Analysing the Waste Potential of Solar PV In India

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Abstract

With growing demand for energy and the shift towards renewable energy, countries like India are targeting energy mixture with alternate sources like solar, wind and water. With the current growth of solar energy use in India, it is predicted that high amounts of Solar Photovoltaic (PV) waste would be generated in the near future which left improperly managed would lead high amount of useful and expensive material ending up in landfills. This research focuses on the potential material generated from the growth of solar PV stock in India.

This research studied the growth of solar PV industry and the spread of Solar PV growth in India. The stock growth of solar PV till 2030 based on India's renewable energy goal of 280 GW solar energy is taken. Further study on End of Life (EOL) management of Solar PV was studied and the best practice scenarios from around the globe for handling Solar PV waste was studied. The circular economy approach for the Solar PV industry was also reviewed. 3 scenarios were created to determine how the waste from these Solar PV would be managed based on the current state in India, using best-case scenario from around the world and circular economy practices. These scenarios were simulated using dynamic material flow analysis to determine the waste inflow and outflow of material based on the defined scenario.

It was determined that more than 21 million tonnes of waste would end up in landfill by 2060 if India does not increase its recycling capabilities. Also, by adapting Germany's WEEE regulation for solar PV waste management, 2 other scenarios are created, which uses extended producer responsibility and would provide India with the capability to handle future Solar PV waste. A comparison of these 2 scenarios showed higher recovery of material in one (423 thousand tonnes) while generating 21 times more waste to landfill than the other (16 thousand tonnes).

It is found that the outflow of tonnes of material is same in all 3 of the scenarios and the highest amount of waste produced by the 280GW target of 2030 would be in 2055 at over 1.6 million tonnes. It is predicted that landfill can end by 2033 or 2044 in the defined scenarios but shows variation in the amount of recovered material would differ between them. Achieving the scenarios put forward would involve coordination between Government agencies, producers of solar PV and the actual users of PVs. A shift to a formal waste management sector would be required and a successful implementation of policies and targets would lead to improvement in multiple Sustainable Development Goals (SDG) for India.

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1. Introduction

The energy consumption growth in India is projected to be one of the fastest in all significant economies by 2040 and renewable power would come only second to coal power (Kumar & Majid, 2020). The demand for renewables in India shows to have a tremendous growth and currently India is one of the top five countries to use solar energy (Kumar & Majid, 2020). India is targeting over 280 GW of solar energy, which is 60% of the 500 Gigawatt (GW) of installed renewable energy capacity by 2030 (MNRE(1), 2021). 25GW of solar energy capacity increase every year is required for the next 10 years to achieve this long-term goal. India has to manoeuvre geopolitical issues and mining problems that can occur in their long-term solar energy goal as major minerals that are required in the solar industry are at a risk due to global supply chain demand (Gautum, et al., 2022). Billions of dollars are spent by the solar industry in India to import solar PVs and components. According to the Ministry of New and Renewable Energy Report (2021) in 2019-20, India imported solar power components worth $ 2.5 billion. For the installation of 25GW of solar capacity each year, the country does not have the domestic manufacturing capacity for which the government has been trying to increase up domestic manufacturing capacities through various steps including increasing taxes on imports (Kumar & Majid, 2020)

1.1. Research Area

1.1.1. Solar Energy in India

With India ranking 4th in installed capacity of renewable energy, the usage of non-fossil fuel energy has increased by 25% as of 2021 and renewable energy is at around 40% mix for energy production as of 2021 (MNRE(1), 2021). India is also cooperating with international institutions and has created the International Solar Alliance (MNRE India (2), 2021). The commitment of top leaders would be instrumental in shifting the world's attention toward renewable energy, especially solar energy. The COP-26 meeting in 2021in which India was part of has come up with a speaking statement toward massive use of solar power in the days ahead. This obviously would create a serious concern for creating a robust infrastructure for reduce, reuse, disposal of end-of-life (EOL) solar photovoltaic (PV). Ellen MacArthur Foundation brings circular economy (CE) to COP-26, they stated that "The transition to renewable energy is vital in order to tackle climate change, but it's only half the story. 45% of global greenhouse gas emissions come from the way we make and use products and food. That means we need to redesign our economy, eliminate waste and pollution, circulate products and materials, and regenerate nature, to reduce emissions and meet the targets set out in the Paris Agreement. We need a circular economy to complete the picture" (Ellen Macarthur Foundation (1), 2021).

1.1.2. Circular Economy

The recent development of circular economy had created organisations such as Ellen MacArthur Foundation and the Platform of Advancing Circular Economy (PACE). In essence, the circular economy is a rethink of the currently prevalent economic model. The current economy operates on a linear model, which adopts a "take-make-dispose" philosophy (Ellen Macarthur Foundation (2), 2013).

The emergence of circular economy started in the 1970s with applications to any resources it stared of as an idea to reduce consumptions of inputs into for industrial production (Stahel, 2016). Using the natural cycle model, CE proposes a change from a linear economy (LE) where resources are extracted, manufactured and disposed to landfills thus creating resilient human activities and are applied in large scale in an industrial environment (Ellen Macarthur Foundation (2), 2013). This concept has gained acceptance to address the issue of sustainability in public policies in governments all over the world with the countries in the European Union (EU) being a leader in achieving results (Arruda, et al., 2021).

Raw materials are extracted from sources of natural resources in the environment, manufactured into products with a finite lifespan, sold and consumed, then disposed as waste once their useful lifespan has been reached in a LE (Arruda, et al., 2021). The linear economy presents several issues which have become increasingly apparent. Firstly, the linear economy is unsustainable from a resource perspective (Sariatli, 2017). Raw materials used for the manufacturing of products is finite and is becoming increasingly scarce with current consumption patterns. Secondly, the generation of waste is in itself a major logistical dilemma (Sariatli, 2017). Significant effort and resources need to be invested to manage the flow of waste, which in the current linear economy paradigm, has no significant value. Thirdly, while waste in the linear economy embodies significant amount of material, the value of these embodied materials is not recognised, and this perpetuates the exploitation of limited natural resources over the resources embedded in waste (Sariatli, 2017)

The circular economy promises a solution to the problems of the linear economy. It starts by recognising the value of waste as a potential source of material, which can be exploited and extracted in a way similar to natural resources (Ellen Macarthur Foundation (2), 2013). This creates an alternative supply of materials, encouraging waste to flow back into the economy, closing resource loops and provides a means to manage waste besides disposal. This in turn satisfies some of the demand for material generated from production, reducing the pressures on scarce natural resources to provide the resources needed in the economy (Ellen Macarthur Foundation (2), 2013)

1.1.3. Material Flow Analysis

MFA has become a fast-growing field of research with increasing policy relevance. All studies are based on the common paradigm of industrial metabolism and use the methodological principle of mass balancing (Bartelmus & Seifert, 2018). MFA is defined as a systematic assessment of material stocks and flows within a defined space in a given period of time (Islam & Huda, 2019) while a Dynamic MFA can be used to assess past, present and future of the stocks and flows of materials (Muller, et al., 2014)

A major field of MFA represents the analysis of the metabolism of cities, regions and national or supranational economies. The accounting may be directed to selected substances and materials or to total material input, output and throughput (Bartelmus & Seifert, 2018).

As a central methodology of Industrial Ecology, a Material flow analysis (MFA) can provide the flows of resources into and from cradle-to-grave life of a solar PV which thus can be mapped and quantified, while a Dynamic MFA will provide a quantity of the in-use and future stocks of materials in solar PVs (Graedel, 2019) as India tries to achieve its 2030 solar power goals. By using an MFA, it would be beneficial to understand flow of materials used in the common solar PVs in India and by using Dynamic MFA it would be possible to determine the amount of material in stocks as India tries to achieve in Solar Energy targets.

Depending on the purpose of study and the availability of data, different modelling approaches, varying temporal scales, inclusion of different processes or the use different end-use operations have been used to create dynamic MFAs (Muller, et al., 2014). Since the first dynamic MFA studies published in 1999 about in the USA and aluminium in Germany, various methodologies have been used to dynamically model MFAs (Muller, et al., 2014). Complete life cycle of copper with a dynamic product residence time model was studies in in North America (Spatari, et al., 2005), estimated lifetimes have been used to model annual steel flow in the UK (Davis, et al., 2007) and a dynamic MFA of plastic flows in Europe was studied using different recycling rates scenarios to find the potential of circular economy (Eriksen, et al., 2020). Thus, by creating different scenarios based on strategies used by other Countries that are an expert in the field of handling EOL waste from solar PV and are shifting to a more circular economy, these scenarios can help determine the potential of waste from solar PV in India.

1.2. Research Questions and Objectives

With the growing amount of solar PV panels in India it is required to understand and predict the amount of EOL waste these would produce in the future so that India can make efforts to create a sustainable or even a circular economy to reduce negative environmental effects as well as create economic benefits from the valuable material present in these solar PVs. Various MFA studies for Solar PV waste have been done in various countries like Italy (Paiano, 2015), Mexico (Domínguez & Geyer, 2017), Australia (Mahmoudi, et al., 2019) and India (Gautam, et al., 2021). As the focus of this study is in India, the research by Gautum, et al (2021) is the most relevant. The study by Gautum, et al (2021) only shows the waste produced from Solar PV from 2020 to 2047 and the projected target for solar energy in India used in the study for 2030 has changed since it was done. The study by Gautum, et al (2022) uses the data from Gautum, et al (2021) to create a circular economy in the Solar PV sector in India but uses a static MFA with a fixed amount of waste generated from PV systems installed till 2030.

The research gaps this study attempts to fill is to find the yearly output of waste from Solar PV from 2000 to 2060 based on the current solar energy target setup by the Indian government for 2030 through a dynamic MFA which would allow to map the flow of material in the solar PV industry in India in the present and the future. The study, also attempts to show a transition to a circular economy by 2060 and show the tonnes of waste processed through different EOL methods in each year till 2060. By creating different future scenarios, it would also be possible to determine the amount of waste produced from solar PV each year, which can provide more insight into different approaches to reduce waste to landfill and transition towards a circular economy. The final goal of this study is to investigate how the different scenarios for managing EOL waste from these Solar PV can help create a better future for India and possibly determine the best approach India could adopt. Thus, the central question of this thesis is therefore:

What is the potential of waste generated from solar PV in India for India's 2030 Solar Energy Goal?

To answer the main research question, a detailed literature review is conducted about sustainable development in India, the solar industry in India, EOL waste management strategies used in other countries for solar PV systems and circular economy strategies for EOL solar PV systems. A literature review of Material Flow Analysis (MFA) is also conducted to understand the analysis tool and how it would contribute to finding the potential amount of waste solar PV systems in India would generate. Following the literature review and collection of data, scenarios are created to analyse the potential of material in EOL solar PV waste using different strategies used for management of EOL Solar PV systems which are reviewed in the literature. These scenarios are further analysed and a suitable scenario is used to define how India should proceed in the future in handling EOL solar PV waste.

Thus, a set of sub research questions are setup to answer the main research question:

1. **What is the current strategies India uses to implement solar energy?**
2. **How does the flow of raw material in the solar power industry in India look like from 2000 to 2060?**
3. **What could be the impacts of adopting the current best-case scenarios from other countries for better EOL solar waste management?**

The first sub-question gives details of how solar PV is implemented throughout India. This will also help us understand the growth of stock of solar PV installed through the years from 2000 to 2030. The second sub-question helps in understanding the flow of material in the solar PV industry in India from 2000 to 2060. The details of commonly used solar PV and the material content of these PVs in India would be found. This will also help understand the EOL activities India does for their solar PV waste. The final sub-question helps in understanding the worldwide practices of EOL solar PV waste which India can adapt to create a sustainable solar PV industry and what changes would have to done in India in order to adapt it. Thus, by finding the stock build-up of solar PV installation in India till 2030, understanding the flow of the material in the solar PV industry in India, and applying worldwide best practices of EOL solar PV waste to India's case, it would be possible to create different scenarios that can be simulated using dynamic material flow analysis to determine what the potential of waste generated by solar PV would be, thus answering the main research question.

2. Literature Review

2.1. Sustainable Development in India

The 17 SDGs and 169 targets are part of the 2030 Agenda for Sustainable Development, which was adopted by 193 member countries at the United Nations General Assembly Summit in September 2015 and took effect on January 1, 2016 (UN Dept of Economic and Social Affairs, 2016). These objectives are the result of an unprecedented consultative process that brought together national governments and millions of citizens from around the world to negotiate and adopt a global path to sustainable development for the next 15 years.

The task of coordinating the SDGs in India has been assigned to NITI Aayog, the Government of India's premier think tank (NITI Aayog (1), 2022). The NITI Aayog has mapped schemes in relation to the SDGs and their targets, and has identified lead and supporting ministries for each target. They have taken a government-wide approach to sustainable development, emphasizing the SDGs' interconnected nature across economic, social, and environmental pillars. States have been advised to map their schemes, including those funded by the federal government, in a similar manner.

Furthermore, the Ministry of Statistics and Programme Implementation (MoSPI) has been at the forefront of discussions to develop national indicators for the SDGs (NITI Aayog (2), 2017). State governments are critical to India's progress on the SDG Agenda, and several have already begun action to implement the SDGs.

According to the latest NITI Aayog's SDG India Index, which shows the country's progress in social, economic, and environmental development over the past year, India has made steady progress toward achieving the United Nations' Sustainable Development Goals (SDGs) in areas such as health, energy, and infrastructure (Bose & Khan, 2022). India's overall score across SDGs has increased from 60 to 66 at the start of 2021 due to national improvements in 'clean water and sanitation' and 'affordable and clean energy' (Sachs, et al., 2022) . India has the highest level of SDG reporting in 2019 among the Asian countries studied by Bose and Khan (2022). In 2022, India's ranking dropped to 60.3, which is even lower than the regional average (Bose & Khan, 2022). The Covid 19 pandemic caused India to perform poorly in dealing with quality education and life on land aspects. In 2021, India had failed to end hunger and achieve food security, achieve gender equality and build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation (Sachs, et al., 2022) . India’s SDG growth from 2019 to 2020 is shown in figure 1.

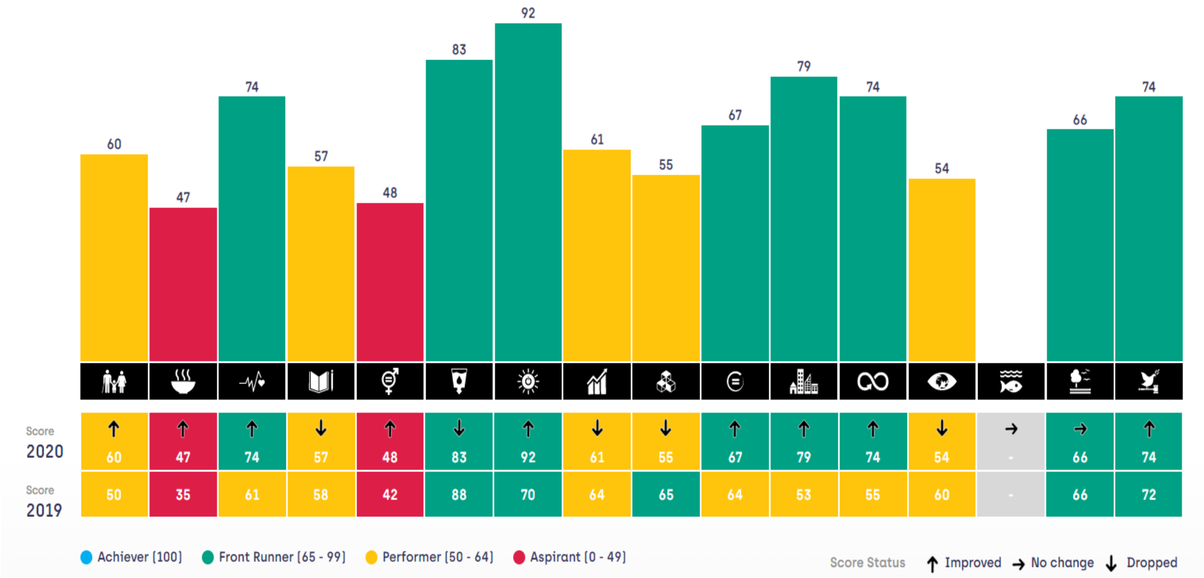

Figure 1: India SDG Goals improvement 2019 to 2020 (NITI Aayog (2), 2018)

India is the third highest emitter of carbon-dioxide and is responsible for 6.9% of global emissions (Dixon, 2018). However, the emissions intensity of India's GDP reduced by 12% between 2005 and 2010. In October 2015, India made a commitment to reduce the emissions intensity of its GDP by 20-25% from its 2005 levels by 2020 and by 33-35% by 2030 (Sachs, et al., 2022). The OECD (2021) predicts India's GDP will be close to $30 thousand by 2060 and the growth from 2000 is given in figure 2. On 2 October 2016 India formally ratified the historic Paris Agreement (NITI Aayog (1), 2022). The Government of India has also adopted a National Action Plan on Climate Change (Pandve, 2009) to address this issue directly, as well as a National Mission for Green India (Ministry of Env, Forest and Climate Change, 2022). These national schemes are complemented by a host of specific programmes on solar energy, enhanced energy efficiency, sustainable habitats, water, sustaining the Himalayan ecosystem, and to encourage strategic knowledge for climate change.

