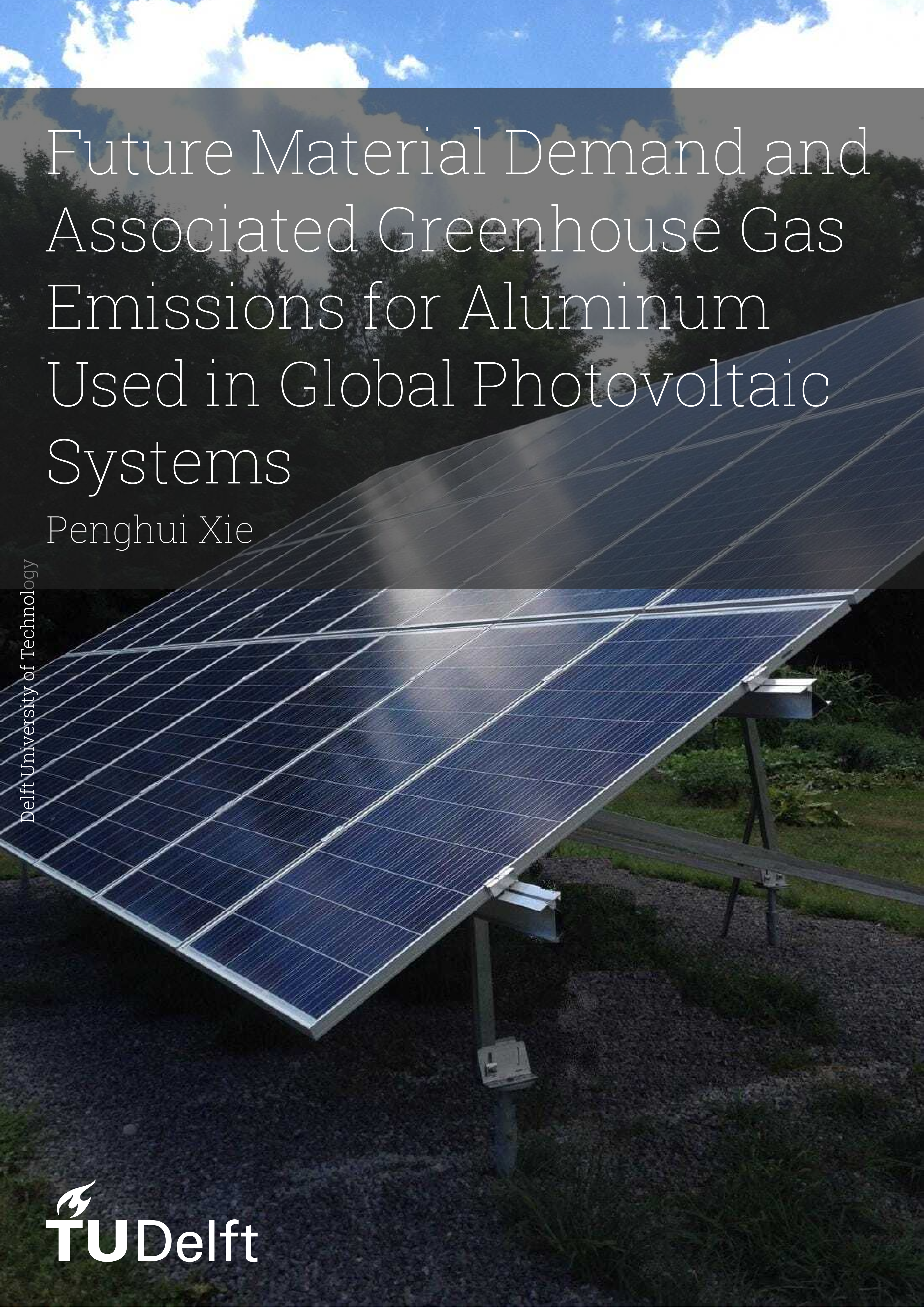

Future Material Demand and Associated Greenhouse Gas Emissions for Aluminum Used in Global Photovoltaic Systems

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Acknowledgements

Two years ago on this day, I was confined to my home in Xinjiang due to the COVID-19 pandemic, anxiously wondering if my upcoming flight to Amsterdam would depart as planned. At that time, I was filled with anticipation for the new challenges ahead, yet also worry about the journey of studying abroad. I am someone with ambition but lacking in action, eager to explore and communicate, yet timid and introverted. I chose to pursue a master's degree abroad to see a broader world, while the unfamiliar surroundings and linguistic environment filled me with anxiety. I always had to force myself to dive into new experiences and then learn to adapt and find comfort in them. During my two years at TU Delft, I had more time to reflect on my emotions. Sometimes, I felt anxious about not being busy enough; other times, I was content to go with the flow. The solitude sometime allowed me to appreciate the beauty of the world peacefully, sometime it left me feeling empty and despondent. In this solitude, I learned to cherish companionship more deeply and to value the moments I was living through. Besides that, although much of the coursework overlapped with my previous studies, I still gained new knowledge and, more importantly, was exposed to different ways of thinking from classmates from various countries.

I want to thank my friends Yunxian, Weiming, Ke, and Fan, for the invaluable companionship and sense of belonging you provided. My memories of this study abroad experience are filled with thoughts of you. I am also deeply grateful to my family for their unwavering support—I love you all. To my dearest friends, Wen and Shiwei, your companionship from afar has been the warmest gift. I also want to thank myself. Even though I didn't spend much time on my studies, and I didn't achieve the grades I wanted, I courageously made it through these two years. For me, this was merely an experiment, a break, and I am willing to accept whatever the outcome may be. All the experiences, thoughts, had become a part of who I am now and who I will be in the future. I celebrate myself for that.

Special thanks to Malte for offering me the opportunity and assistance with this thesis. I'm glad that through this research, I was able to learn about the workings of material flow models, knowing the material consumption in photovoltaic systems, and aluminum production. This thesis has been a valuable experience for me, both in terms of knowledge and personal growth. I also want to thank Chengjian for providing me with significant help and guiding my thoughts—your patience and guidance have been greatly appreciated.

The end of one journey marks the beginning of another. With anticipation for the future, I am ready to embark on this new chapter, just as I was two years ago.

Abstract

As the global energy sector shifts towards electrification to achieve a net-zero future, the demand for photovoltaic (PV) systems is expected to surge. By 2050, an estimated 63.4 TW of installed PV capacity will be required, with annual additions reaching up to 4.5 TW, to help limit global temperature rise to below 2°C. This significant expansion will substantially increase the demand for aluminum, a key material in PV systems. This study presents a material flow model to analyze aluminum demand and its environmental impacts in global PV systems from 2020 to 2050. The model captures the flow of aluminum through module frames, mounting systems, and inverters, while also considering the influence of various parameters such as PV efficiency, aluminum intensity of components, component lifetimes, and recycling rates. In the baseline scenario, cumulative aluminum demand is projected to reach 830.98 mega tonnes (Mt) by 2050. However, through advancements in PV efficiency, reduction in material intensity, extension of component lifetimes, and improvement in aluminum recycling rates, the demand could potentially be reduced to 568.65 Mt.

Despite these mitigation strategies, the rapid growth in PV deployment poses significant challenges for aluminum supply, as global aluminum production is projected to be only 176 Mt by 2050, suggesting substantial supply pressures. Moreover, aluminum production is both energy- and carbon-intensive, contributing significantly to global greenhouse gas emissions. The cumulative emissions associated with aluminum use in PV systems are projected to reach 3534 Mt CO_2eq from 2020 to 2050, highlighting the urgent need for decarbonization in aluminum production. The study emphasizes the critical importance of developing a closed-loop aluminum recycling system for PV components to form a circular economy, which could reduce primary aluminum demand and associated emissions. By adopting a multi-faceted approach, including improvements in technology, materials, and recycling processes, the PV industry can mitigate its environmental impact and support the global transition towards sustainable energy.

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Chapter 1

Introduction

This chapter provides an introduction to the background of the study and provides a basis for the subsequent interpretation of the methodology. Through the content of this chapter, the reader will be able to understand the reality on which the research is based, and thus understand the logic and purpose of the research. The future development prospects of photovoltaic(PV) technology are introduced in section 1.1. Section 1.2 shows the general situation of aluminum consumption in PV systems. In section 1.3, the production of aluminum is introduced. Section 1.4 provides a literature review on aluminum demand of PV systems and the production of aluminum. The research questions of this study are listed in section 1.5. Finally, the purpose of the study is demonstrated in section 1.6.

1.1 Photovoltaic system demand in the future

The global energy landscape is undergoing a significant transformation, with solar PV playing a pivotal role in this transition. In 2022, the cumulative installed capacity of PV systems surpassed 1 TW for the first time. In this year, although PV power generation accounted for just 4.5% of the global electricity production, the newly installed PV capacity accounted for 56% of the global electricity generating capacity added [1]. By the end of 2023, the cumulative installed capacity of PV systems reached 1.4 TW, with 345.5 GW installed in 2023 [2]. The significant growth has positioned PV energy as the leading renewable energy technology in terms of installed capacity.

Considering the technological advancements, environmental considerations, especially the significant reduction in the cost of PV technology leads us to believe that this growth trend will continue. In the global energy transition pathway proposed by Bogdanov et al. in 2021, which includes broad electrification of end-use sectors such as transportation and heating, the installed capacity of PV systems is projected to reach 63.4 TW by 2050. These PV systems would generate 104 PWh of electricity, accounting for 69% of global electricity production at that time [3].

1.2 Aluminum consumption in photovoltaic systems

The main components of the PV system are PV modules, mounting systems, inverters and power distribution equipment. Off-grid PV systems also need to be equipped with energy storage systems, while grid-connected PV systems have additional grid connection equipment. In PV systems, aluminum is mainly used in the manufacture of frames for PV modules, mounting systems and enclosure for inverters. According to Bödeker et al.[4] , 72% of the aluminum used in the PV industry is consumed in construction and mounting facilities, with panel frames and inverters consuming 22% and 6%, respectively. In fact, solar cells also contain small amounts of aluminum, inverters may use aluminum heat sinks, while aluminum cables are also used in some power transmission. These sectors account for a very small proportion of the total aluminum consumption of PV system. Moreover, the values can vary greatly depending on the PV cell type and the design of inverter. In particular, the aluminium consumption of the system still depends on the mounting structure and frame employed, rather than the cell. Therefore, the study tends not to take the cell's aluminum consumption into account, so as to avoid an overly complex classification of photovoltaic systems. Module frames, mounting structures, and inverters are the major sources of aluminum consumption. Despite their significance, only few research focused on them. Consequently, this study aims to focus on these critical aspects.

The aluminum used in PV systems is primarily aluminum alloy, with the most commonly used types being 5754, 6063, 5052, and 6061 alloys [5]. Alloy 5754, 6063, 5052 are mainly used for the frames and supports of PV modules, while the last one is commonly used for the casing of inverters [6]. Alloy 5754 and 5052 primarily consist of aluminum with magnesium as the main alloying element, while the other two alloys contain magnesium and silicon as their primary alloying elements. The aluminum content in these alloys typically ranges from 95% to 99% [7, 8, 9].

Alloy 5754 offers excellent corrosion resistance, making it suitable for long-term outdoor use in PV modules [10]. It provides sufficient structural support while maintaining a lightweight profile, facilitating easier installation and transportation. Its good machinability and weldability allow it to be manufactured into various complex frame shapes. Alloy 6063 has slightly lower strength and corrosion resistance compared to 5754, but it excels in extrusion performance, making it easy to extrude into profiles with complex cross-sections [8]. This makes it well-suited for manufacturing frames and supports. Its good thermal conductivity also aids in the heat dissipation of PV modules. Similarly, alloy 5052 is suitable for module frame due to its thermal conductivity and durability [11]. Alloy 6061 is characterized by its high strength and excellent thermal conductivity, making it suitable for use as the material for inverter casings [6]. These aluminum alloys play crucial roles in enhancing the durability, structural integrity, and performance efficiency of PV systems, ensuring they meet the demanding requirements of outdoor solar installations [12].

1.2.1 Aluminum consumption in module frame

At present, the majority of PV modules are framed to safeguard the edges of the glass and provide mounting points for the modules. Aluminum's potential for indefinite recycling without degradation of its properties makes it an environmentally friendly choice for PV module frames. Aluminum is present in the frames of PV modules in the form of alloys, such as AlMg3. The specific choice of aluminum alloy, such as A5052 or A6063-T6, is determined based on the desired mechanical and chemical properties for the frame [13].

