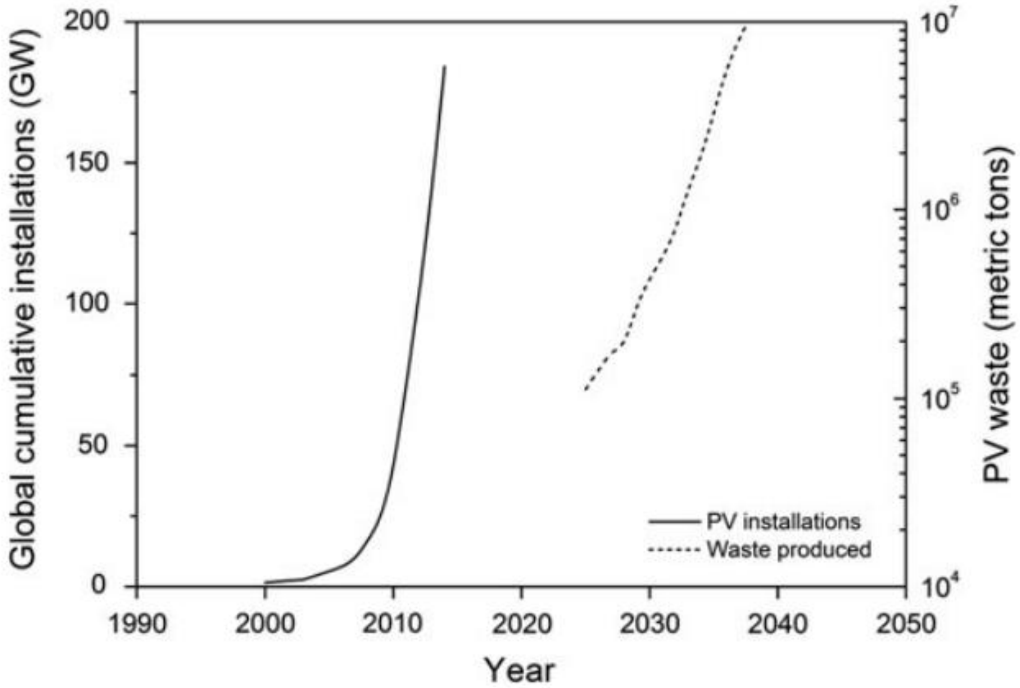


Figure 2: Waste projections for solar PV end-of-life waste.

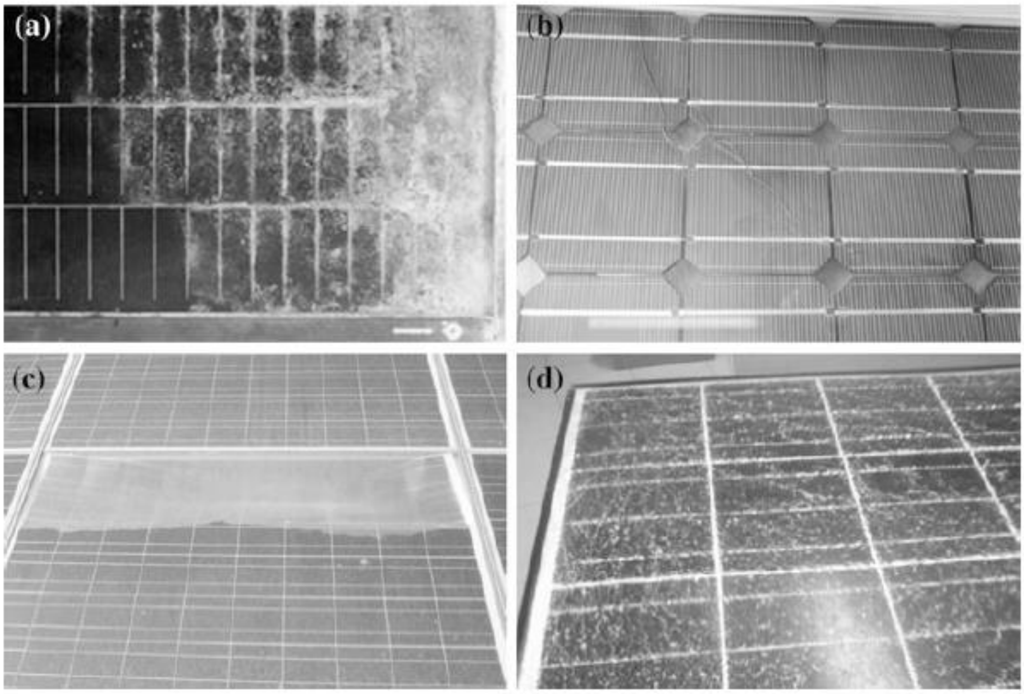


Figure 3: Degradation mechanisms in solar PV modules **(a)** Corrosion **(b)** Panel discoloration **(c)** Panel delamination **(d)** mechanical breakage.

Discoloration in solar panel is mostly caused by irradiation of UV rays. These UV rays cause damage to the encapsulating layer that is made up of ethylene vinyl acetate (EVA). Extreme UV rays severely degrade EVA and increase the transmission losses resulting in reduction of module performance. Delamination and corrosion are caused by high moisture content and high temperatures. Breakages are the result of mechanical damage and shock. Breakages cause the transmission losses of incident solar rays [15].

1.1 Research Objectives

The aim of this thesis is the quantification of the end-of-life renewable waste production because of capacity additions for Pakistan in coming decades. Solar PVs and wind turbine renewable energy technologies are being focused. The main objectives of this thesis are as follows:

- An extensive literature review for identification and quantification of different waste materials in solar PVs and wind turbines after reaching end-of-life according to capacity addition and expansion through Indicative Generation Capacity Expansion Plan (IGCEP) 2047 of Pakistani government.

- Analysis of technical datasheets of wind turbines and solar PVs licenses in Pakistan to calculate per unit and total mass of waste materials to be used for future projections for renewable waste generation.

- Policy recommendations for waste management planning and strategies based on recycling technologies used globally for end-of-life renewable energy waste.

1.2 Scope of Thesis

- Quantification of the material waste generated from renewable energy:
- Solar Power Plants
- Wind Farms
- A complete assessment of renewable waste material generated with capacity addition plan IGCEP 2047 for utility scale power plants.
- Recommendation of suitable recycling techniques feasible for Pakistan
- Life cycle assessment of solar and wind energy

1.3 Proposed Methodology

The proposed methodology involves the gathering of capacity addition renewable energy data for Pakistan through National Electric and Power Regulatory Authority (NEPRA). The data is gathered through commissioned and future licenses of solar and wind energy power plants in Pakistan. The end-of-life waste materials are quantified and projected using the technical data sheets of these renewable power plants. The waste materials are assessed based on hazardous, non-hazardous, and inert metal, polymer, and glass components. Suitable recycling techniques are recommended based on the techniques used worldwide. Waste management processes are discussed to recycle, reuse, and recover useful materials for future use. The data is analyzed through MS excel and future projections are made for end-of-life waste materials. Furthermore, the quantified waste materials are represented through different graphs and figures over the years these waste materials are produced. Proposed methodology is shown in figure 4.

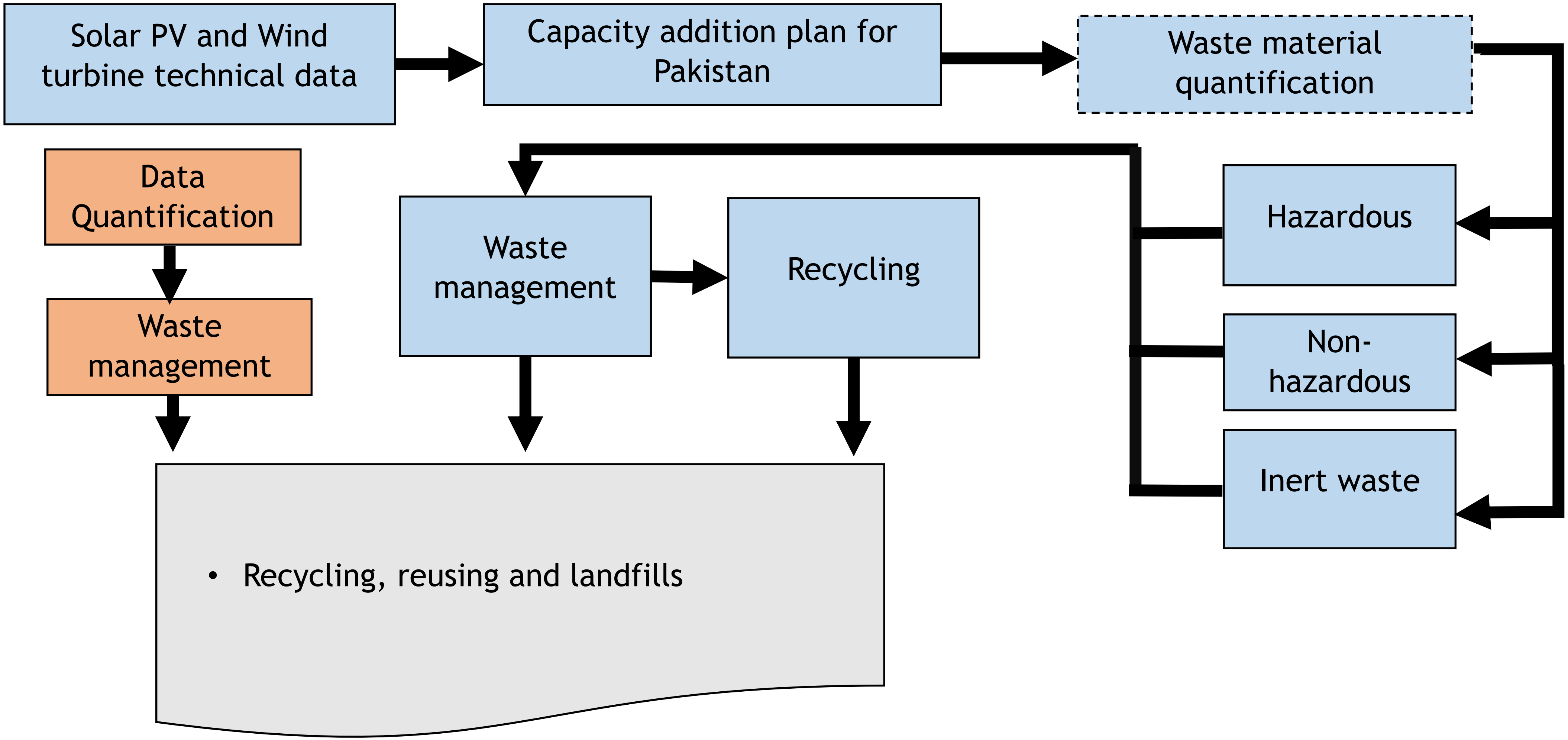


Figure 4: Methodology for end-of-life waste materials quantification for Pakistan.

Chapter 2

2. Literature Review

2.1 Renewable Energy

Solar and wind energy are the major contributors of renewable energy. Solar and wind energy are safer, eco-friendly, and reliable. Renewable energy has brighter prospects to fulfil future energy requirements. In the last decades, the use of renewables for cleaner energy has increased exponentially. Renewable energy will dominate the world energy market in coming decades. By 2050, renewables will be the major source for global energy production. Large scale renewable installations are aiding to reduce the production cost of energy. Various countries are taking keen interests in renewables. In 2018, Saudi Arabia started the process to install a 300 MW solar PV park with the lowest estimated price of 0.0234 USD/kWh [5]. Moreover, with the development of highly efficient materials, the prices for solar energy prices are being reduced. Currently, China is leading the global renewable energy production with an estimate of 50% newly installed renewable energy systems globally are based in China [16]. Global energy production mix is shown in figure 5 [17].

Energy costs of renewable energy are continuously falling due to improved efficiency, development of new materials and manufacturing technologies. Average cost for onshore wind power plants is approximately $0.0576/kWh which is 35% less than the cost in 2010. It is expected that the cost will further reduce in coming years. The costs associated with wind energy are competing and under cutting fossil fuel based power plants [18]. The combination of solar PV and wind energy is becoming economically feasible that can generate low-cost electricity. Renewable energy will become major electricity generation sources in coming years. Transition to renewable energy sources will significantly reduce the pollution to improve the quality of life. Global warming and high carbon emissions are the most important environmental issue at hand. Transition to cleaner energy sources will protect the environment by improving the air quality of cities. The transition can lead to reduced costs for health issues and this way, these finances can be diverted to other important issues. Moreover, to meet the Paris agreement, it is the need of an hour to invest in renewable energy sources. It is anticipated that 70% of reduction in energy production related emissions is required to meet the goals by 2050 to keep global warming under control [7].

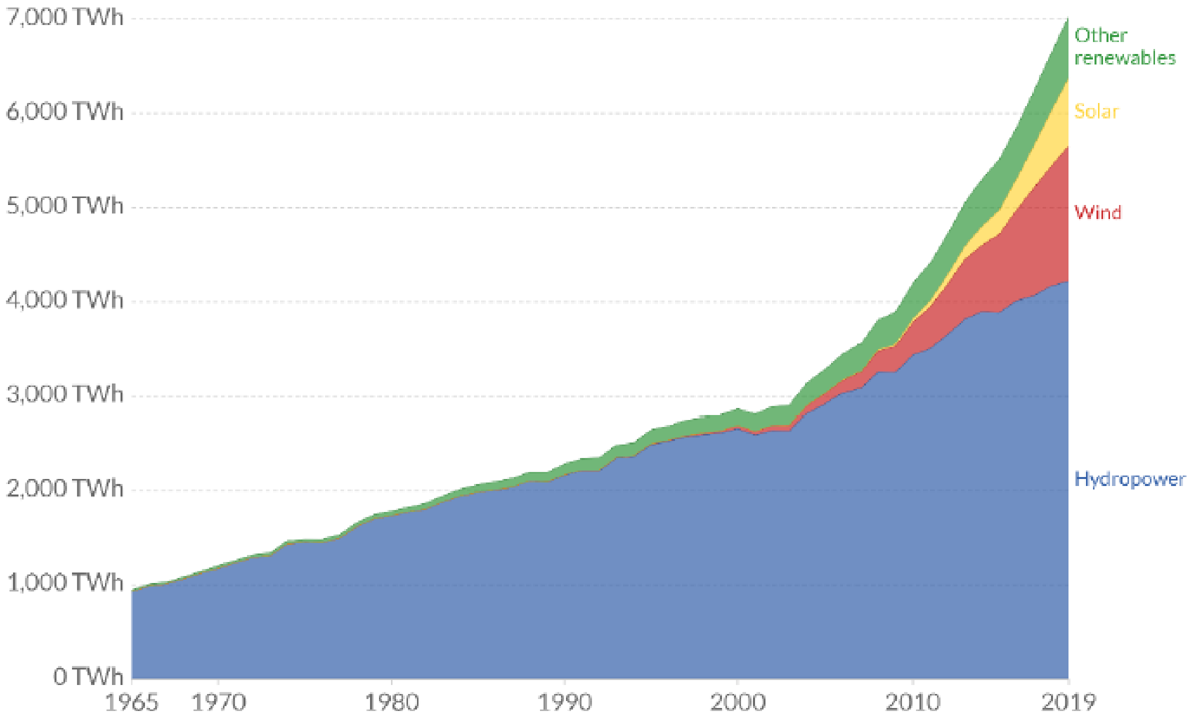


Figure 5: Capacity addition of various energy sources over the year.

With ever increasing installed capacity for renewables, the number of solar PV modules and wind turbines reaching end-of-life is increasing at rapid pace. Solar PV modules can turn into hazardous wastes once the useful life cycle ends. These modules can have harmful impact on the environment if not disposed properly through recycling and effective waste management. In initial years of renewable energy development, end-of-life and waste generation were least concerned. With the increase in renewable installation, proper waste management for end-of-life renewables is required to have minimum environmental impact. It is important to follow reuse, reduce and recycle model of waste disposal for renewables reaching end-of-life. Extensive planning and resources are required to counter the potential waste generation in future. The recycling mechanisms are needed to be developed with required infrastructure. It is need of an hour to establish cost effective recycling and waste management technologies for renewables [19].

2.2 Types of Solar PV Modules

First and second-generation solar PV represent the major technologies for PV modules. First generation consists of mono, poly and amorphous silicon solar cells. Second generation represents thin-film solar cells [20].

2.2.1 First Generation Solar Cells

First generation solar PV modules are widely used and have around 90% of overall solar PV module market share. Monocrystalline solar PV modules can easily be differentiated based on outer coloring and uniformity. Monocrystalline solar cells consist of highly pure silicon. Silicon used in fabrication of crystalline solar PV modules is extracted from SiO_2 or commonly known as quartz. Monocrystalline solar module can easily be distinguished from polycrystalline due to round edges of cells. Polycrystalline solar module has perfect rectangular solar cells [21]. Different crystalline Si solar modules have similar structure with different components. These modules include passive emitter rear-cell, back contact solar module, bifacial module, interdigitated back contact modules and metal-based modules as shown in figure 6 [22].