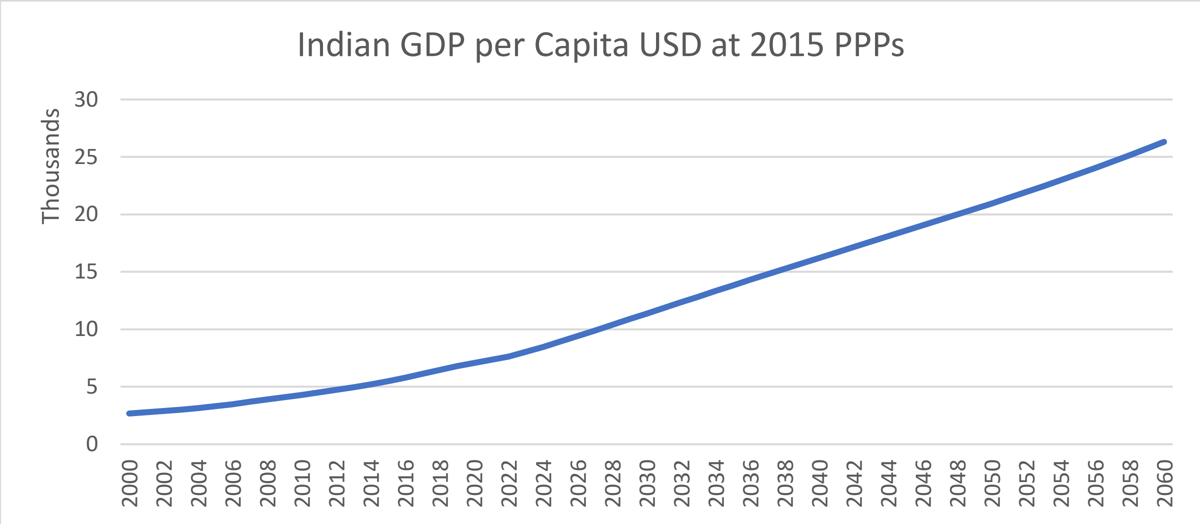

Figure 2: India's GDP per Capita till 2060 *(OECD, 2021)*

SDG Goal 12 Sustainable consumption and production aims at "doing more and better with less," increasing net welfare gains from economic activities by reducing resource use, degradation, and pollution, while increasing the quality of life (UN (1), 2022). Sustainable development will be achieved not only by growing our economies, but minimising waste in the process of doing so. With only 45 of the global with 18% of the population any contamination of environment and water sources can set development back for the Indian Economy. Only 19.9% of India's urban waste is processed (Dixon, 2018). For managing the efficient use of resources and to achieve sustainable consumption and production, The National Policy on Biofuels and the National Clean Energy Fund were also created by the government of India (NITI Aayog (2), 2018)

From all the SDGs goals India is trying to achieve, SDG Goal 12, Responsible Consumption and Production is directly related to the management of EOL Solar PV waste. The improvement of the indicator "Quantity of hazardous waste recycled to total hazardous waste generated" under SDG 12 would be the direct result of any improvement in EOL waste management of solar PV systems. No particular indicator has been defined for other different EOL waste management techniques (recycling, refurbishing or reusing) for valuable materials. Thus, using strategies to improve the EOL waste management of Solar PV waste can help lead India to achieve it's 2030 SDG Goal.

Most of the SDGs are interlinked, for example: responsible management of finite natural resources is required to transition to sustainable societies; and resilient cities can only be developed by addressing social, economic and environmental challenges (UN (2), 2018). Thus, this interlinkage would mean other SDGs would also be affected by improving SDG 12 and a proper trade-off between SDGs have to be made. Other SDGs including SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 9 (industry innovation and infrastructure), SDG 11 (sustainable cities and communities) and 13 (climate action) would be also affected if proper waste management actions are taken for handling Solar PV waste. All these SDGs are currently significant or major challenge for India and show very low SDG scores (NITI Aayog (2), 2018). An improvement in SDG 7 which ensures access to affordable, reliable, sustainable and modern energy (NITI Aayog (2), 2018) could be achieved as the share of renewable energy through solar power would grow. Also, the use of secondary material from recycling in Solar PVs could decrease costs. The creation of new jobs with better labour rights in waste management could be the direct result of proper waste management techniques being employed as well as creating a new economy growth in India where secondary materials are reclaimed from EOL solar PV thus improving SDG 8. The requirement for new recycling technologies and increasing recycling capacity which is part of SDG 9's aim for building of resilient infrastructure to promote sustainable industrialization as well as fostering innovation (NITI Aayog (2), 2018) would improve. Sustainable cities (SDG 11) can be created by properly managing the waste from Solar PV and even lead to reduce of per capita environmental impact of cities. Finally, to combat climate change (SDG 13), creating a sustainable industry would act as an urgent action to reduce greenhouse emissions and combat rising global temperatures.

2.2. Solar Photovoltaics

Solar photovoltaic (PV) deployment has grown at unprecedented rates since the early 2000s and it is anticipated that by early 2030s large volumes of annual waste due to decommissioned PV panels would be generated (IRENA, 2016). Growing PV panel waste presents a new environmental challenge, but also unprecedented opportunities to create value and pursue new economic avenues (IRENA, 2016). India would be one of the top 5 generators of Solar PV waste by 2050, and the tonnes of Solar PV waste generated by these top 5 countries are given in figure 3.

The world's energy consumption for a full year can be achieved with the amount of sunlight hitting earth in an hour and half using solar technologies that convert sunlight into electrical energy either through photovoltaic (PV) panels which can be then used to generate electricity or be stored in batteries or other energy storage devices (Hantula, 2010). Electromagnetic radiation or solar radiation emitted by the sun varies at every location on earth every year varies over the year and this radiation is capture by solar technologies (Hantula, 2010).

PV materials and devices convert sunlight into electrical energy. A single PV device is known as a cell which typically produce around 1 or 2 watts of power (Hantula, 2010). These cells are made of different semiconductor materials which are very thin and are mostly sandwiched between a combination of glass or plastic to protect it from weather hazards in the number of years it spends outdoors (Sarah, et al., 2020)

To meet large or small amounts of electric power requirements, PV cells are connected in chains to form PV panels and many of these panels are connected to form an array to meet the energy requirement (Hantula, 2010). Including the array, the solar PV system also include the mounting structures that point panels toward the sun, along with the components that convert Direct Current to Alternating Current (Hantula, 2010)

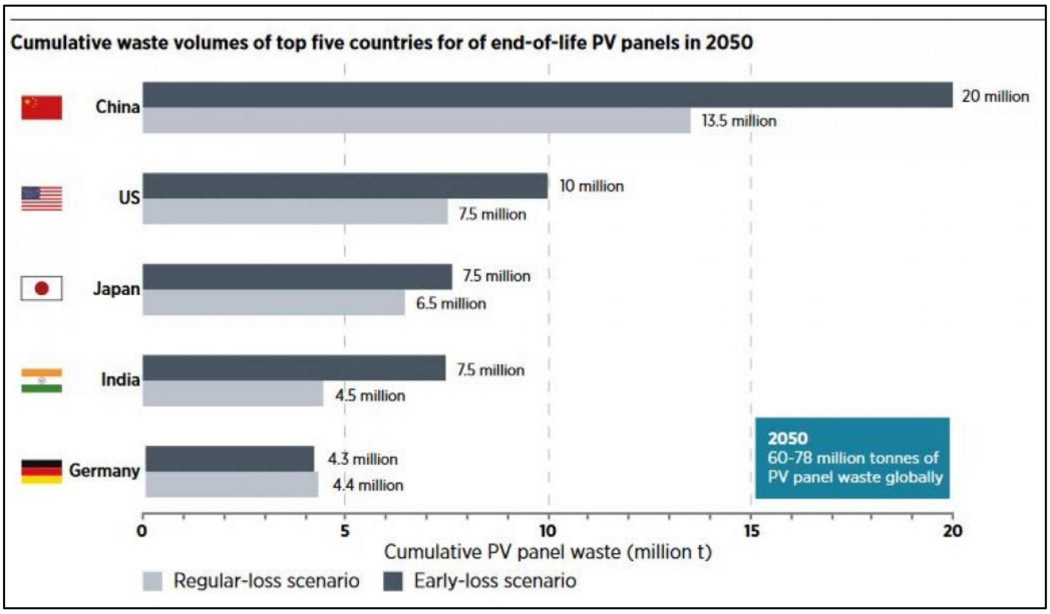

Figure 3: Cumulative waste volume of top five countries for end-of-life PV panels in 2050 (IRENA, 2016)

2.2.1. Solar Energy in India

As aforementioned, the growth of solar energy in India is expected to increase drastically. With low amounts of critical materials, like silicon, being mined and low scale manufacturing of solar components, India depends largely on imports which could create issues as the country tries to achieve its solar energy goals by 2030. It is critical to know the increasing stock of materials in solar PVs so that the India can efficiently manage its resources and decrease dependence on other countries.

In India, there is a huge gap between the energy generation and energy consumption. Around 5000 trillion kWh per year of solar power is estimated as available in India (MNRE(4), 2021).

India has a great potential for solar power and it is estimated so many times of the energy requirement which is about 5000 trillion kWh per year. MNRE (4) (2021) puts the amount of solar radiation incident over India is equal to 4–8 kWh per square meter per day with an annual radiation ranging from 1200–2300 kWh per square meter. The average intensity of solar radiation in India is shown in figure 4.

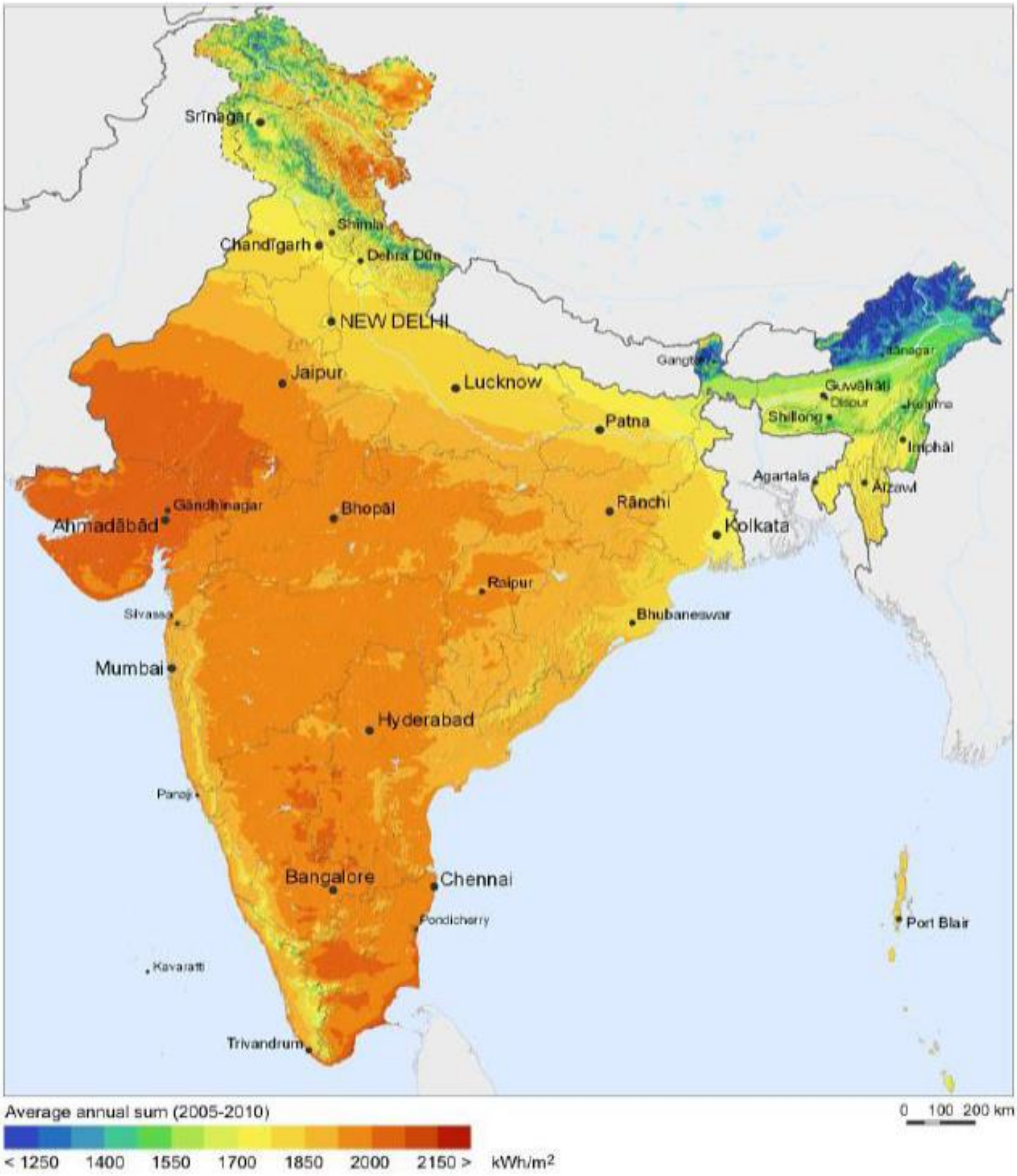

Figure 4: Average intensity of solar radiation in India from 2005 to 2010 *(Suman & Ahamed, 2018)*

The Government of India had set up the Commission for Additional Sources of Energy in the Department of Science and Technology which was later incorporated with the department of Non-Conventional Energy Sources in 1992 so that it can promote R&D in the photovoltaics sector (Raina & Sinha, 2019). Only a 29% of the total required installed capacity of solar energy was achieved in 2002 which led to policies being introduced as part of a 5-year plan from the year 2007-2012 targeting an addition in the installed capacity of 25 GW by 2012 (Raina & Sinha, 2019). A list of targets from 2010 to 2022 for solar energy expansion can be found in figure 5. With 19% of total installed renewable energy becoming solar was brought about by these policies (Raina & Sinha, 2019). With a solar PV target of 100 GW by 2022, the Indian Government also invested INR 30 Billion for 2016-2017 alone (MNRE(4), 2021). The Jawaharlal Nehru National Solar Mission was established by India as a global leader in solar energy which was created by the policy conditions for its large-scale diffusion across the country as quickly as possible (MNRE(4), 2021). India created a new target for 2030 where 500 GW of energy would be renewable where 280 GW of this energy would be from solar energy in 2021 after the COP26 meetings (Gautum, et al., 2022) . India has created plenty of policies to create a country which would have a high percentage of renewable energy in their energy mix.

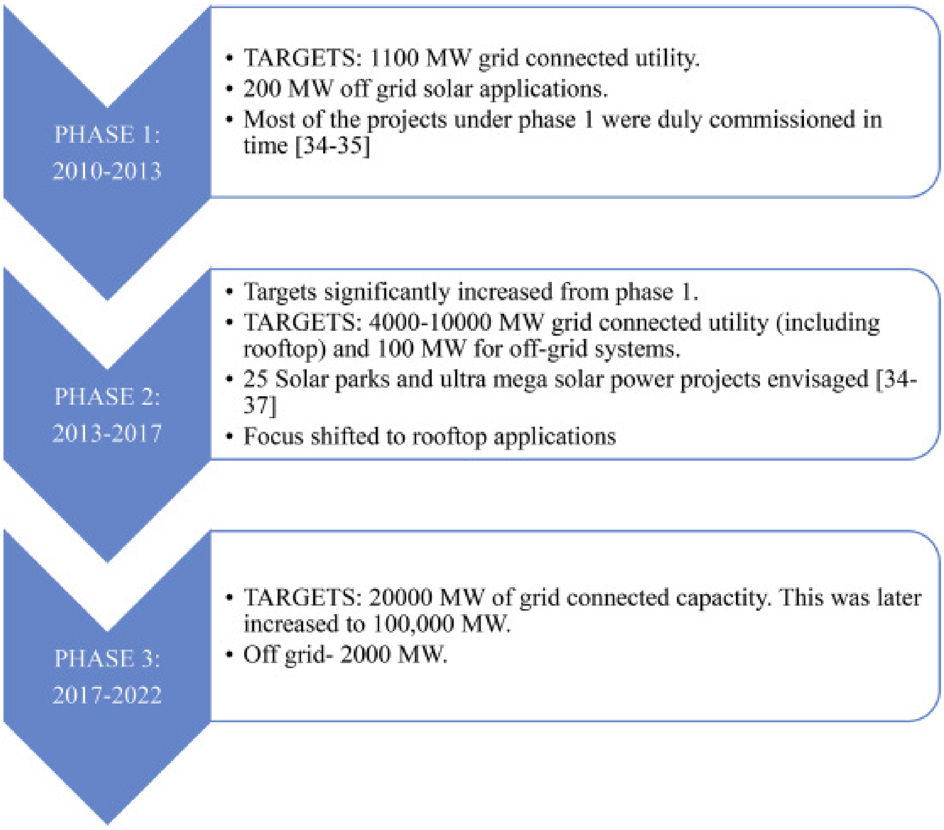

Figure 5: Targets set by India for Solar Energy expansion *(Raina & Sinha, 2019)*

The commonly used solar PVs in India are Monocrystalline and Polycrystalline solar panels (The Economic Times, 2019). Crystalline silicon (c-Si) solar panels contain materials such as Silicon, Silver, Nickel, Aluminium, Copper and Iron (Chakarvarty, 2018). Crystalline silicon provides the highest energy conversion efficiencies and are the most prevalent solar cells available in the commercial market with global market share of 93% and accounting for around 75GW of installed capacity in 2016 (Saga, 2010). Suresh et al. (2019) reported that 90% of Indian PV system installations were dominated by crystalline silicon (c-Si) modules, and the remaining 9–10% consisted of thin film solar modules. Among this 10%, copper-indium-gallium-selenide (CIGS) solar cell systems from an emerging technology have a share of only 1%, whereas cadmium telluride (CdTe) has a 6% share in the global market of utility scale PV installations. The common silicon-based PV and their difference is shown in figure 6 and table 1.

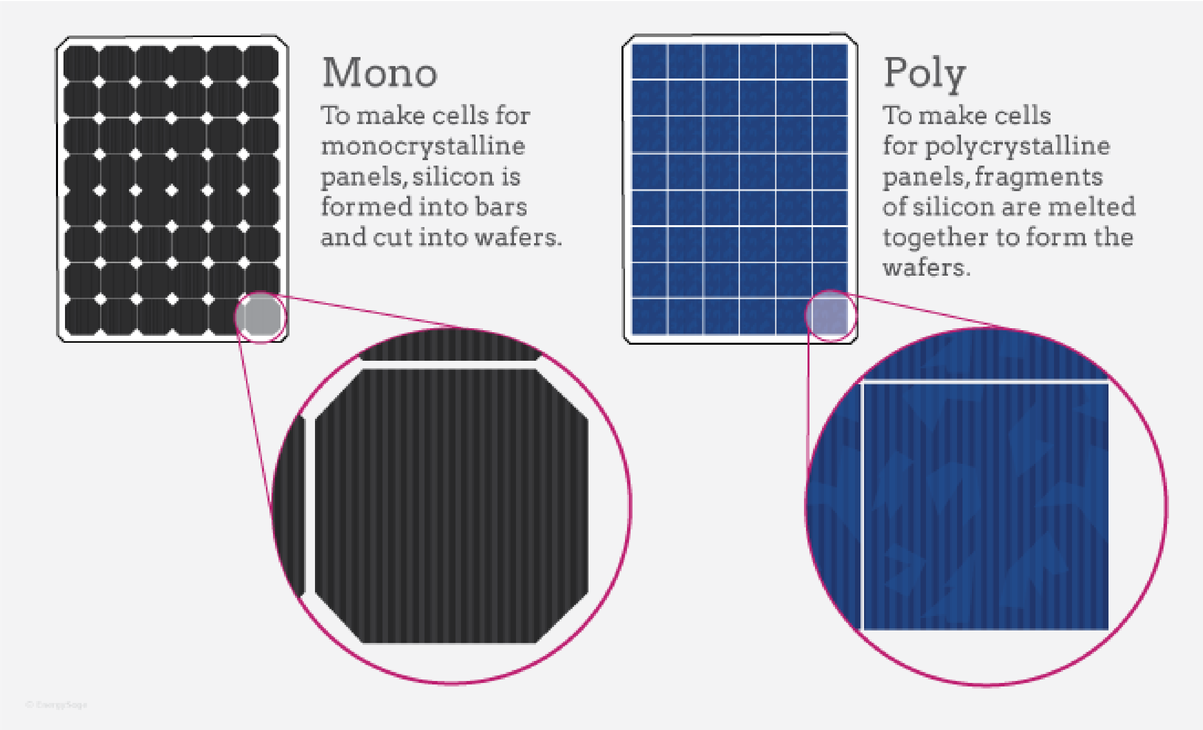

Figure 6: Mono Crystalline (left) and Poly Crystalline (right) *(American Solar Energy Society, 2021)*

	Monocrystalline Panels	**Polycrystalline Panels**
Cost	More Expensive	Less Expensive
Efficiency	More Efficient	Less Efficient
Aesthetics	Solar cells are black hue with round edges	Solar cells are blue-ish hue with no round edges
Lifespan	25+ years	25+ years

Table 1: Key metrics comparison of Monocrystalline and Polycrystalline Solar Panels adapted from American Solar Energy Society (2021)

With low amounts of silicon being generated by India, the country is highly dependent on imports to achieve its solar power targets. China is the main dominating player in global solar cell and module manufacturing and accounted for 97.4% of silicon PV wafers, 78.7% of cells, and 71.3% of modules manufactured globally (IEA, 2019). Around 80% to 90% of the total annual requirement of India's solar components is achieved by importing cells and modules from China (MNRE (3), 2021). Currently, India has about 3 GW of cell manufacturing capacity and approximately 8.2 GW of module manufacturing capacity (MNRE (3), 2021).