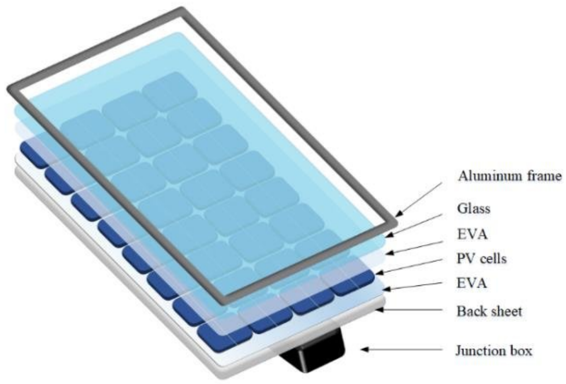


Figure 1.1: PV module structure [14]

Although aluminum remains the predominant choice due to its favorable properties such as light weight, high strength, and corrosion resistance [15], there are other choices for the material of PV module frames. In some cases, steel is used for PV module frames, especially in applications where higher strength is required or cost considerations make steel a more viable option. For floating photovoltaic (FPV) systems, high-density polyethylene (HDPE) can be used due to its durability and buoyancy [15]. It is clear that aluminum alloys dominate the module frame market. The use of steel and HDPE is niche, catering to specific applications. Base on the market status, only aluminum module frame is discussed in this research.

From the perspective of aluminum savings, frameless modules represent a significant innovation in the PV industry. Frameless modules eliminate the need for aluminum frames, which has been shown to reduce the life-cycle global-warming potential of PV modules by 12% [16]. This design not only reduces material demand but also aligns with the growing emphasis on sustainable and eco-friendly energy solutions. As of recent data, frameless modules accounted for a small but growing segment of the market, with a 6% share in 2018 [17]. However, the transition to frameless modules faces challenges. These include ensuring the durability and longevity of modules without the structural support of frames and overcoming market inertia towards traditional framed designs. The ITRPV actually reduced its predicted uptake of frameless modules in its 2021 report compared with previous years, suggesting a reduced confidence in the transition to frameless modules [18].

In fact, after years of practical application, frameless double-glass modules and rubber snap frames have phased out of the market. Frameless double-glass modules aimed to improve mechanical strength by using double-glazed glass, theoretically eliminating the need for an aluminum alloy frame [19]. However, challenges arose during real-world operations. Uneven lamination stress, mechanical stress, and thermal stress at convergence points often led to frameless double-glass modules bending, deforming, and developing hidden cracks in cells or even glass breakage [20]. These issues resulted in revenue loss for PV power stations despite promising laboratory test results.

Similarly, rubber snap frames, structurally resembling frameless double-glass modules, faced controversy due to component deformation issues [21]. Moreover, their organic rubber plastic frame struggled to match the 20-25 year service life of standard PV modules, exhibiting poor environmental friendliness and significant environmental pollution throughout their life cycle. These factors conflict with green and sustainable development principles.

1.2.2 Aluminum consumption in mounting structure

The mounting system in PV systems refers to the structures that support and mount solar panels, typically made from aluminum in various shapes and forms such as brackets, rails, and connectors. Aluminum is primarily used in PV systems as the main material for support structures, such as the main components of mounting brackets and rail systems.

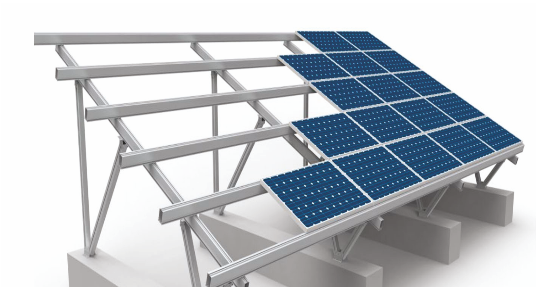


Figure 1.2: PV mounting structure [22]

Aluminum is chosen for PV mounting systems due to several advantageous characteristics: firstly, it exhibits excellent corrosion resistance, capable of withstanding outdoor conditions including moisture and oxidation. Secondly, its lightweight nature facilitates easier handling and installation, reducing structural loads on buildings. Additionally, aluminum is highly workable and ductile, allowing for the manufacture of complex components to meet diverse installation requirements.

Recent advancements in research have focused on reducing aluminum consumption in installation systems while maintaining stability and reliability. Optimization of designs and manufacturing processes has enabled researchers to minimize the amount of aluminum used. By optimizing the design of support structures, researchers have been able to reduce the amount of aluminum required without compromising stability. This includes enhancing the strength of critical connection points and improving overall structural designs [23].

Apart from aluminum, there are alternative materials suitable for PV installation systems, each with specific advantages in lifetime. For instance, magnesium alloys are preferred in cold climates due to their high strength-to-weight ratio. Stainless steel is favored for its excellent corrosion resistance in marine environments. Polymer composites, on the other hand, are gaining attention for their UV resistance and lightweight properties. However, these technologies have not yet been commercialized due to their high cost [15]. At present, the common material of PV support system in the market is aluminum or stainless steel. Especially for ground-mounted PV installations, galvanized steel structures are often preferred due to cost considerations, though aluminum's lower shipping costs and ease of assembly could make it a viable option for large-scale installations as well.

1.2.3 Aluminum consumption in inverters

The composition of inverters includes a variety of materials, with aluminum accounting for a significant portion. Although aluminum is not used in the internal electronic components, it is commonly employed in the casing or enclosure of inverters [4]. The aluminum casing acts as a heat sink, dissipating the heat generated during the inverter's operation, which is crucial for maintaining efficiency and prolonging the inverter's life. The durable and corrosion-resistant nature of aluminum also protects the inverter from environmental factors, further contributing to a longer service life.

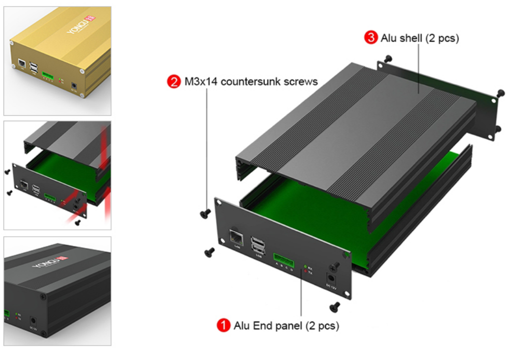


Figure 1.3: The aluminum enclosure of inverter [24]

The selection of aluminum over other materials, such as steel, is primarily due to its lighter weight, higher strength, and enhanced corrosion resistance, which is achieved through the formation of a thin oxide layer. These properties make aluminum an ideal choice for PV systems, ensuring that the systems are not only efficient but also durable and capable of withstanding various environmental conditions.

1.3 Aluminum production

1.3.1 Primary aluminum production

While aluminum is a highly versatile and recyclable metal, primary aluminium production is an energy-intensive process [25].A typical primary aluminum production consists of three processes:Bauxite mining, Alumina Refining and Aluminum smelting[26]. Alumina Refining transforms the bauxite into aluminum oxide, usually the Bayer process is used.Aluminum smelting converts aluminum oxide into aluminum via electrolysis (Hall–Héroult). This is the most energy intensive process and most emission intensive process.

Decarbonizing electricity and reducing direct emissions are two key approaches to mitigate the carbon footprint of primary aluminum production. In particular, electricity-related emissions dominate the 75% of sectoral emissions that smelting represents [27]. This is the source with the greatest variation across the industry (depending on the smelter power mix) - historically dominated by hydropower, but now increasingly by coal and gas combustion [28]. The accelerated deployment of Carbon Capture, Utilization, and Storage (CCUS) in the primary aluminum production process is equally important.[29].

Another potential approach to reducing greenhouse gas emissions in primary aluminum production is the elimination of direct emissions from the electrolysis process. Notably, emissions reduced through this pathway account for approximately 15% of the industry's total global emissions [27]. Feasible technological changes to achieve this include replacing carbon anodes with inert anodes in the smelting process, utilizing hydrogen combustion, or using renewable energy technologies like solar thermal to replace fossil fuels for heat and steam generation [30, 27].

1.3.2 Secondary aluminum production

Secondary aluminum refers to aluminum recycled from scrap, the production process includes scrap collection and sorting, melting and refining. Aluminum scrap is collected and sorted to separate it from other materials, then be melted in furnaces and refined to remove impurities. The refined aluminum is then cast into forms suitable for further use. Secondary aluminum production uses significantly less energy compared to primary production, making it a more environmentally friendly option [31].

Using recycled aluminum production to replace part of primary aluminum production can reduce the consumption of alumina and alleviate the shortage of aluminum. The average energy consumption for primary aluminum production is 13-17 kWh/kg [32], while the energy demand for recycling of aluminum product is just about 5% compare to it [33]. However, Padamata et al.[34] reveals that it generates high volumes of environmentally hazardous salt slag, the problem needs to be considered in recycled aluminum production. It also faces challenges related to the quality and variety of scrap available, which can affect the efficiency and output of the recycling process [35].

Recycling of aluminum in photovoltaic systems

The recycling of aluminum does not degrade its properties, which means it can be recycled indefinitely [36]. However, the recycling of aluminium alloys can be more complicated [37]. Although most PV module frames use the aluminium 5754 alloy (AlMg3), 6000 series (with Mg and Si) can also be used. Whilst it is straightforward to use End of Life (EoL) frames of both series to remanufacture 6000 series frames, use of 6000 series material to manufacture 5000 series frames is more expensive and requires more complex separation and analysis technology [5]. Recycling aluminium frames has the highest economic benefit, at approximately $2.7/m2 module, and recycling aluminium frames can reduce the life-cycle global-warming potential (kg CO2-eq) of PV modules by 12% [16].

In the recycling facilities, discarded PV systems are dismantled, and the aluminum frames and supports are separated from other components. After this, there are two pathways for recycling the aluminum. One pathway involves sending the discarded aluminum to a smelting furnace for melting [38]. During the smelting process, temperature control and the addition of appropriate alloying elements are necessary to ensure the quality of the final product. The molten aluminum is then cast into new ingots, which can be further processed into new aluminum components for use in new systems. This pathway is suitable for aluminum parts that have significant wear and environmental corrosion. The other pathway involves cleaning, repairing, and reprocessing the discarded components (such as re-drilling, cutting, and straightening) before they are used in new PV systems [39, 40]. This pathway is suitable for aluminum parts that are in relatively good physical condition and structurally intact.

Over the past few years, the PV industry has rapidly expanded, and most PV equipment is still in use [41]. By the end of 2016, the total global photovoltaic (PV) waste amounted to 250,000 metric tonnes and is anticipated to grow significantly in the future [42]. As a result, effective EoL management strategies for PV modules need to be developed. Currently, the majority of EoL modules are disposed of in landfills, largely because recycling processes for PV modules are not yet economically viable and regulations in many countries remain underdeveloped [43].

In other aluminum intensive industries, such as window and door frames manufacturing, most discarded aluminum is recycled through remelting [44]. In PV systems, the lifetime of components typically depends on the solar cells. Some PV modules that have reached the end of their lifetime may have aluminum frames suitable for direct reprocessing. Mounting systems might also be in good condition but need reconfiguration due to the replacement of different PV modules [41]. Therefore, both recycling pathways can be applied to aluminum waste from PV systems. The direct reprocessing pathway eliminates the smelting step, reducing environmental impact, but it is currently more costly [45]. Manufacturers, considering economic factors, usually opt for the remelting method to recycle aluminum.

1.4 Literature review

1.4.1 Literature on Aluminum consumption in photovoltaic systems

A PV system contains PV modules, mounting structure, inverter, storage system and other components like cables, connectors. The main components of a typical PV system, except the panels, are defined as the "balance of system" (BOS) [46]. Aluminum is a fundamental component in PV systems, employed in various components such as mounting structure, frames, supports, and electrical connections. With the rapid expansion of the PV industry, it can be predicted that the demand for aluminum will increase greatly. Several studies have noted this potential problem and have calculated and predicted aluminum consumption in PV systems. This section explores recent literature on the quantity and patterns of aluminum consumption in PV systems.