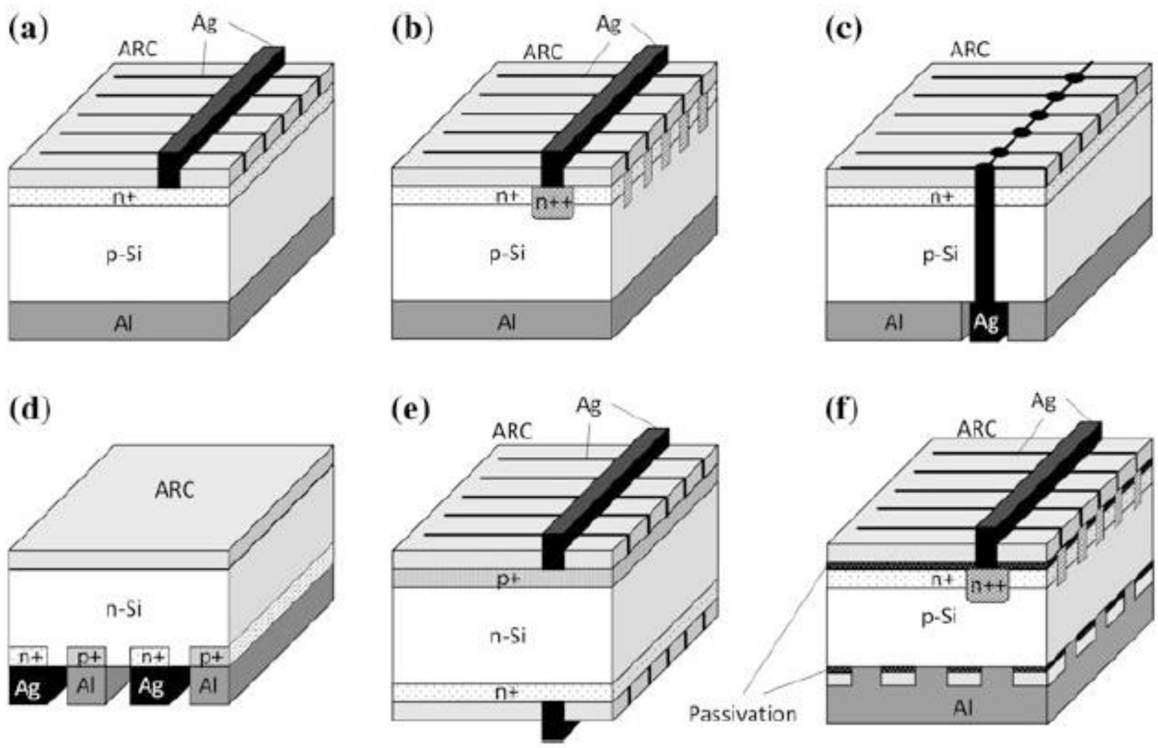


Figure 6: Structures of different Si-based solar cells and modules. **(a)** Commercial solar cell **(b)** Selective emitter **(c)** Metal wrapped through **(d)** Back contact interdigitated **(e)** Bifacial **(f)** Passive emitter rear solar cells.

2.2.2 Second Generation Solar cells

Second generation thin film solar cell modules provide cost effective and efficient energy solutions. Thin films are formed with the deposition of layers on a given substrate. Only a few micrometers layer of active material is required to harvest the solar energy efficiently. Thin film solar modules require much less material than crystalline solar modules. But second generation solar cells have lower efficiencies than first generation, but the deficiency in efficiency is compensated by low production costs. Amorphous silicon, CdTe, and CIGs are the examples of second-generation solar cells [23].

2.3 Solar Panel Waste Generation

Solar PV modules are based on different materials, size and efficiency. First generation solar technology that is based on crystalline Si represents around 90% of market share. First generation solar cells include mono and polycrystalline Si solar modules. Second generation solar technology includes cadmium telluride (CdTe), copper indium gallium diselenide (CIGS) and thin films. The market share of second-generation solar PV modules is around 9%. Third generation solar cells are still in development phase and it is expected to see them in market in coming years [24]. Currently, increasing efficiency and reducing costs are being emphasized, completely overlooking the end-of-life management of solar panels. End-of-life management includes the waste management and treatment of decommissioned solar PVs [20]. The massive increase in solar PV installation leads to the generation PV waste once these solar modules research end-of-life. Average life cycle assessment of solar panel is around 30 years. It is expected solar waste by the end of 2030 will research an alarming figure of 8 Mt [25]. Solar PVs installed in late 1990s are near to end-of-life and pose serious environment implications if not disposed properly. Lack of waste management laws and regulation make this enormous volume of solar PVs waste hard to dispose of [26]. European union and some other developed countries have regulatory framework and regulations to mitigate the harmful effects of solar PVs waste. European union has revised the waste electronic and electrical (WEEE) directive to incorporate solar PVs end-of-life waste. To reduce the environmental impact and pollution, it is important to make relevant policies for disposal of solar PVs waste [27]. Different research studies have focused on the recycling of solar PV waste and life cycle assessment [28], [29]. Handful of studies have focused on end-of-life waste management [30]. Salim el al. [31] analyzed the barriers, drivers and enabling factors for end-of-life waste management of solar PV waste. Moreover, a complete framework was presented for a smooth transition of current supply chain of PV to incorporate waste management. Kim and Park [32] analyzed PV waste generation based on installed capacity. Various studies focused region wise on the need for end-of-life waste management. Recycling cost for PV waste is much higher than landfill disposal that is why major manufacturers try to avoid recycling. Si based PV modules are difficult to recycle due to these high costs. These modules usually end up in landfills [33]. Solar PV modules contain hazardous and toxic metals such as Te, Cd, Ga and In. These materials are safety and health hazard if not disposed properly. In landfills, these materials can leach into underground water to pollute it can cause severe heavy metal poisoning. The harmful effects of these materials must be studied to come up with proper solution.

2.4 Factors Influencing End-of-life Solar Waste

Physical damage and end of life cycle are the primary reasons for the end-of-life solar waste disposal. Solar PV modules can prematurely fail due to physical impacts and extreme weather conditions. Glass layer of solar panel can shatter due to these impacts into small pieces. Glass pieces do not fall apart due to polymer EVA layer that keeps pieces intact. Breakage of glass sheet causes the panel to lose functionality. During the life cycle, solar PV modules are exposed to heating, cooling, stresses, mechanical loads and moistures. These factors can significantly reduce the performance of solar PV module causing power loss and power breakdown. Early failures of solar panels are mostly associated with manufacturing defects or fault in design. Manufacturing defects can be controlled through proper screening and optimizing the process parameters. Sometimes, solar panels fail due to random events such as hailstorms that can occur at any time during the life cycle [34]. High temperature can cause internal stresses leading to fatigue failure of solar PV module. Internal stresses are caused by the difference in expansion co-efficient of various Solar PV components [35]. Another reason for end-of-life is the decrement of efficiency. Efficiency of solar can decrease between 0.5 to 3% each year. Stresses, temperature variations, moisture and thermal cycles contribute to reduction of efficiency.

2.5 Solar PV waste projections and forecasting

Even though sizable numbers of installed PV modules have still not managed to reach the end of life, there has been reported PV waste flow because of early failures, mechanical damages or early losses. According to the latest IRENA report on end-of-life solar PV modules, based on early and regular loss scenarios, 0.043-0.25 million tonnes of PV waste was accumulated in 2016. Failures for solar PV modules due to reliability issues are shown in figure 7. Furthermore, an exponential increase in PV installations will result in significant waste generation in the future. According to IRENA, 60-78 million tonnes of PV waste will be generated by 2050. China, the United States, Japan, India, and Germany will be the top five waste-generating countries by 2050. PV waste volumes and material recovery correspond to additional raw material contents capable of producing 2 billion new panels worth USD 15 billion. According to local forecasts of PV waste specific to Australia, 1-8 million tonnes of discarded modules can be accumulated until 2060, with a 1.2-billion-dollar value. Because of new waste stream addition due to PV panels, most forecasting studies in the literature employ the input-output forecasting model [36]. Figure 8 depicts the PV waste generated till 2050 based on the literature available on PV waste forecasting [37].

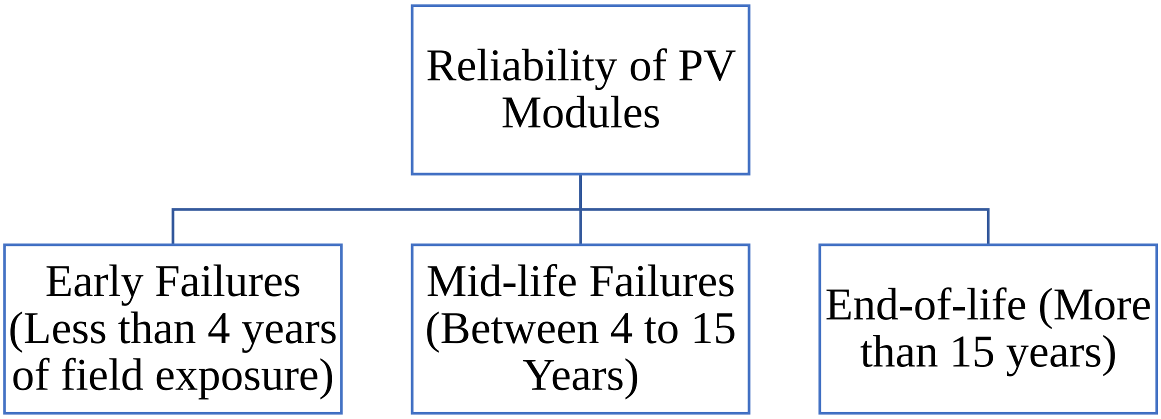


Figure 7: Reliability and mid-life failures for solar PV modules.

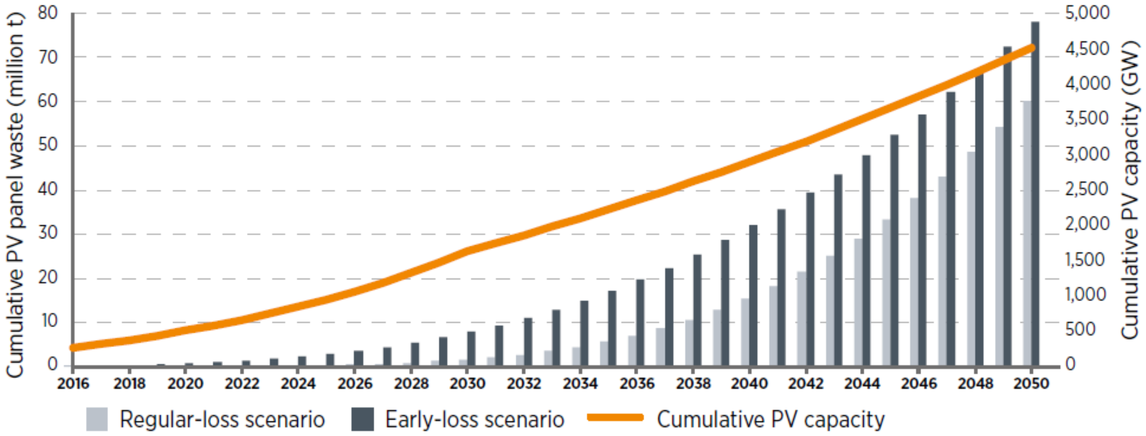


Figure 8: Global solar PV waste forecasting till 2050.

Specialized PV waste projections studies are required across every country to guide policy decisions on developing proper recycling plans and hazardous material disposal plans. Forecasting research studies can assist in quantification of the profitability of critical material recovery and reusing costs. Regional, local monitoring and reporting centers can provide a comprehensive picture and ensure prompt and efficient decisions for policy making for end-of-life waste disposal.

2.6 Wind Energy

Wind energy is one of the most economical and promising energy sources. The demand for wind energy is growing exponentially in Europe, USA, India, Pakistan, Middle East and Australia. It is estimated that around 52% of total investment in renewable energy is towards wind energy in Europe [37]. The total capacity for wind reached 750 GW by 2020. From 2008 onwards, Europe has installed more than 210 GW of wind turbines to produce clean energy. More than 15% of European energy is produced through onshore and offshore wind farms. The total capacity of Europe will suppress 300 GW by the end of 2023 [38].

Wind energy is the torch bearer for renewable energy transition. Life cycle assessment (LCA) of wind turbines proves the fact that these turbines produce more than 50 times of energy it takes to produce them over lifetime [39]. Due to high content of steel, many part of wind turbine can easily be recycled. The blades of wind turbine are made of composite material, and it is difficult to recycle composite given the nature and structure of composite materials. Lack of recycling processes of turbine blades make it difficult to dispose them properly [40].

2.7 End-of-Life Wind Turbine Waste

Wind energy is known as renewable energy source, but detailed ecological studies reveal the environmental impact for the manufacturing and disposal of these turbine once end-of-life is reached. Wind turbines are primarily made up of composite materials and go through energy extensive processes. Studies related to end-of-life wind turbine wastes are important to know the overall impact of these turbines on environment. Moreover, the life cycle of wind farms is not more than 25 to years. Europe has decommissioned about 650 MW of wind turbines [41].

2.8 Life Cycle Assessment of Solar PV and Wind Energy

Environmental impact of the raw materials, and final products must be considered for every industry. Every industry should ensure environmental sustainable products by reducing the amount of raw materials and by analyzing the life cycle of products. Reducing, reusing, and recycling of materials have positive impacts on environment and resources. Different strategies are employed to assess the environmental impact of any product. These strategies and recommendations include Pollution Prevention Guidelines (PPGs), Environmental Management Systems (EMS), ISO 14000/14001, and Design for Environment (DE) [33]. Life cycle assessment includes various stages of product life and whole value chain including raw materials, manufacturing, transportation, recycling, and end-of-life waste management. Different stages of life cycle of a product are shown in figure 9 [42]. It is important to have a detailed analysis for various stages of a product life cycle to minimize the environmental impact. Life cycle analysis and management provide a very detailed information regarding design, conception, maintenance, manufacturing, and end-of-life [43].

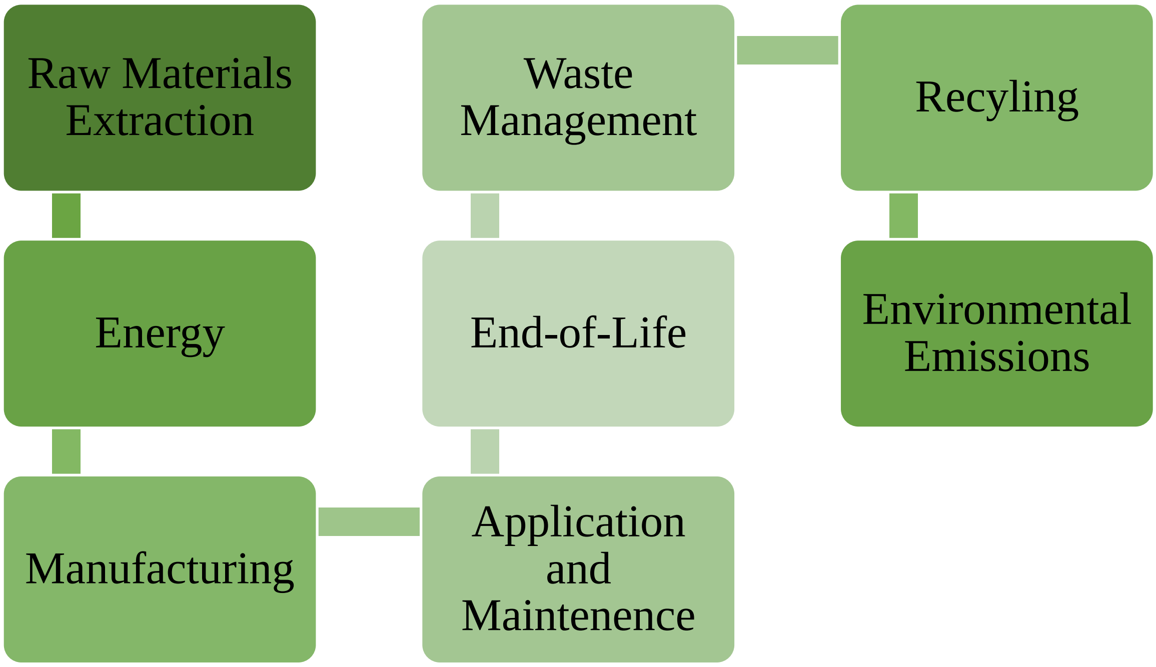


Figure 9: General Life Cycle assessment of any product.

2.9 End-of-Life Waste Management

End-of-life is defined as the point where the product can no longer function as intended. It can be due to premature failure or any defect. End-of-Life waste management is an analysis of the processes that are to take place while disposing the products when the life cycle of a product is completed. Economic prospects and environmental factors make these products valuable even after they no longer function as intended. The aim is shifted from cost effective disposal to recycling and reusing the materials for new application and to salvage the useful materials. Moreover, these days the society is more aware of environmental implications and several regulations are in place to prevent hazardous materials to contaminate our environment. The hazardous materials need special handling and care while disposing off. This way the environmental impact can be minimized [44].

End-of-life management includes four various strategies that may be used according to any given material as shown in figure 10 [45]. These strategies are: Reduce, Reuse, Recycle and Recover. Another least desirable strategy, landfill, is added along these four strategies. End-of-life pyramid includes these strategies in such a way that a strategy that is the most preferred is at the top while the least preferred one is at the bottom. The selection of any strategy is based on economic and environmental concerns. It is more desirable to use the strategy at the top but different materials require different processes for end-of-life waste management.

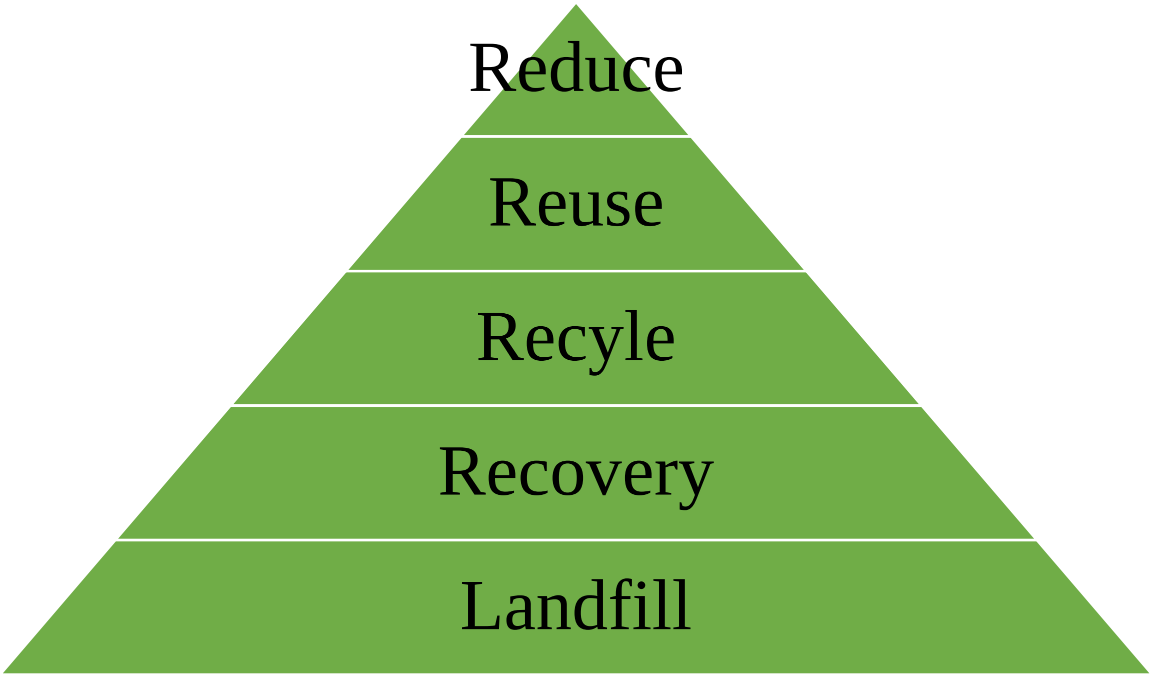


Figure 10: End-of-life waste management scheme.