Figure 7: Typical rooftop Solar PV installations and BOS in India (Photo by Author taken in Kerala, India (25 July 2020))

The lifetime of Crystalline Silicone based technology used in Mono Crystalline and Polycrystalline technologies are assumed to have a life time of 25 to 30 years after which they are converted to waste (Rajput, et al., 2016). As a result, it is expected that large amounts of PV modules will be discarded in the near future leading to a huge number of materials that can be recovered from the waste streams. A typical crystalline silicon solar PV module contains approximately 75% of the total weight from the module surface (glass), 10% polymer, 8% aluminium of the frame, 5% silicon from the solar cells, 1% copper from interconnectors and less than 0.1% silver and other precious metals (Lunardi, et al., 2018). Due to the mix of valuable material and the commodity value as shown in table 2, it can be assumed the cost of 1GW of Solar PV panels would be really high and the recovery of these materials within them would be of economic value for India.

Material	Percentage	Commodity Value in Dollar (2022)
Au	0.010%	280368.8
Ag	0.009%	63955.15
Fe	12.210%	8538.8
Mg	0.820%	1906.71
Ni	0.001%	52.4
Pb	0.003%	68.86
Si	1.230%	4276.19
Sn	0.001%	197.45
Ta	0.001%	43.21
Al	69.280%	161566.1
Ti	0.001%	0.01
Zn	2.940%	8933.34
Cd	0.005%	57.9
Cu	13.320%	100303.6
Cr	0.001%	33.13
Ga	0.001%	2981.79
In	0.001%	2324.79
Mn	0.001%	0.01
Mo	0.001%	179.92
Se	0.001%	508.43
Te	0.002%	1985.23

Table 2: Material composition of 1GW Si based solar PV system and their commodity value as of 2022

2.3. EOL Solar waste Management

2.3.1. Worldwide Best Practices for EOL Solar Installations

Many countries around the world have implemented policies and goals for managing their EOL solar PV waste. These helps transition countries to better manage their resources and recover valuable material from EOL products. The leading country in handling EOL solar PV waste management is Germany which has a very mature market with high implementation of solar PVs while UK also follows the EU directives but has a young market for solar implementation (IRENA, 2016). Japan, China and US are also leading markets which would end up with high amounts solar PV waste just like India, but none of these countries have created solar specific EOL management efforts and these wastes end up with general electronic waste (IRENA, 2016).

New requirements collection and recycling in Germany came into place in October 2015 under the revised EU Waste from Electrical and Electronic Equipment (WEEE) which was revised into German Law under the Electrical and Electronic Equipment Act (ElektroG) (Chowdhury, et al., 2020). The agency Stiftung EAR was founded during the implementation of the WEEE directive with the purpose of regulating the National Register for Waste electrical equipment and provided with sovereign right by the German Federal Environmental Agency (IRENA, 2016). The Stiftung EAR registers and coordinates with e-waste producers, but also provides containers and pickup from the public (IRENA, 2016). The accountability of collecting, sorting, dismantling, recycling or disposing the e-waste separately from other e-waste falls under the producer of the products thus creating Extended Producer Responsibility (EPR) (OECD, 2001; IRENA (1), 2016). EPR acting as an environmental policy approach creates a situation in which the post-consumer stage of a product's life cycle falls under the physical and financial responsibility of the producer (OECD, 2001). A set amount of financial guarantee which has to be provided by the producer of the electronic equipment as shown in table 2 is setup under the WEEE directive but the guarantee calculation changes for B2C and B2B (IRENA, 2016). This guarantee makes owners of solar PV return their products for proper EOL management. A separate collection and treatment system for solar PV panels also creates a system where proper tracking of the materials from solar PV waste occurs. Germany is currently the only country to have good economy of scale for recycling EOL solar PV systems (IRENA, 2016)

Category	**Type of equipment**	**Presumed return rate**	**Presumed medium-life expectancy**	**Average maximum-life expectancy**	**Presumed disposal costs/ group**
Consumer equipment and PV panels	PV panels for use in private households	30%	20 years	40 years	EUR 200/t

Table 3: Factors for calculating guaranteed sum for PV panels under German EOL solar PV management policy *(IRENA, 2016)*

With a young market of solar implementation, UK follows the EU WEEE directive also and it came into effect in January 2014 (IRENA, 2016). The financing system differs from that of Germany but the effectiveness has not been seen due to the young market (IRENA, 2016). The details of the collected waste have to be registered in the UK, but the treatment of the waste can occur abroad as the economy of scale does not favour dedicated recycling facilities for solar PV alone (Vekony, 2021).

USA is another big economy which will end up with high amounts of solar PV waste. There is no federal regulation for the management of EOL solar PV waste but state level regulatory initiatives like in the US state of California has a project to administer and regulate the processing of wastes related to solar equipment promotes recycling in order to reduce the dumping of harmful substances into landfills (Suresh, et al., 2019). As is well known, China has become the world leader in the installation of PV panels, even in the absence of any policies for recycling and waste treatment but a five-year plan from 2016 to 2020 show that EPR would come into waste treatment regulatory framework (Xu, et al., 2018). Japan also has not regulatory framework for treatment of EOL solar PV and thus the waste ends up with general waste management, but the country is leading in research and development of recycling and dismantling solar PV modules (IRENA, 2016).

2.3.2. Indian Recycling status

India being one the largest markets for solar PV in the world by 2050 has no particular rules for proper management of EOL solar PV modules but have put forward guidelines for producers to follow WEEE waste management rules which still do not have mechanisms in place for the system to work (Rathore & Panwan, 2021). Only 4% of e-wastes were recycled in 2015 and 2017, but the collection goal was set for 20% in 2017 which would rise to 70% in 2023 (Suresh, et al., 2019). Only a capacity to handle 0.4 million tonnes per annum of e-waste was reported by the Indian government in 2020 (Rathore & Panwan, 2021). This puts India in a difficult situation with no infrastructure to handle the future EOL Solar PVs or even e-waste.

Out of all the e-waste that is collected in India, it is reported that 95% of these wastes are handles by a nonformal sector while the rest in only handled by formal sector registered companies (Kaushik & Herat, 2020). These non-formal sectors are all over India and generally employ rag pickers and unskilled labour (Suresh, et al., 2019). The unskilled labour is mostly exposed to hazardous chemicals and unsafe work environments which lead to many health problems among these workers while the inadequate nature of these operations lead to hazardous substances leaching into air, soil and water (Monika & Kishore, 2010). Monika & Kishore (2010) also report that only in the city of Delhi around 25000 workers including woman and children are employed to handle the 10,000 to 20,000 tonnes of e-waste. The non-formal sector focuses on recovery of gold, silver, aluminium and other valuable material with low efficiency while critical material like tantalum, indium, cadmium is not recovered (Kaushik & Herat, 2020). The low amounts of e-waste that is processed through the formal sector are only segregated, dismantled through shredders and the by-product slag treated while the processed waste is then send to developed countries for recovery of precious material (Suresh, et al., 2019).

In order to address the requirement of cost-effective environmentally-friendly technology for e-waste management the Department of Information Technology of India has been promoting R&D with the focus on recovery of valuable materials, minimum waste to landfill and zero emission to air, land and water (Suresh, et al., 2019). The Central Pollution Control Board reports the companies or organizations that are approved for EPR which shows around 2000 of them being authorized for e-waste management (CPCB, 2022). The awareness level of e-waste generated by the local population and the proper management of these e-wastes that was researched for India was shown to be high but it was also found a low level of awareness for the hazards improper treatment of these wastes can have on health and environment (Mor, et al., 2021).

The EOL e-waste management in India is dismal with low amount of waste being processed. There is no focus on EOL solar PV system management which is a treasure trove of material that India would waste with their ambitious goals for implementing solar energy. With the current e-waste capacity only 10% of the solar PV waste can be recycled as part of the mixed waste management (Suresh, et al., 2019).

2.3.3. Circular Economy in Solar Industry

A circular economy as discussed in section 1, focuses on an economy in which the value of material in EOL waste as potential source of secondary materials which can be used in a similar way to primary natural resources (Ellen Macarthur Foundation (2), 2013).

A CE is a systemic transformation of society, where waste and pollution are designed out, products and materials are kept in use in the economy and natural systems are regenerated (Arruda, et al., 2021). The two main objectives of CE are for economies to have to minimize resource extraction from the lithosphere and instead rely of regenerative forms of resource production and extraction while at the same time the economies have to minimize the dispersion and loss of materials, resulting in the preservation of material quality and recovery from existing stocks and preventing emissions into the environment (Arruda, et al., 2021). Figure 8 shows a typical CE by Ellen Macarthur Foundation.

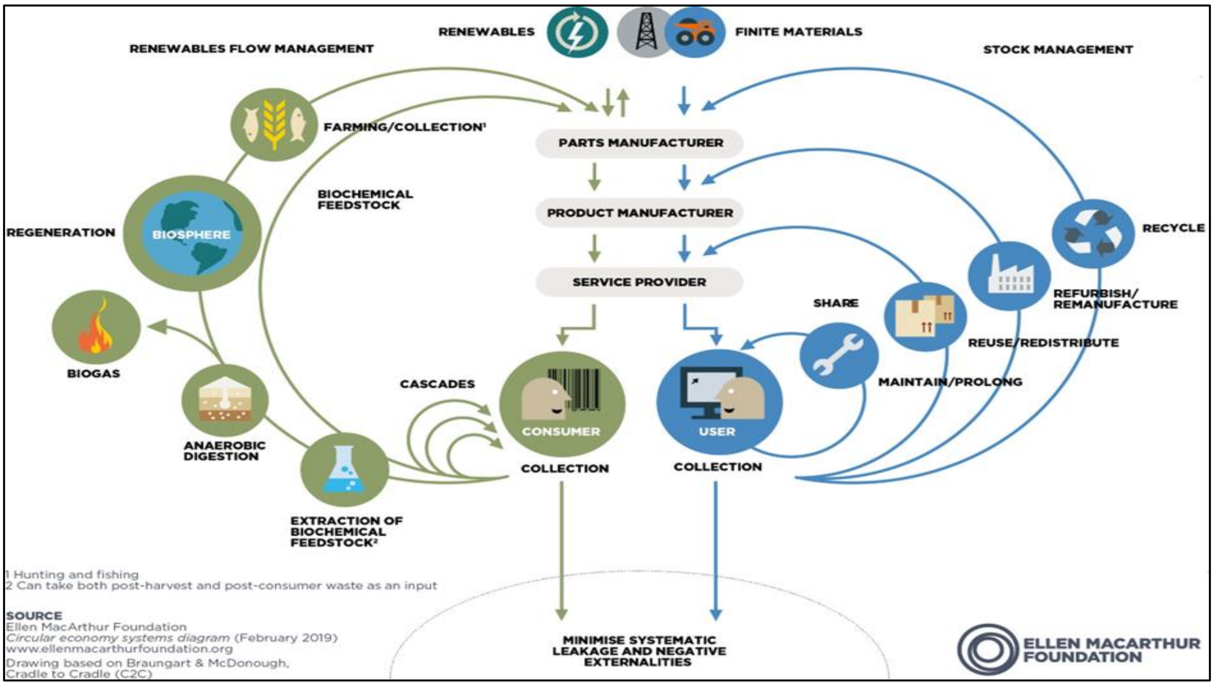

Figure 8: Circular Economy *(Ellen Macarthur Foundation (3), 2019)*

The framework of a circular economy (cradle-to-cradle opportunities) and the classic waste reduction principles of the 3Rs (reduce, reuse, and recycle) can also be applied to PV panels (IRENA, 2016). The use of the 9R framework, which includes refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover, for circular economy can be applied to solar PV also (Potting, et al., 2017). According to Gautum, et al. (2022), the preferred approach for EOL Solar PV waste in India is recycling, refurbishment and remanufacturing as part of the 9R framework. The most preferred option is the reduction of material in PV panels and thus an increase in high-efficiency technology and efficient mass production can be seen which is brough about by a strong market growth, scarcity of raw materials and downwards pressure on PV panel prices like that is seen in India (IRENA, 2016). The reuse option which can be done through refurbishment or remanufacturing is the next best option after reduce with recycling being the least preferred (excluding of landfilling) which only takes place after the first two options have been exhausted (Potting, et al., 2017).

Considerable material saving has been seen in the latest technology solar PV through resource and material efficiency but the mix of materials in a PV panel has not significantly changed in the past years (IRENA, 2016). Research shows hazardous materials like lead, cadmium and selenium are being researched while other researches focus on reducing the overall amount of material per panel to reduce cost (IRENA, 2016).

Early discovery of defects or damage can lead to refurbishment, repair or even replacement which has to be part to be taken care of by the producer or service partner as part of an EPR. Replacements can be provided with repaired Solar PV panels with a reduced market price of 70% of the original price while partly repaired products can be sold in second hand markets (IRENA, 2016). Large number of online solar websites like SecondSol.de and pvXchnage.com in Germany are expanding throughout the world and India could follow the band wagon to create websites similar to these. According to the Weibull statistics applied to the PV forecast by IRENA (2016), a proportion of installed panels may remain intact even after an average lifetime of 30 years in a regular loss scenario.

The processes of recycling mono or multi crystalline silicon solar PV are well developed (Lunardi, et al., 2018). Most economies in the world do not have sufficient quantity or solar PV waste or the economic incentive to create recycling plants dedicated to it (IRENA, 2016). Germany has proven to be the only country that has a good economy of scale for the recycling of solar PV due to their mature market (IRENA, 2016). EOL PV panels that are recycled with general e-waste are mostly mechanically separated with high recovery of material for the mass of the panel mass but valuable material in small amounts is not recovered. (Lunardi, et al., 2018). Construction of dedicated PV panel recycling plants would be required in the future which would recover valuable material and maximize revenue.

Aluminium and silver are among the most valuable components that can be retrieved to date, while an economically viable recycling procedure for glass has proven more difficult to establish as costs for collection and reprocessing are high (IRENA, 2016). The Indian government also reports it is creating an action plan for the electronics and electrical industry based on the EU Circular Economy Action Plan which would focus on reducing the pressure on natural resources (MeitY, 2021). Research by Gautum, et al. (2022) shows that the with proper expansion of small enterprises, informal sector and formal sector combined with proper legislation and control can be prepared to do recycling (25% Closed Loop), refurbishment (65%), remanufacture (10%).

2.4. Material Flow Analysis

This study uses an MFA tool for quantifying and analysing the stocks and flows of the Solar PV industry in India to determine the EOL waste of Solar PV. A model for an MFA system consists of processes and flows, and operates on the principle of the conservation of mass and energy (Bartelmus & Seifert, 2018).

For decision makers a comprehensive and systematic account can be provided by a MFA (Allesch & Brunner, 2015). Owing to the different conceptual backgrounds, a diversity of MFA concepts has been developed (Bartelmus & Seifert, 2018), (Bringezu & Moriguchi, 2002). The approaches differ in terms of (1) scale or size of the system evaluated (e.g., whole economy of a country, specific parts of an economy, regional areas, industrial sites, and private households), (2) materials investigated (goods and/or substances), and (3) databases used (e.g., material flows derived from national or international econometric statistics, physical substance flows measured by specific sampling, and analysis campaigns) (Allesch & Brunner, 2015). With the main principle of MFA being mass balance, the total input into a system has to be equal to the all outputs plus changes in stock.

A system defined by system boundaries in a particular time and space with material flows linking the processes are required to conduct an MFA (Allesch & Brunner, 2015). A process is defined as transformation, transport, or storage of one or more materials. Flows are the ratio of mass per time (e.g., tonnes per year), and are sometimes given as mass per time and cross-section (e.g., tonnes per capita and year) (Bartelmus & Seifert, 2018; Allesch & Brunner, 2015). The term material can be used for both substances and goods.

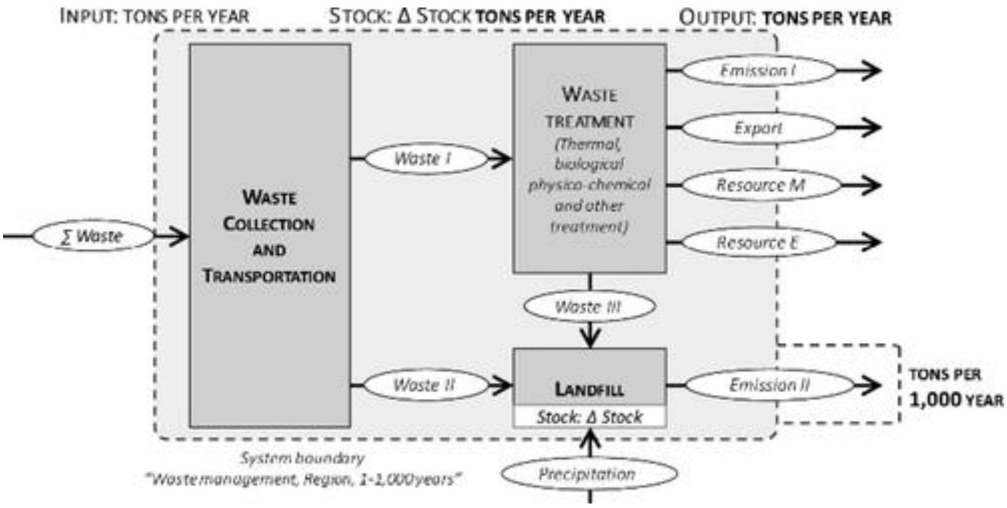

Figure 9: A typical MFA system with system boundaries, processes and flows *(Brunner & Rechberger, 2005)*

Within the field of MFA, a subdivision into investigations of goods and substances can be discerned according to Brunner & Rechberger (2005). At the level of goods is the analysis of stocks and flows like personal computer, waste from electrical and electronic equipment (WEEE), Solar PV systems, municipal waste. At the level of substances, the stock and flow of substance like minerals or molecules are measure. The last level of MFA investigation is the level of goods and substance which is a combination of stocks and flows of goods and the substances used in a particular system.