Lennon et al.[18] predicted that growth to 60 TW of PV could require up to 486 Mt of aluminium by 2050. The CPP (Cost Per Power) is 8.1 Mt/TW, where the cost means the aluminum consumption in weight. They obtained the global capacity and added annual capacity from ITRPV's broad electrification scenario and its path towards a net zero emission economy in 2050. They assumed the PV market comprises rooftop and utility-scale systems, and only rooftop installations use aluminium in their mounting. The module efficiencies are predicted to increase from 20.5% in 2020 to 21.9% in 2030, and keep the same rate from 2030 to 2050. The size of the modules are predicted to be 2.5 m^2 and 2.0 m^2 for utility-scale modules and rooftop modules.

Underwood et al. [47] used a learning Curve for PV toward net-Zero emissions by 2050 to estimate the CPP of metals in PV systems. Aluminum consumption in the PV industry is primarily from module frames, the inverter, and mounting. The total aluminum CPP varies significantly depending on whether the array is rooftop (13.6–22.6 Mt/TW) or ground-mounted (6.5–9.7 Mt/TW). Aluminum usage for inverters is similar between roof-top and utility systems, around 1–2.75 Mt/TW, depending on size. It is noted that these values are significantly higher than older inverters before 2004, which relied more heavily on steel. Due to aluminum's lower density, roof-top consumption is heavily dominated by aluminum mounting (7.5–13.7 Mt/TW). Ground-mounted systems however typically use steel, due to its durability and low cost, without weight concerns. Such a value is within range for a roof-top PV system with aluminum mounting, but substantially higher than that of utility-scale systems. The aluminum consumption at the cell level is insignificant.

The World Bank study[26] assumed a static aluminum consumption of 186 Mt, which is based on the REmap scenario of 8.5 TW. The CPP is 22 Mt/TW. It used data from IEA Energy Technology Perspectives report 2016 and 2017 and the International Renewable Energy Agency's (IRENA) 2019 Global Energy Transformation: A Roadmap to 2050, to identify the amount of minerals needed.

1.4.2 Literature on environmental impacts of Aluminum production

The primary production of aluminum, which includes bauxite mining, alumina refining, and aluminum smelting, is responsible for significant environmental burdens. Key environmental impacts include high energy consumption, greenhouse gas (GHG) emissions, and solid waste generation [27]. For instance, the electrolysis process in aluminum smelting is a major contributor to environmental burdens, particularly when powered by fossil fuels like coal and natural gas [48, 49].

Ma et al.[50] compared Pedersen and Bayer processes using life cycle assessment. The results showed that Bayer process has the best performance for climate change, about 30% reduction compared to the Pedersen process, while the Pedersen has benefits for mineral scarcity –mainly attributable to the coproduction of pig iron.

Saevarsdottir et al.[30] supposed that the energy consumption for all melters should be reduced, particularly for those with electricity from fossil fuels. Besides that, better annode effect control, shorter alumina underfeeding periods and higher and more uniform average alumina concentrations in the electrolyte contribute to the mitigation of PEC emission intensity.

Balomenos et al.[51] described the sustainable development routes for Bayer process and Hall–Héroult process. The utilization of red mud waste as industrial feedstock for pig iron and mineral wool production can significantly increase the total exergy efficiency of the Bayer process, and eliminate the solid wastes. The high energy and exergy cost of Hall–Héroult process is related primarily to the cost of electricity generation. Therefore, an effective emission reduction strategy is to use renewable energy to replace fossil energy power generation.

Recycling aluminum significantly reduces environmental impacts compared to primary production. The energy required to produce recycled aluminum is only 5% of that needed for primary aluminum, and recycling can save more than 94% of the potential impacts related to global warming and fossil fuel depletion [52].

1.5 Research question

Aluminum is a metal resource with a high emission intensity during its production process. In previous material flow analyses of PV systems, aluminum has been identified as one of the most consumed material [53]. Existing research highlights the significant demand for aluminum driven by the rapid expansion of PV systems [18, 41]; however, these studies often rely on simplified assumptions, without conducting sensitivity analyses on key parameters or discussing potential mitigation strategies. The demand for aluminum in PV systems is influenced by various factors, including system capacity, components type, and installation area. From a global perspective, factors such as the total capacity of PV systems, average PV efficiency, material intensity of PV devices, and recycling rates of both components and materials, collectively determine the aluminum demand for global PV systems. This study aims to explore the following questions by applying different assumptions to the material flow models of PV system components and the aluminum they contain:
a) By 2050, what will be the global aluminum demand for PV systems?
b) What factors influence aluminum demand in PV systems?
c) What is the potential for reducing aluminum demand in PV systems?
d) What are the greenhouse gas emissions of producing the aluminum needed in PV systems?

1.6 Research goal

The goal of this study is to estimate future material demand and associated greenhouse gas emissions of aluminum used in PV systems up to 2050, so that provide information and reference for research on the material flow analysis and global warming potential calculation of PV systems. Multiple scenarios was built for analysing the impact of four key parameters (PV efficiency, material intensity, components' lifetime and Al recycling rate) on the results. The estimation built six scenarios, including a baseline scenario, four optimistic scenarios and a combination scenario. In each optimistic scenario, the conservative assumption of one of the four key parameters is replaced by an optimistic one, so that the mitigation potential brought by this parameter could be discussed. The combination scenario applies optimistic assumptions on all of the four key parameters. Its results shows the comprehensive potential on mitigating the aluminum demand and associated environmental impacts in global PV systems.

Chapter 2

Research Methodology

This chapter is an explanation of the methodology of the study. This study focuses on the material use and associated environmental impact of aluminum in PV systems. Material flow analysis (MFA), sometimes referred to as substance flow analysis [54], is used to observe the aluminum flow. The environmental impact is calculated base on the aluminum flow and emission intensity. The research scope is introduced in section 2.1. The model and calculation are detailed explained in section 2.2. This study use multiple scenarios for aluminum demand projection, the different assumption used as well as the data source are showed in section 2.3. The validation of model is shown in section 2.4

2.1 Research scope

Time scope

The study period spans from 2020 to 2050. The Paris Agreement aims to limit the increase in global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C. Scientists believe that to achieve this goal, the world must reach net-zero emissions by 2050, making this year a crucial milestone for global energy transition. The starting point of 2020 was chosen because around this time, PV systems began to be deployed on a large scale. Moreover, combined the historical data from 2020 to 2024 with the learning rate (LR), this study is able to make assumptions about future changes in key parameters.

System scope

PV systems can be categorized into various types based on the technology used, scale, and application scenario. To study the flow of aluminum within PV systems, special attention needs to be given to the installation structures. According to the installation systems used, PV systems can be divided into ground-mounted PV systems, rooftop PV systems, building-integrated photovoltaic systems (BIPV), and floating PV systems.

Ground-mounted PV systems require stable foundations and supports on the ground, leading to higher aluminum usage compared to rooftop PV systems. Some tracking systems also increase aluminum consumption due to their mechanical and control components. For ground-mounted systems, alternative materials like stainless steel are often chosen over aluminum for cost control, despite being heavier, because of their higher strength and durability. Stainless steel is a better choice for PV systems in high wind pressure or extreme climate conditions.

Rooftop PV systems are divided into slanted-roof and flat-roof PV systems. Slanted-roof PV systems leverage the roof's angle, directly mounting PV modules onto the roof. However, the diverse angles and structures of slanted roofs usually require customized mounting systems. These complex installation systems require more connectors, fasteners, and reinforcement components, which increase aluminum consumption. In contrast, flat-roof PV systems have simpler mounting structures, generally needing only adjustable supports to set the angle of the PV modules. The standardized bracket design reduces aluminum usage.

BIPV systems incorporate PV modules as part of the building materials, integrating them directly into roofs, walls, or windows. Therefore, the aluminum consumption of BIPV systems should be considered part of the building material consumption and is not included in this study.

Floating PV systems use floats and connectors to create a stable platform on the water surface, with mounts used to secure PV modules on the floats, typically using aluminum alloys or stainless steel. Since floating PV technology is still niche with a low degree of market penetration and lacks comprehensive market share data, it is not included in this study.

As introduced in section 1.2, module frames, mounting structures and inverter enclosures are the main body of aluminum consumption in PV systems. Thus, the subjects of the study are Aluminium used in mounting structure, module frame and inverter enclosure of open-ground PV systems and roof-top PV systems.

2.2 Research model

Figure 2.1 illustrates the flow of aluminum within global PV systems. Aluminum enters the system through the installation of PV components such as frames. The aluminum contained in operational PV systems constitutes the stock. Each year, as some PV components deployed in previous years reach the end of their lifetime, the aluminum they contain enters the discard pool. Depending on the recycling rate for that year, some of the discarded PV components are processed into the recycling system, where the aluminum is re-melted. The re-melted aluminum is then used in new PV components, re-entering the system within the year. All of the re-melted aluminum are assumed to used in PV system, while no secondary aluminum from other resources comes to the system. The total aluminum inflow for a given year, minus the inflow of secondary aluminum, represents the demand for primary aluminum for that year.

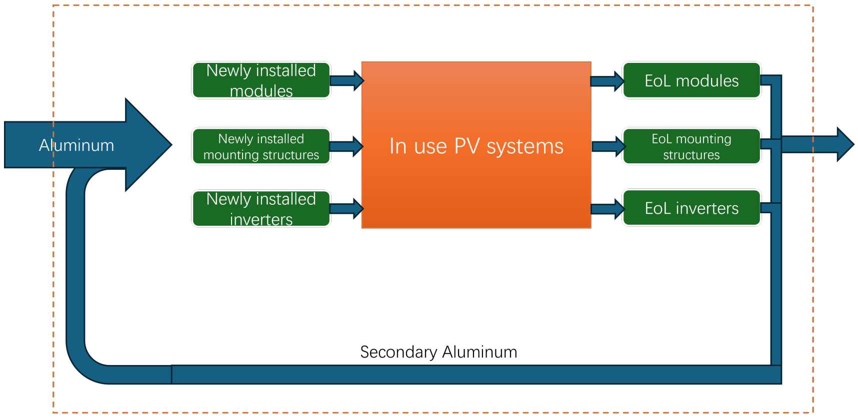


Figure 2.1: Diagram of the flow of aluminum in PV system

Figure 2.2 shows a stepwise calculation scheme of this study. The blue box contains the data inputs, the yellow box contains the results related to aluminum demand, and the orange box contains the results related to environmental impact. The white box includes the information and parameters necessary for the calculations, among which the four highlighted parameters were used for scenario analysis in this study.

The first step of this study is to obtain the expected PV installation in each year from 2020 to 2050. Using data on PV installation and the market shares of different types of PV systems, the annual demand for various PV components can be determined. Subsequently, by analyzing the flow of PV components as products within the system and considering the aluminum intensity of these components, now it is sufficient to calculate the inflow, stock, and outflow of aluminum in the system. It is important to note that the aluminum intensity for inverters is measured in kg/kWp, meaning the aluminum consumption is directly related to the installed capacity. In contrast, the aluminum intensity for module frames and mounting systems is measured in kg/m^2, meaning the aluminum consumption is related to the installation area. Therefore, for module frames and mounting systems, it is necessary to first convert the capacity cohorts into area cohorts using the PV efficiency. Finally, by applying the annual aluminum outflow and the recycling rate, the inflow of secondary aluminum and primary aluminum can be estimated. Combining the aluminum demand with emission intensity of aluminum production, the global warming potential could be estimated.

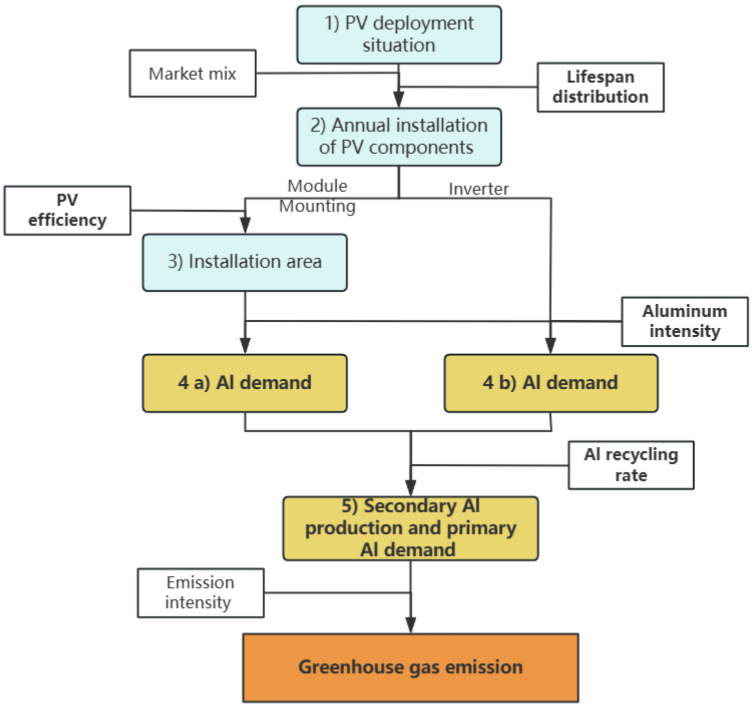


Figure 2.2: Calculation model framework

2.2.1 Photovoltaic deployment and market mix of components

The broad electrification scenario indicates that the total capacity of installed PV needs to be at least 60 TWp by 2050 with annual installations of 4.5 TWp being required [3, 55]. This ambitious target is projected because of the extremely low cost of PV generated electricity compared to all other energy sources. A logistic curve was fitted to the given points in the scenario and was used as the PV installation curve until 2050, as shown in figure 2.3. Logistic growth curves were applied in previous studies to estimate PV deployment [56]. The annual PV shipments are calculated with an assumed average lifetime of 25 years for all PV systems.