2.9.1 Reduce

According to the manufacturers, photovoltaic panels have lengthy lifecycles with warranty durations of 25 years or more. Short innovation cycles have allowed newer PV panels to have longer warranty periods (more than 32.5 years), implying a reduced rate of degradation year after year. Furthermore, the total power per module is increasing (800Wp modules have been introduced), implying that fewer panels will be required to meet the same energy demands in the future. Solenergy has introduced concentrator photovoltaic (CPV) panels, which allow cells to be upgraded onsite to extend their lifetime to 40 years or more [46]. The development of standards such as American National Standard, NSF/ANSI 457 Sustainability Leadership Standard for Photovoltaic Modules,Life cycle certification, Solar evalution by Silicon Valley Toxic Coalition, and media initiatives such as PV magazine are taking into account the sustainability aspect of photovoltaic panels. The NSF/ANSI 457 standard defines device performance measurement requirements and corporate performance measures that demonstrate market leadership in sustainability. These performance criteria are meant to serve as the foundation for conformity assessment programs like 3rd party certifications or lengthy registrations [47]. In the Solar PV product lifecycle, resource efficiency is also becoming more important. The European Commission established the "Ecodesign Working Plan 2016-2019" to analyze criteria for determining the sustainability of solar PV [33]. It investigates the potential of sustainable product policies like Eco-design, Energy Labeling, and Ecolabel, as well as Green Public Procurement for PV panels and inverters. An ecolabel is a device or tool that employs a different criteria to assess reliability, environmental impact, and technical performance to assist experts and users in identifying high-performing modules from environmental and technical perspectives. In 2015, the European Union Eco labelling board to include PV panels. The European Commission is expecting to have the legislation proposal by the end of 2022 [48].

2.9.2 Reuse

According to IRENA report, defects, and faults from the initial four years of use, manufacturing, and transportation can be found in 80% of the PV waste stream. It is estimated that 45-65% of such waste PV modules can be repaired or refurbished. Reusing, repairing, and refurbishment of solar PV modules are currently informal and not standardized or systemized. Currently, such repair services are performed by private companies without the assistance of the manufacturers. There are currently no standards for categorization, reliability analysis, certifications, or labelling of used PV modules. If the PV panel failure is caused by faulty frames and mounting clamps, faulty bypass diodes, faulty wire connectors in junction boxes, or Potential Induced Degradation (PID), repair and refurbishment may be the only option available.

PV-Rec is a useful one-of-a-kind repair and recycling process for defected PV modules that is relied on accurate failure testing, analysis and selection techniques. To detect defects, the panel is subjected to Current-Voltage (I-V) testing and characterization at Standard/Benchmark Testing Conditions (STC), Electro-luminescence, infra-red imaging testing, and visual check prior to repair. After repair and refurbishment, the panels are characterized through I-V testing to specify the new current, power, and voltage outputs. Refurbishing and repairing a PV module is dependent on the reason of failure and the layout of the PV system during initial life. The "Cell-Doctor" system can select, separate, and isolate different non-defective areas in solar cells and modules. It was developed and created by the European Union (EU) project known as REPTILE and subsequently revised by another EU-funded project known as ECO SOLAR. The goal is to put "Cell Doctor" to the test in to assess solar cells from end-of-life modules that are returned to the factory to recycle and reuse [49].

PV module repair and refurbishment companies include pvXchange, Rinovasol, Second Sol, Reparar works, along with Solar-pur Gmbh. SecondSol and pvXchange provide an online global market for new and used solar modules and related products. Rinvasol provides international services for recycling and refurbishment as well as IECEE CB Scheme certification. Depending on the type of defect, SecondSol analyzes repair and refurbishment costs that can range between 20 € to 90 € per panel or module. CIRCUSOL is an European Union project known as H2020 that aims to standardize the recycling, repairing, refurbishing, and reusing PV value chains, as well as to develop appropriate technical standards and regulations for growing end-of-life business paths and opportunities for PV panels. Its goal is to create and test a Product Service System (PSS) that will facilitate circular economic models. Product Service Providers are in charge of determining the best end-of-life path and co-creating service offerings for end users [50].

2.9.3 Recycling

Recycling of solar photovoltaic modules has already been studied since the late 1990s, when the first patent for c-Si PV module recycling was submitted in 1995. Due to the dangerous, toxic and rare material composition of the modules, there has been a strong emphasis on development and research for recycling thin-film devices such as Cadmium Telluride (CdTe). With a great focus on sustainability, First Solar has built a closed-loop process to handle end-of-life CdTe modules. They maintain industrial recycling plants in Germany, Ohio, and Malaysia.

Even though crystalline silicon has been used in the majority of PV module installations, there is just a single commercial PV module recycling plant in comparison with the existing recycling plants for thin-film devices and modules. Due to a lack of economic feasibility, PV waste is currently processed in laminated glass/metal recycling centres. Waste PV panels are also reported to be discarded in a landfill. According to recent reports, waste PV panels from Italy were smuggled into African and Middle Eastern countries [51]. Salvaged raw materials from photovoltaic panels waste can help to meet rising installation requirement, reduce price volatility in PV production, and improve energy security [52].

With the recycling of recovered materials from recycling to manufacture new modules, the Energy Payback Time (EPT) for a PV module may be successfully reduced from around 3.3 years to 1.6 years in Germany as well as from 2.6 years to 1.6 years in Italy. End-of-life recycling significantly minimises the environmental impact of the PV module manufacturing and usage [40]. The c-Si PV recycling method has been widely investigated in the literature, with 128 patents filed worldwide. In PV recycling, the delamination process of the polymer (EVA) backsheets from the solar panel core is the most crucial process step. The junction box along with the aluminium frames are first mechanically detached from the PV modules. Mechanical, thermal, and chemical delamination techniques are the most used [53].

Mechanical delamination combined with removal of Al frame and junction box is the most broadly applied commercial PV recycling process. Glass, e-waste, and aluminium are the materials recovered using mainly mechanical techniques. Such procedures use little energy and are simple to integrate with current glass, metallic and e-waste recycling processes. Without chemical methods, silicon along with these metals such as copper, silver, tin and lead are difficult to separate in these processes. Given that the recovery goals enforced by Waste Electrical and Electronic Equipment (WEEE) regulations are set as a percentage of the total mass of PV panels. Such mechanical processes of solar panels are sufficient to achieve the targets, provided that aluminium and glass correspond for 88% of photovoltaic panel by weight [54].

As the polymer sheets goes through pyrolysis, thermal delamination techniques provide pure material and the recovery of materials such as glass and materials from PV core comprising silicon and other metals. The majority of commercially available back sheets material contain traces of fluorine. Based on the research and literature, such back sheets are typically removed prior to thermal delamination. It is advantageous because the burning of halogenated polymers involves exhaust gas control. Furthermore, due to thermal delamination, metallic connections in PV cells may melt and disseminate at high temperatures into other recoverable materials such as glass and silicon panels. Purification processes are thus required for the retrieval of highly pure silicon. There seems to be a gap in research in investigating the potential for heat recovery from exhaust gases. EVA is dissolved in either organic or inorganic solvents in chemical delamination techniques. The treatment duration was first determined in days, but ultrasonic irradiation facilitated rapid disintegration. Chemical delamination remains in the lab, and further research is needed to determine the additional environmental effect caused by the introduction of chemical solvents [55].

Regardless of the delamination methods, it is obvious from the research that chemical methods are required to extract the trace metal elements of Photovoltaic modules. As a result, researching the environmental effects of the recycling method becomes crucial. The debate over design of recycling methods has also analyzed, with some PV producers working on removing toxic (Lead) and valuable (Silver) metal components from future PV modules [56]. Recycling-friendly design of PV modules should make it simple to recover metals used in solar cells such as copper, silver, tin, lead, and aluminium. It must stress on successful module delamination for recycling. Apollan Solar has devised a better design for dismantling PV modules termed as New Industrial Solar Cell Encapsulation (NICE). Instead of soldering and encapsulation, this method uses pressure contacts to link cells. As a result, it is simple to disassemble for repair and recycling [46].

2.9.4 Recovering and Disposing

The IEA PVPS Task 13 has analyzed the human health hazards associated with PV panel waste owing to panel disposal in non-standardized landfills, panel breaking, and fire. Because of relevant stakeholders, lead (Pb) content in c-Si PV panels has been selected for investigation. Pb exposure-point concentrations from c-Si PV are at least an order of magnitude lower than USEPA health screening values in air, soil, and water for both only one estimate and Monte Carlo uncertain simulations. Pb concentrations from one panel on fire exposure were likewise found to be within the Acute Exposure Guideline Levels (AEGL) and Protective Action Criteria (PAC) for all average periods and screening criteria being tested [57].

There is a study gap to analyze the disposal of PV modules in landfills whilst assessing the danger due to antimony, tin, copper, and other toxic PV panel components, similar to the analysis performed for Lead [52]. Heat recovery from the controlled burning of c-Si solar PV panels must be evaluated for exhaust gases emitted by materials such as fluorine based back sheets along with lead. Current PV waste research shows that c-Si PV panels are not harmful when dumped properly in sanitary landfills. As a result, it is critical to emphasize the importance of sustainable end-of-life waste management of Solar PV modules as a potential opportunity for new economic opportunities. Recycling of c-Si PV modules allows for recycling of useful materials, which reduces future material needs for manufacturing while also creating new jobs.

2.10 PV Solar Panel Components

A single silicon panel or module is a combination of silicon solar cells that are connected by using silver (Ag). These cells are sandwiched in between plastic and glass sheets on Al frame. The components of single PV module are shown in figure 11 [36]. Solar PV modules are considered as e-waste mainly because of electrical parts and components. Approximately 90% weight of a single module is due to Al frames and glass. The most important material in solar PVs is silicon. Silicon is a semiconductor material and is extracted through quartz. The common materials used in solar PVs are explained below [58].

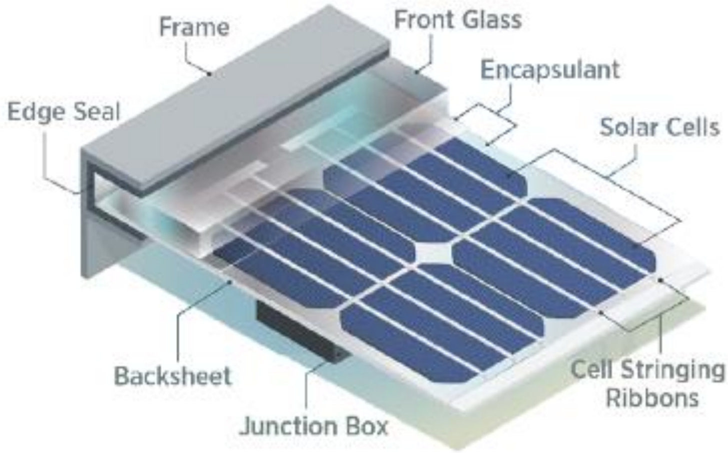


Figure 11: Components of Solar PV module.

2.10.1 Metals

PV modules consist of non-ferrous and ferrous metals. Commonly used metals in solar PVs are copper and aluminum and copper. It is estimated that around 10% of PV module is based on these metals [27].

2.10.2 Glass

Glass is the most used material in solar PVs. Glass provides the protection of thin semiconductor material wafers. Glass encapsulates the modules to provide protection from dust, moisture and other abrasive particles. Around 90% of a solar PV module weight consists of glass encapsulation [59].

2.10.3 Aluminum

Aluminum is extracted through bauxite ores. Extraction of Al is an energy extensive process. Al is one of the most recycled metals. Recycling Al only needs 5% of energy required for extraction from ores. Recycling Al has positive environmental and economic impact. Some of other advantages of Al are light weight, good conductor, corrosion resistance and ease in processing. Solar PV modules use Al for frame and for back coating. Fine powder of Al is used for back coating [60].

2.10.4 Silicon

Solar PV modules require a pure form of Si. Production of Si is energy extensive process. It is important to recycle Si cells and wafer to reduce the dependency on newly produced Si material. One solution is to reuse defected and faulty Si material, but the solution is not highly efficient in terms of economic prospects. Another solution is to reduce the amount of Si used in solar PV modules. The use thin wafers can significantly reduce the need for Si material. Substitute materials for Si are being developed to minimize the use of Si [61].

2.10.5 Silver

Silver is known to have one of the highest electrical and thermal conductivities. Moreover, silver has higher optical reflectivity. Due to these properties, silver is extensively used in solar PV modules. Silver is used as current collectors in solar PV modules [62].

2.10.6 Germanium

Geranium is known as precious metal. Around 70% of germanium is produced by USA, Russia and China. Germanium is one of the most important semiconductors materials. Due to availability issues, the price for germanium is significantly higher. In most of the applications, germanium is being replaced with Si. These days, germanium is used in combination with Si as dopant for semiconductor applications [15].

2.10.7 Indium

Indium is mostly produced by Asian region. China has one the largest deposits of indium and known to produce around 60% of total indium produced. Indium is valuable with high prices. This is the primary reason to recover and recycle indium. The recycling of indium is significantly higher than raw production. In solar PV modules, indium is used in Si solar cells and CIGS/CIS as absorber layers. Indium is a semiconductor material that is used in combination with selenium, copper and gallium. Indium is used as transparent conduction layer for reducing internal resistance of Si solar cell [63]. Some other applications of indium include diodes, LEDs, and conductors.

2.10.8 Plastic

Plastic material is used in securing connecting wires and frames. Moreover, plastic material such as Ethylene Vinyl Acetate is employed for encapsulation application in solar PV modules [64].

2.11 Wind Turbines Materials

Materials produced upon reaching end-of-life for wind farm are listed in table 1 as under [37], [65].

Table 1: Components of the wind turbine.

Materials	**Findings**
Aluminum	More than 90% of Al can be recycled while 10% of total Al waste ends up in landfills.
Iron and steel	All type of steel and iron material used in manufacturing of turbines.
Polymers	Thermosetting and thermoplastic resin materials
Sealants and adhesives	Materials used in polishing and gluing process
Copper	More than 90% of Cu is recycled while remaining 10% ends up in landfills.
Lubricants	Used in periodical maintenance and daily operations.
Electronics and electrical equipment	All electrical equipment along with magnetics and circuit boards.
Ceramic and glass	Wind turbine blades are made up of carbon or glass fiber composites.

2.12 Recycling of Solar PV Modules

Research work on recycling solar PV modules started in 1990s. Early on, it was aimed to recover first generation Si solar panels without any significant damage to reuse them later on. Separating encapsulating material was labor intensive work. Separating glass, Si cells, polymers and other metals was done using chemical and thermal processes. Recycling technologies and methods for end-of-life waste management differ based on the modules type and various components in it. For Si-based solar modules, various mechanical methods such as sorting, and crushing are being implemented worldwide. Metals are recovered for further processing and recycling. Similarly, glass is easily recycled into low grade glass products. To move further with any recycling process, it is important to know about economic aspects, recovery of useful materials and quality of recycled materials. Different technologies are under development phase to be implanted in recycling of solar PV modules [66].

Thermal processes recover materials such as Si, glass encapsulation and electrode materials. Major advantage for thermal approach is the possibility to recover Si cells and glass without any damage. These materials can be further processed and recycled, adding to the value for thermal processes. Defected modules with cracking and inherent flaws can be recycled to recover Si and other raw materials. Thermal processes are required to be carried out at mass scale to make them efficient and economical. Moreover, high consumption of energy is another issue with thermal processes and recycling methods. Heat recovery processes can be used in thermal processing to recover energy from excessive heating. Mechanical recycling methods involve scribing of glass and non-glass layers, cutting and crushing of encapsulation layers. Cutting and scribing can recover glass components with out any damage. While other methods are used to recycle the broken glass components. Similar to glass, other materials can be recovered with out any damage. Mechanical methods may require further chemical treatments to separate and recover various components such as Si wafers and metals. Energy required for mechanical technologies are much lower than thermal processes, but mechanical methods can be combined with different thermal treatments for recycling and improving the recovery rate. The chemical processes such as solvent treatments are used to separate encapsulation from solar PV module to recover Si wafers and cells without any damage. But these chemical processes require longer time and liquid waste is generated as well. Due to environmental concerns these treatments may not to be feasible and suitable for large scale. At small scale, these treatments can be used in combination with other mechanical and thermal method to recover useful materials. Etching and acid treatments are the chemical methods used to recover the metals and Si cells [67].

2.12.1 Thermal Processing

In thermal process, solar PV module is burnt in a furnace at temperature around 600°C. Combustible materials are burnt, and remaining Si, glass and other metallic components are recovered manually. Polymer material can cause carbonization that can be neutralized through altering the operating conditions of furnace. Similarly, fluoride gases may be produced by burning polymers with fluoride traces. Si wafers are recovered by etching after manual sorting. These Si wafers can be processed again to form a PV module. Thermal processing is not enough to recycle and reuse all the components of a PV modules yet, it is the most effective end-of-life waste management process for solar PV modules [68].