While a static MFA works great in providing insights into material demand or emission within a system, a dynamic MFA allows to explore the historical or future of material stocks and flows for a system (Muller, et al., 2014)

3. Research Methodology

This chapter discusses and analyses the waste generated from solar PV installation in India.

A literature review was conducted to determine and quantify the data on installed capacity of Solar PV in India. Further investigation provided details of the material content and the cost of materials in the Solar PV installation. Based on the Indian solar energy goal for 2030 for an installed capacity of 280 GW is taken as the capacity India would have in 2030. Further growth is out of scope for this research. The waste generated from this installed capacity in 2030 will exist till 2060 due to the maximum average lifespan of 30-year (IRENA, 2016) of Silicon solar PV systems, and this point would be used as the final year for up to which the waste generated from the Solar PV systems would be analysed.

After setting the system boundaries and collection of data, a program code in python is used to run a dynamic stock model for the installed capacity of solar power in India and the waste generated from the EOL waste from Solar PVs. 3 scenarios are created based on the literature studied in chapter 2. These scenarios help in understanding the potential of waste generated from EOL solar PV systems in India based on the application of different real world and theoretical strategies applied to waste management of EOL Solar PV systems.

3.1. System Boundaries and Units of Measurement

The system boundaries define the area in which the solar PV material flow analysis would be conducted. In this research, the country of India is taken as the geographical area where solar PV would be manufactured, installed and then scrapped.

The country of India is used as the geographical area for measuring the installed capacity of solar PV modules in Giga Watt (GW). The inflow, outflow and stock for material flow analysis will have the units in GW. The time period of measurement of the installed solar PV modules is taken from 2000 to 2030. The year 2030 is taken as the peak of India’s installed solar capacity based on India’s solar energy goals as discussed in the literature section. The waste generated from these installed solar PV modules is measure till the year 2060 due to the long lifespan of solar PV modules.

Silicon technologies are assumed to have a life time of 25-30 years after which they are converted to waste (Rajput, et al., 2016). Due to the maximum average lifespan of 30 years, a Weibull distribution curve with an alpha shape factor of 5.37 based on the regular loss scenario by IRENA (2016) is taken as the survival curve of the lifespan for the solar PV systems which would be installed in India till 2030. Two assumptions made for these analyses are that silicon PV technologies will continue to dominate the PV market in the future and the proportions and mass of raw material in the PV module system will remain constant with time.

To obtain the material content per GW of Solar PV system, the Si based PV system weight of 102678.5 tonnes/GW is taken. This is based on the research of Rajput et.al. (2016) analysis of material content of common solar PV systems used in India.

3.2. Dynamic Material Flow Analysis

MFAs in the level of waste generated from Goods i.e., the waste generated from weight (ton) of solar PV system installed per Giga Watt (GW) is investigated in this research.

A stock driven dynamic material flow analysis follows the equations shown below where t is the year.

$$inflow(t) = \frac{\boldsymbol{stock(t)} - \sum_{\tau=t_0}^{t-1} [\, inflow(\tau) \times f(t-\tau) \,]}{f(0)}$$

$$netflow(t) = \boldsymbol{stock(t)} - \boldsymbol{stock(t-1)}$$

$$outflow(t) = inflow(t) - netflow(t)$$

To conduct the dynamic material flow analysis of solar PV in India, it is necessary to acquire data of the installed solar PV capacity in GW till the year 2030 based on the system boundaries. The 2030 goal of 280 GW discussed in the system boundaries act as the final Cumulative GW installed. From the literature review it was possible to determine the capacity installed per year from 2000 to 2022. An equal annual incremental increase in capacity from 2022 to 2030 is taken to obtain expected installed capacity for these years. The cumulative GW installed from the year 2000 to 2030 is given in table 4. The cumulative GW installed act as the stock for the dynamic stock driven model for the material flow analysis. This data will act as the base data for use in the material flow analysis in the different scenarios that is discussed in the later section. No increase in installations from 280 GW in 2030 is considered in this analysis.

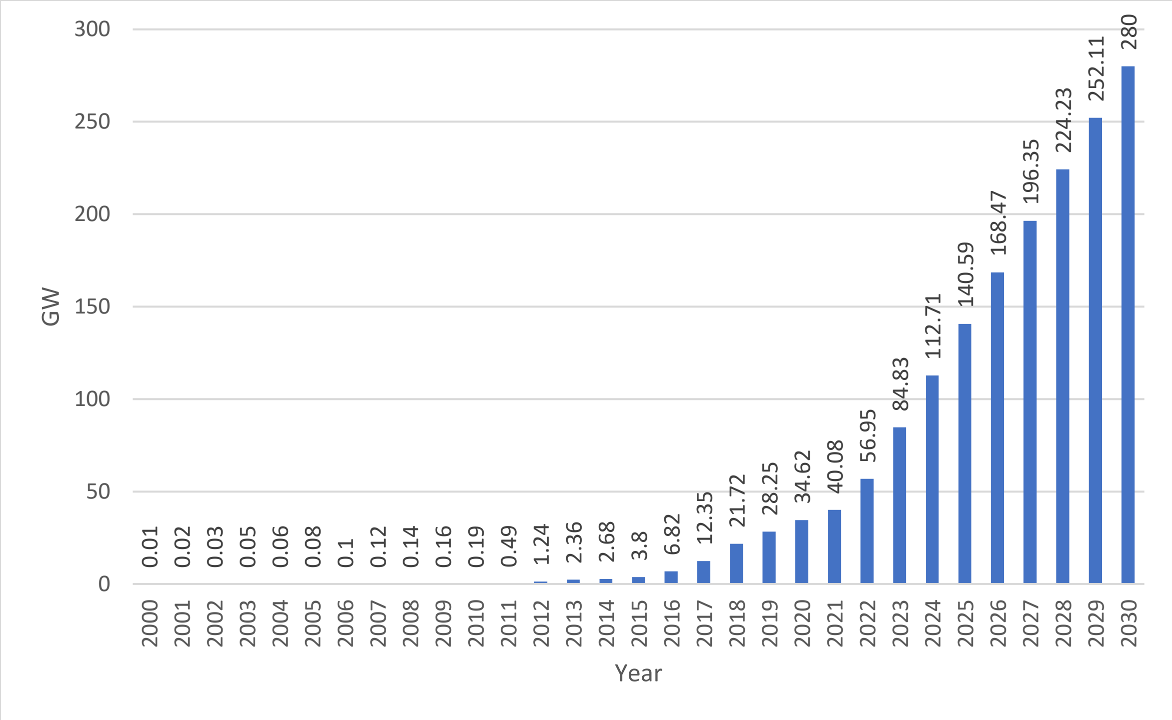

Figure 10: Cumulative GW of Solar PV in India from 2000 to 2030

3.2.1. Python Code and Microsoft Excel

The Dynamic stock model code created by J van Oorschot, T Fishman (2022) would be used to generated the dynamic stock driven model to obtain the inflow and outflow of the defined system. The full program code can be found in the appendix. A modification has been done to the code to obtain the amount of material that would end in landfill and to obtain recovered material each year.

The input data includes the stock build-up of GW of solar PV systems from 2000 to 2030 as shown in figure 10. This data is stored in an Excel file which is used by the python code. Also, the material recovery rate for each of the scenarios is also taken to find landfill and recovered material information.

Using the Weibull distribution curve defined earlier, the code provides the Inflow and Outflow of the material in GW and is exported to an excel file stock_flow_timeseries. The inflow and outflow for the stock of GW installed in India from 2000 to 2060 is shown in figure 10.

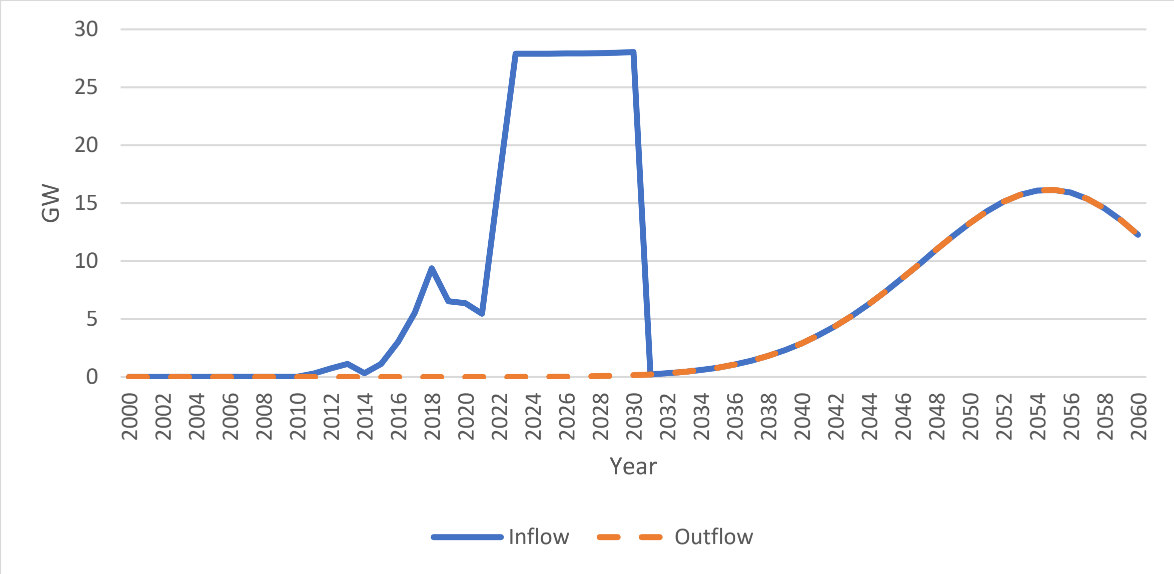

Figure 11: Inflow and Outflow for Stock of solar PV installed in India from 2000 to 2060

In this material flow analysis code, the Inflow of material in GW is the amount of primary and secondary material required to build the solar PV installation while the Outflow is the Solar PV which has reached its EOL. When the addition (Net addition to stock) of more GW of Solar Power to the stock is 0, which occurs after 2030, means that no additional capacity of solar PV is being added after 2030.

The python code then uses the recovery rate provided in input data to find the material recovered and landfilled depending on the scenario. Using this recovery rate, the percentage of recovered can be used on the Outflow data to find the amount of material ending in landfill and which is recovered. Multiplying the recovery rate with the outflow gives the recovered material while the remaining would end up in landfill.

Material Recovered = Outflow x Recovery Rate

Material Landfilled = Outflow – Material Recovered

The output of data generated by the python code is exported to Excel files for further analysis.

According to the scenarios defined in section 3.3., the Material Recovered is then split into different EOL activities according to the percentages. This helps to find the ton of waste in each of these activities. This is done in new Excel file (Tons of in EOL activity) using the output data generated by the python code.

3.3. Scenarios

With high amounts of potential materials available in waste generated from EOL solar PVs, India would have to take different strategies to recover these potential materials. By creating different scenarios based on strategies, it is possible to simulate the future of these materials and discover the best possible route for India to create a sustainable or even a circular economy in Solar PV industry.

In this research a difference between open and closed loop recycling is taken. In an open-loop recycling the material recycled would be used as raw material for any industry in India while a closed-loop recycling system focuses on using the recycled material in the Solar PV industry itself. Refurbishment means the restoration of the PV panels to bring it up to date and remanufacture means the use of parts from discarded Solar PV in a new Solar PV as per the 9R framework by Potting, et al. (2017).

3.3.1. Scenario 1

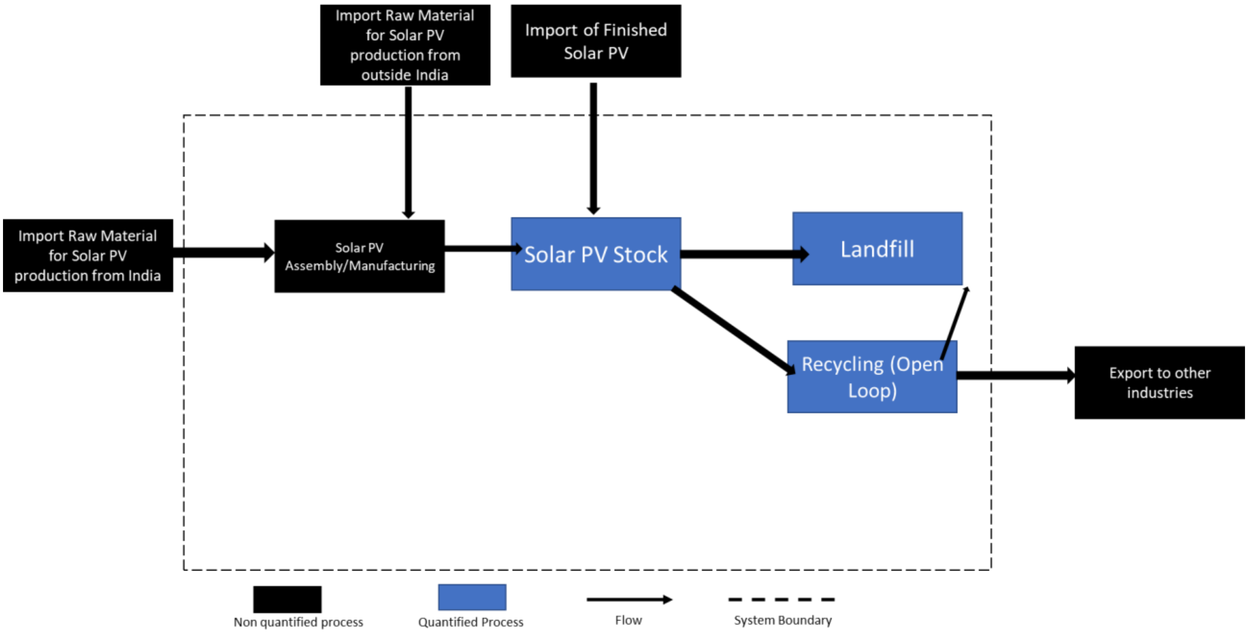

Figure 12: System boundary, flow and processes involved in Scenario 1

Scenario 1 or the Unsustainable scenario is the scenario in which India's focus is not related to end-of-life waste generated from solar PV installation. Recycling in closed loop, refurbish or remanufacture is not even considered by the Indian government. The informal sector continues to be the major dominator of waste recovery of material while formal sector or private companies are not the focus of the Government. The system boundaries, flow and processes involved in this scenario is shown in figure 12.

Around 90% of the waste generated from Solar PV installation ends in Landfill in 2020 according to Suresh et.al (2019). 10% Recycling in Open loop recycling of solar PV occurs in the formal and informal sector during 2020 mixed with other e-waste products (Suresh, et al., 2019). Furthermore, with India's goals not focusing on EOL e-waste, an assumption is taken that a 15% recycling rate in open loop of solar PV e-waste mixed with other e-waste would be expected by 2030 as no actual projection for the development of recycling in India is found. Also, no expected increase in recycling would be seen after 2030 and majority of the installed capacity by 2030 would end up in landfill.

The material recovery rate for each year in Scenario 1 is as shown in figure 13.

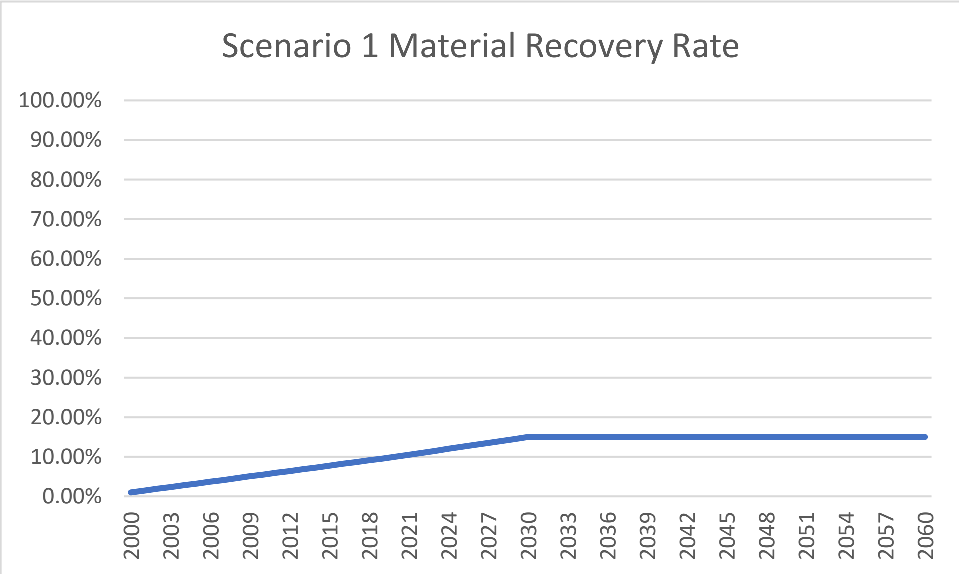

Figure 13: Percentage of material recovered in Scenario 1

3.3.2. Scenario 2

The World's Best-case scenario or scenario 2 follows the EU regulations for WEEE and Solar PV, in particular the regulations used in Germany is used to find the amount of material from waste generated from solar PV that can be recovered. The German/EU regulations are found in literature to be the current best scenario in any country for the recovery of EOL material from solar PV waste alone (IRENA, 2016). The application of the Germany's Extended Producer Responsibility model makes sure end of life solar PV are properly treated and the materials recovered are used as secondary material in manufacture of other products. Figure 14 shows the system boundary, flows and processes for scenario 2.