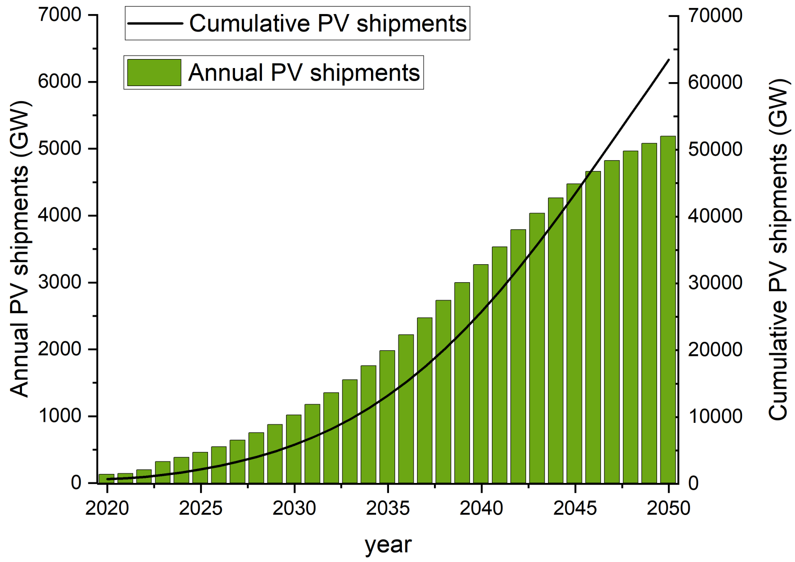


Figure 2.3: Expected PV deployment under broad electrification scenario.

In section 2.1, the classification of PV systems is introduced. Lennon et al. [18]applied a 50% market share for rooftop PV systems and the remaining 50% for utility-scale PV systems globally in their study. We follow this assumption. Assuming all utility-scale PV systems use open-ground mounting systems, they can be divided into two categories based on the primary materials used: aluminum and stainless steel. The market shares of different mounting systems are relatively complex. We consulted the Solar Mounting System Directory [57] and compiled statistics based on detailed product information. The directory lists 812 open-ground mounting systems, with 220 explicitly stating that their support structures are made of aluminum, while 231 use stainless steel. Based on this data, We assumed that 48.8% of the utility-scale PV systems use aluminum open-ground mounting systems while stainless steel open-ground mounting systems account for 51.2%.

It's worth noting that some products indicate they use both stainless steel and aluminum, which is a common practice. Mounting systems include many small components besides the support structure; even within the support structure, there are distinctions between rails and supports. Different components have different strength requirements and therefore use different materials. However, different product designs use different materials, and related information is difficult to obtain and compile. From a global PV system perspective, making detailed and accurate assumptions about material consumption is challenging. Therefore, although it is an interesting topic, this study only discusses mounting systems with only one material.

Rooftop PV systems use either flat-roof mounting systems or slanted-roof mounting systems. Similarly, based on the Solar Mounting System Directory's statistics, there are 640 flat-roof mounting systems and 738 slanted-roof mounting systems listed [57]. Thus, this study assumes that within rooftop PV systems, the share of flat-roof mounting systems is 46.4%, while slanted-roof mounting systems account for 53.6%. Regarding the market share of PV modules with different frame types, ITRPV's results 2021 reported reports that frameless modules accounted for 7% of the market in 2020. Base on the situation illustrated in section 1.2.1, We applied a constant share of frameless module from 2020 to 2050. Both open-ground mounting systems and rooftop mounting systems are designed to accommodate both framed and frameless PV modules. Thus the share of frameless module is 7% in each type of PV system.Table 2.1 shows the market shares of components in the global PV market.

Table 2.1: Market share of PV components

Type	Market share
Modules	
frameless	7%
Al framed	93%
Mounting systems	
open-ground(made of Al)	24.4%
open-ground(made of steel)	25.6%
flat-roof	23.2%
slanted-roof	26.8%
Inverters	
utility-scale	50%
residential	50%

2.2.2 Photovoltaic components flow calculation

Given the projected deployment of PV systems and market mix of components, we can derive the annual flow of components using the principle of material balance and the distribution of component losses. One thing should be noted is that the calculation of inverters flow and the calculation of mounting structures and modules flow is different, because the demand for inverters in PV systems is usually measured in terms of capacity in unit of GWp, while the demand for modules and mounting structures is usually measured in area (this study does not assume the size of a single product and therefore cannot calculate the number of products required) in unit of m^2 , so the calculation of PV components flow is divided into two categories.

Inverters flow calculation

The principle of material balance is represented by equation (2.1). We assume that the first year of the study period (2020) is the initial year for PV system installations, denoted as year 1, with the inflow of all components for that year representing the initial stock ($C_{in,i}[1] = C_{stock,i}[1]$). Starting from the second year, some of the PV components that were deployed in previous years will reach their EoL and exit the system, as shown in equation (2.2b).

$$C_{in,i}[t] = C_{stock,i}[t] - C_{stock,i}[t-1] + C_{out,i}[t] \tag{2.1}$$

$$C_{out,i}[t] = \begin{cases} 0 & \text{for } t = 1 \quad (2.2a) \\ \sum_{t'=1}^{t-1} C_{out,i}[t, t'] & \text{for } t \geq 2 \quad (2.2b) \end{cases}$$

Where $C_{in,i}[t]$ is the annual capacity inflow (demand) of component type i in year t, in the unit of GWp, $C_{stock,i}[t]$ is the capacity stock of component type i at year t in the unit of GWp, $C_{out,i}[t]$ is the annual capacity outflow of component type i in the unit of GWp, which represent the annual end-of-life components that were deployed in various years before year t. $t'(t' < t)$ is the year in which the component was deployed. $C_{out,i}[t, t']$ indicates the capacity of component type i which was deployed in year t' and reach the end of life in year t in the unit of GWp.

The lifetime losses reflect a random loss event in the components service life. In this research, the lifetime losses are modelled using a two-parameter Weibull lifetime probability distribution function as shown in equation (2.3) and is routinely applied in reliability and failure analysis, as conducted in current literature [41, 58, 59].

$$W_c(r) = 1 - exp\left(-\frac{r}{\beta}\right)^{\alpha} \quad (2.3)$$

$$C_{out,i}[t, t'] = C_{in,i}[t'] \times W_c\left(t - t'\right) \quad (2.4)$$

Where $W_c(r)$ denotes the percentage discarded from a cohort after r years of use, $W_c(t - t')$ presents the percentage discarded in year t of the deployment in year t', α is a shape parameter controlling failure rate, and β is the mean lifetime of the cohort, which is the lifetime expectation of components in this study. We applied different assumed lifetimes to the various types of components, they can be found in section 2.3.4. We chose a conservative α value of 2.49 as reported in the early loss scenario by IRENA and IEA-PVPS 2016 reports [60].

Modules and mounting structures flow calculation

The flow of one kind of module or mounting structure depending on the capacity of the PV systems appling them. With the equations used for inverters flow calculation, the flow of PV system appling component type i (i = module or mounting structure) could be calculated.

To calculate the aluminum flow in module frames and mounting structures, it is necessary to determine the annual installation area of these components, which directly influence the aluminum demand. After the calculation of the annual demand for PV capacity appling component type i in the unit of GWp, which refers to the peak power output of a PV system under standard test conditions (STC). The PV efficiency could be used to convert capacity cohorts into area cohorts, as formula (2.5) has shown.

$$A_i[t] = \frac{C_{in,i}[t] \times 10^9}{\eta[t] \times I_{STC}} \tag{2.5}$$

Where $A_i[t]$ is the installation area of component type i (i = frame or mounting structure) in year t in the unit of m^2, $\eta[t]$ is the PV efficiency in year t. I_{STC} is the irradiance level under STC in the unit of W/m^2, its value is 1000 W/m^2. We discuss two different scenario for PV efficiency, which is described in section 2.3.2.

2.2.3 Aluminum flow calculation

Using the aluminum intensity for each component, the annual aluminum inflow, which is the annual aluminum demand, could be calculated. Three components in PV systems are considered in this model. For module frames, the annual aluminum demand calculation follows equation (2.6a). For mounting systems, the calculation follows equation (2.6b). The aluminum demand of frames and mountings depend on the installed PV area and their aluminum intensity. For inverters, the calculation follows equation (2.6c), the aluminum demand depend on the installed capacity and components' aluminum intensity.

$$M_{Al,in,i}[t] = \begin{cases} \dfrac{A_i[t] \times AI_{i,frm}[t]}{10^9} & \text{for } i = frame \quad (2.6a) \\ \dfrac{A_i[t] \times AI_{i,mtn}[t]}{10^9} & \text{for } i = mounting \quad (2.6b) \\ \dfrac{C_{in,i}[t] \times AI_{i,inv}[t]}{1000} & \text{for } i = inverter \quad (2.6c) \end{cases}$$

Where $M_{Al,in,i}[t]$ is the mass of aluminum inflow of component type i in year t in the unit of mega tonne (Mt). $AI_{i,frm}[t]$ is the aluminum intensity of component type i (frame) in year t in the unit of kg/m^2. $AI_{i,mtn}[t]$ is the aluminum intensity of component type i (mounting) in year t in the unit of kg/m^2. $AI_{i,inv}[t]$ is the aluminum intensity of component type i (inverter) in year t in the unit of kg/kWp. We applied different learning rates of the aluminum intensity mitigation, which is described in section 2.3.3.

With the principle of material balance and the distribution of component losses, the flow of aluminum in global PV system could be derived. The equation used are shown below. The parameter definitions are similar to those for capacity calculations.

$$M_{Al,out,i}[t] = \begin{cases} 0 & \text{for } t = 1 \quad (2.7a) \\ \displaystyle\sum_{t'=1}^{t-1} M_{Al,out,i}[t, t'] & \text{for } t \geq 2 \quad (2.7b) \end{cases}$$

$$M_{Al,st,i}[t] = M_{Al,in,i}[t] + M_{Al,st,i}[t-1] - M_{Al,out,i}[t] \tag{2.8}$$

Where $M_{Al,out,i}[t]$ is the mass of aluminum outflow of component type i in year t in the unit of Mt, $M_{Al,st,i}[t]$ is the mass of aluminum stock of component type i in year t in the unit of Mt.

Recycling aluminum in PV systems is a significant concern. By refurbishing and reusing EoL components, we can greatly diminish the demand for manufacturing new parts, thus saving resources. Furthermore, extracting and re-melting aluminum from EoL components can further reduce the need for primary aluminum. Moreover, aluminum's secondary production requires only 5% of the energy required for primary production [61] and generates just 3–5% of the emissions from primary production [62, 63].

Two recycling pathways for the aluminum components are discussed in section 1.3.2. The pathways involving refurbishment and remanufacturing face cost-control challenges and have not yet been widely adopted. Previous studies have developed PV material flow models that consider the reuse of PV panels as secondary PV panels, and have calculated the impacts on material consumption and waste management [41]. In this study, we do not consider the recycling path where EoL PV components are refurbished for reuse. Instead, we assume that all the aluminum from the recycled components is separated and re-melted. Equation (2.9) is used to calculate this part of aluminum. knowing the quantity of secondary aluminum, we can calculate the demand for primary aluminum, and the flow of aluminum in global PV systems could be obtained.

$$M_{SA,in,i}[t] = M_{Al,out,i}[t] \times R[t] \times \delta \tag{2.9}$$

$$M_{PA,in}[t] = M_{Al,in}[t] - M_{SA,in}[t] \tag{2.10}$$

Where $M_{SA,in,i}[t]$ is the mass of secondary aluminum inflow of component type i in year t in the unit of Mt, $M_{PA,in,i}[t]$ is the mass of primary aluminum inflow of component type i in year t in the unit of Mt, $R[t]$ is the recycling rate of aluminum in year t. δ is the attrition rate of aluminum recycling.