Kitakyushu Foundation for the Advancement of Industry (FAIS), Science and Technology, Japan, introduced a technique to recycle alumiuium frames, remove back sheet and thermally decompose encapsulating material. Whole process employs an automated system using controller systems from loading of PV modules to unloading of recovered materials after processing. First step in the process involves the Al frames using air cylinder-based actuator. Al frames are recyclable. After this, the back sheets are removed and disposed in accordance with industrial waste guidelines. Encapsulation materials are decomposed using muffle furnace. Furnace is heated up to 500°C and decomposition gases are burned out to minimize the environmental impact. After these processes, Si cells, electrodes, glass components are recovered. The same process can be used for thin films and CIS solar modules. CIS solar modules may require some additional steps. This process has high recycling yield as most of the components can be recovered unharmed. Recovered glass can be utilized in the formation of float glass. Further research is being carried out by Shinryo cooperation to improve this recycling process [69]. Figure 12 shows the remains of Si solar module after thermal treatment [15].

Figure 12: Remaining components of Si module after thermal treatment.

2.12.2 Chemical Processing

Chemical approach involves the immersion of PV modules in chemical solution to separate various components. Chemical reactions aid the separation process. Generally, it takes longer to separate components using chemical processes but recovery yield for Si wafers is much higher than thermal processes. In 1990s, BP solar used nitric acid as solvent for chemical processing. Nitric acid dissolves encapsulations and other useful materials are recovered undamaged. Si cells are etched using NaOH and further processed for reuse. Disposal of nitric acid after chemical processing has serious environmental hazards. To overcome these environmental issues, the use of organic solvent is proposed. Organic solvents can partially dissolve encapsulation materials. The efficiency and yield of organic solvent are significantly less than nitric acid [53].

Solvents were developed by Yokohama Oils industries to eliminate and separate the encapsulating material from solar PV laminated structures. First step is to separate terminal boxes and frames from module. The back sheet is separated using mechanical methods. Remaining module is submerged into the selected solvent to further separate glass, encapsulation layers, Si wafers and electrode materials. Glass obtained from solar PV module is usually undamaged during solvent treatment and can be recycled to reuse. Remaining layers of PV module are crushed for further alkali treatment process. Electrode materials and Si are recovered through this process. Additional processing steps may be required for the separation of Ag from Si wafer. Chemical treatments require immersion of modules for at least 24 hours to recover useful materials. Organic solvents are already developed to mitigate the harmful effects of acids. Organic solvents are employed after the separation of glass encapsulation and mechanical treatments such as grinding, cutting, and crushing [70].

Korean Research Institute for Chemical Technology developed a recycling technique for solar PV modules through organic solvent treatment along with the use of ultrasonication. Ultrasonication is used to overcome the shortcoming of chemical processing as chemical treatments require longer time. This recycling techniques was able to recover Si cells with out any damage. Some additional processing steps are required to separate and recover metal from Si solar cells [71]. Chemical technologies can be combined with mechanical and thermal processes such as the use of acids or hydroxides for chemical etching. Loser Chemie employs water and aluminum chloride for the separation of electrodes from Si wafers. Silver used in solar PV modules can be separated with the use of nitric acid. As discussed earlier, the chemical treatments are not feasible at mass scale due to economic and environmental issues. Moreover, chemical treatments require longer processing time [72]. Table 2 shows comparison between various recycling methods. Figure 13 shows dissolution of EVA layer in organic solvent [15].

Table 2: Comparison between different recycling methods and technologies.

Recycling Technology	**Method**	**Advantage**	**Disadvantage**	**References**
	Acid dissolution	- Back sheet and metallic electrode removal - Solar cell recovery	- Environmental concerns and emissions - Defects due to action of acid.	[73]

Delamination	Organic solvents	- Removal of organic and polymer layers - Reuse and recycling of chemical waste	- Process time is dependent on the area of a module - High economic costs - Health hazards	[74]
	Physical/Mechanical Disintegration	- High process efficiency	- Waste mixed with other materials - Damage to the module and recovered materials	[75]
	Ultrasonication	- Speed up dissolution processes - Removal of polymer layers	- Post-treatment of waste material - High cost	[76]
	Thermal Treatments	- Recovery of solar cells - Separation of polymer layers	- Energy extensive process - Environmental concerns	[77]
	Mechanical Processes	- No chemicals are required - Low energy processes	- Unable to separate dissolved materials	[78]

Material Separation		- Easy availability of equipment and apparatus - Simple and easy processing		
	Chemical etching	- Recovery of purer materials - High efficiency of the process	- Various chemicals are used - Energy extensive processes - High temperature	[79]

Figure 13: EVA layer dissolution by an organic solvent.

2.12.3 Mechanical Processing

Mechanical processing is a widely used technique to separate and recover glass from solar PV modules. Mechanical processing involves cutting, crushing, and scraping of encapsulation and glass layers. Mechanical methods are designed to recycle laminated solar modules to separate metals, polymers, and glass by adding additional processing steps. Mitsubishi developed a method to recover encapsulating glass by scrapping. The primary aim is to recover glass materials without any damage and contamination with encapsulating material. Equipment and setup for this method can process a single module under one minute. Recovered glass is further processed for reuse. Remaining glass pieces can be refined to recover Ag and other high value materials. Figure 14 shows recycling methods and recovery of useful materials.

Toho Kasei Co., Ltd mechanically separated non-glass components and layers. Back sheets and encapsulating layers are scrapped off mechanically. Electrode materials and Si cells are separated the similar way in addition to these layers. Further processing with different solvent enables to separate the back sheet, encapsulating layers, electrodes, polymers and Si. Recovered polymers can be recycled or used as fuel to recover pure Si. Back sheets usually end up in landfills as industrial waste. Even after mechanical separation, small amount of encapsulating layer can be found on glass. Recovered glass is further processed in solvent to remove the trace amount of encapsulating layer. Module can also be submerged into solvent in the start to ease mechanical scrapping. Only drawback for this process is high processing time [80]. Figure 15 shows recycling of various solar modules.

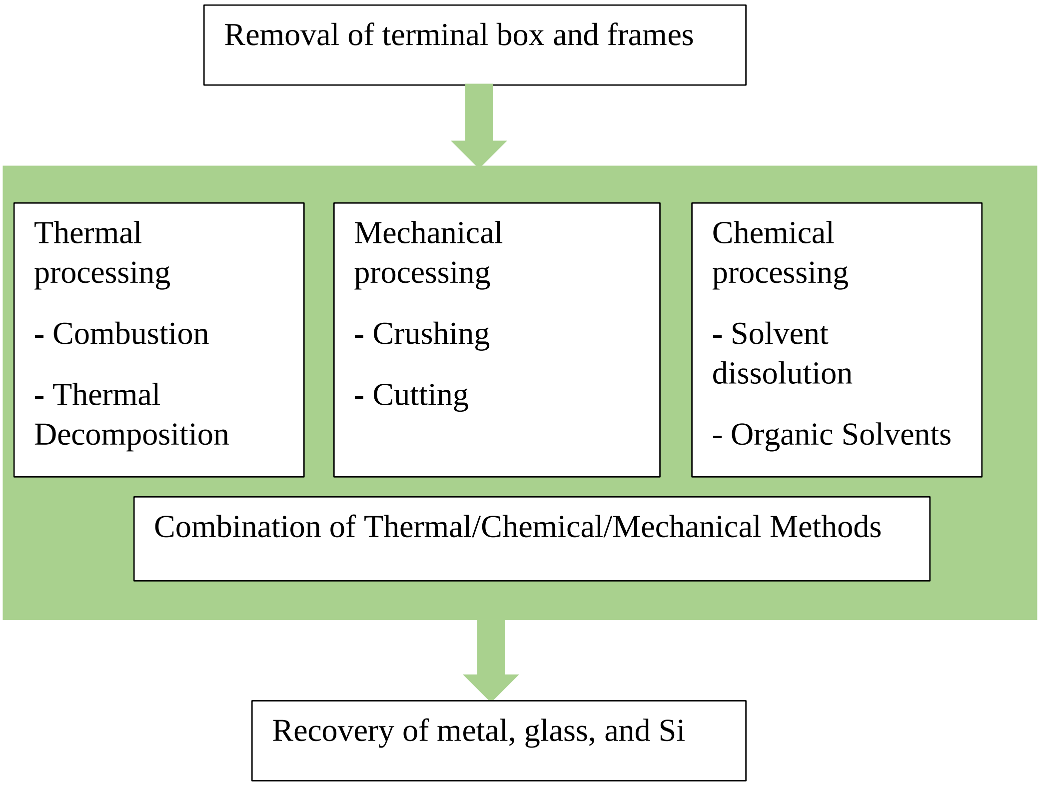


Figure 14: Recycling Methods and recovery of useful materials.

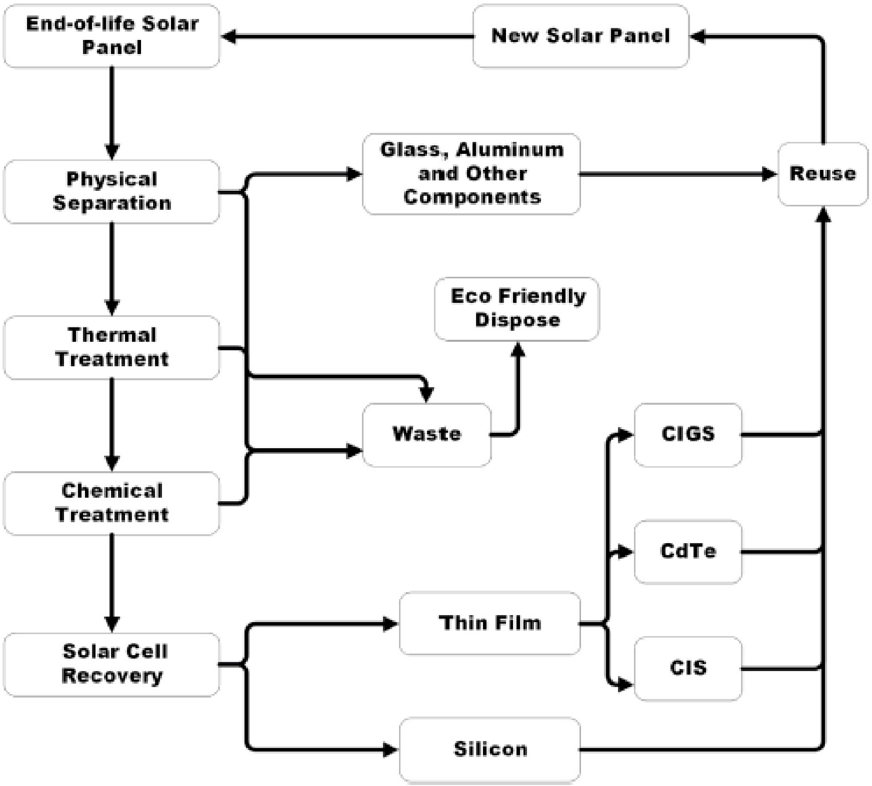


Figure 15: Recycling of various solar modules.

2.13 Second life of Solar Modules

Most discarded solar panels are still functional, even if the glass is cracked and the panel seems to be in poor shape at first glance. Repowering solar farms will make a significant contribution to using the large amount of abandoned solar panels that are still in good condition. There are several second-life options for second-hand solar panels. Within this study, second-life techniques are divided into two major categories: remanufacturing and repurposing. The primary distinction between the two scenarios is the chopping into separate rectangular sizes. Repurposing involves the cutting of use of new solar panels, but remanufacturing does not. For the remanufacturing instance, the solar cells should first be evaluated to see if the remaining efficiency is still appropriate.

Furthermore, used panels provide underdeveloped countries with an economical way to boost their share of green power. Secondary solar markets in the Middle East, Africa, Latin America, and the Caribbean are expected to grow considerably by 2020. According to the European Commission's 2019 study "Energy predictions for African nations," diesel-powered generators supply a large portion of electrical energy in Africa [98]. Reused solar panels, when remanufactured at a low cost, might serve as a bridging option to minimise diesel-generated power at least during the day. As more old automobile batteries reach the second-life market, these systems might be coupled to second-life battery storage systems. Renewable off-grid solutions built from used equipment might be manufactured and delivered. The second example stated above is the reuse of discarded solar panels to extend their lifespan. In this regard, repurposing includes breaking solar panels into separate sizes to broaden the range of possible applications. Solar panels with individual voltage and power levels require reconfiguration. Furthermore, the resulting low-power panels are smaller in size and hence far more versatile in terms of application and installation. Because of their lower size, second-hand solar panels may be used for RV projects, for example, as they can be simply put on the RV's rooftop. Solar panels of standard size would be far too large. Off-grid powering of communication equipment or other facilities such as 5G or lighting is another application case that would require battery storage. Because these devices use minimal energy, they might be powered by recycled solar panels of lower sizes. [6] As the Internet of Things (IoT) grows in popularity, solar systems might even be used indoors. Indoor use of smaller second-hand solar panels would be considerably easier and less expensive, as resealing the potentially broken front glass would be unnecessary.

The use of standard-sized solar panels in an off-grid power plant is another example of repurposing. Solar panels paired with a used battery might supply renewable energy from used equipment to power mobile devices such as cell phones, tablets, or laptop computers. This strategy was chosen as the primary use case for this investigation. The following chapter four describes the development of a prototype for such a system.

However, a profitability study would be required for each conceivable use case to demonstrate the viability of a commercial objective. Nonetheless, a fee for collecting old solar modules might be imposed, which will assist to maintain the cost of second-hand items as low as feasible.

In either case, whether refurbished or repurposed, there may be country-specific restrictions governing the treatment and resale of used solar modules. Companies in USA, for example, must be licenced to process solar energy waste. However, such regulations mostly pertain to the recycling of discarded solar panels. It is difficult to determine which restrictions apply to the secondary solar sector in the United States.

The warranty is one of the most important items to consider when reselling second-hand solar panels. In most circumstances, the manufacturer's original warranty is non-transferable. As a result, even if the solar panels have not fulfilled the 25-year guarantee period, secondary usage would void their warranty.

To compensate for missing warranties, the first solar equipment reseller businesses began evaluating all incoming solar panels and giving a limited guarantee at their own risk. This helps to dispel any concerns clients may have about purchasing old solar panels.

2.14 Early Failure in Solar Modules

Light erosion (0.5%-5%) is the most common problem observed in new solar panels, with poor design and manufacturing flaws being the major reasons [13,19,22]. According to Fig. 5, other reasons of panel failure include electrical equipment such as junction boxes, fuse boxes, charge controllers, and cabling, as well as grounding concerns [24,25]. Solar panels suffered from deterioration of the anti-reflective coating layer of colorless ethylene vinyl acetate (EVA) put to the glass in the early years of manufacture, as well as faults owing to broken solar cells [26]. Figure 16 shows the reasons for early failures in solar PV modules.

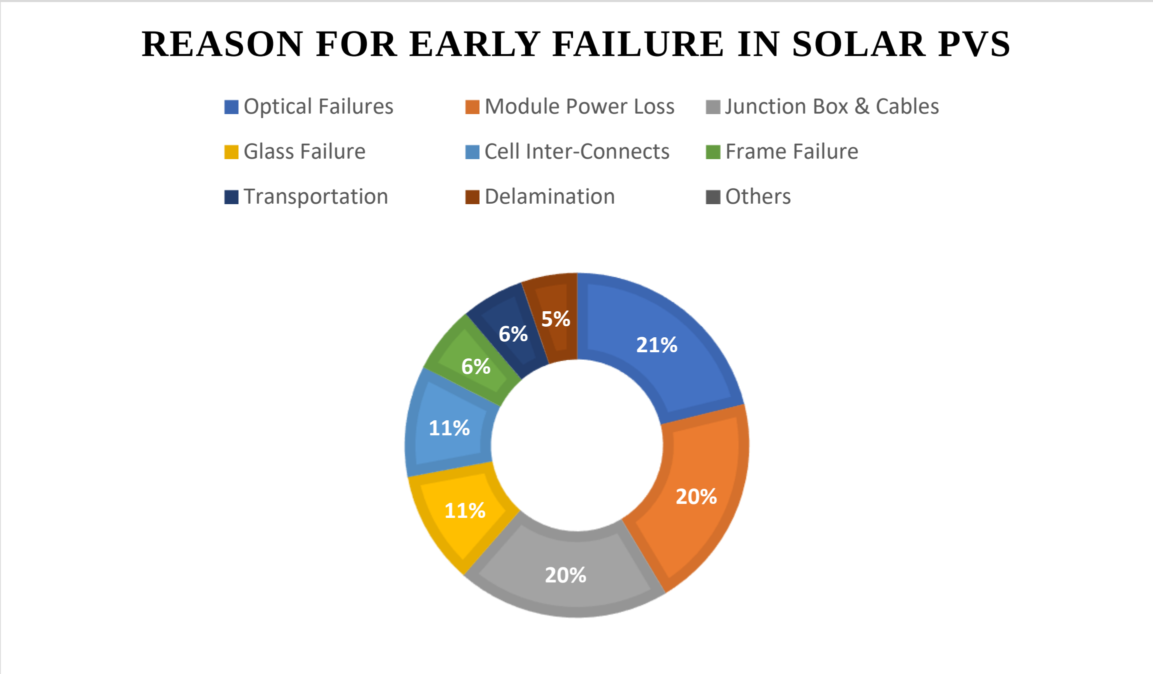


Figure 16: Reasons for early failures in solar PV modules [5].

2.15 End-of-life Solar Waste Policies

The effectiveness of PV waste disposal and management is dependent on the monitoring and waste quantification over PV modules. These factors keep the check for transport of solar waste through international border and to assure the suitable waste treatment or recycling techniques for the panels. Solar panels and solar companies must be registered to have inventory data for the raw materials that are used in the manufacturing of solar panels. Moreover, the panels must be monitored throughout various processes such as transportation, collection, and marketing. Current regulations demonstrate lack of any central organization that enforces and legislates preventative waste treatment plan in order to accomplish the three key components of sustainability, which include a closed-loop and tightly monitored supply chain, economic feasibility, and minimum environmental impact. One of the critical factors in proper PV waste treatment policy execution is associated with a central authority, which means that when PV waste is moved to another third-party country, it still falls under the legislation and authority of a global organization. It is critical to ensure that the most recent standards, policies, and legislations on the treatment of solar waste panel are being followed. Regulations and policies adopted by different countries are explained in table 3 [81].