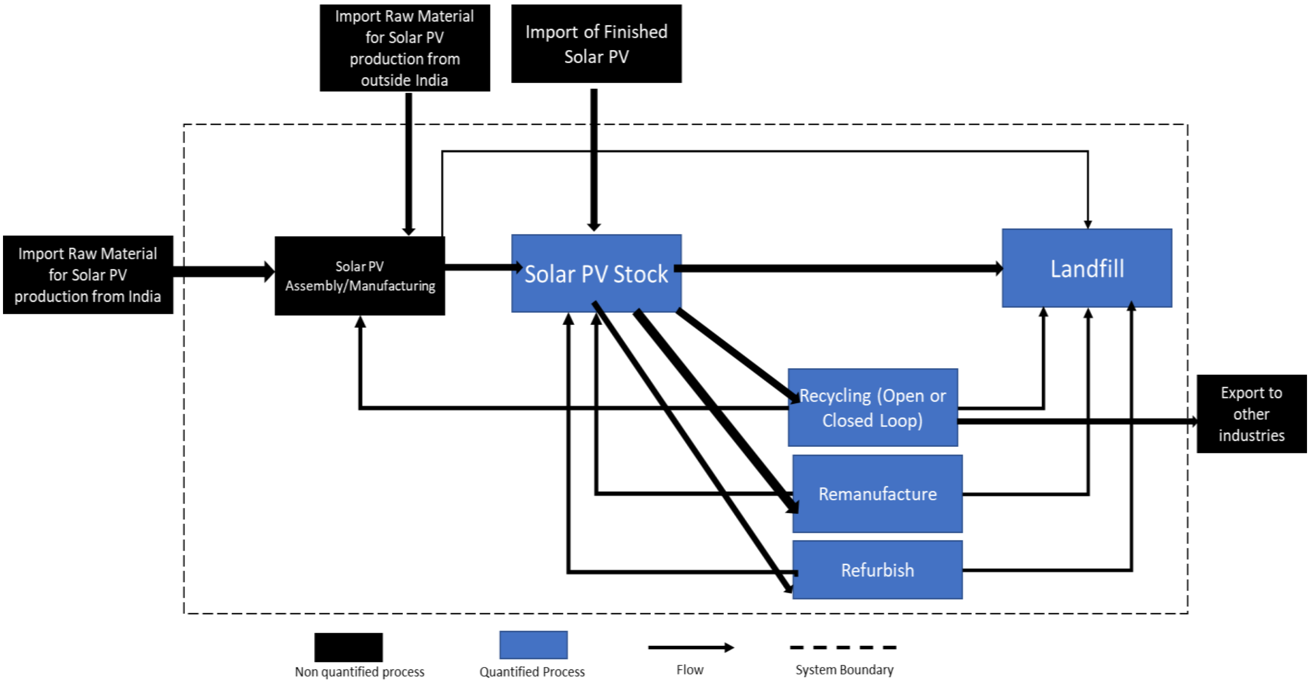

Figure 14: System boundary, flow and processes involved in Scenario 2 and 3

90% waste ends in Landfill with 10% Recycling in Open loop in the year 2020 which developed from 0% in 2000 based on literature researched similar to Scenario 1. An increase and shift to open loop recycling from 2020 to achieve a target of 85% recycling of solar PV by 2030 based on Germany regulations so that India can improve SDG goal 12 by 2030 is taken for this scenario. Following the target of 2030, a gradual percentage decrease in open loop recycling to achieve Recycling (25% Closed Loop), Refurbishment (65%), Remanufacture (10%) by 2060 based on the research by Gautam et.al (2022) and CEAP is considered for this scenario. Compared to Scenario 1, this scenario focuses on achieving a circular economy by including different EOL activities after 2030. Compared to the 15% recycling in 2030 for scenario 1, scenario 2 has 85% in 2030.

The material recovered per year for this scenario is given in figure 15.

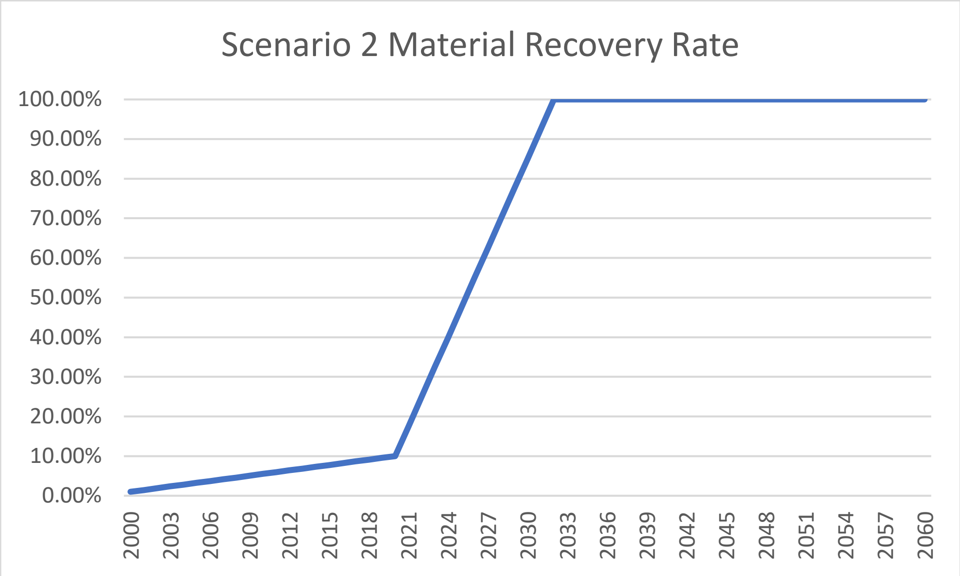

Figure 15: Percentage of material recovered in Scenario 2

3.3.3. Scenario 3

Scenario 3 or the Practical Scenario is build based on practical approach so that the Indian Government has a larger time scale compared to scenario 2 to develop its EOL solar PV waste management system. The 90% waste ends in Landfill with 10% Recycling in Open loop till 2020 based on historical data is used similar to scenario 1 and 2. An increase and shift to open loop recycling from 2020 to achieve a target of 85% recycling of solar PV by 2040 based on Germany regulations so that India can improve SDG goal 12 by 2040 is taken for this scenario. Following the target of 2040, a gradual percentage decrease in open loop recycling to achieve Recycling (25% Closed Loop), Refurbishment (65%), Remanufacture (10%) by 2060 based on the research by Gautam et.al (2022) and CEAP is considered for this scenario. Compared to scenario 1, scenario 3 focuses on circular economy in 2060 similar to scenario 2. The difference between scenario 2 and 3 is that, the target for 85% recycling is 10 years ahead in 2040 for the latter. Figure 14 shows the system boundary, flows and processes for scenario 3.

The rate of material recovery is shown in figure 16.

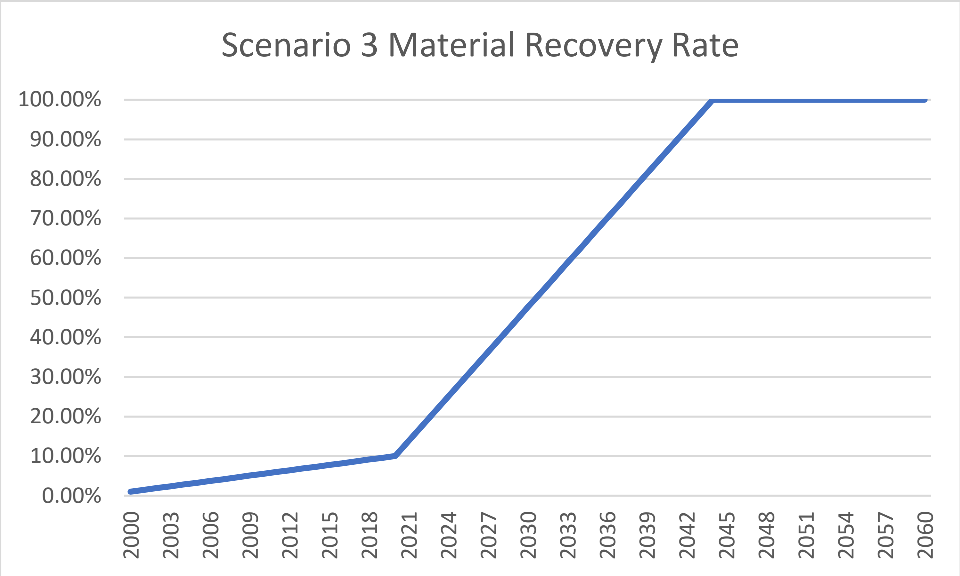

Figure 16: Percentage of material recovered in Scenario 3

4. Results

Based on what is discussed in different Scenarios for India's material flow in the Solar PV industry, the data collected for the stock of solar PV installations in India till 2030 and the assumed material recovery rates for end-of-life solar PV is used to run the python code for Dynamic stock driven model. The results obtained includes the inflow and outflow of the material from EOL solar PV and the material recovered or landfilled.

Based on the inflow and outflow data generated for the 280GW goal of 2030, it is seen that the highest amount of material is Aluminium, Iron and Copper as shown in figure 17. Figure 17 is created using the direct inflow and outflow outputted by running the python program code. The inflow and outflow of material after 2030 is the same for all 3 scenarios due to the fact that no new solar PV is being installed. It has to be noted that after 2030 there are no new Solar PVs being installed thus a steep downward trend is seen. The program code assumes that the recovery of material after 2030 is used as secondary material for production, which is why the inflow and outflow after 2030 is the same even though no new solar PV is installed.

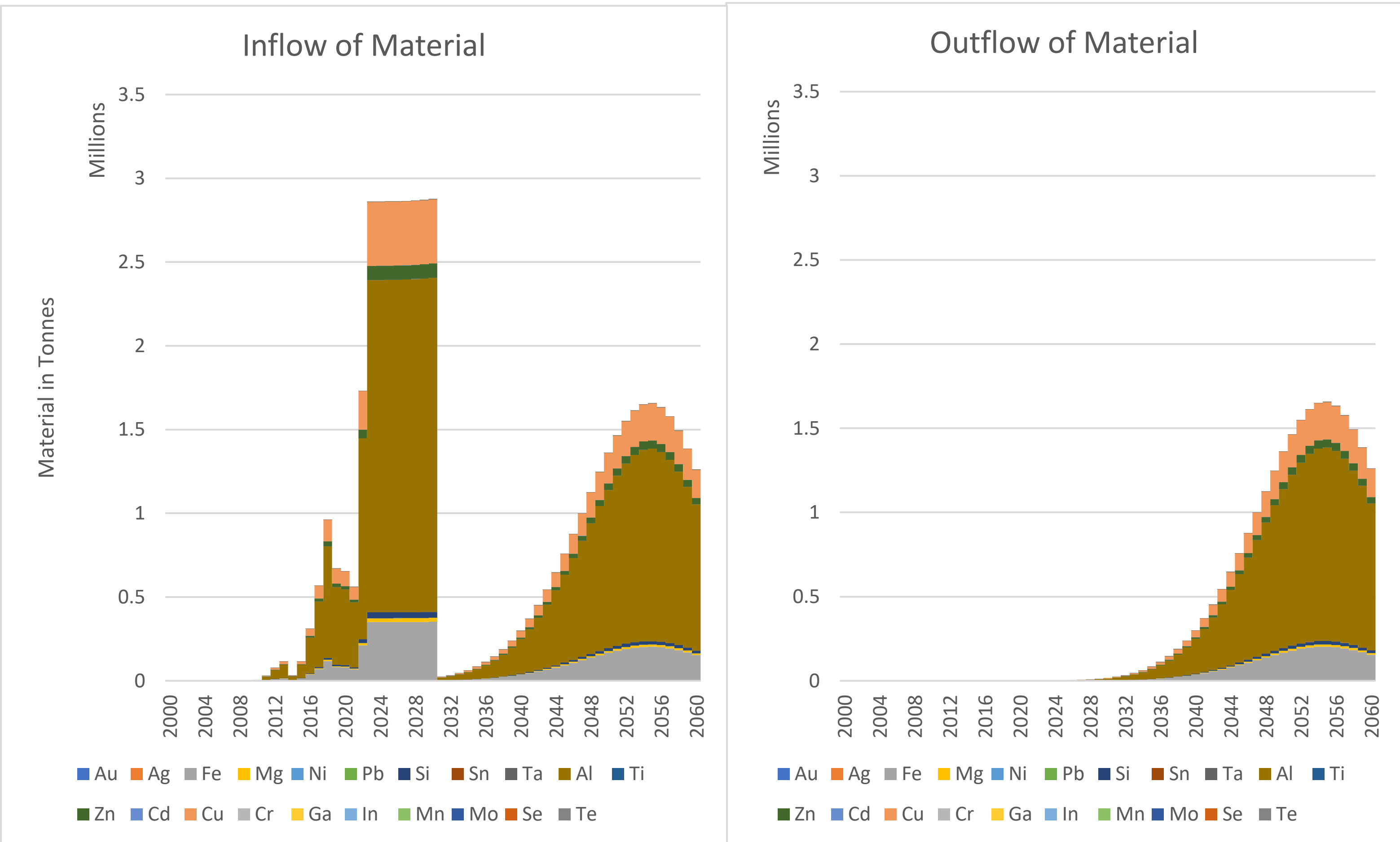

Figure 17: Inflow(left) and Outflow (right) of different materials for 280GW 2030 Goal

4.1. Scenario 1

The outflow of material for Scenario 1 is as shown in figure 18. It is seen that high volumes of the waste from EOL solar PV systems end up in landfill while a small percentage of only 2 million tonnes of solar PV systems would be recycled by in 2055 which is the highest amount recycled any year from 2000 to 2060 as seen in figure 18.

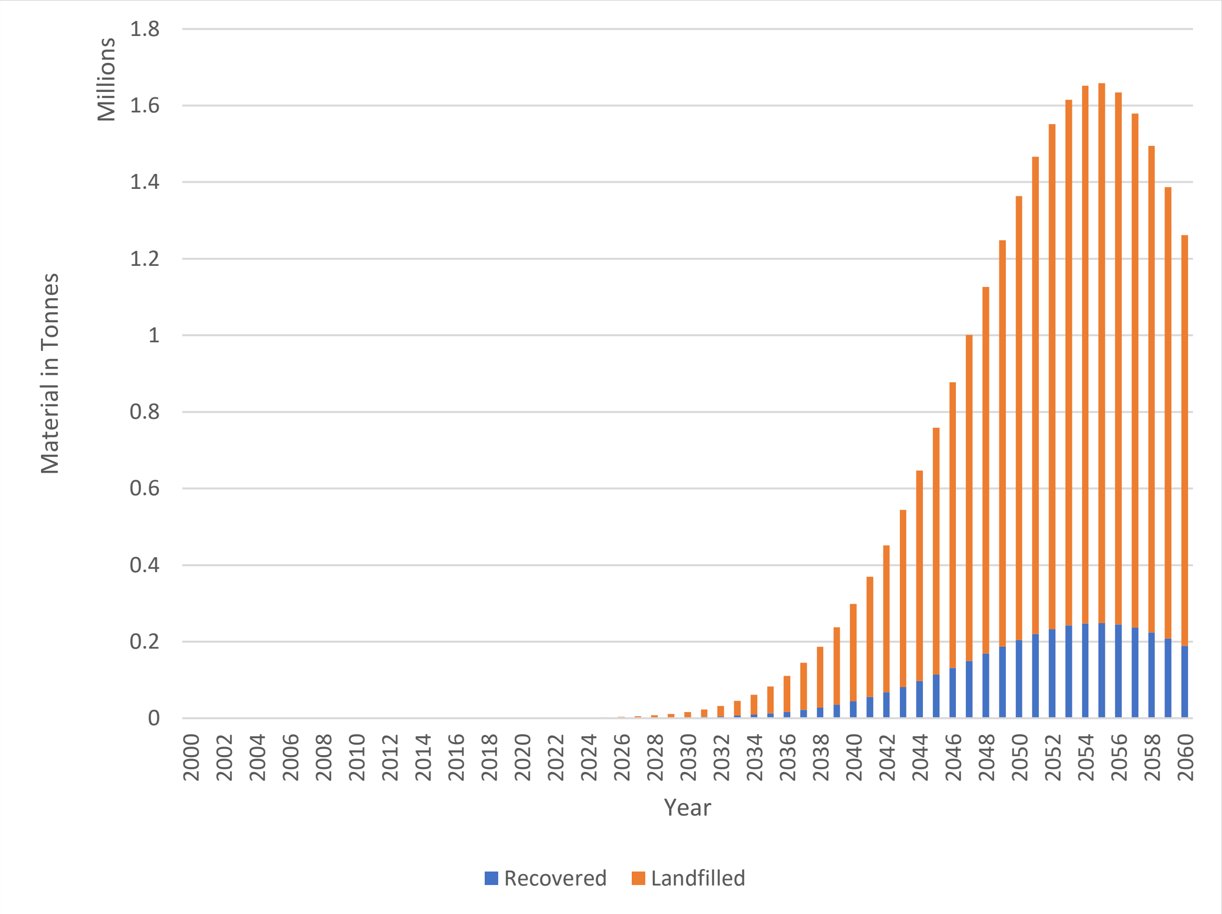

Figure 18: Material recovered and landfilled for Scenario 1

3.74 million tonnes of Solar PV waste are only recycled from 2000 to 2060 with higher amount only being recycled after 2030.

4.1.1. Material Processed in Scenario 1

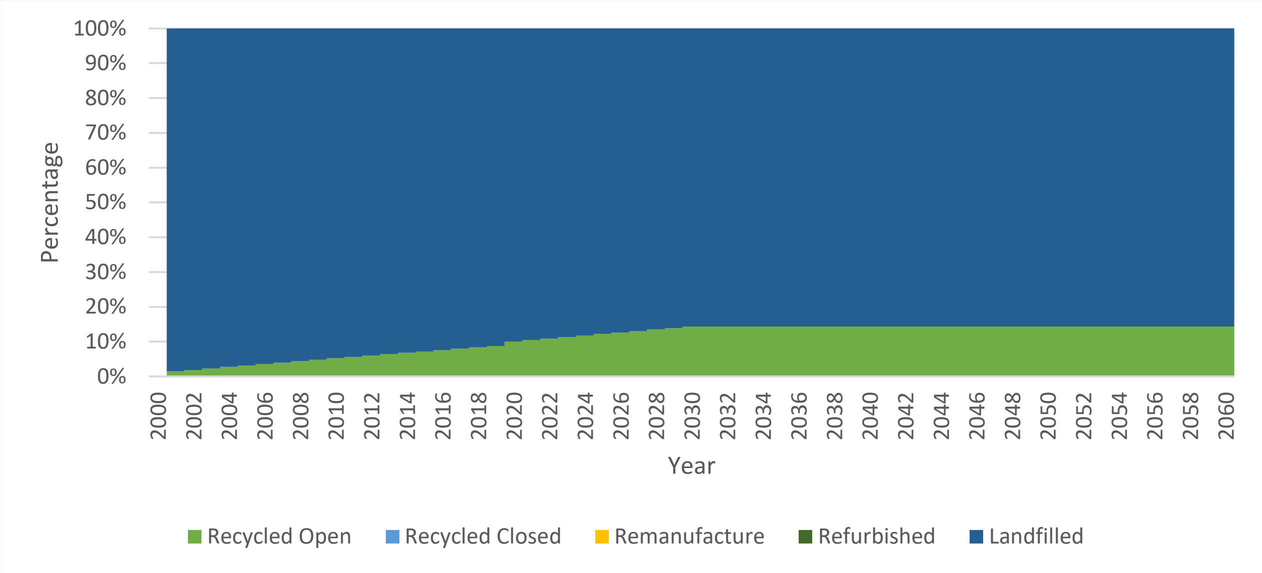

Figure 19: Percentage of Material processed in each EOL strategies in Scenario 1

In Scenario 1 high percentage of material end in landfill as seen in figure 19. With the non-formal sector dominating the recycling sector, the quality of material recovered would be low as these are processed with other e-waste. Thus, the economic value of the recovered material would also be low. Circular economy activities are not focused on by the Indian government which leads to no Remanufacturing or Refurbishment.