The assumptions related to recycling rate is described in section 2.3.5. We assumed the remelting process typically incurs a loss of 3% of the aluminum ($\delta = 0.97$). This loss rate can vary depending on the type of furnace used and the condition of the aluminum scrap. For instance, electric furnaces are generally more efficient and have lower metal loss rates, around 0.5% to 3%, compared to fossil-fuel-fired furnaces, which have a higher loss rate of about 5% to 8% [64, 65]. The loss primarily occurs due to oxidation and the formation of dross during the melting process [66].

The aluminum flow of the entire PV systems is the sum of that of all components, and the cumulative aluminum demand could be calculated by add up the annual demand from 2020 to 2050, as shown in equations below.

$$M_{Al,in}[t] = \sum_{i=1}^{n} M_{Al,in,i}[t] \tag{2.11}$$

$$M_{PA,in}[t] = \sum_{i=1}^{n} M_{PA,in,i}[t] \tag{2.12}$$

$$M_{SA,in}[t] = \sum_{i=1}^{n} M_{SA,in,i}[t] \tag{2.13}$$

$$M_{Al,st}[t] = \sum_{i=1}^{n} M_{Al,st,i}[t] \tag{2.14}$$

$$M_{Al,out}[t] = \sum_{i=1}^{n} M_{Al,out,i}[t] \tag{2.15}$$

$$M_{Al,in,cum} = \sum_{t=2020}^{2050} M_{Al,in}[t] \tag{2.16}$$

$$M_{PA,in,cum} = \sum_{t=2020}^{2050} M_{PA,in}[t] \tag{2.17}$$

$$M_{SA,in,cum} = \sum_{t=2020}^{2050} M_{SA,in}[t] \tag{2.18}$$

$$M_{Al,out,cum} = \sum_{t=2020}^{2050} M_{Al,out}[t] \tag{2.19}$$

Where $M_{Al,in}[t]$, $M_{PA,in}[t]$, $M_{SA,in}[t]$, $M_{Al,st}[t]$ and $M_{Al,out}[t]$ refer to the aluminum inflow, primary aluminum inflow, secondary aluminum inflow, aluminum stock and aluminum outflow of the entire PV systems in year t in the unit of Mt, respectively. $M_{Al,in,cum}$, $M_{PA,in,cum}$, $M_{SA,in,cum}$ and $M_{Al,out,cum}$ refer to the cumulative aluminum inflow (demand), cumulative primary aluminum inflow, cumulative secondary aluminum inflow and cumulative outflow of the entire PV systems from 2020 to 2050 in the unit of Mt.

2.2.4 Global warming potential calculation

In last step we got the primary aluminum and secondary aluminum demand of PV systems in each year. By applying the emission intensity of the two aluminum production, the total global warming potential (GWP) could be calculated with the equation (2.20).

$$GWP[t] = EI_{PA}[t] \times M_{PA,in}[t] + EI_{SA}[t] \times M_{SA,in}[t] \tag{2.20}$$

$$GWP_{cum} = \sum_{t=2020}^{2050} GWP[t] \tag{2.21}$$

Where $GWP[t]$ is the global warming potential of aluminum used in PV system in year t in the unit of Mt CO_2 equivalent (Mt CO_2eq), $EI_{PA}[t]$ is the emission intensity of primary aluminum production in year t in the unit of kg CO_2eq/kg, $EI_{SA}[t]$ is the emission intensity of secondary aluminum production in year t in the unit of kg CO_2eq/kg, GWP_{cum} is the cumulative global warming potential of aluminum used in PV system from 2020 to 2050 in the unit of Mt CO_2eq.

Stolz et al. based on their updated life cycle inventories, calculated that the emission intensities of primary aluminum and secondary aluminum are 9.31 kg CO_2eq/kg and 0.849 kg CO_2eq/kg, respectively [67]. According to estimates by the International Aluminium Institute (IAI), by 2050, the world will still require 75 to 90 million tons of primary aluminum annually. To keep emissions within the industry's allocated carbon budget, the average emission intensity of primary aluminum needs to be reduced to 2.5 kg CO_2eq/kg to align with the 'Beyond 2°C Scenario' (B2DS). The emission intensity of recycled aluminum should be reduced to 0.5 kg CO_2eq/kg [27]. Therefore, this study assumes a linear reduction in the emission intensity of primary aluminum from 9.31 kg CO_2eq/kg in 2020 to 2.5 kg CO_2eq/kg in 2050, and for secondary aluminum, a reduction from 0.849 kg CO_2eq/kg in 2020 to 0.5 kg CO_2eq/kg in 2050.

2.3 Scenario settings

2.3.1 Factors in consideration

The study model indicates that within the given system scope, four main factors significantly impact aluminum consumption for PV systems: PV efficiency, aluminum intensity of components, component lifetime, and aluminum recycling rate. Higher PV efficiency means that less area is needed to meet the same capacity demand. Reducing the PV system area not only decreases land use but also reduces the number of required modules and the layout area of the installation system, thereby reducing overall aluminum consumption. Lower aluminum intensity in components means that less aluminum is required for the same capacity of PV systems. Longer component lifetime means that the components and the aluminum within them remain in the system for a longer period, thus reducing the demand for new components and aluminum. Increasing the aluminum recycling rate in PV systems can boost the inflow of secondary aluminum, thereby reducing the demand for primary aluminum.

This study uses scenario analysis to examine the impact of these factors. In the baseline scenario, relatively conservative assumptions are used for model parameters. Based on the baseline, more optimistic assumptions for the above four key factors are individually applied to create new scenarios. Thus, there will be four new scenarios, each adopting more optimistic model parameters in different aspects compared to the baseline scenario. By comparing their results with those of the baseline scenario, the impacts of these factors can be analyzed. Finally, one scenario will incorporate all optimistic model parameters, resulting in the least aluminum consumption. This scenario represents the most optimistic estimate of global aluminum consumption for PV systems in this study.

In fact, the total demand for global PV system capacity and the area of individual solar panels also impact aluminum consumption. A decrease in PV demand will inevitably reduce any investments related to PV systems. Larger solar panel areas mean that the same area of PV systems will consume less aluminum for frames and support structures. Specifically, larger PV panels have a smaller perimeter-to-area ratio, thus reducing the material required for frames and support structures. This study does not consider the impact of these two factors.

Firstly, with all other factors remaining constant, aluminum consumption is directly proportional to PV capacity. This effect is direct and significant, including it in the scenario analysis could overshadow other factors, making the analysis less effective. Secondly, in the context of energy transition, a decrease in demand for PV capacity implies an increase in demand for other energy products, which will undoubtedly lead to greater resource consumption and environmental impact elsewhere. The transfer of these resource inputs is difficult to study; therefore, this research assumes the same PV capacity demand across all scenarios, with specific assumptions detailed in section 2.2.1.

Lennon et al., in their prediction of future aluminum consumption for PV systems, used areas of 1.8 m^2 and 2.2 m^2 for rooftop and ground-mounted PV systems, respectively, assuming future area growth [18]. These parameters are based on actual products. However, globally, PV module products vary widely, with sizes differing by manufacturer, model, and type. There is no sufficient reason to choose a fixed product size to represent global PV systems. Therefore, this study uses data in kg/m^2 to represent the aluminum intensity of PV components. This metric indicates the aluminum consumption per unit area of a module, thus avoiding the need to assume module area. Additionally, the reduction in aluminum intensity results from various technological advancements, including structural light-weighting and the development of larger module designs. Hence, in this study, the impact of changes in module area is incorporated into the change in aluminum intensity.

2.3.2 Estimations on photovoltaic efficiency

The learning curve theory is widely used in current research on projecting the future trends [55, 47]. Learning Curve Theory is a concept used to understand how productivity and efficiency improve with experience over time [68]. The rapid increasing of PV deployment lead to the learning of PV technology, which result in an improvement of PV efficiency. We use a learning curve to reflect the result of learning, as shown in equation (2.22).

$$\eta_t = \alpha \times C_{st}[t]^{-\frac{ln(1-LR)}{ln(2)}} \tag{2.22}$$

Where α is the prefactor, $C_{st}[t]$ refers to the global PV stock (PV deployment) in year t in the unit of GWp, LR refers to the learning rate at which PV efficiency increases for every doubling of PV deployment.

Xu et al. built the technology development roadmap for silicon-based PV, which projected an average PV efficiency of 28.7% in 2050 [56]. With the formula above (equation (2.22)), we found that an average LR of 3.4% is needed to achieve that efficiency level in 2050. α is calculated as 0.165 accordingly. We use this set of assumptions in the baseline scenario.

A more optimistic assumption about the pace of technological progress in PV systems is applied in improvement scenario . In this scenario, a higher learning rate of 7.9%, sourced from the 2021 ITRPV report, is used [55]. The α is calculated as 0.099 accordingly. It is important to note that the PV efficiency from 2020 to 2024 remains consistent with the baseline scenario. These learning rates are applied to the assumed PV efficiency from 2024 to 2050.

2.3.3 Estimations on aluminum intensity

The assumptions of components' aluminum intensity include the assumptions of initial aluminum intensity (2020 value) and the trends from 2020 to 2050. We applied 3.98 kg/m^2 (open-ground mountings), 2.52 kg/m^2 (flat-roof mountings), 2.84 kg/m^2 (slanted-roof mountings), 0.52 kg/kWp (utility-scale inverters), 0.65 kg/kWp (residential inverters) as the initial aluminum intensity of components. These values are based on data from the ecoinvent database (version 3.10) [69]. For module frames, Lennon et al. used 1.2 kg/m^2 as the initial module frames aluminum intensity in their research, base on parameters of a 600 W Tina Vertex module [18]. This study follows this assumption.

Due to the learning of relative knowledge about PV components manufacturing, the material intensity (include aluminum intensity) keep deceasing, we use a learning curve to project the decreasing in the future, as shown in (2.23).

$$AI_{i,t} = \alpha \times C_{st}[t]^{\frac{ln(1-LR)}{ln(2)}} \tag{2.23}$$

Where $AI_{i,t}$ is the aluminum intensity of component type i, α is the prefactor. Regarding the future trend of aluminum consumption in PV system components, Lennon's study assumes that the aluminum consumption for PV rooftop mounting decreases from 2.84 kg/m^2 at a rate of 0.5% per year, reaching approximately 2.4 kg/m^2 by 2050 [18]. In our baseline scenario, the annual reduction rate of 0.5% is converted to a learning rate over cumulative installed capacity (2.6%). Under this learning rate, the aluminum consumption for slanted-roof mounting decreases from 2.84 kg/m^2 in 2020 to 2.4 kg/m^2 by 2050, consistent with the assumptions in Lennon's study. The learning rate of aluminum intensity is not distinguished among different components due to a lack of specific data. The α is include in Table 2.2, which summarizes the conservative assumption made on aluminum intensity.

Table 2.2: The conservative assumptions on aluminum intensity of PV components

Components type	Learning rate	Prefactor(α)	Initial value	2050 value
module frame	2.6%	1.541	1.20 kg/m^2	1.01 kg/m^2
open-ground mounting	2.6%	5.110	3.98 kg/m^2	3.36 kg/m^2
flat-roof mounting	2.6%	3.235	2.52 kg/m^2	2.13 kg/m^2
slanted-roof mounting	2.6%	3.646	2.84 kg/m^2	2.40 kg/m^2
utility-scale inverter	2.6%	0.668	0.52 kg/kWp	0.44 kg/kWp
residential inverter	2.6%	0.835	0.65 kg/kWp	0.55 kg/kWp

In improvement scenario, an optimistic assumption about the pace of technological progress in Lightweight design of PV components (module frame, mounting structure, inverter enclosure) is applied. The more optimistic assumption about aluminium intensity is to increase the learning rate to 5.9%. Underwood assumed a learning rate over cumulative PV install capacity of 7.9% for each material cost per power (CPP) in PV system, including aluminum [47]. According to my assumption on PV efficiency (a learning rate of 3.4%), the calculated learning rate should be 5.9% for aluminum intensity to reach the learning rate of 10% for aluminum CPP. The α for components are listed in the summary of the optimistic assumption as shown in Table 2.3.