Table 3: Policy and Regulations for end-of-life solar waste in different countries.

Country	Policy and Regulations
USA	• Waste management regulations are applied to solar waste. • Solar waste is considered hazardous according to senate bill 489. • Introduction of tax rebates on recycling of solar waste. • Development of national recycling plan to encourage recycling and treatment of solar waste. • Tracking and quantification of solar waste over time. • Development of cost-effective recycling methods. • Creation of Solar Energy Industries Association (SEIA) for the implementation of recycling plans.
Europe	• Standardization of collection, recycling, and disposal of solar waste. • Manufacturers are responsible for waste collection and recycling. • Development of infrastructure for solar waste recycling. • Encouragement of solar waste recycling. • Legislations regarding health, safety, environmental protection and toxicity of solar waste. • Standardization to hazardous material removal.

	• Development of monitoring systems for solar waste.
Korea	• Legislations and policies for solar waste recycling and management. • R&D for solar waste treatment technologies. • New and strict rules regarding end-of-life waste management.
Japan	• Development of regulatory framework for end-of-life solar waste. • Regulation on reusing, disposing, transporting and collection of solar waste.
Pakistan	• Pakistan Environmental Protection Act (PEPA) for preservation of environment and waste disposal. • Hazardous substance rule. • PEPA prohibits the discharge of hazardous substances that violates the National Environment Quality Standards (NEQS). • Development of Environment Protection Agency (EPA).

2.16 Research Gap Identification

The following research gaps are identified for end-of-life waste management from literature review in chapter 2, 3 and 4:

- Lack of waste material quantification for solar and wind turbine waste for the capacity addition plan IGCEP 2047 of Pakistan.
- Lack of waste disposal and management policies for renewable end-of-life waste for Pakistan.
- Lack of recycling technologies and life cycle assessment for wind and solar energy in Pakistan.

Chapter: 3

3. Materials and Methods

3.1 Solar PV Waste Quantification

Waste materials for end-of-life solar waste are quantified as hazardous, critical, base materials, precious metals, ceramic, and polymers. Apart from solar PV modules, other waste materials include inverters, mounting structures, cables, and batteries. Waste materials for solar PV modules are quantified in table 4 following the data gathered from the literature [82]. The data for solar PV capacity addition is collected through Renewable Energy licenses issued by National Electric Power Regulatory Authority (NEPRA), Islamic Republic of Pakistan [83]–[93].

To calculate material waste generated through the capacity addition of solar PV modules in Pakistan, equations 1, 2 and 3 are used. Weight percentages for waste materials such as Pb, Mg, Ag, Cu, Al, Ni, Sn, Zn, Si, Steel, glass and EVA are taken from the literature [82]. Material waste for each material is calculated by using the equation 4 [57]. Values for laminate thickness, frame weight and density are taken from International Energy Agency (IEA)[57]. Values for module surface area, module efficiency, the total number of modules, module weight and commission year are taken from the respective licenses issued by National Electric and Power Regulatory Authority, Pakistan.

3.2 Methodology to Quantify Solar PV Module Waste

Extensive research is carried out through a literature review to design a methodology for the quantification of solar PV waste materials in Pakistan. Following equation (1), (2),(3) and (4) are used to quantify the waste materials for solar PV modules [57]. To ensure the correctness of calculated waste data, the results were compared with the compositional and weight percentage values available in literature. Table 4 shows the quantification of waste materials in weight percentage based on literature [82], [94]. Tables 5 and 6 show technical data for solar power plants installed in Pakistan based on IGCEP 2047 plan calculated based on equations presented below. The calculated data in tables 5 and 6 are used to quantify waste materials and future projections for end-life waste materials. Solar PV modules are categorized into first, second and third generation solar PV technologies. As for Pakistan, most of the installed solar plants are based on first generation solar technology, therefore waste material for only first-generation solar plants is calculated. No solar power is commissioned to the date with second or third generation solar technologies. The end-of-life year for each solar plant is calculated based on 25-year life cycle. The total amount of different waste materials such as EVA, Steel, Al, Ag, Mg, Cu, Si Zn, Sn, Ni, Pb and glass are calculated in tonnes based on the installed capacity in Pakistan. Values such as module surface area, efficiency and efficiency are based on technical data sheets for each solar power plant. The status for each solar solar power plant is either installed (I), commissioned (C) or committed (CA) as shown in table.

Total Laminate Waste (m^3) **=** *Module Surface Area x Module Laminate thickness (m) x Total Number of Modules* (1)

Total Frame Waste = (Module Surface Area x Frame Waste (kg/m^2) x Total Number of Modules)/Frame Density (kg/m^3) (2)

Total Waste (m^3) = Total Laminate Waste + Total Frame Waste (3)

Material Weight (tons) = (Material Weight Percentage/100) x (Module Weight (kg) x 0.001(conversion factor)) x Total Number of Modules (4)

3.3 PV Module Materials

The critical materials are categorized and highlighted in table 4 constituting materials required to manufacture solar PV modules to produce clean energy and flourish green economy. The weight percentage of each material is presented in the table 4. It is believed that supply chain interruptions and price changes connected to with international manufacturing will harm renewable industry in Pakistan or any other country. Pakistan is not a producer of these important metals. Any initiative to recycle key metals will benefit the domestic market of these materials and reduce the dependency on material imports. Metal, glass and steel have the highest weight percentages of 9.51, 65.4 and 6.5 weight percentage in each single solar PV module.

Table 4: Quantification of waste materials for end-of-life solar PV modules.

Material		**Weight Percentage**
Hazardous Material	Pb	0.1257%
Critical Materials	Mg	0.520%
Precious Metals	Ag	0.0577 %
Base Material	Cu	0.731 %
	Al	16.5 %
	Ni	0.00106%
	Sn	0.0000586%
	Zn	0.00000781 %
Other Metals	Si	0.791%
	Steel	9.51%
Ceramic and Polymer	Glass	65.4%
	EVA	6.5%

Table 5: Technical data for solar power plants installed in Pakistan. Waste materials are quantified, and future projections are made for end-life waste materials.

Sr. No.	Power Plant Name	Installed Capacity (MW)	Status	Commission Date	Module Surface Area (m^2)	Module Efficiency (%)	Module Laminate Thickness (m)	Frame Weight (kg/m^2)	Frame Density (kg/m^3)	Number of Modules	Module Weight (kg)	Module Mass (kg/m^2)	End-of-Life Year	Total Module Laminate Waste (m^3)	Total Frame Weight (m^3)	Total Weight (m^3)
1	**QA Solar**	100.0	I	**2015**	1.630	15.40	0.005	2.13	2700	400,000	18.20	11.17	**2040**	3,260.00	514.36	3,774.36
2	**Appolo Solar**	100.0	I	**2016**	1.635	15.60	0.005	2.13	2700	391,600	18.20	11.13	**2041**	3,201.33	505.10	3,706.43
3	**Best**	100.0	I	**2016**	1.635	15.60	0.005	2.13	2700	391,600	18.20	11.13	**2041**	3,201.33	505.10	3,706.43
4	**Crest**	100.0	I	**2016**	1.635	15.60	0.005	2.13	2700	391,600	18.20	11.13	**2041**	3,201.33	505.10	3,706.43

5	**Safe**	10.0	I	**2016**	2.208	17.00	0.005	2.13	2700	46,750	21.20	9.60	**2041**	516.12	81.43	597.55
6	**Helios**	50.0	I	**2019**	1.970	16.24	0.005	2.13	2700	156,260	34.00	17.26	**2044**	1,539.24	242.86	1,782.10
7	**HNDS**	50.0	I	**2019**	1.970	16.24	0.005	2.13	2700	156,260	34.00	17.26	**2044**	1,539.24	242.86	1,782.10
8	**Access Electri**	10.5	I	**2020**	2.186	20.60	0.005	2.13	2700	22,248	24.00	10.98	**2045**	243.17	38.37	281.54
9	**Access Solar**	12.0	I	**2020**	2.186	20.60	0.005	2.13	2700	25,623	24.00	10.98	**2045**	280.06	44.19	324.25
10	**Siache n**	100.0	C	**2022**	2.500	20.00	0.005	2.13	2700	200,016	32.50	13.00	**2047**	2,500.20	394.48	2,894.68
11	**Zhenfa Solar**	100.0	C	**2022**	1.600	16.15	0.005	2.13	2700	382,440	20.00	12.50	**2047**	3,059.52	482.72	3,542.24

12	**Meridian**	50.0	C	**2022**	1.970	16.24	0.005	2.13	2700	156,260	34.00	17.26	**2047**	1,539.16	242.85	1,782.01
13	**Zorlu Solar**	100.0	C	**2024**	3.100	20.90	0.005	2.13	2700	155,792	38.70	12.48	**2049**	2,414.78	381.00	2,795.77
14	**Candidate**	256.0	CA	**2024**	1.970	16.24	0.005	2.13	2700	156,260	34.00	17.26	**2049**	1,539.16	242.85	1,782.01
15	**Candidate**	827.0	CA	**2028**	1.970	16.24	0.005	2.13	2700	156,260	34.00	17.26	**2053**	1,539.16	242.85	1,782.01

Table 6: Material Quantification of solar power plants installed in Pakistan.

		Material Content for Total No. of Modules																							
		Mg		Ag		Cu		Al		Ni		Sn		Zn		Si		Steel		Glass		EVA		Pb	
Sr. No.	Power Plant	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt	%	Mt
1	QA Solar	5.20.E-01	37.86	5.77.E-02	4.20	7.31.E-01	53.22	1.65.E+01	1,201.20	1.06.E-03	7.72.E-02	5.86.E-05	4.27.E-03	7.81.E-06	5.69.E-04	7.91.E-01	57.58	9.51.E+00	692.33	6.54.E+01	4,761.12	6.50.E+00	473.20	4.67.E-03	0.34
2	Appolo Solar	5.20.E-01	37.06	5.77.E-02	4.11	7.31.E-01	52.10	1.65.E+01	1,175.97	1.06.E-03	7.55.E-02	5.86.E-05	4.18.E-03	7.81.E-06	5.57.E-04	7.91.E-01	56.38	9.51.E+00	677.79	6.54.E+01	4,661.14	6.50.E+00	463.26	4.67.E-03	0.33
3	Best	5.20.E-01	37.06	5.77.E-02	4.11	7.31.E-01	52.10	1.65.E+01	1,175.97	1.06.E-03	7.55.E-02	5.86.E-05	4.18.E-03	7.81.E-06	5.57.E-04	7.91.E-01	56.38	9.51.E+00	677.79	6.54.E+01	4,661.14	6.50.E+00	463.26	4.67.E-03	0.33

4	**Crest**	5.20.E-01	37.06	5.77.E-02	4.11	7.31.E-01	52.10	1.65.E+01	1,175.97	1.06.E-03	7.55.E-02	5.86.E-05	4.18.E-03	7.81.E-06	5.57.E-04	7.91.E-01	56.38	9.51.E+00	677.79	6.54.E+01	4,661.14	6.50.E+00	463.26	4.67.E-03	0.33
5	**Safe**	5.20.E-01	5.15	5.77.E-02	0.57	7.31.E-01	7.24	1.65.E+01	163.53	1.06.E-03	1.05.E-02	5.86.E-05	5.81.E-04	7.81.E-06	7.74.E-05	7.91.E-01	7.84	9.51.E+00	94.25	6.54.E+01	648.18	6.50.E+00	64.42	4.67.E-03	0.05
6	**Helios**	5.20.E-01	27.63	5.77.E-02	3.07	7.31.E-01	38.84	1.65.E+01	876.62	1.06.E-03	5.63.E-02	5.86.E-05	3.11.E-03	7.81.E-06	4.15.E-04	7.91.E-01	42.02	9.51.E+00	505.25	6.54.E+01	3,474.60	6.50.E+00	345.33	4.67.E-03	0.25
7	**HNDS**	5.20.E-01	27.63	5.77.E-02	3.07	7.31.E-01	38.84	1.65.E+01	876.62	1.06.E-03	5.63.E-02	5.86.E-05	3.11.E-03	7.81.E-06	4.15.E-04	7.91.E-01	42.02	9.51.E+00	505.25	6.54.E+01	3,474.60	6.50.E+00	345.33	4.67.E-03	0.25
8	**Access Electric**	5.20.E-01	2.78	5.77.E-02	0.31	7.31.E-01	3.90	1.65.E+01	88.10	1.06.E-03	5.66.E-03	5.86.E-05	3.13.E-04	7.81.E-06	4.17.E-05	7.91.E-01	4.22	9.51.E+00	50.78	6.54.E+01	349.20	6.50.E+00	34.71	4.67.E-03	0.02

9	**Access Solar**	5.20.E-01	3.20	5.77.E-02	0.35	7.31.E-01	4.50	1.65.E+01	101.47	1.06.E-03	6.52.E-03	5.86.E-05	3.60.E-04	7.81.E-06	4.80.E-05	7.91.E-01	4.86	9.51.E+00	58.48	6.54.E+01	402.18	6.50.E+00	39.97	4.67.E-03	0.03
10	**Siachen**	5.20.E-01	33.80	5.77.E-02	3.75	7.31.E-01	47.52	1.65.E+01	1,072.59	1.06.E-03	6.89.E-02	5.86.E-05	3.81.E-03	7.81.E-06	5.08.E-04	7.91.E-01	51.42	9.51.E+00	618.20	6.54.E+01	4,251.34	6.50.E+00	422.53	4.67.E-03	0.30
11	**Zhenfa Solar**	5.20.E-01	39.77	5.77.E-02	4.41	7.31.E-01	55.91	1.65.E+01	1,262.05	1.06.E-03	8.11.E-02	5.86.E-05	4.48.E-03	7.81.E-06	5.97.E-04	7.91.E-01	60.50	9.51.E+00	727.40	6.54.E+01	5,002.32	6.50.E+00	497.17	4.67.E-03	0.36
12	**Meridian**	5.20.E-01	27.63	5.77.E-02	3.07	7.31.E-01	38.84	1.65.E+01	876.62	1.06.E-03	5.63.E-02	5.86.E-05	3.11.E-03	7.81.E-06	4.15.E-04	7.91.E-01	42.02	9.51.E+00	505.25	6.54.E+01	3,474.60	6.50.E+00	345.33	4.67.E-03	0.25
13	**Zorlu Solar**	5.20.E-01	31.35	5.77.E-02	3.48	7.31.E-01	44.07	1.65.E+01	994.81	1.06.E-03	6.39.E-02	5.86.E-05	3.53.E-03	7.81.E-06	4.71.E-04	7.91.E-01	47.69	9.51.E+00	573.37	6.54.E+01	3,943.06	6.50.E+00	391.89	4.67.E-03	0.28

14	**Candidate Solar 1**	5.20.E-01	27.63	5.77.E-02	3.07	7.31.E-01	38.84	1.65.E+01	876.62	1.06.E-03	5.63.E-02	5.86.E-05	3.11.E-03	7.81.E-06	4.15.E-04	7.91.E-01	42.02	9.51.E+00	505.25	6.54.E+01	3,474.60	6.50.E+00	345.33	4.67.E-03	0.25
15	**Candidate Solar 2**	5.20.E-01	27.63	5.77.E-02	3.07	7.31.E-01	38.84	1.65.E+01	876.62	1.06.E-03	5.63.E-02	5.86.E-05	3.11.E-03	7.81.E-06	4.15.E-04	7.91.E-01	42.02	9.51.E+00	505.25	6.54.E+01	3,474.60	6.50.E+00	345.33	4.67.E-03	0.25

Chapter: 4

4. Wind Turbines Waste Quantification

Methodology and calculation for end-of-life waste materials are discussed in this section. For the case of Pakistan, the data for wind turbines are gathered through respective licenses granted by NEPRA Pakistan. Waste materials for wind turbines are quantified and projections are made for the year 2035 to 2050 according to IGCEP 2047. Calculations require data from various credible sources. In a wind turbine, the waste material generation is dependent on the initial materials used and quantify these amounts over the coming years according to capacity addition [18].

4.1 Material and Methods

Generated waste materials at end-of-life wind turbines are Al, Cu, steel and iron-based materials, polymer, lubricants, electronics, sealants, ceramic, and glass. Electronics include switch gears and cable systems of wind turbines along with other electronic subsystems [37]. When a wind turbine reaches end-of-life all systems and components are dismantled to restore the original form the site. The waste generated also includes the concrete structures used to support wind turbines. For a base case, 2 MW Vestas wind turbine is used to quantify the waste materials as shown in table 7 [65]. The most installed wind turbines are geared turbines and some of the common models for wind turbines are Vestas (V900-V100), Senvion (MM92), and Nordex (N90-N100) [65]. Geared wind turbines represent up to 90% of total installed capacity in Pakistan while less than 10% of turbines are gearless. Cumulative waste for end-of-life wind turbines is calculated in tons keeping in view the capacity addition for Pakistan renewable energy planning by NEPRA. Table 8 shows technical data and cumulative material quantification based on calculations from NEPRA licensed wind turbines. The total installed capacity of wind energy in Pakistan is 1696.3 MW till 2022. A further 2048 MW of wind energy will be installed by the end of 2025 according to the licenses issued by NEPRA.

The thesis and analysis include turbine materials, cables, base structures, and switchgears. The analysis uses 2 MW vestas wind turbine to quantify the data as technical data for all the wind turbines of Pakistan was not available.

Life cycle of wind turbines can range up to 35 years but for the analysis average value of 25 years was taken. End-of-life time was calculated based on this assumption. Once end-of-life for a wind turbine is reached, the turbine is decommissioned and removed to restore the area to original form. Apart from end-of-life, various components of wind turbines are replaced over time. These parts include turbine blades, gear boxes, About 15% of wind turbines are prone to gear box replacement while less than 3% of turbines are prone to blade replacement over life cycle [95]. Gearbox in any wind turbine represents around 40% of total weight. According to study by Liu and Barlow [96], on average the gearbox of any wind turbine is replaced 3 times over the life time.