4.2. Scenario 2

The outflow of material for Scenario 2 is as shown in figure 20. It is seen that by implementing the material recovery system process according to this scenario leads to low amounts of material ending in the landfill. The 85% recycling target as per the German Policy which Germany has achieved which was discussed in literature is taken as the target for 2030, India could have enough capacity to slowly switch from open loop recycling to closed loop recycling, refurbishing and remanufacture by 2060.

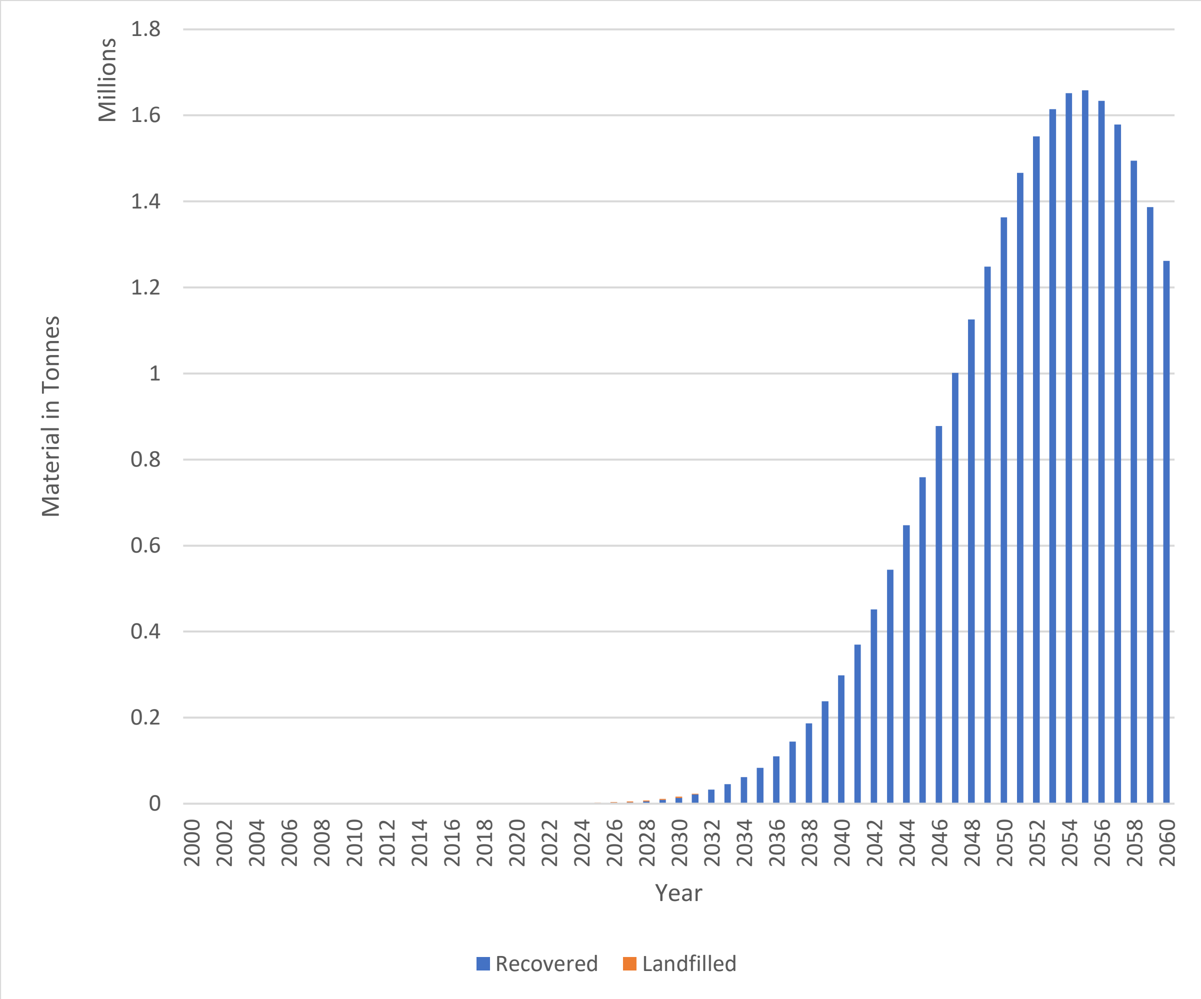

Figure 20: Material recovered and landfilled for Scenario 2

The tonnes of waste that are recycled is of high quantity as seen in figure 20.

With only 16 thousand tonnes of material ending in landfill from 2000 to 2060, the amount of waste ending up in landfill is almost eradicated by the year 2032 in this scenario. This means a development of capacity to process solar PV EOL waste should be developed in 10 years' time from the year 2022. 24.9 million tonnes of material would be recovered through various EOL strategies from 2000 to 2060. The requirement of processing 1.65 million tonnes of waste in 2055 is the highest amount that would occur in this scenario.

4.2.1. Material Processed in Scenario 2

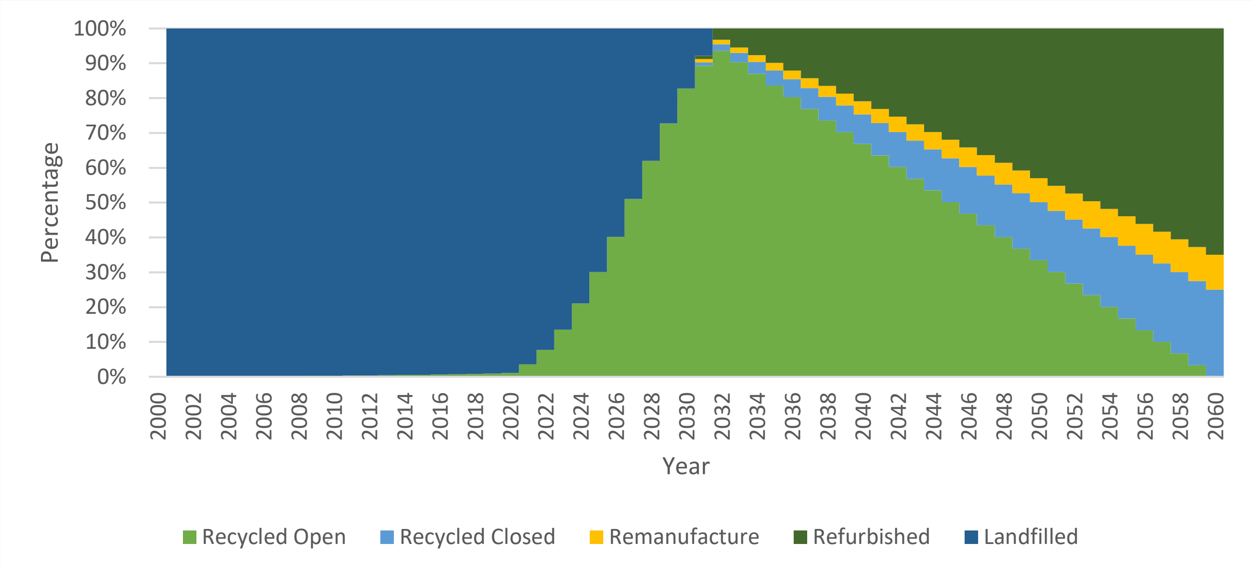

Figure 21: Percentage of Material processed in each EOL strategies in Scenario 2

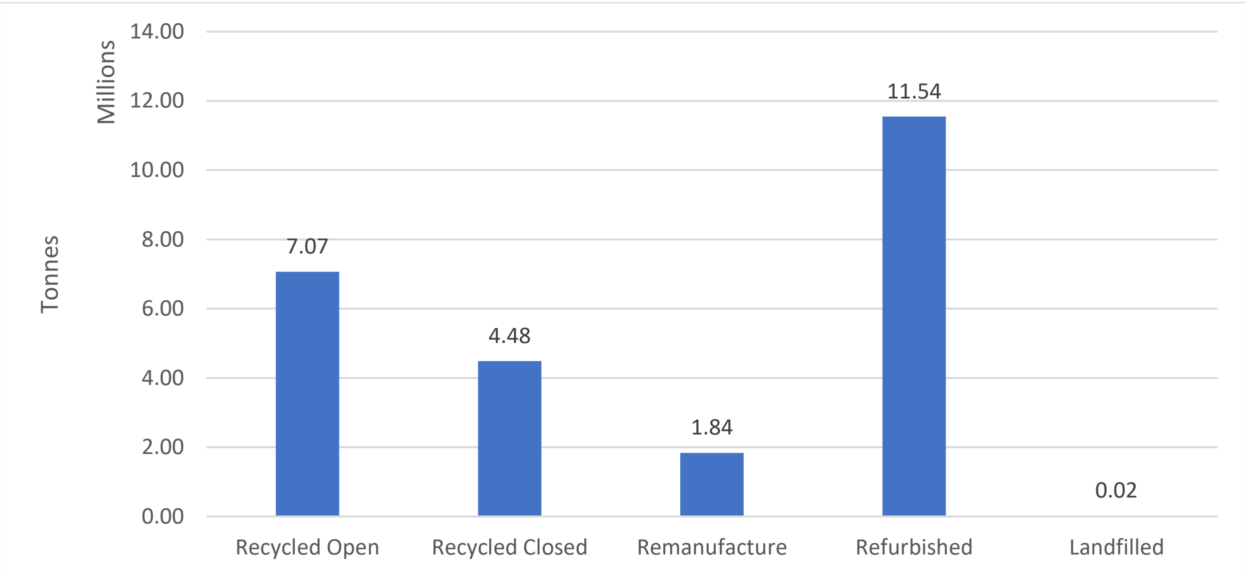

Figure 22: Total tonnes processed through different EOL activities from 2000 to 2060 for Scenario 2

In scenario 2, due the implementation of the German Solar PV waste handling policy the amount of landfilled solar PV waste is low. To achieve this, the Indian Government has to enact policies and build infrastructure to recycle 85% of the solar PV waste by 2030. With a current capacity to recycle only 0.4 million tonnes of e-waste (Suresh, et al., 2019), India would have to develop recycling facilities to handle really high amounts of solar PV waste alone. No landfill for Solar PV waste would be achieved by 2033 in this scenario. As seen in figure 22, the highest amount of materials would be processed through refurbishment followed by open loop recycling in scenario 2.

Remanufacture, Refurbishment and Closed Recycling occurs from 2031. With the highest amount of waste predicted in 2055, that year would have 53% of refurbishment (895 thousand tonnes), 20% in closed loop recycling (345.9 thousand tonnes), 16% in open loop recycling (277 thousand tonnes) and the rest (126.5 thousand tonnes) being remanufactured.

4.3. Scenario 3

Scenario 3 is comparable to Scenario 2 in many aspects due to similar goals followed. The major difference would be that 85% material is recovered by 2040 in this scenario which gives more amount of time for India to build its infrastructure to handle EOL solar PV systems.

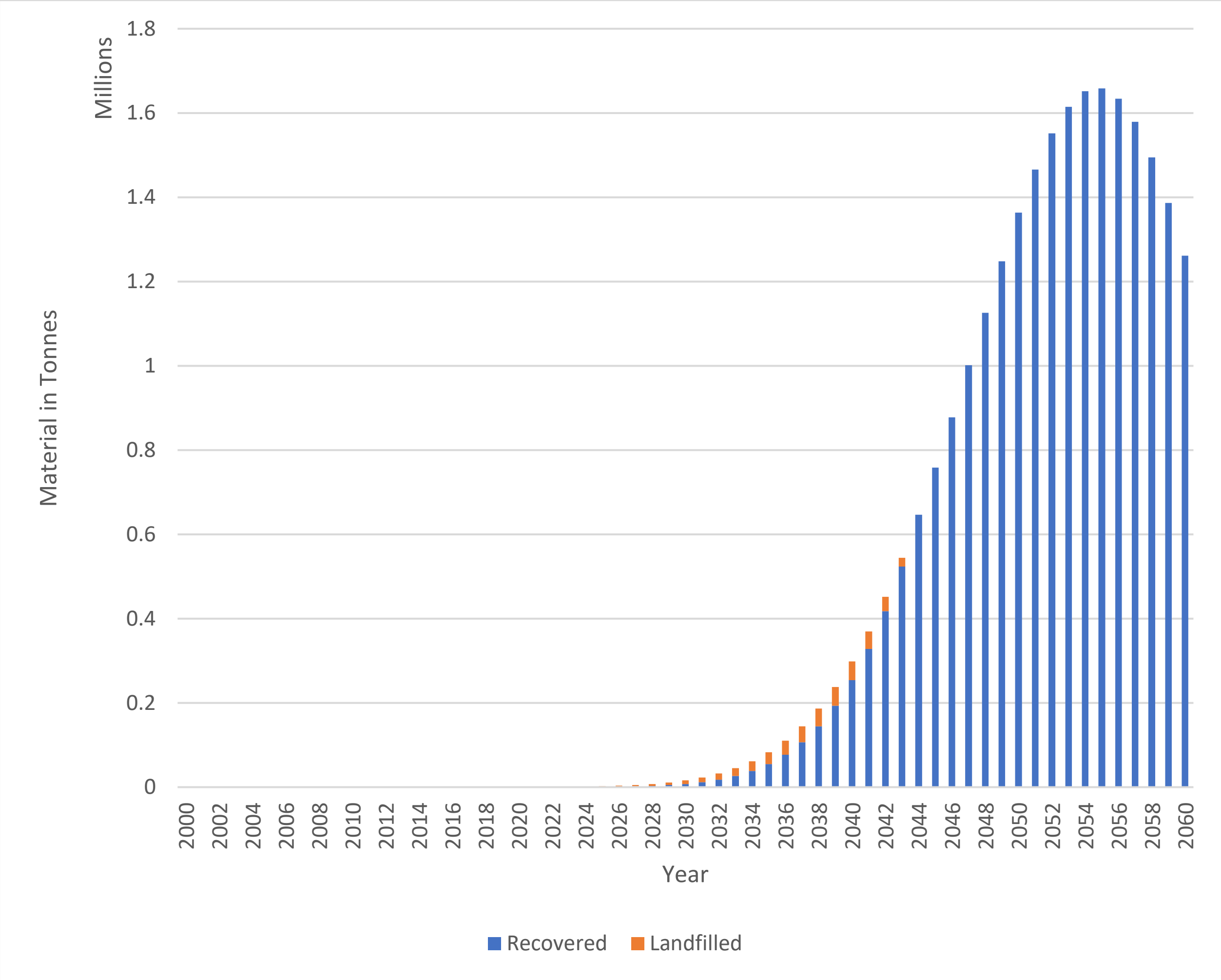

Figure 23: Material recovered and landfilled for Scenario 3

Higher amount of Solar PV waste would end up in the landfill due to the extended target to achieve 85% recycling by 2040. 423 thousand tonnes of material would end up in landfill while 24.5 million tonnes of material would be recovered from 2000 to 2060. The landfill of material is predicted to stop in 2044 in this scenario while the highest amount of waste to be processed is 2055.

4.3.1. Materials Processed in Scenario 3

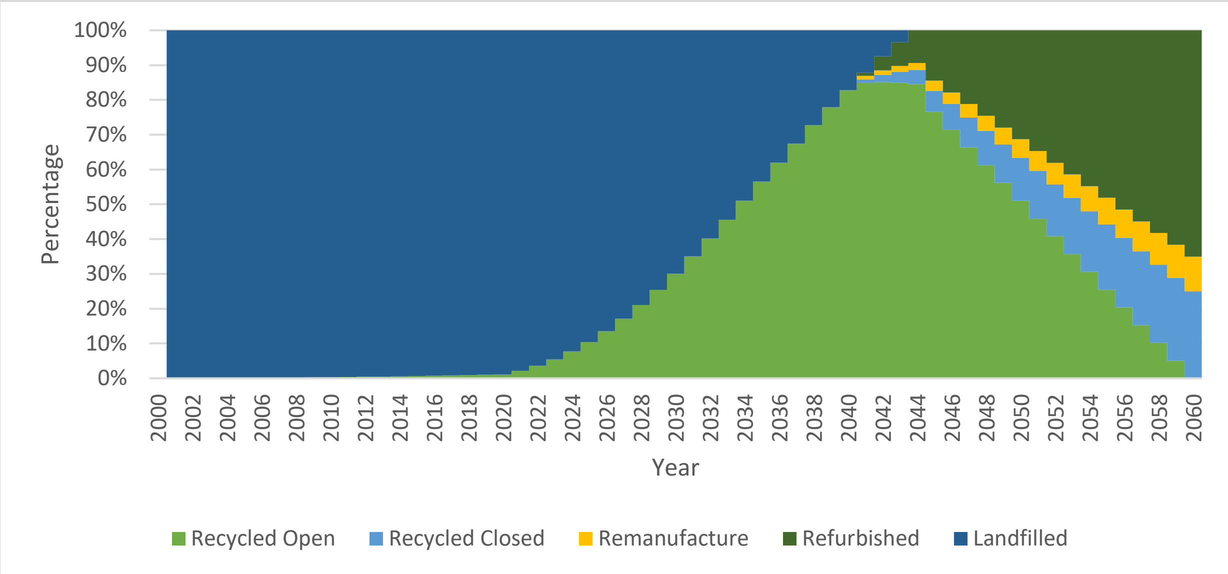

Figure 24: Percentage of Material processed in each EOL strategies in Scenario 3

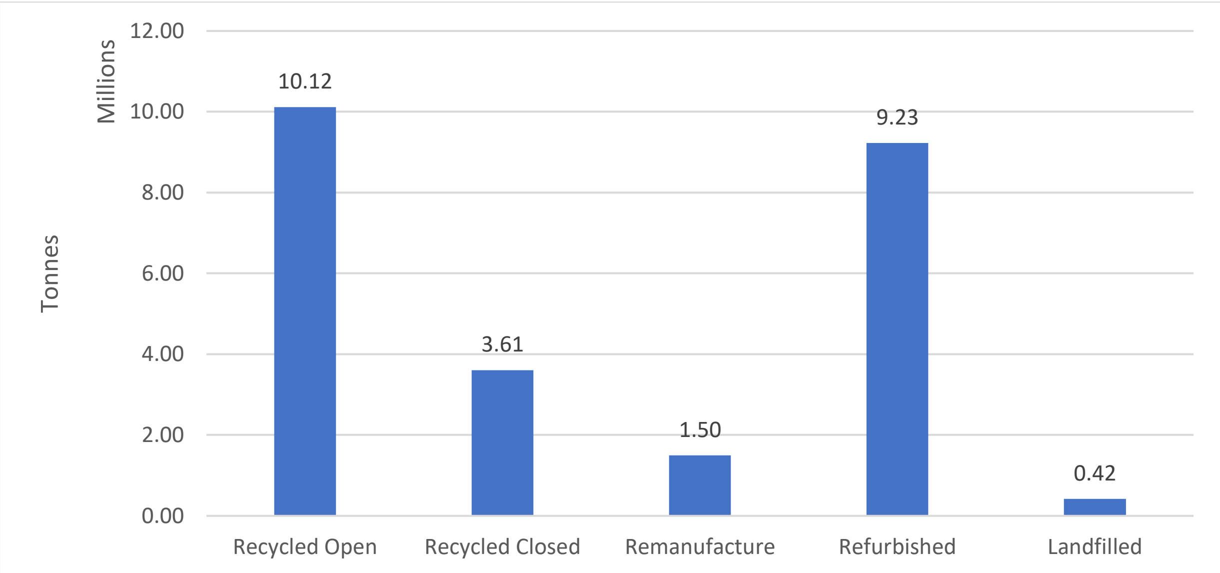

Figure 25:Total tonnes processed through different EOL activities from 2000 to 2060 for Scenario 3

With a larger time-scale to achieve 85% recycling of Solar PV waste in Scenario 3 would mean a slower shift to a circular economy. But this extended target would provide India the required time to build infrastructure, create regulations and educate the local populace for the proper treatment of waste generated from Solar PV. Landfill of solar PV waste is predicted to stop by 2044 in this case. Figure 25 shows that open loop recycling would process the highest amount of material followed by refurbishment in scenario 3.