Table 2.3: The optimistic assumptions on aluminum intensity of PV components.

Components type	Learning rate	Prefactor(α)	Initial value	2050 value
module frame	5.9%	2.130	1.20 kg/m^2	0.81 kg/m^2
open-ground mounting	5.9%	7.065	3.98 kg/m^2	2.69 kg/m^2
flat-roof mounting	5.9%	4.473	2.52 kg/m^2	1.70 kg/m^2
slanted-roof mounting	5.9%	5.041	2.84 kg/m^2	1.92 kg/m^2
utility-scale inverter	5.9%	0.923	0.52 kg/kWp	0.35 kg/kWp
residential inverter	5.9%	1.154	0.65 kg/kWp	0.44 kg/kWp

2.3.4 Estimations on lifetime of components

The typical lifetime of PV modules and mounting systems is generally about 25 to 30 years. This estimate considers the time during which the panels can produce energy efficiently before their performance declines significantly. Most solar panels come with warranties that guarantee performance for this duration, although they can still produce electricity beyond this period at reduced efficiency levels [70, 71, 72]. In contrast, inverters usually have a shorter lifetime of about 15 to 20 years. This discrepancy is due to the different operational and environmental stresses that inverters face compared to the relatively static PV panels [73].

In the baseline scenario, We assumed a lifetime of 25 years for both PV modules and mounting systems, and 15 years for inverters, regardless of type. In the lifetime improved scenario, the expected lifetime of each component is increased by 5 years.

2.3.5 Estimations on aluminum recycling rate

The aluminum recycling rate in the building industry is approximately 85% [64], while in the automotive industry, it was 91% in 2017 [74]. The EoL aluminum's recycling rates are estimated at 34– 63% [62, 75, 76, 77]. The recycle of PV components have large potential. Aluminum is one of the most easily recyclable materials in PV components. In previous research on PV recycling, aluminum is considered to be fully recyclable [78, 79, 80]. In this research, two estimations are made on aluminum recycling rate. The conservative estimate projects a linear increase from 34% [62] in 2020 to 75% [18] by 2050, while the more optimistic estimate anticipates a linear rise from 34% in 2020 to 99% by 2050.

2.3.6 Scenario summary

Table 2.4 summarizes the parameters used in the baseline scenario. The data sources and assumptions are discussed earlier in this section. Table 2.5 outlines the changes made in each improved scenario relative to the baseline scenario and assigns a number to each scenario. In the results analysis, these numbers will be used to refer to the respective scenarios.

Table 2.4: Parameters used in Baseline scenario

Parameters	Value
The deployment of global PV systems (GW)	Increasing follows a logistic curves, reach to 63.4 TW in 2050 [56]
Market mix of PV mounting structure	Aluminum open-ground mounting 24.4% Steel open-ground mounting 25.6% Aluminum flat-roof mounting 23.2% Aluminum slanted-roof mounting 26.8%
Market share of frameless module	7%
PV efficiency	21.1% in 2020 increases to 28.7%, learning rate (LR) 3.4%
Frame Al intensity (kg/m^2)	1.2 kg/m^2 in 2020 decreases to 1.01 kg/m^2 in 2050,LR 2.6%
Open-ground mounting Al intensity (kg/m^2)	3.98 kg/m^2 in 2020 decreases to 3.36 kg/m^2 in 2050,LR 2.6%
Flat-roof mounting Al intensity (kg/m^2)	2.52 kg/m^2 in 2020 decreases to 2.13 kg/m^2 in 2050,LR 2.6%
Slanted-roof mounting Al intensity (kg/m^2)	2.84 kg/m^2 in 2020 decreases to 2.40 kg/m^2 in 2050,LR 2.6%
Utility-scale inverter Al intensity (kg/kWp)	0.52 kg/kWp in 2020 decreases to 0.44 kg/kWp in 2050,LR 2.6%
Residential inverter Al intensity (kg/kWp)	0.65 kg/kWp in 2020 decreases to 0.55 kg/kWp in 2050,LR 2.6%
lifetime of components	module and mounting structure 30 years inverter 15 years
Recycling rate of aluminum	34% in 2020 linearly increases to 75% in 2050
Emission intensity of primary aluminum production	9.31 kg CO_2eq/kg in 2020 linearly decreases to 2.5 kg CO_2eq/kg in 2050
Emission intensity of secondary aluminum production	0.849 kg CO_2eq/kg in 2020 linearly decreases to 0.5 kg CO_2eq/kg in 2050

Table 2.5: Scenario settings

Scenario	Description
Baseline	conservative assumptions applied
Eff LR_7.9%	the LR of PV efficiency changed from 3.4% to 7.9%
Alint LR_5.9%	the LR of Al intensity changed from 2.6% to 5.9%
LT+5y	lifetime of frame and mounting structure changed from 25 years to 30 years inverter's changed from 15 years to 20 years
Recycle_99%	the Al recycling rate increases more rapidly 34% in 2020 increasing to 99% in 2050
Combination	Combine all of the above changes in efficiency LR, aluminum intensity LR, components lifetime and recycling rate

2.4 Validation

In previous studies, Lennon et al. [18] also projected global aluminum demand for PV systems from 2020 to 2050. Their study scope is similar to this research, but they also considered the aluminum consumption of cells. However, their results showed that this demand accounts for less than 0.2% of the total demand. They predicted that, without considering any system degradation or component retirement, the cumulative aluminum demand would be 486.5 Mt. When assuming a system energy degradation rate of 0.5% per year, the cumulative aluminum demand increases to 508.8 Mt. Their study did not use a material flow model but instead represented system degradation using the energy degradation rate. This research applies the assumptions from their study (excluding cell consumption) to the model and incorporates the component lifetime and Weibull distribution assumptions from this study's baseline. By comparing the results, the model's reliability is validated. The results are shown in Figure 2.4. Until 2050, the overall aluminum demand is 528.40 Mt. The 3.9% error arises from differences in the assumptions regarding system energy degradation and component retirement, as discussed in section 2.3.4.

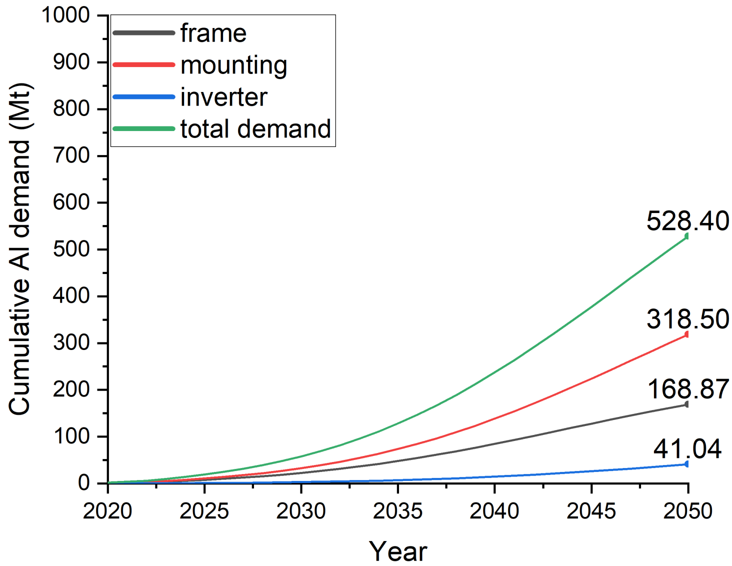


Figure 2.4: Cumulative aluminum demand in validation scenario with similar assumptions from Lennon's study.

Chapter 3

Result and Discussion

In this chapter, the aluminum demand and the associated greenhouse gas emission were estimated for the required PV capacity predicted for the broad electrification scenario. Through scenario analysis, the aluminum demand mitigation potential of several factors are shown by the results.

3.1 Cumulative aluminum demand

Figure 3.1 presents the cumulative aluminum demand for global PV systems under various scenarios. Figure 3.1(a) shows the cumulative aluminum demand in baseline scenario. The overall aluminum demand until 2050 is 830.98 Mt. The demand in mounting structure, frame and inverter accounts for 63.9%, 30.8% and 5.3%.

This demand is much higher than that from Lennon's study (486 Mt). The primary reason concerns the different assumptions about the PV market. In Lennon's study, all open-ground mounting systems were assumed to use stainless steel, and this type of mounting system accounted for 50% - 60% of the total from 2020 to 2050. In our study, based on the variety of products available in the market, we assumed that aluminum open-ground mounting systems and stainless steel open-ground mounting systems would account for 24.4% and 25.6% of the total share, respectively.

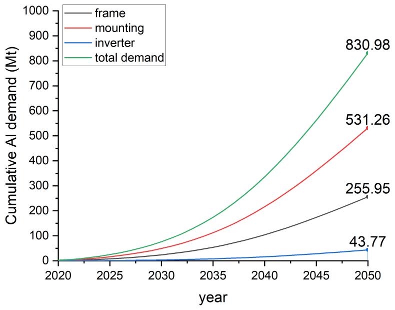
As shown in figure 3.1(b), compared to the baseline, Eff LR_7.9 scenario sees an increase in the learning rate of PV efficiency from 3.4% to 7.9%, resulting in a 15.9% reduction in cumulative aluminum demand. Higher PV efficiency reduces the area required to install PV systems of the same capacity, thereby saving aluminum in module frames and mounting structures. The aluminum consumption for inverters remains unaffected in this scenario. Figure 3.2 compares the PV installation areas between baseline scenario and Eff LR_7.9% scenario. The cumulative area in Eff LR_7.9% scenario ($2.17*10_{11}$ m^2) is 16.9% less than in baseline scenario ($2.61*10_{11}$ m^2), which aligns closely with the 16.7% reduction in aluminum consumption for module frames and mounting. The efficiency gap between the two scenarios widens annually due to technological advancements, leading to a more pronounced difference in annual installation areas. In 2050, the installation area in baseline scenario is $1.81*10_{10}$ m^2, while in Eff LR_7.9% scenario it is $1.41*10_{10}$ m^2, only 78% of that in baseline.

As shown in figure 3.1(c), in Alint LR_5.9% scenario, the learning rate for reducing aluminum intensity in components increases from 2.6% to 5.9%, leading to a 15.5% reduction in cumulative aluminum demand. This scenario demonstrates the most significant reduction in aluminum demand, except for the combined scenario.

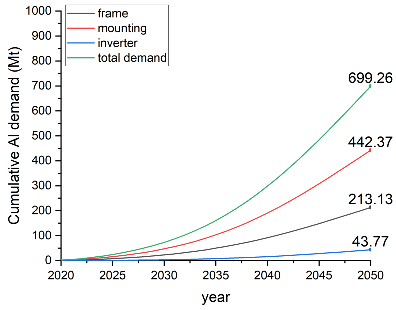
In LT+5y scenario, extending the lifetime of various components by 5 years results in only a 4.1% reduction in cumulative aluminum demand, as shown in figure 3.1(d). This is because the expansion of the PV market between 2020 and 2035 is limited; by 2035, the shipped capacity of global PV systems is only 20.8% of that in 2050. In the baseline scenario, the expected lifetime of modules and mounting structures is 25 years, and according to the Weibull curve, 75.6% of components installed in 2035 will still be in use by 2050. In LT+5y scenario, with an expected lifetime of 30 years, 83.4% of similar components will still be in use by 2050. Most PV systems installed post-2035 have not yet reached the end of their lifetime in the baseline scenario. Thus, extending the lifetime of PV components does not significantly impact aluminum consumption by 2050. However, it is noteworthy that only 36.8% of products with a 25-year lifetime remain usable after 25 years, compared to 53.0% for those with a 30-year lifetime. The discard curve for PV systems shows a lag relative to the installation curve. Given the rapid increase in PV installations around 2035, many components will reach their end of life by around 2060. Extending the study period by 10 years would make the impact of increasing component lifetime more pronounced.

Figure 3.1(e) shows that recycle_99% scenario enhances the learning rate of aluminum recycling, which increases the proportion of secondary aluminum in the aluminum inflow without affecting the total aluminum demand. Therefore, it shows the same aluminum demand in components and PV systems as that in baseline scenario.