Table 7: Waste materials after end-of-life for wind turbine.

Materials	**Weight (tons/MW)**
Steel and iron-based materials	102.67
Cu	0.844
Al	2.1
Polymers	5.22
Lubricants	0.34
Ceramic and glass	9.54
Electronics	1.2
Sealants	0.14

Table 8: Technical data and cumulative material quantification for NEPRA licensed wind turbines.

					S&IM (tons)		Cu (tons)		Al (tons)		Polymers (tons)		Lubricants (tons)		C&G (tons)		Electronics (tons)		Sealants (tons)		
Sr. No.	**Power Plant Name**	**Year**	**Installed Capacity (MW)**	**Status**	**Per MW**	**Total**	**Per MW**	**Total**	**Per MW**	**Total**	**Per MW**	**Total**	**Per MW**	**Total**	**Per MW**	**Total**	**Per MW**	**Total**	**Per MW**	**Total**	**End-of-Life Year**
1	FWEL-II	**2010**	50.0	I	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2035**
2	FFC	**2012**	49.5	I	102	5082	0.844	41.78	2.1	104	5.22	258.4	0.34	16.83	9.54	472.2	1.2	59.4	0.14	6.93	**2037**
3	Zorlu Wind	**2012**	56.4	I	102	5791	0.844	47.6	2.1	118.4	5.22	294.4	0.34	19.18	9.54	538.1	1.2	67.68	0.14	7.896	**2037**
4	FWEL-I	**2013**	50.0	I	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2038**

5	Three Gorges I	**2013**	49.5	I	102	5082	0.844	41.78	2.1	104	5.22	258.4	0.34	16.83	9.54	472.2	1.2	59.4	0.14	6.93	**2038**
6	Yunus	**2013**	50.0	I	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2038**
7	Metro Power	**2014**	50.0	I	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2039**
8	Sachal	**2014**	49.5	I	102	5082	0.844	41.78	2.1	104	5.22	258.4	0.34	16.83	9.54	472.2	1.2	59.4	0.14	6.93	**2039**
9	Sapphire	**2015**	52.8	I	102	5421	0.844	44.56	2.1	110.9	5.22	275.6	0.34	17.95	9.54	503.7	1.2	63.36	0.14	7.392	**2040**
10	UEP	**2015**	99.0	I	102	10164	0.844	83.56	2.1	207.9	5.22	516.8	0.34	33.66	9.54	944.5	1.2	118.8	0.14	13.86	**2040**
11	Master	**2016**	52.8	I	102	5421	0.844	44.56	2.1	110.9	5.22	275.6	0.34	17.95	9.54	503.7	1.2	63.36	0.14	7.392	**2041**

12	Act	**2017**	30.0	I	102	3080	0.844	25.32	2.1	63	5.22	156.6	0.34	10.2	9.54	286.2	1.2	36	0.14	4.2	**2042**
13	Hawa	**2017**	49.7	I	102	5103	0.844	41.95	2.1	104.4	5.22	259.4	0.34	16.9	9.54	474.1	1.2	59.64	0.14	6.958	**2042**
14	Three Gorges II	**2017**	49.5	I	102	5082	0.844	41.78	2.1	104	5.22	258.4	0.34	16.83	9.54	472.2	1.2	59.4	0.14	6.93	**2042**
15	Three Gorges III	**2017**	49.5	I	102	5082	0.844	41.78	2.1	104	5.22	258.4	0.34	16.83	9.54	472.2	1.2	59.4	0.14	6.93	**2042**
16	Tricon A	**2017**	49.7	I	102	5103	0.844	41.95	2.1	104.4	5.22	259.4	0.34	16.9	9.54	474.1	1.2	59.64	0.14	6.958	**2042**
17	Jhimpir	**2018**	49.7	I	102	5103	0.844	41.95	2.1	104.4	5.22	259.4	0.34	16.9	9.54	474.1	1.2	59.64	0.14	6.958	**2043**
18	Tricon B	**2018**	49.7	I	102	5103	0.844	41.95	2.1	104.4	5.22	259.4	0.34	16.9	9.54	474.1	1.2	59.64	0.14	6.958	**2043**

19	Tricon C	**2018**	49.7	I	102	5103	0.844	41.95	2.1	104.4	5.22	259.4	0.34	16.9	9.54	474.1	1.2	59.64	0.14	6.958	**2043**
20	Act 2	**2019**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2044**
21	Master Green	**2019**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2044**
22	Tricom	**2020**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2045**
23	Artistic Wind	**2021**	49.3	I	102	5062	0.844	41.61	2.1	103.5	5.22	257.3	0.34	16.76	9.54	470.3	1.2	59.16	0.14	6.902	**2046**
24	Gul Ahmed	**2021**	50.0	I	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2046**
25	Metro Wind	**2022**	60.0	C	102	6160	0.844	50.64	2.1	126	5.22	313.2	0.34	20.4	9.54	572.4	1.2	72	0.14	8.4	**2047**

26	Lakeside	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**
27	NASDA	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**
28	Artistic Wind 2	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**
29	Din	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**
30	Gul Electric	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**
31	Liberty Wind 1	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**
32	Liberty Wind 2	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1. 2	60	0.14	7	**2047**

33	Indus Energy	**2022**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2047**
34	Western	**2024**	50.0	C	102	5134	0.844	42.2	2.1	105	5.22	261	0.34	17	9.54	477	1.2	60	0.14	7	**2049**
35	Trans Atlantic	**2024**	48.0	C	102	4928	0.844	40.51	2.1	100.8	5.22	250.6	0.34	16.32	9.54	457.9	1.2	57.6	0.14	6.72	**2049**
36	Candidate Wind	**2024**	1000.0	CA	102	1E+05	0.844	844	2.1	2100	5.22	5220	0.34	340	9.54	9540	1.2	1200	0.14	140	**2049**
37	Candidate Wind 2	**2025**	1000.0	CA	102	1E+05	0.844	844	2.1	2100	5.22	5220	0.34	340	9.54	9540	1.2	1200	0.14	140	**2050**

Chapter: 5

5. Results and Discussion

5.1 Solar PV Modules

A detailed analysis is carried out based on the technical data for solar PV calculated in table 3,4 and 5. It is important to investigate the licenses issued by NEPRA and IEA report to identify and calculate data such as capacity addition, installed capacity and efficiency of solar modules. Solar PV licenses by NEPRA had technical data such as installed capacity in MW, total number of modules but data for frame density, laminate thickness, frame weight and frame density were missing. The values for these data were collected from the report International Energy Agency (IEA) report [57]. A total of 15 solar PV power plant installations were analyzed based on given technical data as shown in table 5. Each installation is either categorized as installed, commissioned, or committed according to the current status. The total installed capacity for solar power plants stands at 782.5 MW till 2022. Further 100 MW will be added till 2024. By 2028, 1083 MW of solar power energy will be added to installed capacity. The cumulative installed capacity for solar energy will reach 1965.5 MW by the end of 2028 for Pakistan. According to given data, 1 MW of capacity addition will add 17.42 m^3 of end-of-life solar waste. By the end of 2053, the total solar waste will be 34,239.89 m^3 as shown in figure 17. Average life cycle of 25 years is considered based on the literature and technical data sheets issued by NEPRA. Solar PV waste will start to accumulate from year 2040 based on 25 years of life cycle. The total waste generated by the end of year 2053 is based on module weight, total number of modules, frame weight, frame density, laminate thickness, and module weight. Waste materials generated in addition to solar module waste include fuse box, meters, controller, mounting structures, invertors, and transformers. These materials are not included in the final analysis to simplify the results and due to lack of credible data for these materials. The major quantities of solar PV module waste are for glass, steel, Al and EVA. Semiconductor materials such as Si and Zn are used for solar cells while Cu is used for metallic contacts and connecting wires. The presence of Pb is health hazard as according to the guidelines of IEA [57]. The disposal of Pb is crucial to avoid the harmful environmental impact and health hazards.

Figures 17 and 18 show cumulative waste material quantities of end-of-life for EVA, Steel, Al, Ag, Mg, Cu, Si, Zn, Sn, Ni, Pb and glass that are 5.04E+3, 7.37E+3, 1.28E+4, 4.47E+1, 4.02E+2, 5.67E+2, 6.13E+2, 6.06E-3, 4.54E-2, 8.22E-1, 3.83E0, 5.07E+4 tons respectively for solar power plants installed in Pakistan till 2053 based on the data collected through respective licenses and IEA report. Similarly, figure 19 shows a total frame waste of 4,666.09, total module laminate waste of 29,573.80 and total cumulative waste of 34,239.89 m^3 generated at end-of-life solar PV modules in Pakistan based on installed capacity.

5.1.1 Recycling of Solar Modules in Pakistan

Recycling of solar modules is important to protect the environment and recover useful materials. Currently Pakistan lacks any of recycling mechanism or framework for solar module recycling once end-of-life is reached. However, Pakistan has departments such as Environmental Protection Agency (EPA) to make a detailed framework for the recycling of solar modules. Moreover, waste management departments can work along EPA for suitable disposal of solar modules. United Agency of International Development (USAID) is also encouraging Pakistani government and private companies to establish long term and sustainable solar recycling methods to ensure the recovery of various materials from solar modules. Solar waste is termed as e-waste that requires special handling. The material yield estimations for solar module recycling are presented in table 9. The recycling yields for these materials are taken from various sources and recycling techniques. Some of these techniques are at lab scale, while some are at pilot scale and few techniques are commercialized to be used for solar PV recycling. Most of the recycling facilities are based on countries like USA, UK, European Union, Korea, Japan, China and Brazil. Pakistan is still far away from proper establishment of solar industries. But the solar market in Pakistan is growing rapidly owing to the increased demand of solar panels. The recycling yield for metals is more than 90% in most of the recycling techniques and only negligible amount of these metals will end up in landfills. Metals such as Al, steel and Cu have high recovery yield. Most of these materials are used in mounting structures, electric contacts, frame of module, and cables.

Table 9: Recycling yield of different materials in solar modules.

Material	Recycling Yield %	References
Al	99.7	[97]
Ag	95	[79]
Cu	99.9	[79]
Ti	52	[98]
Zn	27	[98]
Ni	41	[98]
Sn	32	[99]
Mg	33	[98]
Pb	96	[99]
Si	99.9	[100]
Glass	95	[97]
Steel	90	[82]

Currently, the most suitable and successful techniques for Pakistan to recycle and recover metals and glass are thermal and mechanical treatments. Thermal treatment can remove EVA from solar module from burning it. The temperature for thermal treatment can reach up to 600°C, the high temperature ensures the complete removal of EVA layer to recover Si cells from solar modules after post treatments such as etching. The recovery yield for Si and glass in thermal treatment is more than 90% [101].

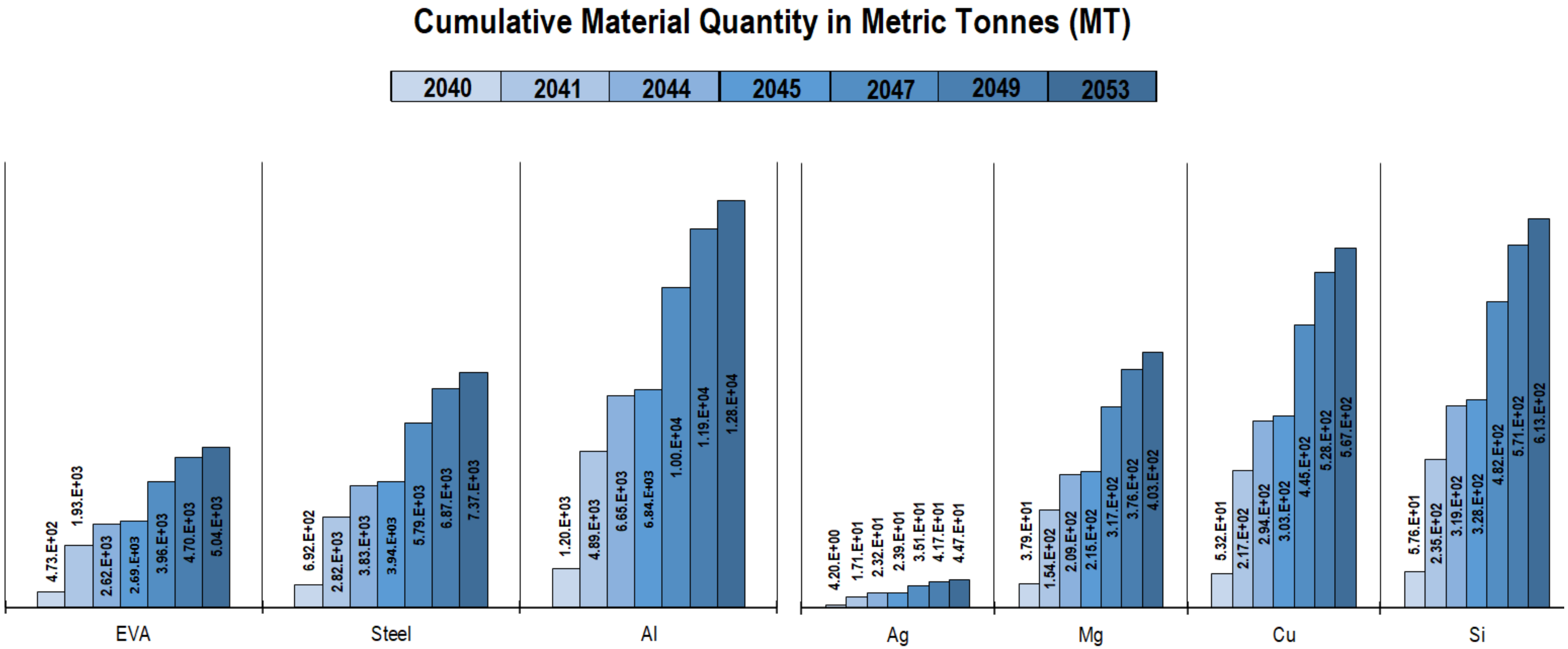


Figure 17: Cumulative Material Quantity for EVA, Steel, Al, Ag, Mg, Cu and Si for solar power plants installed in Pakistan.

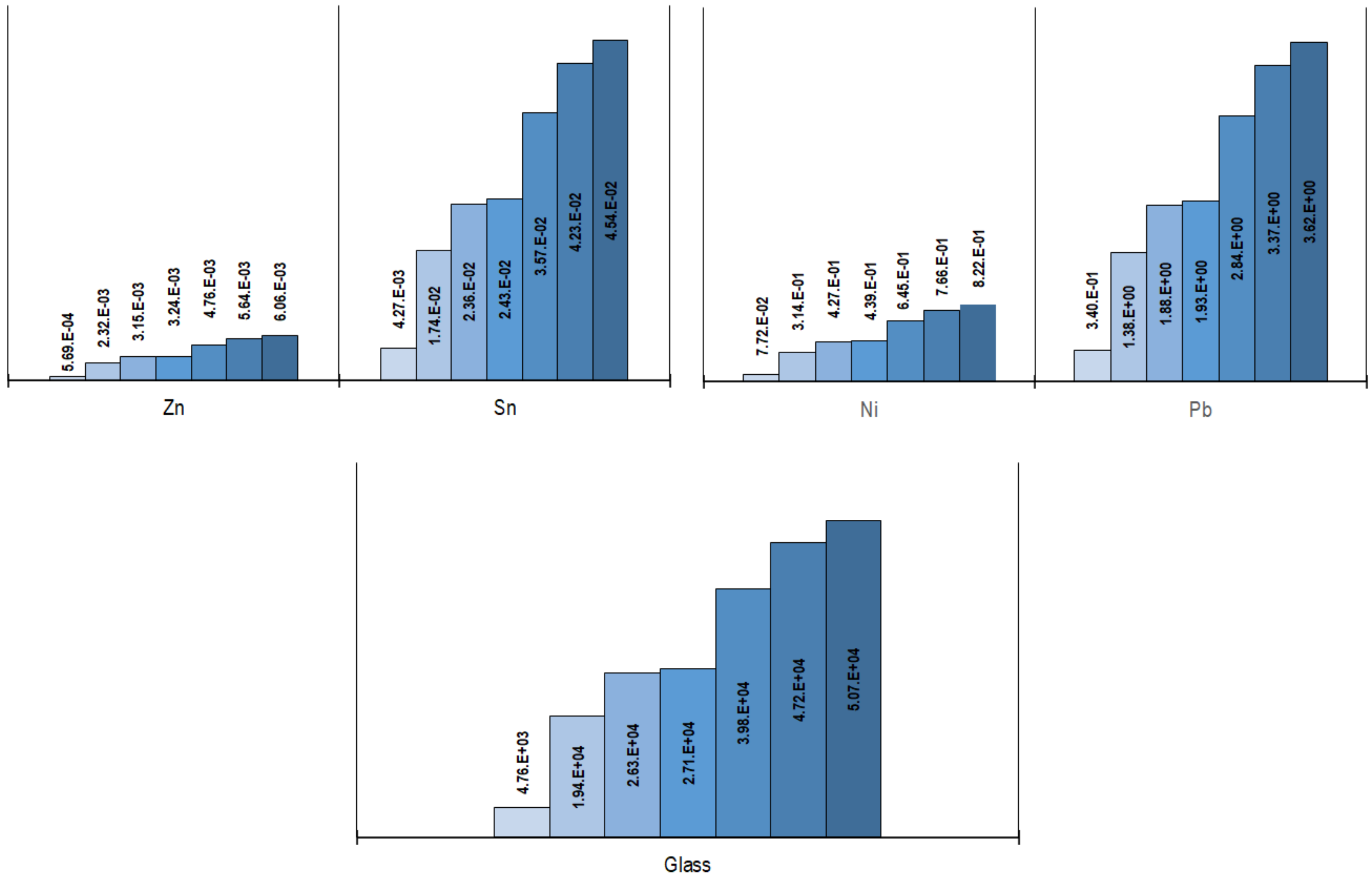
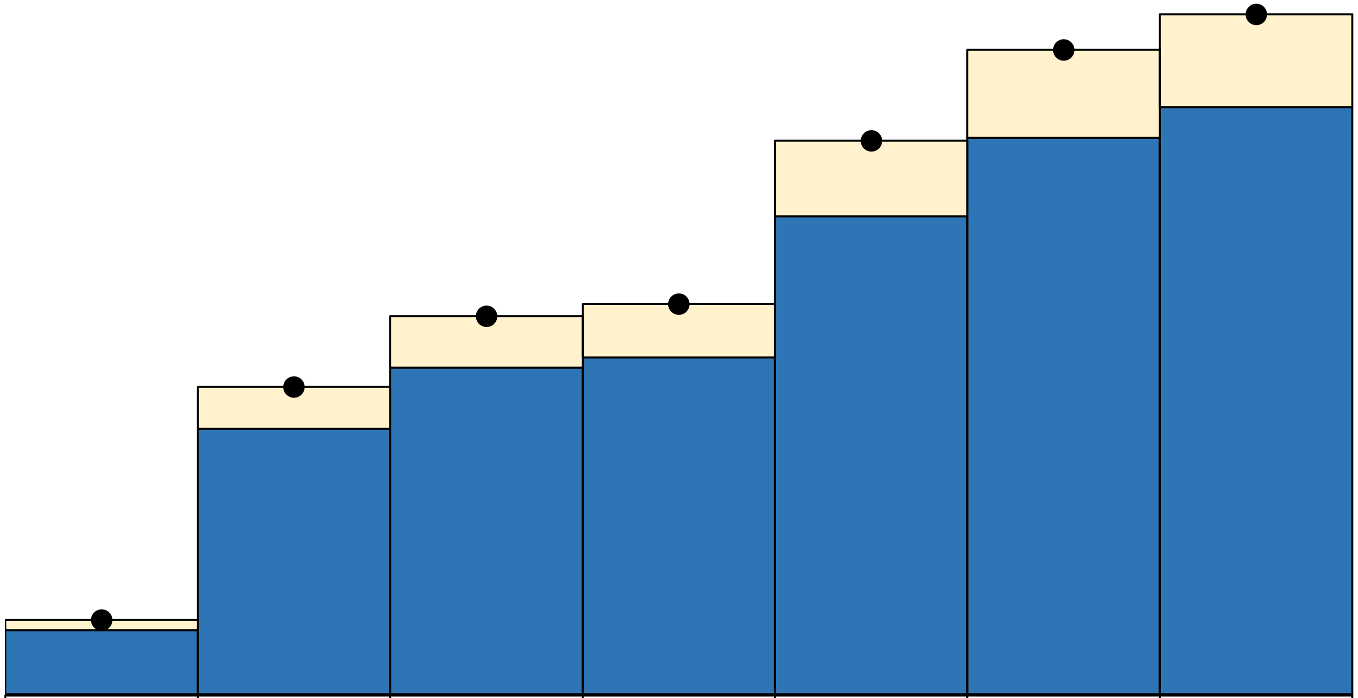