With circular economy activities starting from 2041 would mean that for the highest amount of waste being generated for the 2030 goal in 2055, the highest percentage (25%) of material would be recycled in open loop (423 thousand tonnes) while 18% (309.8 thousand tonnes) would be processed through a closed loop. Refurbishment would be at 48% (798.6 thousand tonnes) while remanufacture would have 7% (126.5 thousand tonnes) being processed.

5. Discussion

This chapter provides the authors reflection on the method and results to generate insights in underlying limitations, challenges and opportunities of achieving the scenarios that have been developed. These insights put this study in a broader context and identify areas for improvement and further research.

5.1. General Discussion

The Indian Government has setup ambitious efforts to expand their renewable energy with 280 GW of Solar Energy installed by 2030 (MNRE(1), 2021). The trend towards installing Solar PV throughout India is expected to keep growing due to the cheap cost of solar panels and the rising cost of energy. The rapidly rising volume of PV waste has to be handled in a responsible manner and urgent action has to be taken for regulations for proper PV waste treatment. Circular economy being one of the leading frameworks in reducing a country's material consumption and increasing sustainability would be the ultimate goal for India.

Multiple actors would be involved in properly transitioning the Solar PV industry in India to a sustainable and maybe a circular economy in the future. The information in this research can help these actors make the right choices for the sustainable future of the Solar PV industry in India. The first main actor involved in this transition would be the Indian Central Government ministries including the Ministry of New and Renewable Energy (MNRE) which is involved in creating policies for the spread of renewable energy sources throughout the Country and the Central Pollution Control Board (CPCB) which is involved in tracking companies providing EPR for e-waste management. The second main actor would be the Producers and Importers of Solar PV who would have do EPR. Furthermore, the information in this research provides Consumers who purchase solar PV with information on benefits of proper EOL management of solar PV and future researchers can use the information for further research into economic and environmental benefits of proper EOL management of Solar PV. A summary of the actors and benefits the information in this research provides them is shown in table 4.

Ministry of New and Renewable Energy of India (MNRE)

- Use waste from Solar PV data to create Policies and proper targets that India should achieve in sustainable EOL practices for Solar PV (Scenario 2 and 3 can be used as reference)
- Learn about the EPR system from Germany’s ElektroG for Solar PVs based on scenarios 2 and 3 which can thus be adapted.
- Adapting the Financial Guarantee, based on Germany’s WEEE directive, which has to be provided by the producers and sellers of the Solar PV to B2C and B2B (IRENA, 2016)
- Understand there is a requirement to create policies for the collaboration between the formal sector and informal sector to complete the e-waste management supply chain.
- Impelment scenarios 2 or 3 to improve India's SDG score

Central Pollution Control Board of India (CPCB)

- Learn about the requirements to create a system to track and enforce EPR based Germany's Stifung EAR organization under the ElektroG
- Development of a supply chain to ensure proper collection of Solar PV after EOL is done by producers
- The tonnes of waste from Solar PV data in this research can be used to ensure proper tonnes of waste is collected and processed.

Producers and Importers of Solar PV

- For setting up Recycling, Refurbishment and Repair Centres for Solar PV, the waste data can help decide on capacity to be handled each year
- Understand that a financial guarantee has to be provided which has been setup by the MNRE to consumers
- Producers understand the benefit of proper EOL management of Solar PV and the valuable material within Solar PVs
- A requirement to use the labour from informal waste recycling sector could be a good method to build a proper collection and dismantling supply chain

Solar PV Users/ Public

- The literature informs about the benefits to environment in proper EOL management of Solar PV and provide information on the financial guarantee they would receive for being part of the EPR
- The waste data of Solar PV provides insight into why proper disposal of Solar PV at EOL according to a EPR contract with the producer is required
- Solar PV users understand that there are various other methods for EOL solar PV

Future Researchers

- Use of waste data to develop economic models for financial benefits of proper EOL management of Solar PV
- Use of waste data to develop environmental benefits of proper EOL management of Solar PV using Life Cycle Assessment
- Track flow of valuable material that could be recovered from Solar PV

Table 4:Different actors and the benefits of this research

From the results we can conclude that each of the scenario defined for India would generate different amount of waste that would be handled through different EOL activities. The results provide the tonnes of waste material that would be produced but the actual amount of material that would be recovered after processing through different EOL would have to analysed further. With the common solar PVs being crystalline silicone dominating the Indian market at 90% (Suresh, et al., 2019) with a lifespan of 25 to 30 years (Rajput, et al., 2016) was only considered.

The scenario models are always associated with a certain level of uncertainty, as future events and developments are impossible to predict with full accuracy. Out of the 3 scenarios the Scenario 1 is not ideal for progress of the country. Without any intervention in EOL solar PV waste management as seen in scenario 1, it is predicted that more than 21 million tonnes of valuable material would end up in landfill, while the other 2 scenarios show a more optimistic future for India. With 21 million tonnes of Solar PV ending up in landfill in scenario 1, the amount of valuable material lost is too high for India to simply loose. With the highest amount of waste from Solar PV being generated in 2055 for the 280GW goal of 2030, the management and recovery of waste would not work in favour of India's economic growth and future sustainability. Furthermore, in Scenario 1 the material recovered which would be of low quality would not be beneficial for India. These high amounts of waste which ends up in landfills and the low quality of material recovered are a concern for MNRE and CPCB to act on to improve the overall sustainability of India. The MNRE has to consider these large tonnes of waste as potential sources of useful material and create interventions to avoid material going to waste.

The success of scenario 2 or 3 depends on many new policies as well as restructuring of the whole e-waste management sector in India which have to be done by the MNRE, CPCB and the Producers of solar PV. A big shift to a formal sector from an informal sector would be required. The Indian e-waste sector is mainly an informal sector with high amounts of unskilled labour (Kaushik & Herat, 2020) which is considered to not change in scenario 1, thus leading to very low amount and quality of recycled material. According to Gautam, et al. (2022), this dominance of the informal sector causes a mismanagement of e-waste. The high number of potential employees, more than 1% of India's population (Sengupta, et al., 2022), that can be formalized for the purpose of collection and segregation of waste is something the Indian Government and Solar PV Producers needs to focus on for a sustainable future. Alternately, Producers with the help of MNRE Policies can also setup collection and dismantling supply chains using the labour in the informal sector who are readily available throughout India (Sengupta, et al., 2022), thus creating a collaboration between the informal and formal sector. According to Sengupta et al. (2022), identifying and registering clusters of the existing informal supply chain of workers at the state level by the CPCB can help integrate or create a collaboration between the informal sector with formal sector for e-waste management in India. Most of the current informal clusters are run by a middleman who employs workers for the collection and make use of manual or motorized rickshaws (Sengupta, et al., 2022). As part of the EPR scheme deployed by the MNRE and CPCB, these middlemen can be identified and used by the formal sector Producers to expand their supply chain. Thus, the workforce of the informal sector would be used for the collection, segregation and dismantling purposes, while Producers would process the dismantled waste according to the regulations. This shift would require investment in educating, providing good salaries or an incentive system, and the development of safe environments for handling solar PV waste by the Producers and the Indian Government for the workers in the informal sector in each of the identified clusters (Sengupta, et al., 2022). The formalization of the informal sector could lead to decreased efficiency for collection of waste due to bureaucracy involved in the formal sector while a healthy collaboration between the 2 sectors could create the best of both worlds (Borthakur, 2022). A mutual integration of the formal and informal sector is however the only way to ensure sustainable and safe recycling processes while at the same time improving the lively hood of the workforce in the informal sector (Borthakur, 2022). Ultimately, for a country with complex socio-economic, political and environmental realities, considerable brainstorming is required by the MNRE, CPCB, Formal recyclers, informal recyclers and other stakeholders to decide on an integrated approach or create a new waste management system with both sectors remaining separate. With only a capacity of handling 0.4 million tonnes per annum of e-waste as seen in 2020 (Suresh, et al., 2019) further investment would be required by the Indian Government to increase this capacity as it is predicted that more than 1.6 million tonnes of solar PV waste alone would be generated in 2055.

The regulatory requirement of scenario 2 or 3 to work in India, is that the German ElektroG law to be adapted for India by the MNRE. This law would have to create requirement for collection and recycling of solar PV waste and also an agency which would coordinate with solar PV producers (Chowdhury, et al., 2020). This would create a proper EPR regulations and system. The selection of the German ElektroG laws were taken as it was found to be creating profitable economy of scale in recycling Solar PV (IRENA, 2016). The policy and its financial guarantee would have to heavily adapted for the Indian Solar PV market. The current recycling rate of Solar PV in Germany is set at 85% and is providing good economy of scale (Chowdhury, et al., 2020). The economy of scale of the Solar PV waste generated in India has not been considered in this research and the possibility of successfully achieving a positive economy of scale would have to further researched by other researchers. It has to be also noted that in a regular loss scenario where life span of solar PV is taken as 30 years without attrition as seen in figure 3, IRENA (2016) predicts that in 2050, India and Germany have similar amounts of Solar PV waste which could mean that the economy of scale may work out.

The recycling goal setup for scenario 3 provides India the time to develop its infrastructure and regulations at a loss of 21 times (42 thousand tonnes) the material as that of scenario 2 (2 thousand tonnes) to landfill. With a predicted end of landfill for scenario 2 as 2033 while for scenario 3 is 2044, the MNRE has to consider the trade-offs while selecting the scenario. India’s achievement in SDG goals in the area of health, energy and infrastructure is growing steadily (Bose & Khan, 2022) and has raised SDG indicators like SDG 6.2 (Population using at least basic sanitation services) to 100% in 5 years which involved creating sanitation for 500 million people (Sachs, et al., 2022) pose as great examples of India government’s effort in achieving sustainable targets. As highest amount of the material from the stock build-up of solar PV installed till 2030 start reaching its EOL period by 2055, it would make sense for the MNRE to create policies and targets for the proper EOL solar PV waste management expansion based on scenario 3 compared to scenario 2 as significant more time is available for India to develop regulations and infrastructure due to high capacity of material to be handled. The ultimate choice of using the targets for recycling in 2030 or 2040 depends on the MNRE and CPCB coordination with the producers and importers of solar PV as they have to build capacities and supply chains to handle the high amount of waste that has been predicted.

Furthermore, both Scenario 2 and 3 focuses on a shift to a circular economy by 2060. For Scenario 2 the switch starts from 2031 and Scenario 3 it starts from 2041. This is an ambitious target for India which has no active circular economy practices in any major industry. According to Gautum, et al. (2022), the preferred approach for EOL Solar PV waste in India is recycling (25%), refurbishment (65%) and remanufacturing (10%) as part of the 9R framework. Their study shows that proper development of the solar PV industry, formalizing the informal sector and proper EPR could lead to these percentages in India and has thus been used for scenario 2 and 3. Comparing scenario 2 and 3 from 2000 to 2060 shows that refurbishment would handle the highest amount of waste in scenario 2 while in scenario 3 it would handle more waste through open loop recycling. For the highest amount of waste predicted in 2055, the Solar PV industry would have to handle 53% of refurbishment (895 thousand tonnes), 20% in closed loop recycling (345.9 thousand tonnes), 16% in open loop recycling (277 thousand tonnes) and the rest (126.5 thousand tonnes) being remanufactured in scenario 2 while in scenario 3 refurbishment would be at 48% (798.6 thousand tonnes), 25% (423 thousand tonnes) of material would be recycled in open loop, 18% (309.8 thousand tonnes) would be processed through a closed loop, and remanufacture would have 7% (126.5 thousand tonnes) being processed. This would mean that Producers of solar PV have to setup not only recycling technology but create a closed loop system where secondary material for manufacturing new Solar PVs as well as create refurbishment and remanufacture capabilities to handle such high capacities.

The success of circular economy would also depend on public awareness in the proper disposal of EOL solar PV waste which can be created through surveys and advertisements related to circular economy which have to promoted by the MNRE, CPCB and the producers of solar PV. The public would also have to be aware of EPR while a way for public to monitor the collection and recycling sector in India setup by the CPCB would boost public interest. A creation of a second-hand market where the solar PV is sold for a discounted cost has to be developed for Refurbished and Repaired solar PVs to be distributed (IRENA, 2016). Circular economy in a Solar PV industry has only been researched and has not been proven to be successful in any part of the world, but achieving any percentage in circular economy EOL activities in Solar PV is beneficial environmentally than landfilling (IRENA, 2016).

It was reported that around 1 million tonnes of e-waste were generated in 2020 (CPCB, 2020) and it's estimated that 161 million tonnes of e-waste would be generated in 2050 (Sengupta, et al., 2022). The solar PV waste stream estimated in this research is to be only 1.3 million tonnes of waste in 2050 which is only 1% of the total e-waste being produced in India. The solar PV stream may not be a major focus of the India government due to higher tonnes of other e-waste, thus the EOL solar PV waste may end up being processed with other e-waste in the future. However, the Solar PV just like most of the electronics used in India is imported from foreign countries, mainly China, which provides India with an opportunity to recover the valuable materials like rare earth metals from EOL products that India do not have deposits of. This would thus provide a secondary stream of valuable metals without the requirement of importing costly materials as primary raw materials.

The improvement of the indicator "Quantity of hazardous waste recycled to total hazardous waste generated" under SDG 12 (NITI Aayog (2), 2018) would be the direct result of any improvement in EOL waste management of solar PV systems. No particular indicator has been defined for other different EOL waste management techniques (recycling, refurbishing, remanufacture or reusing) for valuable materials which would have to be created if India shifts to a circular economy. The formalising of the current informal sector of waste management which is required for the EPR system to run successfully would create economic growth as well as create safe working environments with a defined wage scale that would improve SDG 8 (decent work and economic growth). The growth of recycling, refurbishment and remanufacture would require the growth of industry, innovation and sustainable infrastructure (SDG 9) as expenditure on research and development would increase due to investment from the government to achieve the targets setup in scenario 2 and 3. The proper collection system developed as part of the EPR by the CPCB and the producers as well as the education for users of Solar PV received about proper EOL management would improve scores on SDG 11 (sustainable cities and communities). Finally, the creation of a circular economy or even targeting lesser landfills would improve SDG 13 (climate action) as greenhouse gases can be reduced through better material management.

5.2. Limitations and future studies

This research attempts to provide information on how much tonnes of waste would be produced by India's goal to grow its renewable energy by using solar PV. The Solar PV taken into consideration is only Crystalline Silicone based Solar PVs which dominate 90% of the market in India (Suresh, et al., 2019) and is taken as the only Solar PV used in India till 2030. No consideration of the build-up of solar PV stock after 2030 has not been taken. Considering the stock after 2030 could change the values of outflow after 2030 thus changing the capacity of solar PV waste India would have to handle. The research also does not take into consideration of all the different types of solar PV in the Indian market. Thin film solar panels and Amorphous silicon panels are not considered while Solar panels used in purposes other than electricity production like in water heaters are also not considered. More analysis on the material cost that flows into the solar PV industry and the value of material after EOL activities has to be also considered.

The scenarios created are a few suggestions on how the future of Solar PV industry in India could look like. The scenarios only focus on the EOL activities and have not taken into consideration that material intensity of Solar PVs can change, which would change overall material requirement.

The results provide the tonnes of material that would be processed through different EOL activities like Recycle, refurbish, reuse or landfill. The actual material that would be recovered after processing through these EOL activities has not been determined in this research. A vast number of policies would have to be created by the MNRE to create a successful EPR in the solar PV industry. The investment required in building up infrastructure is not studied in this research and the possibility of actually handling this much amount of waste efficiently is hypothetical. The success of merging the informal sector with the formal sector for e-waste management would be a challenge and would require proper planning and regulations. The final possibility of scenario 2 or 3 occurring would depend on the economic feasibility and the possibility of creating an economy of scale for recycling would have to be studied. The materials that can be extracted effectively from the solar PV panels is not studied in this research and would depend on the recycling technology used, thus decreasing the tonnes of material that can be extracted. This would thus change the inflow and outflow of material in all the scenarios presented here.

Further study can determine the Solar PV capacity for each state in India and build collection, separation and processing centres based on projected Solar PV installation so that transport supply chain distances can be managed. This study can act as a reference to actually develop circular supply chains and study further on economic feasibility setting up a circular solar PV industry. The waste data from the Solar PV can also be used in life cycle analysis to determine environmental impacts.

Although there are limitations, this study can still be used to develop recycling capacities in India based on the waste tonnes that have been generated. The study provides a general method on how to create scenarios based on different EOL waste handling methods and simulate future material flows for a country. It also provides the reader with knowledge about the Solar PV industry and possible solutions to properly managing its EOL waste in India.

6. Conclusion

A summary and the findings from this study regarding the research question and the objectives are provided in this chapter.