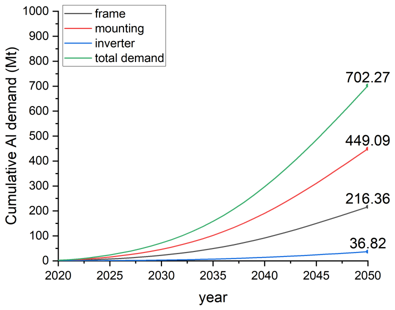
As shown in Figure 3.1(f),combination scenario integrates improvements from the previous scenarios, resulting in a cumulative aluminum demand of 568.65 Mt, a 31.6% reduction compared to the baseline. The aluminum consumption reduction potential in Combination scenario is not merely an additive effect of the previous scenarios. Specifically, higher PV efficiency and longer component lifetime reduce the overall demand for PV components, diminishing the impact of reduced aluminum intensity in components. Additionally, the benefits of increasing the learning rates for PV efficiency and aluminum intensity, as well as extending component lifetimes, require time to accumulate. By 2035, the cumulative aluminum demand in baseline scenario is 174.13 Mt, while in Combination scenario it is 143.60 Mt, showing a minor difference. This indicates that the potential for reducing aluminum consumption largely manifests in the latter 15 years of the study period.



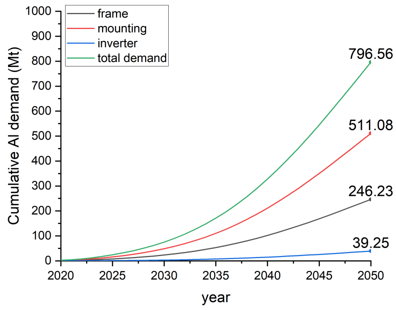
(a) Baseline



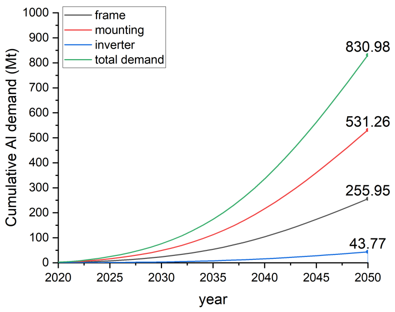
(b) Scenario: Eff LR_7.9%



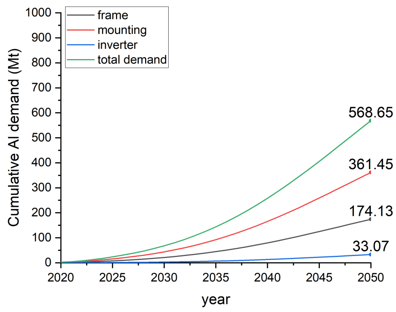
(c) Scenario: Alint LR_5.9%



(d) Scenario: LT+5y



(e) Scenario: Recycle_99%



(f) Combination

Figure 3.1: Cumulative aluminum demand under different scenarios

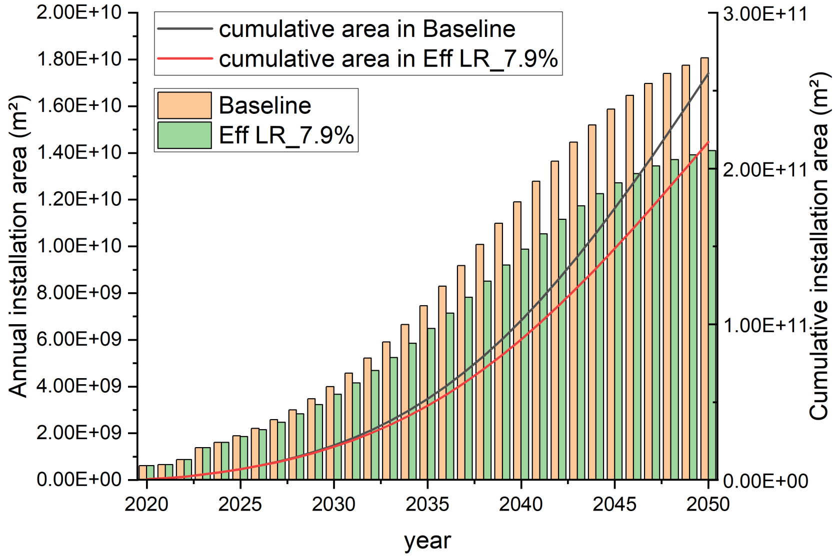


Figure 3.2: Installation area of PV system under baseline scenario and Eff LR_7.9 scenario.

3.2 Annual aluminum demand

Figure 3.3(a) show the annual aluminum demand under baseline scenario. Demand from module frames, mounting systems, and inverters is shown separately. The total annual demand continues to grow from 2020 to 2050, with the fastest growth occurring between 2030 and 2035. By 2045-2050, the demand stabilizes. In contrast, the annual demand for primary aluminum peaks in 2048 and then begins to decline. This decline is due to the rapid increase in secondary aluminum supply. The inflow of secondary aluminum becomes noticeable around 2030, with almost no visible impact before that. This is when the first batch of PV components reaches 10-year operational life. The lag in the EoL component curve compared to the installation curve, along with the annually increasing aluminum recycling rate, leads to a growing proportion of secondary aluminum in the total supply. By around 2060, secondary aluminum is expected to replace primary aluminum as the main supply source.

By 2050, the global aluminum demand for PV systems is projected to be 55.74 Mt, with recycled secondary aluminum meeting 19.5% of this demand. Primary aluminum will still constitute 80.5% of the demand, amounting to 44.85 Mt. From a component perspective, the aluminum demand for mounting systems is 35.35 Mt, accounting for 63.4% of the total demand. Module frames and inverters account for 30.6% (17.03 Mt) and 6.0% (3.36 Mt) of the total demand, respectively, which is consistent with the overall distribution of cumulative demand.

Figure 3.3(b) shows the annual aluminum demand under Eff LR_7.9% scenario. Compared to baseline, the accelerated increase in PV efficiency slows the growth trend of annual aluminum demand for module frames and mounting systems, with the impact primarily observed in the latter 15 years. In this scenario, the annual aluminum demand in 2035 is 21.25 Mt, which is a reduction of 3.02 Mt compared to baseline (24.27 Mt). By 2050, the annual demand grows to 44.24 Mt, compared to 55.74 Mt in baseline, resulting in a difference of 11.50 Mt. The growth in overall aluminum demand is suppressed. However, since the inflow of PV components changes little in the first 15 years, the number of EoL PV components before 2050 remains relatively stable, allowing the output of secondary aluminum to continue growing steadily. This causes the peak demand for primary aluminum for module frames and mounting systems to occur a year earlier, in 2047, before it begins to decline. Overall, the main contribution of higher PV efficiency is the effective reduction in aluminum demand. However, this does not significantly impact the timeline for achieving a circular system where secondary aluminum becomes the main supply.

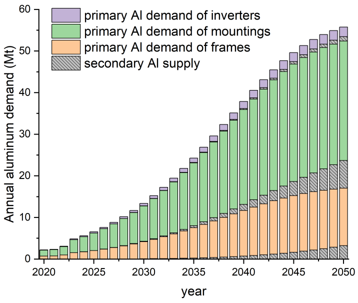
Alint LR_5.9% scenario exhibits a similar situation to Eff LR_7.9% scenario, as shown in Figure 3.3(c). The reduction in aluminum intensity of PV components directly and effectively decreases aluminum demand, with the cumulative effect of technological advancements becoming more pronounced in the latter 15 years. The only difference is that in Alint LR_5.9% scenario, the aluminum demand for inverters is also reduced. However, since the aluminum demand for inverters accounts for less than 10% of the total aluminum demand in the entire PV system, this change has a negligible impact on the overall aluminum demand.

In the discussion of cumulative demand, it was found that extending the lifetime of PV components by five years has a minimal impact on global aluminum demand for PV systems up to 2050. The effect on annual demand is even smaller, to the point where it is difficult to observe, as shown in Figure 3.3(d). The average lifetime of inverters increases from 15 years to 20 years; given the 30-year study period, the change in the number of EoL inverters and aluminum demand for them might be interesting. However, since the aluminum demand for inverters constitutes a small portion of the entire PV system, its impact is insignificant and does not warrant detailed discussion.

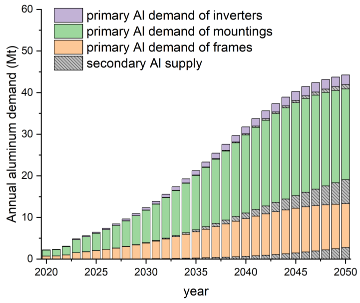
The impact of increasing aluminum recycling rates is concentrated on the inflow of secondary aluminum. Figure 3.3(e) shows the annual aluminum demand under Recycle_99% scenario. In 2050, the secondary inflow is 14.04 Mt, a 28.9% increase compared to baseline (10.89 Mt). However, this only reduces the primary aluminum demand by 7.0% in 2050. This is interesting. Back to baseline scenario, the recycling rate of aluminum in PV systems reaches 74% by 2050, while most of the PV equipment installed previously has not yet reached its EoL. Considering that the aluminum recycling rate will continue to rise, that means even under conservative assumptions, the outlook for aluminum recycling in PV systems is promising. In Recycle_99% scenario, the recycling rate increases to 99% by 2050. From the perspective of EoL components recycling , the benefits are substantial. However, since most components are still in use at this time, the effect on reducing aluminum demand is relatively limited.

In Combination scenario, the most optimistic scenario, the annual aluminum demand is decreased significantly, as shown in Figure 3.3(f). It's noteworthy that the last three years' aluminum demands are almost same, 32.71 Mt in 2048, 32.80 Mt in 2049, 32.83 Mt in 2050, with a 41.4% reduction compared to baseline. It can be said that in this scenario, aluminum demand will stop growing in 2050. This is exciting news. Additionally, in this scenario, the demand for primary aluminum also peaks earlier than in other scenarios, reaching 27.56 Mt in 2045. Moreover, the benefits of extending the lifetime of PV components will become increasingly evident in the future, as discussed before. With the number of EoL components growing rapidly, combined with the already saturated aluminum recycling rate, the shift to a global PV system primarily supplied by secondary aluminum will be accelerated.

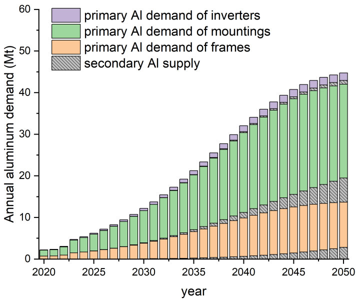
In baseline scenario, the primary aluminum demand reach 44.9 Mt at 2050, as for comparison, the global primary aluminium production in 2023 is 70.6 Mt [81]. To control it to less than 40% of primary aluminum production in 2020, all optimistic estimations need to be applied, as shown in Figure 3.4. However, if the recycling of aluminum cannot be applied successfully, the aluminum demand in the Combination scenario will also exceed the 40% line. The recycling of aluminum in PV system will be a crucial pathway for avoiding the aluminum supply risk in the future. Aluminum is a crucial metal in many industries, such as construction and aerospace. Even though it accounts for 40% of global aluminum production capacity, this represents a significant risk for any single industry. On a positive note, global aluminum production capacity continues to evolve, with recent years showing steady growth. Moreover, in all scenarios considered in this study, the demand for primary aluminum is expected to peak before 2050. It is anticipated that secondary aluminum from system recycling will gradually become the primary source of supply, leading to a rapid decline in the demand for primary aluminum.



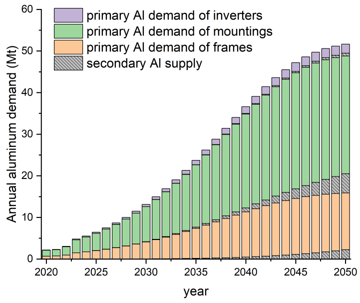
(a) Baseline



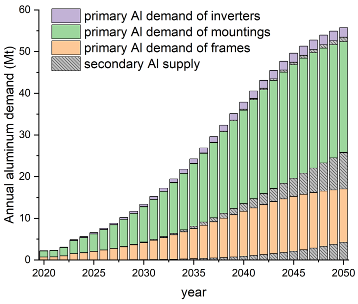
(b) Scenario: Eff LR_7.9%



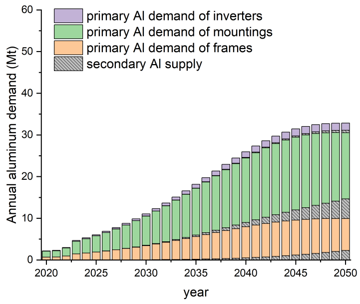
(c) Scenario: Alint LR_5.9%



(d) Scenario: LT+5y



(e) Scenario: Recycle_99%



(f) Combination

Figure 3.3: Annual aluminum demand under different scenarios.