Figure 18: Cumulative Material Quantity for Zn, Sn, Ni, Pb and glass for solar power plants installed in Pakistan.



	2040	2041	2044	2045	2047	2049	2053
Total Frame Waste	514.36	2,111.08	2,596.80	2,679.35	3,799.40	4,423.24	4,666.09
Total Module Laminate Waste	3,260.00	13,380.11	16,458.59	16,981.82	24,080.70	28,034.64	29,573.80
Total Waste	3,774.36	15,491.19	19,055.39	19,661.17	27,880.10	32,457.88	34,239.89

(Values in m^3)

Figure 19: Quantification of total frame waste, total module laminate waste and total waste generated at end-of-life solar PV modules in Pakistan based on installed capacity.

5.2 Wind Turbines

The calculation for end-of-life wind turbine materials starts from the manufacturing of various components and relative weight percentages. The data for per MW for each material is taken from literature from 2 MW vestas wind turbine. The data was used to quantify the waste for Pakistan capacity addition. Values such as wind capacity and commissioning date were taken from NEPRA licenses for wind turbines. The quantity of blade materials is determined by the power rating that is a turbine with high power rating requires bigger blades and more material for blade manufacturing. The relationship between power rating and blade size is not directly proportional and both are dependent on each other.

Pakistan has total of 33 installed wind energy power plants with installed capacity of 1696.3 MW till 2022 while 2048 MW of new wind power plants will be installed by the end of 2025 according IGCEP 2047 plan of Pakistan and NEPRA planning. With average life of 25 years, the waste material will start to accumulate in 2040. End-of-life waste includes all the waste materials generated during life cycle such as during operations, transportation, and during maintenance. But to simplify the analysis and lack of data for these factors, maintenance and operation waste materials are not included in this analysis. Some other sources for waste generation are accidents, system upgradation, testing, defects, and manufacturing waste. According to the future projection a total of 463,109.49 tons of wind turbine end-of-life waste will be generated by the end of 2050 as shown in figure 19. 84.12% of this waste will comprise of steel and iron materials, 7.82 % of ceramic and glass, 4.28% of polymers, 1.72% of Al, 0.98% of electronics, 0.69% of Cu, 0.28% of lubricants and 0.11% sealants as shown in figure 21.

5.2.1 Recycling of Wind Turbines

Upon reaching end-of-life, the wind turbines are dismantled and decommissioned. The wind turbines are not repaired or recommissioned. The components and parts of wind turbines can be recycled, recovered, or end up in landfills. Unlike solar modules, it is easy to separate various components of wind turbines. 90% of wind turbine metallic components can be recycled while remaining 10% percent ends up in landfill. While polymer-based components can be processes via thermal treatments such as incineration. The turbines blades are made up of glass fibers and more than 50% of these materials along with polymers are incinerated. Materials such as fiber glass and polymers are not easy to handle due to extreme difficulties in recycling. Coolants and lubrications are treated and used for other sectors and industries. The recycling yield, landfill and incineration percentages for different components of wind turbines are presented in table 10.

Table 10: Recycling, landfill, and incineration percentages for wind turbine components.

Materials/Components	**Recycling %**	**Landfill %**	**Incinerated**
Al	90	10	-
Steel	90	10	-
Lubricants	50	-	50
Polymers	-	50	50
Other Materials	-	100	-

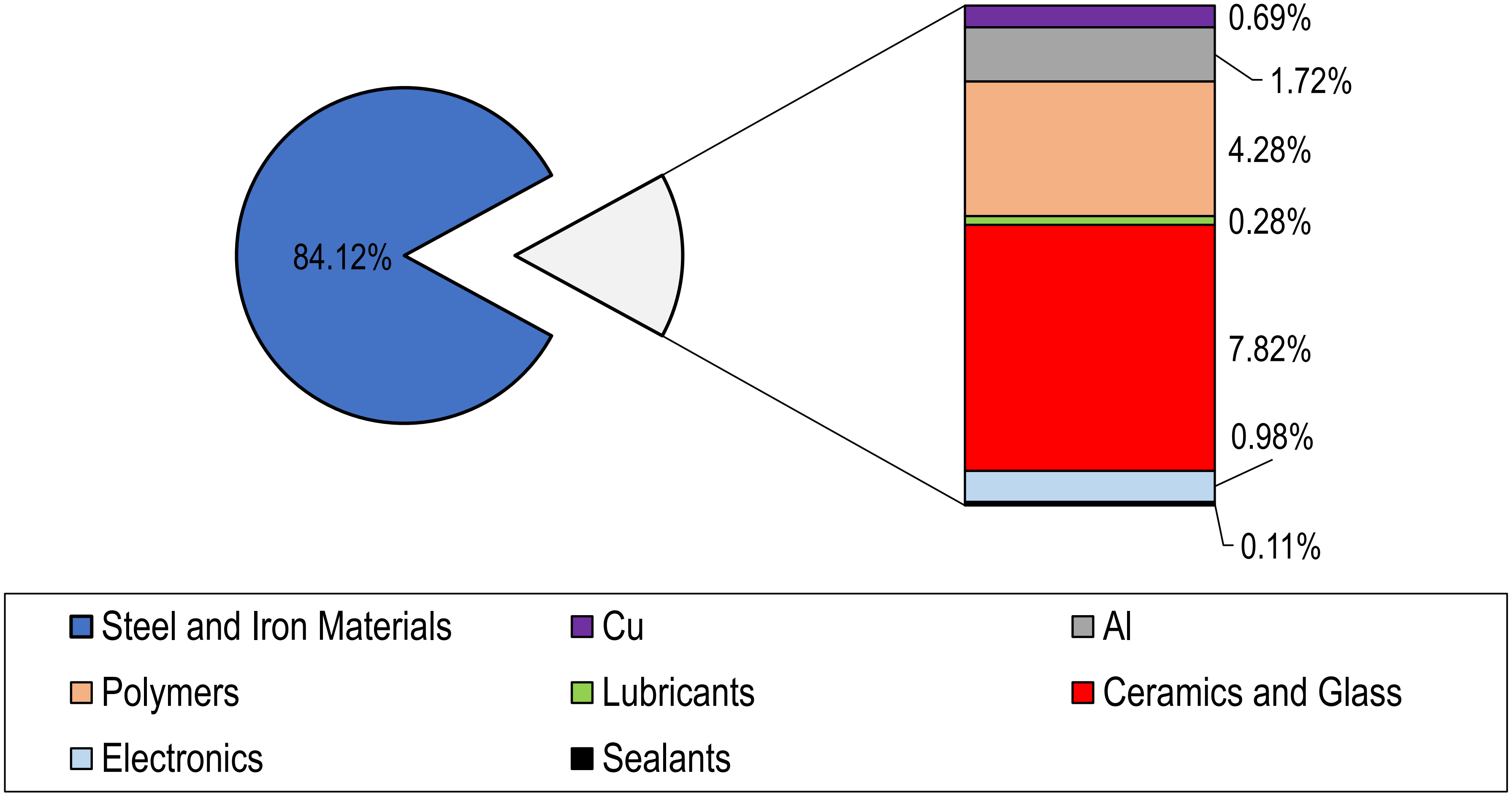


Figure 20: Percentage of different materials in cumulative waste generation till 2050

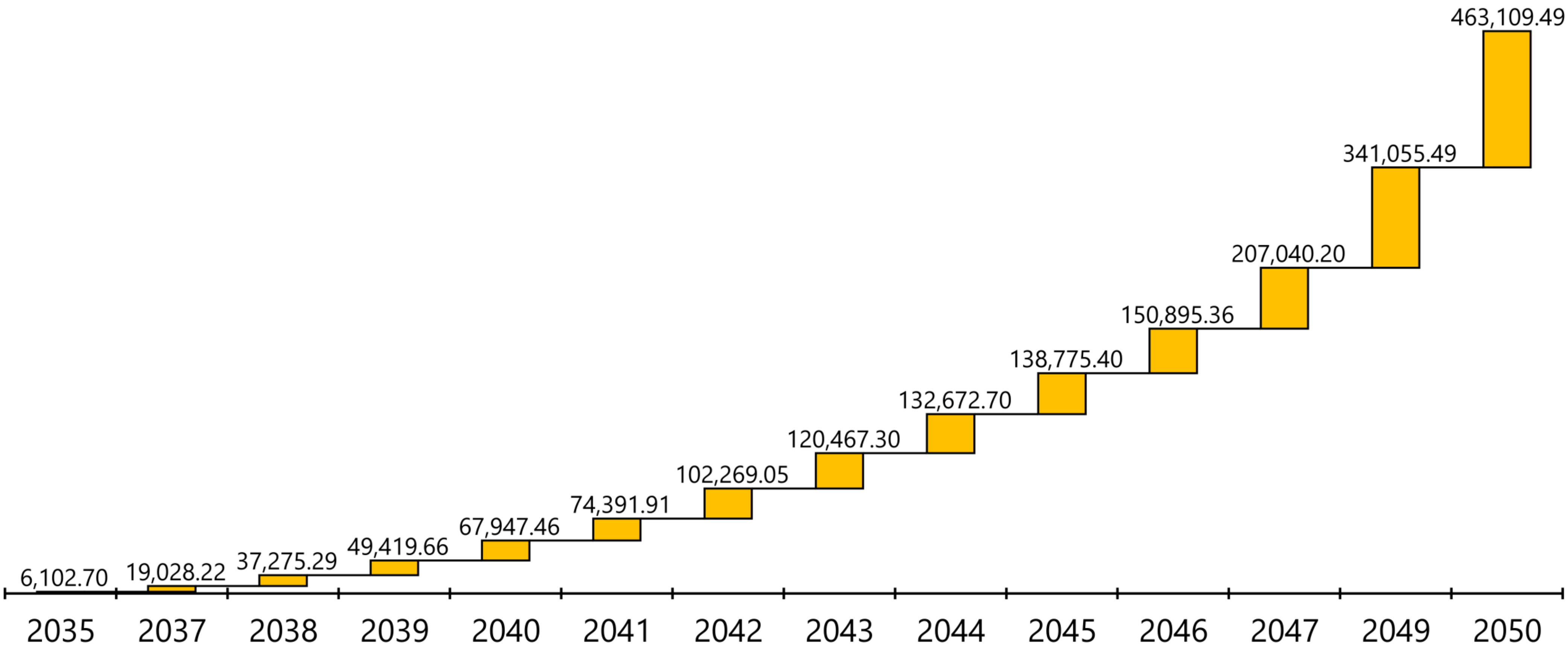


Figure 21: Cumulative end-of-life waste for wind turbines till 2050 according to the installed capacity in Pakistan.

Conclusion

Installation of large number of wind and solar energy power plants provide green and renewable energy. But like all products, the renewable energy comes with end-of-life waste materials. To mitigate the harmful effects of these waste materials, recovery, and recycling of useful materials are carried out. Valuable metals and other materials are recovered from solar PV modules and wind turbines. The thesis analyzes and projects the total amount of end-of-life waste materials generated for solar and wind energy based on Pakistan's capacity addition plan. The total installed capacity for solar and wind power plants stands at 782.5 MW and 1696.3 MW by the end of 2022. By 2028, 1183 MW and 2048 MW of solar and wind power capacity will be added respectively. Average life for solar panel and wind turbines is approximately 20 to 30 years. By the end of 2053, the total solar and wind energy waste of 34,239.89 m^3 and 463,000 tons will be generated respectively. The major quantities of solar PV module and wind turbine waste are for glass, steel, Al, iron materials, ceramic, and EVA. Waste management and disposal techniques for these materials are not easy to implement and are expensive. Currently, the most cost-effective solution for solar and wind waste is landfills. But landfill can leach the toxic materials into the underground water causing various water borne diseases. Thermal, mechanical, and chemical recycling techniques are used around the world for solar and wind waste. Pakistan needs to introduce suitable disposal policies and technologies for the generated waste to avoid any harmful implications.

Recommendations

- The analysis should be extended to total CO_2 emission, Pb concentrations and energy consumptions in various solar modules and wind energy.
- The analysis should be extended to quantify the renewable waste materials generated due to mid-life failures. Mid-life failures produce the equal amount of waste materials next to end-of-life.
- It is recommended for the stakeholders to pay a recycling fee for end-of-life materials for renewables that can ease the financial burden from the government.
- Waste management techniques such as landfills and incineration must be discouraged due to harmful environmental impacts.

- Government of Pakistan should implement waste regulation and environmental policies for waste treatment, recycling, and management. A comprehensive framework must be designed keeping in view the future renewable waste materials projections.
- More resources must be poured for the research and development of recycling techniques that are feasible for Pakistan.

References

[1] Ip. IPCC, “Summary for Policymakers” in Global warming of 1.5° C. An IPCC Special Report on the impacts of global warming of 1.5° C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.,” *The context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. World Meteorological Organization Geneva, Switzerland, p. 32, 2018.

[2] D. Gielen, F. Boshell, D. Saygin, M. D. Bazilian, N. Wagner, and R. Gorini, “The role of renewable energy in the global energy transformation,” *Energy Strategy Reviews*, vol. 24, pp. 38–50, 2019.

[3] J. A. Rosas-Flores, E. Zenón-Olvera, and D. M. Gálvez, “Potential energy saving in urban and rural households of Mexico with solar photovoltaic systems using geographical information system,” *Renewable and Sustainable Energy Reviews*, vol. 116, p. 109412, 2019.

[4] M. Bolinger, J. Seel, C. Warner, and D. Robson, “Utility-Scale Solar, 2021 Edition: Empirical Trends in Deployment, Technology, Cost, Performance, PPA Pricing, and Value in the United States [Slides],” Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States), 2021.

[5] M. S. Chowdhury *et al.*, “An overview of solar photovoltaic panels’ end-of-life material recycling,” *Energy Strategy Reviews*, vol. 27, p. 100431, 2020.

[6] “Global installed wind energy capacity 2021,” *Statista*. https://www.statista.com/statistics/268363/installed-wind-power-capacity-worldwide/ (accessed Aug. 02, 2022).

[7] D. Gielen *et al.*, “Global energy transformation: a roadmap to 2050,” 2019.

[8] K. R. Abbasi, M. Shahbaz, J. Zhang, M. Irfan, and R. Alvarado, “Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy,” *Renewable Energy*, vol. 187, pp. 390–402, 2022.

[9] G. A. Heath *et al.*, “Research and development priorities for silicon photovoltaic module recycling to support a circular economy,” *Nature Energy*, vol. 5, no. 7, pp. 502–510, 2020.

[10] P. Alves Dias, C. Pavel, B. Plazzotta, and S. Carrara, “Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system,” *Publications Office of the EU (europa. eu)*, 2020.

[11] Z. W. Zhong, B. Song, and P. E. Loh, “LCAs of a polycrystalline photovoltaic module and a wind turbine,” *Renewable Energy*, vol. 36, no. 8, pp. 2227–2237, 2011.

[12] resources.solarbusinesshub.com, “Global Market Outlook for Photovoltaics 2013-2017,” *Solar Business Hub | Resources*. https://resources.solarbusinesshub.com/solar-industry-reports/item/global-market-outlook-for-photovoltaics-2013-2017 (accessed Aug. 03, 2022).

[13] N. R. Wheeler *et al.*, “Degradation pathway models for photovoltaics module lifetime performance,” in *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)*, Jun. 2013, pp. 3185–3190. doi: 10.1109/PVSC.2013.6745130.