The main question this research answers is: "**What is the potential waste generated from solar PV in India for India's 2030 Solar Energy Goal?** with sub research questions:

1. **What is the current strategies India uses to implement solar energy?**
2. **How does the flow of raw material in the solar power industry in India look like from 2000 to 2060?**
3. **What could be the impacts of adopting the current best-case scenarios from other countries for better EOL solar waste management?**

To answer the first and second research sub-question, a detailed literature review was conducted about the solar PV industry and the targets for sustainable solar energy in India. India has an abundant potential for solar energy and has been heavily investing in expanding its solar energy mix. A 280 GW goal of solar energy has been targeted by India for 2030. This would be a high amount of material India would have to use. Majority of the solar panels are imported from China. India has only 8.5 GW of manufacturing capacity of solar PV modules which is very low for the capacity India is aiming at. The commonly used solar PV panels in India were identified as mono crystalline and poly crystalline solar panels dominating 90% of the market which have a lifetime period of 25-30 years. The solar PV system includes the panels, the mounting structure and the connectors. Aluminium is the highest amount of material due to the mounting structure. Glass also makes up high amounts of the volume. Other precious metals like silver, gold, copper and critical materials like indium and selenium exist in the solar PV system. India has no dedicated recycling plants to handle large scale solar PV waste. India has 10% recycling rate of e-waste as of 2020 and a small growth has only been seen as of 2022. 95% of the e-waste in India are recycled by a non-formal sector comprising of unskilled labour, health hazards and environmental hazards. Only valuable material like gold, silver and aluminium is recovered. The formal sector which only does separation and shredding of the e-waste send most these to developed countries for material recovery of valuable metals.

To answer third sub-question, further literature was conducted on the top 5 countries predicted to have the highest amount of waste from solar PV which was found to be China, USA, Japan, India and Germany. India and Germany are predicted to have similar amounts of Solar PV waste. Of the top 5 countries Germany is the only one which has a dedicated regulations and systems in place for the proper management of EOL solar PV waste. Germany is set to be the first solar energy market that reaches profitability in recycling procedures, as rising amounts allow economies of scale to set in and boost the learning curve.

Finally, to answer the main research question, a dynamic MFA was used to help in analysing the waste potential of EOL solar PV in India from the information from literature. By defining a system boundary with flows and processes we understood how resources flow in that solar PV industry. Thus, by defining these, it was possible to create scenarios that India can follow to become a circular economy in the solar PV industry. Scenario 1 focused on the current recycling condition in India. Only 10% of the solar PV waste was recycled in an open loop with only a 15% open recycling seen by 2030 which would be the highest recycling rate till 2060. This scenario showed that 21 million tonnes of valuable material from Solar PV waste would end up in landfill as India continues to not intervene by setting up proper EOL management practices. Scenario 1 is non ideal for the sustainable development of India and a future following this has to be avoided by the Indian Government.

Scenario 2 used the German WEEE regulation which is the best practice worldwide as answered in the third sub-question to raise recycling rate in India to 85% by 2030 from the existing 10%. This was followed by a switch to circular economy which targets recycling (25% Closed Loop), refurbishment (65%), remanufacture (10%) could be achieved by India by 2060. Scenario 3 was similar to Scenario 2, but the aim of this scenario was to reach a target of 85% open recycling by 2040 from 10% in 2020 based on the German WEEE regulation so as to provide increased time for India to develop its regulations and infrastructure to handle the high amount of waste from Solar PV. The 2060 goal for a circular economy remained the same. It was found that the outflow of tonnes of material is same in all 3 of the scenarios and the highest amount of waste produced by the 280GW target of 2030 would be in 2055 at over 1.6 million tonnes. Landfill is predicted to end in 2033 for scenario 2 while 2044 for scenario 3. Scenario 3 would lose 21 times (42 thousand tonnes) material to landfill compared to scenario 2. Comparing scenario 2 and 3 from 2000 to 2060 shows that refurbishment would handle the highest amount of waste in scenario 2 while in scenario 3 would handle more waste through open loop recycling. For the highest amount of waste predicted in 2055, the Solar PV industry would have to handle 53% of refurbishment (895 thousand tonnes), 20% in closed loop recycling (345.9 thousand tonnes), 16% in open loop recycling (277 thousand tonnes) and the rest (126.5 thousand tonnes) being remanufactured in scenario 2 while in scenario 3 refurbishment would be at 48% (798.6 thousand tonnes), 25% (423 thousand tonnes) of material would be recycled in open loop, 18% (309.8 thousand tonnes) would be processed through a closed loop, and remanufacture would have 7% (126.5 thousand tonnes) being processed.

Achieving scenario 2 or 3 depends on multiple actors including the MNRE, CPB, Producers/ Importers of Solar PV and the users of Solar PV. The MNRE has to setup policies and targets to achieve one of these scenarios while the CPB has to track and manage the EPR system that would be developed. The adaptation of the financial guarantee for EOL solar PV has to also be decided by the MNRE and Producers. A transition to a formal sector from an informal one would have to be done by the MNRE and the Producers, where labour available in the informal sector is employed to create a supply chain for the proper collection of EOL solar PV so that correct waste management procedures can be applied. Furthermore, the CPB and Producers has to educate users on the reason for proper EOL management of Solar PV for the EPR to be successful.

Although solar PV waste would only be 1% of the e-waste generated by India in 2050, the materials embodied in Solar PVs are valuable especially due to the fact that most of the solar PV in India is imported. Furthermore, improvements in SDGs mainly SDG 12 as well as 7 (affordable and clean energy), 8 (decent work and economic growth), 9 (industry, innovation and infrastructure), 11 (sustainable cities and communities) and 13 (climate action) can be seen due to the proper EOL management of Solar PV.

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Appendix 1: Dynamic MFA Python Code

```
import os
import sys
abspath = os.path.abspath(sys.argv[0])
dname = os.path.dirname(abspath)
os.chdir(dname)
import pandas as pd
import numpy as np
import scipy.stats
from os import chdir

from dynamic_stock_model import DynamicStockModel
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt

input_data = pd.read_excel("GWinstalledinput.xlsx", "Input")

print(input_data)

stock_flow_timeseries = pd.read_excel(r'GWinstalledinput.xlsx', sheet_name='Input')
stock_flow_timeseries = stock_flow_timeseries.set_index(['Year'])
time_max = stock_flow_timeseries.shape[0]
timesteps = np.arange(0, time_max)


# %% 2. create a single survival curve

# # Weibull distributed survival curve
curve_shape = 5.37
curve_scale = 30
curve_surv = scipy.stats.weibull_min.sf(timesteps, curve_shape, 0, curve_scale)

# %% 3. create survival curve matrix

# create survival curve matrix with placeholder zeros
curve_surv_matrix = pd.DataFrame(0, index=timesteps, columns=timesteps)

# populate the survival curve matrix with shifted curves, column by column using slices
for time in timesteps:
    curve_surv_matrix.loc[time:, time] = curve_surv[0:time_max - time]

# %% 4. stock driven model

# create survival matrix with placeholder zeros
cohort_surv_matrix = pd.DataFrame(0, index=timesteps, columns=timesteps)

# iteratively calculate the inflow in stock_flow_timeseries, and
# multiply the inflow times the shifted curves to get the cohorts' behavior over time
```

```
for time in timesteps:
    stock_flow_timeseries['Inflow'].iloc[time] = (stock_flow_timeseries['Cumulative GW
Installed'].iloc[time] - cohort_surv_matrix.loc[time, :].sum()) / curve_surv_matrix.loc[time, time]
    cohort_surv_matrix.loc[:, time] = curve_surv_matrix.loc[:, time] *
stock_flow_timeseries['Inflow'].iloc[time]

# set row index to years instead of timesteps
cohort_surv_matrix.index = stock_flow_timeseries.index

# calculate outflows and NAS (Net addition to stock) using the cohort_surv_matrix
stock_flow_timeseries['NAS'] = np.diff(stock_flow_timeseries['Cumulative GW Installed'],
prepend=0)  # prepending 0 assumes no initial stock
stock_flow_timeseries['Outflow'] = stock_flow_timeseries['Inflow'] - stock_flow_timeseries['NAS']


# %% 5. Export output data to Excel
cohort_surv_matrix.to_excel('cohort_surv_matrix1.xlsx')
stock_flow_timeseries.to_excel('stock_flow_timeseries1.xlsx')

#%% 7. Applying recycling rate to the outflow (% from 2030 onwards)
exportDSM = stock_flow_timeseries
exportDSM = exportDSM.reset_index(level=0)
NewColumn1 = []
NewColumn2= []
for index, row in exportDSM.iterrows():
    if exportDSM.loc[index, 'Year'] >= 2000 and exportDSM.loc[index, 'Year'] <= 2060:
        NewColumn1.append(exportDSM['Outflow'][index]-
(exportDSM['Outflow'][index]*exportDSM['Scenario1'][index]))
        NewColumn2.append(exportDSM['Outflow'][index]*exportDSM['Scenario1'][index])
exportDSM['Outflow'] = pd.DataFrame(NewColumn1)
exportDSM['Recovered']= pd.DataFrame(NewColumn2)

#%% 8. Applying recycling to new inflow where the demand of virgin material is reduced and
replaced with recycled material
NewColumn = []
for index, row in exportDSM.iterrows():
    if exportDSM.loc[index, 'Year'] >= 2000 and exportDSM.loc[index, 'Year'] <= 2060:
        NewColumn.append(exportDSM['Inflow'][index]-exportDSM['Outflow'][index])
exportDSM['Inflow'] = pd.DataFrame(NewColumn)

exportDSM.to_excel(r"C:\Users\johnt\Desktop\Thesis\Future1.xlsx")
```

Scenario 1.txt Scenario 2.txt Scenario 3.txt dynamic_stock_model.txt

Appendix 2: Input Data for Python Code

Year	Yearly GW Install	Lifetime	Cumulative GW Installed	Inflow	Outflow	Scenario1	Scenario2	Scenario3
2000	0.01	30	0.01			0.01	0.01	0.01
2001	0.01	30	0.02			0.0145	0.0145	0.0145
2002	0.02	30	0.03			0.019	0.019	0.019
2003	0.03	30	0.05			0.0235	0.0235	0.0235
2004	0.03	30	0.06			0.028	0.028	0.028
2005	0.05	30	0.08			0.0325	0.0325	0.0325
2006	0.05	30	0.1			0.037	0.037	0.037
2007	0.07	30	0.12			0.0415	0.0415	0.0415
2008	0.07	30	0.14			0.046	0.046	0.046
2009	0.09	30	0.16			0.0505	0.0505	0.0505
2010	0.1	30	0.19			0.055	0.055	0.055
2011	0.39	30	0.49			0.0595	0.0595	0.0595
2012	0.85	30	1.24			0.064	0.064	0.064
2013	1.51	30	2.36			0.0685	0.0685	0.0685
2014	1.17	30	2.68			0.073	0.073	0.073
2015	2.63	30	3.8			0.0775	0.0775	0.0775
2016	4.19	30	6.82			0.082	0.082	0.082
2017	8.16	30	12.35			0.0865	0.0865	0.0865
2018	13.56	30	21.72			0.091	0.091	0.091
2019	14.69	30	28.25			0.0955	0.0955	0.0955
2020	19.93	30	34.62			0.1	0.1	0.1
2021	20.15	30	40.08			0.105	0.175	0.1375
2022	36.8	30	56.95			0.11	0.25	0.175
2023	48.03	30	84.83			0.115	0.325	0.2125
2024	64.68	30	112.71			0.12	0.4	0.25
2025	75.91	30	140.59			0.125	0.475	0.2875
2026	92.56	30	168.47			0.13	0.55	0.325
2027	103.79	30	196.35			0.135	0.625	0.3625

2028	120.44	30	224.23			0.14	0.7	0.4
2029	131.67	30	252.11			0.145	0.775	0.4375
2030	148.33	30	280			0.15	0.85	0.475
2031	0	30	280			0.15	0.925	0.5125
2032	0	30	280			0.15	1	0.55
2033	0	30	280			0.15	1	0.5875
2034	0	30	280			0.15	1	0.625
2035	0	30	280			0.15	1	0.6625
2036	0	30	280			0.15	1	0.7
2037	0	30	280			0.15	1	0.7375
2038	0	30	280			0.15	1	0.775
2039	0	30	280			0.15	1	0.8125
2040	0	30	280			0.15	1	0.85
2041	0	30	280			0.15	1	0.8875
2042	0	30	280			0.15	1	0.925
2043	0	30	280			0.15	1	0.9625
2044	0	30	280			0.15	1	1
2045	0	30	280			0.15	1	1
2046	0	30	280			0.15	1	1
2047	0	30	280			0.15	1	1
2048	0	30	280			0.15	1	1
2049	0	30	280			0.15	1	1
2050	0	30	280			0.15	1	1
2051	0	30	280			0.15	1	1
2052	0	30	280			0.15	1	1
2053	0	30	280			0.15	1	1
2054	0	30	280			0.15	1	1
2055	0	30	280			0.15	1	1
2056	0	30	280			0.15	1	1
2057	0	30	280			0.15	1	1
2058	0	30	280			0.15	1	1
2059	0	30	280			0.15	1	1

2060	0	30	280			0.15	1	1

GWinstalledinput.xlsx

Appendix 3: Inflow and Outflow output

Year	Yearly GW Install	Lifetime	Cumulative GW Installed	Inflow	Outflow	Scenario1	Scenario2	Scenario3	NAS
2000	0.01	30	0.01	0.01	0	0.01	0.01	0.01	0.01
2001	0.01	30	0.02	0.01	1.17E-10	0.0145	0.0145	0.0145	0.01
2002	0.02	30	0.03	0.01	4.83E-09	0.019	0.019	0.019	0.01
2003	0.03	30	0.05	0.02	4.27E-08	0.0235	0.0235	0.0235	0.02
2004	0.03	30	0.06	0.01	2E-07	0.028	0.028	0.028	0.01
2005	0.05	30	0.08	0.020001	6.67E-07	0.0325	0.0325	0.0325	0.02
2006	0.05	30	0.1	0.020002	1.8E-06	0.037	0.037	0.037	0.02
2007	0.07	30	0.12	0.020004	4.2E-06	0.0415	0.0415	0.0415	0.02
2008	0.07	30	0.14	0.020009	8.77E-06	0.046	0.046	0.046	0.02
2009	0.09	30	0.16	0.020017	1.69E-05	0.0505	0.0505	0.0505	0.02
2010	0.1	30	0.19	0.03003	3.03E-05	0.055	0.055	0.055	0.03
2011	0.39	30	0.49	0.300052	5.16E-05	0.0595	0.0595	0.0595	0.3
2012	0.85	30	1.24	0.750084	8.4E-05	0.064	0.064	0.064	0.75
2013	1.51	30	2.36	1.120132	0.000132	0.0685	0.0685	0.0685	1.12

2014	1.17	30	2.68	0.320201	0.000201	0.073	0.073	0.073	0.32
2015	2.63	30	3.8	1.120302	0.000302	0.0775	0.0775	0.0775	1.12
2016	4.19	30	6.82	3.02045	0.00045	0.082	0.082	0.082	3.02
2017	8.16	30	12.35	5.530675	0.000675	0.0865	0.0865	0.0865	5.53
2018	13.56	30	21.72	9.371018	0.001018	0.091	0.091	0.091	9.37
2019	14.69	30	28.25	6.531545	0.001545	0.0955	0.0955	0.0955	6.53
2020	19.93	30	34.62	6.372368	0.002368	0.1	0.1	0.1	6.37
2021	20.15	30	40.08	5.463667	0.003667	0.105	0.175	0.1375	5.46
2022	36.8	30	56.95	16.87573	0.005727	0.11	0.25	0.175	16.87
2023	48.03	30	84.83	27.88897	0.008969	0.115	0.325	0.2125	27.88
2024	64.68	30	112.71	27.89399	0.01399	0.12	0.4	0.25	27.88
2025	75.91	30	140.59	27.90162	0.02162	0.125	0.475	0.2875	27.88
2026	92.56	30	168.47	27.91301	0.033012	0.13	0.55	0.325	27.88
2027	103.79	30	196.35	27.92976	0.049759	0.135	0.625	0.3625	27.88
2028	120.44	30	224.23	27.95401	0.074014	0.14	0.7	0.4	27.88
2029	131.67	30	252.11	27.98862	0.108623	0.145	0.775	0.4375	27.88

2030	148.33	30	280	28.04725	0.15725	0.15	0.85	0.475	27.89
2031	0	30	280	0.224494	0.224494	0.15	0.925	0.5125	0
2032	0	30	280	0.315994	0.315994	0.15	1	0.55	0
2033	0	30	280	0.438487	0.438487	0.15	1	0.5875	0
2034	0	30	280	0.599791	0.599791	0.15	1	0.625	0
2035	0	30	280	0.80869	0.80869	0.15	1	0.6625	0
2036	0	30	280	1.074725	1.074725	0.15	1	0.7	0
2037	0	30	280	1.407887	1.407887	0.15	1	0.7375	0
2038	0	30	280	1.818191	1.818191	0.15	1	0.775	0
2039	0	30	280	2.315131	2.315131	0.15	1	0.8125	0
2040	0	30	280	2.906999	2.906999	0.15	1	0.85	0
2041	0	30	280	3.60009	3.60009	0.15	1	0.8875	0
2042	0	30	280	4.3978	4.3978	0.15	1	0.925	0
2043	0	30	280	5.299648	5.299648	0.15	1	0.9625	0
2044	0	30	280	6.30029	6.30029	0.15	1	1	0
2045	0	30	280	7.388582	7.388582	0.15	1	1	0
2046	0	30	280	8.546799	8.546799	0.15	1	1	0

2047	0	30	280	9.75012	9.75012	0.15	1	1	0
2048	0	30	280	10.9665	10.9665	0.15	1	1	0
2049	0	30	280	12.15708	12.15708	0.15	1	1	0
2050	0	30	280	13.27725	13.27725	0.15	1	1	0
2051	0	30	280	14.27843	14.27843	0.15	1	1	0
2052	0	30	280	15.11077	15.11077	0.15	1	1	0
2053	0	30	280	15.72648	15.72648	0.15	1	1	0
2054	0	30	280	16.08395	16.08395	0.15	1	1	0
2055	0	30	280	16.15222	16.15222	0.15	1	1	0
2056	0	30	280	15.9153	15.9153	0.15	1	1	0
2057	0	30	280	15.37595	15.37595	0.15	1	1	0
2058	0	30	280	14.55799	14.55799	0.15	1	1	0
2059	0	30	280	13.50655	13.50655	0.15	1	1	0
2060	0	30	280	12.28583	12.28583	0.15	1	1	0

stock_flow_timeseries
1.xlsx

Appendix 4: Conversion of GW to Tonnes in each EOL Activity

Tons in EOL Activity.xlsx