[14] A. Ndiaye, A. Charki, A. Kobi, C. M. F. Kébé, P. A. Ndiaye, and V. Sambou, “Degradations of silicon photovoltaic modules: A literature review,” *Solar Energy*, vol. 96, pp. 140–151, Oct. 2013, doi: 10.1016/j.solener.2013.07.005.

[15] T.-Y. Wang, “Recycling of solar cell materials at the end of life,” in *Advances in Solar Photovoltaic Power Plants*, Springer, 2016, pp. 287–317.

[16] K. Lo, “A critical review of China’s rapidly developing renewable energy and energy efficiency policies,” *Renewable and Sustainable Energy Reviews*, vol. 29, pp. 508–516, 2014.

[17] H. Ritchie, M. Roser, and P. Rosado, “Energy,” *Our World in Data*, Nov. 2020, Accessed: Aug. 02, 2022. [Online]. Available: https://ourworldindata.org/energy

[18] I. R. E. Association, “Future of Wind: Deployment, Investment, Technology, Grid Integration and Socio-Economic Aspects (A Global Energy Transformation paper). Abu Dhabi: International Renewable Energy Agency.” International Renewable Energy Agency Abu Dhabi, United Arab Emirates, 2019.

[19] P. Nain and A. Kumar, “A state-of-art review on end-of-life solar photovoltaics,” *Journal of Cleaner Production*, p. 130978, 2022.

[20] N. C. McDonald and J. M. Pearce, “Producer responsibility and recycling solar photovoltaic modules,” *Energy Policy*, vol. 38, no. 11, pp. 7041–7047, 2010.

[21] S. Sharma, K. K. Jain, and A. Sharma, “Solar cells: in research and applications—a review,” *Materials Sciences and Applications*, vol. 6, no. 12, p. 1145, 2015.

[22] V. Avrutin, N. Izyumskaya, and H. Morkoç, “Semiconductor solar cells: Recent progress in terrestrial applications,” *Superlattices and Microstructures*, vol. 49, no. 4, pp. 337–364, Apr. 2011, doi: 10.1016/j.spmi.2010.12.011.

[23] M. A. Green, “Third generation photovoltaics: solar cells for 2020 and beyond,” *Physica E: Low-dimensional Systems and Nanostructures*, vol. 14, no. 1–2, pp. 65–70, 2002.

[24] D. Sica, O. Malandrino, S. Supino, M. Testa, and M. C. Lucchetti, “Management of end-of-life photovoltaic panels as a step towards a circular economy,” *Renewable and Sustainable Energy Reviews*, vol. 82, pp. 2934–2945, 2018.

[25] Re. E. IRENA, “Accelerating the global energy transformation,” *International Renewable Energy Agency, Abu Dhabi*, 2017.

[26] M. M. Aman *et al.*, “A review of Safety, Health and Environmental (SHE) issues of solar energy system,” *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1190–1204, 2015.

[27] P. Nain and A. Kumar, “Identifying issues in assessing environmental implications of solar PVs-related waste,” *Recent Developments in Waste Management*, pp. 71–90, 2020.

[28] F. Cucchiella, I. D'Adamo, S. L. Koh, and P. Rosa, "Recycling of WEEEs: An economic assessment of present and future e-waste streams," *Renewable and sustainable energy reviews*, vol. 51, pp. 263–272, 2015.

[29] A. Zyoud *et al.*, "Recycled polycrystalline CdS film electrodes with enhanced photo-electrochemical characteristics," *Materials Science in Semiconductor Processing*, vol. 74, pp. 277–283, 2018.

[30] A. Wade, P. Sinha, K. Drozdiak, and E. Brutsch, "Beyond waste–the fate of end-of-life photovoltaic panels from large scale PV installations in the EU. The socio-economic benefits of high value recycling compared to re-use," in *Proceedings of the 33rd European Photovoltaic Solar Energy Conference and Exhibition*, 2017, pp. 1507–1514.

[31] H. K. Salim, R. A. Stewart, O. Sahin, and M. Dudley, "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review," *Journal of cleaner production*, vol. 211, pp. 537–554, 2019.

[32] H. Kim and H. Park, "PV waste management at the crossroads of circular economy and energy transition: the case of South Korea," *Sustainability*, vol. 10, no. 10, p. 3565, 2018.

[33] M. Masoumian and P. Kopacek, "End-of-life management of photovoltaic modules," *IFAC-PapersOnLine*, vol. 48, no. 24, pp. 162–167, 2015.

[34] P. Nain and A. Kumar, "Understanding the possibility of material release from end-of-life solar modules: A study based on literature review and survey analysis," *Renewable Energy*, vol. 160, pp. 903–918, 2020.

[35] M. Aghaei *et al.*, "Review of degradation and failure phenomena in photovoltaic modules," *Renewable and Sustainable Energy Reviews*, vol. 159, p. 112160, May 2022, doi: 10.1016/j.rser.2022.112160.

[36] S. Weckend, A. Wade, and G. A. Heath, "End of life management: solar photovoltaic panels," National Renewable Energy Lab.(NREL), Golden, CO (United States), 2016.

[37] N. Tazi, J. Kim, Y. Bouzidi, E. Chatelet, and G. Liu, "Waste and material flow analysis in the end-of-life wind energy system," *Resources, Conservation and Recycling*, vol. 145, pp. 199–207, 2019.

[38] W. Europe, "Wind energy in Europe: Outlook to 2020," *Wind Europe: Brussels, Belgium*, 2017.

[39] P. Enevoldsen, "A socio-technical framework for examining the consequences of deforestation: A case study of wind project development in Northern Europe," *Energy Policy*, vol. 115, pp. 138–147, Apr. 2018, doi: 10.1016/j.enpol.2018.01.007.

[40] M. Hoefer, "Wind Turbine Blade Recycling: An Economic Decision Framework." Researchgate, 2015.

[41] D. Fraile, A. Mbistrova, I. Pineda, P. Tardieu, and L. Miró, "Wind in power 2017: Annual combined onshore and offshore wind energy statistics," *WindEurope: Brussels, Belgium*, p. 25, 2018.

[42] U. E. P. Agency, “Guidance for 2006 assessment, listing and reporting requirements pursuant to sections 303 (d), 305 (b) and 314 of the Clean Water Act.” US Environmental Protection Agency Washington, DC, 2005.

[43] S. Gerbinet, S. Belboom, and A. Léonard, “Life Cycle Analysis (LCA) of photovoltaic panels: A review,” *Renewable and Sustainable Energy Reviews*, vol. 38, pp. 747–753, 2014.

[44] D. Saner, T. Walser, and C. O. Vadenbo, “End-of-life and waste management in life cycle assessment—Zurich, 6 December 2011,” *The International Journal of Life Cycle Assessment*, vol. 17, no. 4, pp. 504–510, 2012.

[45] *Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)*, vol. 312. 2008. Accessed: Aug. 02, 2022. [Online]. Available: http://data.europa.eu/eli/dir/2008/98/oj/eng

[46] N. Arora *et al.*, “Greening the Solar PV Value Chain,” *European Union—Resource Efficiency Initiative (EU-REI) Project: New Delhi, India*, 2018.

[47] “Sustainability, N.I.S.A.N.S.f., Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters. 2019.”.

[48] L. T. Peiró, D. Polverini, F. Ardente, and F. Mathieux, “Advances towards circular economy policies in the EU: The new Ecodesign regulation of enterprise servers,” *Resources, Conservation and Recycling*, vol. 154, p. 104426, 2020.

[49] “Lorenzo, F.R., Automatic inspection tool for 50% less scraped solar cells Eco-Solar Factory, 2018.”.

[50] J. A. Tsanakas *et al.*, “Towards a circular supply chain for PV modules: Review of today’s challenges in PV recycling, refurbishment and re-certification,” *Progress in Photovoltaics: Research and Applications*, vol. 28, no. 6, pp. 454–464, 2020.

[51] E. Bellini, “Italian PV panels sent for recycling were instead smuggled to Syria and Africa,” *Retrieved January*, vol. 6, p. 2022, 2020.

[52] S. Mahmoudi, N. Huda, Z. Alavi, M. T. Islam, and M. Behnia, “End-of-life photovoltaic modules: A systematic quantitative literature review,” *Resources, Conservation and Recycling*, vol. 146, pp. 1–16, 2019.

[53] K. Komoto *et al.*, “End-of-life management of photovoltaic panels: trends in PV module recycling technologies,” National Renewable Energy Lab.(NREL), Golden, CO (United States), 2018.

[54] S. Kusch and M. Alsheyab, “Waste electrical and electronic equipment (WEEE): a closer look at photovoltaic panels,” *Proceedings of the 17th international multidisciplinary scientific geoconference SGEM*, vol. 29, pp. 317–324, 2017.

[55] T. Dobra, D. Vollprecht, and R. Pomberger, “Thermal delamination of end-of-life crystalline silicon photovoltaic modules,” *Waste Management & Research*, vol. 40, no. 1, pp. 96–103, 2022.

[56] P. Baliozian *et al.*, “The international technology roadmap for photovoltaics and the significance of its decade-long projections,” in *Proceedings of the 37th European PV Solar Energy Conference and Exhibition*, 2020, vol. 7, p. 11.

[57] P. Sinha, G. Heath, A. Wade, and K. Komoto, “Human health risk assessment methods for PV, Part 3: Module disposal risks, International Energy Agency (IEA) PVPS Task 12, Report T12-16: 2020,” 2019.

[58] M. P. Tsang, G. W. Sonnemann, and D. M. Bassani, “Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies,” *Solar Energy Materials and Solar Cells*, vol. 156, pp. 37–48, Nov. 2016, doi: 10.1016/j.solmat.2016.04.024.

[59] J. Deubener, G. Helsch, A. Moiseev, and H. Bornhöft, “Glasses for solar energy conversion systems,” *Journal of the European Ceramic Society*, vol. 29, no. 7, pp. 1203–1210, 2009.

[60] J. Tao and S. Yu, “Review on feasible recycling pathways and technologies of solar photovoltaic modules,” *Solar Energy Materials and Solar Cells*, vol. 141, pp. 108–124, 2015.

[61] D. Oteng, J. Zuo, and E. Sharifi, “A scientometric review of trends in solar photovoltaic waste management research,” *Solar Energy*, vol. 224, pp. 545–562, 2021.

[62] P. Dias, S. Javimczik, M. Benevit, H. Veit, and A. M. Bernardes, “Recycling WEEE: Extraction and concentration of silver from waste crystalline silicon photovoltaic modules,” *Waste management*, vol. 57, pp. 220–225, 2016.

[63] Z. Zhang *et al.*, “Optimization of indium recovery from waste crystalline silicon heterojunction solar cells by acid leaching,” *Solar Energy Materials and Solar Cells*, vol. 230, p. 111218, 2021.

[64] B. Sharma, Y. Goswami, S. Sharma, and S. Shekhar, “Inherent roadmap of conversion of plastic waste into energy and its life cycle assessment: A frontrunner compendium,” *Renewable and Sustainable Energy Reviews*, vol. 146, p. 111070, 2021.

[65] P. Garrett and K. Ronde, “Life Cycle Assessment of Electricity Production from a V90-2.0 MW Gridstreamer Wind Plant,” *Vestas Wind Systems A/S*, 2011.

[66] Y. Xu, J. Li, Q. Tan, A. L. Peters, and C. Yang, “Global status of recycling waste solar panels: A review,” *Waste Management*, vol. 75, pp. 450–458, May 2018, doi: 10.1016/j.wasman.2018.01.036.

[67] L. Frisson *et al.*, “Recent Improvements in Industrial PV Module Recycling,” in *Sixteenth European Photovoltaic Solar Energy Conference*, Routledge, 2000.

[68] V. Fiandra, L. Sannino, C. Andreozzi, F. Corcelli, and G. Graditi, “Silicon photovoltaic modules at end-of-life: Removal of polymeric layers and separation of materials,” *Waste Management*, vol. 87, pp. 97–107, 2019.

[69] K. Komoto, S. Oyama, T. Sato, and H. Uchida, “Recycling of PV Modules and its Environmental Impacts,” in *2018 IEEE 7th World Conference on Photovoltaic Energy*

Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Jun. 2018, pp. 2590–2593. doi: 10.1109/PVSC.2018.8547691.

[70] "Yokohama Oils & Fats Industry, Development of an Advanced Recycling Treatment System for Photovoltaic Modules with Novel EVA Stripper, Fiscal year 2011-2012 NEDO contract report, 2012."

[71] S. Kang, S. Yoo, J. Lee, B. Boo, and H. Ryu, "Experimental investigations for recycling of silicon and glass from waste photovoltaic modules," *Renewable Energy*, vol. 47, pp. 152–159, 2012.

[72] W. Palitzsch and U. Loser, "Economic PV waste recycling solutions—results from R&D and practice," in *2012 38th IEEE Photovoltaic Specialists Conference*, 2012, pp. 000628–000631.

[73] T. M. Bruton, "Re-cycling of high value, high energy content components of silicon PV modules," in *Proc. of 12th EC-PVSEC*, 1994, pp. 303–304.

[74] T. Doi, I. Tsuda, H. Unagida, A. Murata, K. Sakuta, and K. Kurokawa, "Experimental study on PV module recycling with organic solvent method," *Solar energy materials and solar cells*, vol. 67, no. 1–4, pp. 397–403, 2001.

[75] G. Granata, F. Pagnanelli, E. Moscardini, T. Havlik, and L. Toro, "Recycling of photovoltaic panels by physical operations," *Solar Energy Materials and Solar Cells*, vol. 123, pp. 239–248, 2014.

[76] Y. Kim and J. Lee, "Dissolution of ethylene vinyl acetate in crystalline silicon PV modules using ultrasonic irradiation and organic solvent," *Solar energy materials and solar cells*, vol. 98, pp. 317–322, 2012.

[77] T.-Y. Wang, J.-C. Hsiao, and C.-H. Du, "Recycling of materials from silicon base solar cell module," in *2012 38th IEEE Photovoltaic Specialists Conference*, 2012, pp. 002355–002358.

[78] L. Krueger, "Overview of first solar's module collection and recycling program," in *EPIA 1st international conference on PV module recycling*, 2010, vol. 26.

[79] C. E. Latunussa, F. Ardente, G. A. Blengini, and L. Mancini, "Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels," *Solar energy materials and solar cells*, vol. 156, pp. 101–111, 2016.

[80] "Toho Kasei Co., Ltd., Development of high-performance recycling technology using wet-method for crystalline Si PV modules, FY2015 NEDO debriefing session, Oct. 2016."

[81] S. Mahmoudi, N. Huda, and M. Behnia, "Critical assessment of renewable energy waste generation in OECD countries: Decommissioned PV panels," *Resources, Conservation and Recycling*, vol. 164, p. 105145, 2021.

[82] A. Domínguez and R. Geyer, "Photovoltaic waste assessment in Mexico," *Resources, Conservation and Recycling*, vol. 127, pp. 29–41, 2017.

[83] “Access Electric (Private) Limited, Generation Licence No. SPGL/05/2014, Licence Application No. LAG-244, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[84] “Appolo Solar Development Pakistan Limited (ASDPL), Generation Licence No. SPGL/12/2015 Licence Application No. LAG-296, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[85] “Best Green Energy Pakistan Limited (BGEPL), Generation Licence No. SPGL/13/2015 Licence Application No. LAG-293, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[86] “Crest Energy Pakistan Limited (CEPL), Generation Licence No. SPGL/14/2015 Licence Application No. LAG-294, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[87] “Helios Power (Private) Limited (HPPL), Grant of Generation Licence No. SPGL/20/2017, Licence Application No. LAG-367, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[88] “HNDS Energy (Private) Limited (HEPL), Grant of Generation Licence No. SPGL/21/2017, Licence Application No. LAG-369, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[89] “Quaid-e-Azam Solar Power (Private) Limited, Generation Licence No. SPGL/04/2014 Licence Application No. LAG-252, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[90] “Safe Solar Power (Private) Limited (SSPPL). Licence No. SPGL/07/2014, Licence Application No. LAG-256, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[91] “Siachen Enemy Limited (SEL), Grant of Generation Licence No. SPGL/24/2017, Licence Application No. LAG-357, National Electric Power Regulatory Authority Islamic Republic of Pakistan .”

[92] “Zhenfa Pakistan New Energy Company (Private) Limited (ZPNECPL), Grant of Generation Licence No. SPGL/19/2O17, Licence Application No. LAG-358, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[93] “Zorlu Solar Pakistan (Private) Limited (ZSPPL) , Grant of Generation Licence No. SPGL/23/2017, Licence Application No. LAG-391, National Electric Power Regulatory Authority Islamic Republic of Pakistan.”

[94] S. Mahmoudi, N. Huda, and M. Behnia, “Photovoltaic waste assessment: Forecasting and screening of emerging waste in Australia,” *Resources, Conservation and Recycling*, vol. 146, pp. 192–205, 2019.

[95] N. Tazi, E. Châtelet, and Y. Bouzidi, “Using a hybrid cost-FMEA analysis for wind turbine reliability analysis,” *Energies*, vol. 10, no. 3, p. 276, 2017.

[96] P. Liu and C. Y. Barlow, “Wind turbine blade waste in 2050,” *Waste Management*, vol. 62, pp. 229–240, 2017.

[97] A. Paiano, “Photovoltaic waste assessment in Italy,” *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 99–112, 2015.

[98] S. F. Sibley, *Overview of flow studies for recycling metal commodities in the United States*. US Department of the Interior, US Geological Survey Reston, VA, USA, 2011.

[99] M. Goe and G. Gaustad, “Strengthening the case for recycling photovoltaics: An energy payback analysis,” *Applied Energy*, vol. 120, pp. 41–48, 2014.

[100] Y. K. Yi, H. S. Kim, T. Tran, S. K. Hong, and M. J. Kim, “Recovering valuable metals from recycled photovoltaic modules,” *Journal of the Air & Waste Management Association*, vol. 64, no. 7, pp. 797–807, 2014.

[101] K. Larsen, “End-of-life PV: then what?,” *Renewable energy focus*, vol. 10, no. 4, pp. 48–53, 2009.