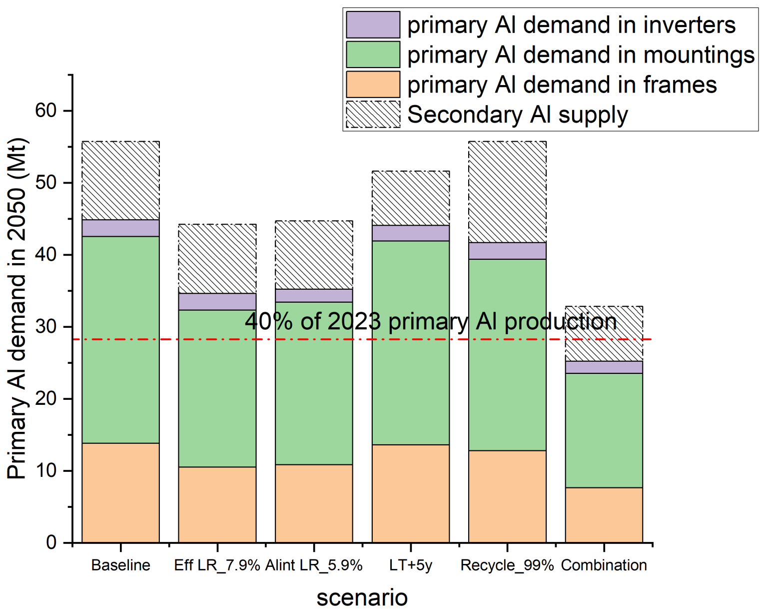


Figure 3.4: Primary aluminum demand in 2050

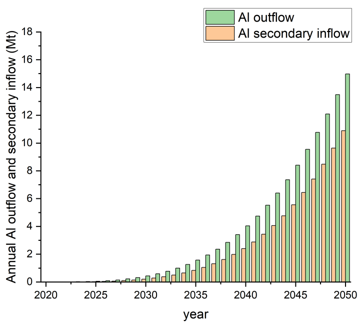
3.3 Aluminum recycling potential

The influences of the important factors on aluminum recycling situation can be observed in Figure 3.5. Except for the initial year, there are EoL components generated in every year. A portion of these components is recycled, with the aluminum re-entering the system as secondary aluminum. Figure 3.5(a) illustrates the annual growth of outflow and secondary inflow under baseline scenario. The secondary inflow increases at a faster rate due to rising recycling rates. However, since the outflow is also rapidly growing, the net outflow stabilizes between 2045 and 2050. Net outflow represents the un-recycled waste. This study focuses on aluminum in PV systems, so the net outflow pertains only to the loss of this metal, without considering its environmental impact. Nonetheless, if the entire PV modules are not properly disposed of, the heavy metals they contain pose a potential environmental hazard [72]. In 2050, the global aluminum outflow from PV systems is projected to be 14.97 Mt, with a secondary inflow of 10.89 Mt. In comparison, the aluminum inflow that year is expected to be 55.74 Mt.

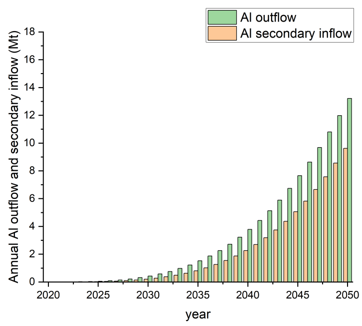
The installation curve of global PV systems and the Weibull distribution of the lifetime of PV components determine the shape of the outflow curve. Figure 3.5(b) and Figure 3.5(c) shows that, the increase in PV efficiency and the reduction in aluminum intensity of components not only decrease aluminum demand but also reduce aluminum outflow and recycling volumes. In LT+5y scenario, the longer expected lifetime of components slows the growth rate of the outflow curve, resulting in an outflow of 10.36 Mt by 2050, as shown in Figure 3.5(d), which is a 30.8% decrease compared to baseline. In Recycle_99% scenario shown in Figure 3.5(e), the rapidly increasing recycling rate causes the annual aluminum outflow and secondary inflow to be closely aligned. From the figure, it can be observed that the annual outflow rises sharply after 2040. According to the assumptions in Recycle_99% scenario, the average aluminum recycling rate in PV systems reaches 77% by 2040, indicating that most of the EoL components are being recycled.

Figure 3.5(f) shows the recycling situation of Combination scenario. The combine of all optimistic estimations made the outflow increasing much slower, lower than 5 Mt until 2045, and reach to 8.1 Mt in 2050.Thanks to the high recycling rate, most of the outflow is converted into secondary inflow and recycled. The net outflow generated each year is minimal, with the highest value being 0.76 Mt in 2045.

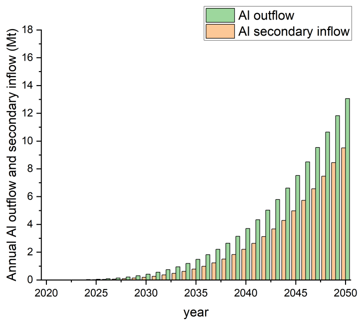
Table 3.1 summarizes the average aluminum recycling rate of the scenarios above. It is evident that extending the lifetime of components (LT+5y) significantly reduces the aluminum outflow within the study period, decreasing it by 32.9%. Scenarios 2 and 3 also reduce cumulative outflow by 8.8% and 10.3%, respectively, due to the decreased aluminum inflow. In Recycle_99% scenario, advancements in recycling technology increase the average recycling rate from 65.7% in the baseline to 82.9%, resulting in an additional 19.68 Mt of cumulative secondary inflow. Although this does not meet 40% of the aluminum demand in 2050 under the baseline scenario, the rapid growth in cumulative outflow afterward will make the resource-saving and economic benefits of higher recycling rates more pronounced. In Combination scenario, despite the average recycling rate reaching 82.7%, the combination of various improvements significantly reduces the cumulative outflow, resulting in only 52.42 Mt of secondary aluminum. The net aluminum outflow is reduced to 10.96 Mt, shows a 72.1% decrease compared to baseline (39.24 Mt), promoting sustainable resource development.



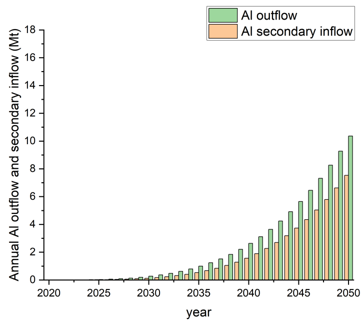
(a) Baseline



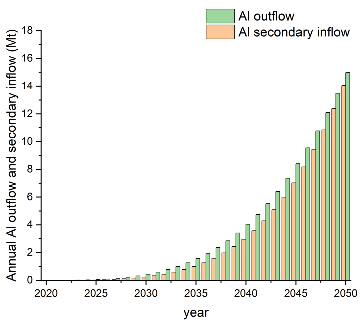
(b) Scenario: Eff LR_7.9%



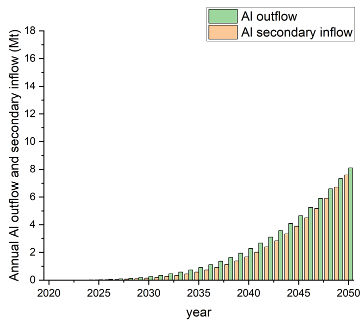
(c) Scenario: Alint LR_5.9%



(d) Scenario: LT+5y



(e) Scenario: Recycle_99%



(f) Combination

Figure 3.5: Aluminum outflow and secondary Aluminum inflow under different scenarios.

Table 3.1: Average aluminum recycling rate and net outflow in scenarios from 2020 to 2050.

scenario	cumulative Al outflow (Mt)	cumulative secondary Al inflow (Mt)	average recycling rate	net Al outflow (Mt)
Baseline	114.35	75.11	65.7%	39.24
Eff LR_7.9%	104.33	68.34	65.5%	35.99
Alint LR_5.9%	102.57	67.21	65.5%	35.36
LT+5y	76.71	50.52	65.9%	26.19
Recycle_99%	114.35	94.79	82.9%	19.56
Combination	63.38	52.42	82.7%	10.96

3.4 Aluminum Stock of Global Photovoltaic system

The aluminum stock within PV systems is essential not only for assessing resource demand but also for framing aluminum as an "urban mineral," which holds significant implications for recycling and resource management strategies. The concept of ürban mineralsr̈efers to materials that are embedded in the urban infrastructure and can be recovered and reused. Aluminum is a prime example of an urban mineral due to its extensive use in various applications, including PV systems. The urban mining of aluminum involves extracting this valuable metal from end-of-life products, buildings, and other infrastructures rather than from natural ore deposits [82].

Figure 3.6 shows the aluminum stock under the different scenarios in this study. Figure 3.6(a) refers to baseline scenario, where the total aluminum stock until 2050 is 716.63 Mt, with module frames, mounting structures, and inverters accounting for 31.0%, 64.5%, and 4.5%, respectively. Compared to the distribution of demand, the share of inverters in the stock is smaller. These proportions can be used to compare the CPP of each component. Under the broad electrification scenario of ITRPV, global PV system installations are projected to reach 63 TW by 2050. The average CPP is 11.38 Mt/TW, meaning that an average 1 kW PV system requires 11.38 kg of aluminum: 3.53 kg for module frames, 0.51 kg for inverters, and 7.33 kg for mounting systems.

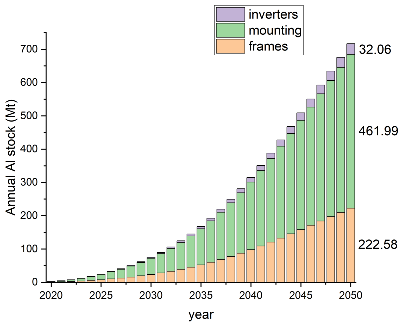
Compared to baseline, the 2050 aluminum stock in Eff LR_7.9% scenario and Alint LR_5.9% scenario decreased by 17.0% and 16.3%, respectively. Both reductions are due to technological advancements that reduce the aluminum CPP of newly installed PV systems. Therefore, although the global capacity of PV systems is rapidly increasing, the accumulation of aluminum stock has slowed down relatively.

In LT+5y scenario, however, the aluminum stock increased by 0.4%. Although the impact is minimal, this reflects the hindrance of extending component lifetimes on technological updates. Older components exit the market later, reducing the number of new components with better technology being installed. Consequently, the average efficiency of products in the existing market decreases, and average resource consumption increases. From an urban mining perspective, extending the lifetime of components not only reduces resource input during these years but also provides more urban mineral accumulation for the future. These components, still in use, can be recycled in the future using more advanced and efficient technologies, which is overall highly beneficial for resource recycling.

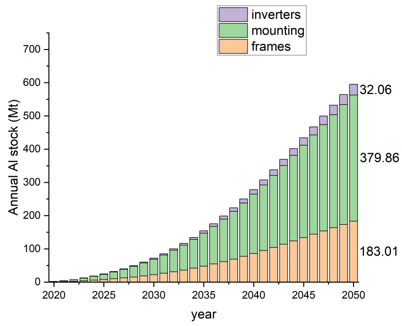
Recycle_99% scenario only changes the aluminum recycling rate, so its aluminum stock situation is the same as the baseline. Nevertheless, urban mining is closely related to the recycling rate of resources. Urban minerals have development potential, and converting this potential into benefits requires efficient recycling methods. Therefore, more urban minerals can drive the development of recycling technologies, stimulating an increase in recycling rates. The development of waste recycling technology determines the conversion rate of urban mineral potential and benefits.

Combination scenario decreases the stock by 29.5%, as shown in figure 3.6(f). With the increase of PV efficiency and the decrease of aluminum intensity of components, the accumulation speed of aluminum stock has slowed down significantly. Most equipment operates for no more than 10 years, which means that aluminum stock will continue to accumulate over the next 20 years. However, a mature recycling system can provide a stable resource supply for future PV equipment construction, creating an ideal resource recycling scenario.

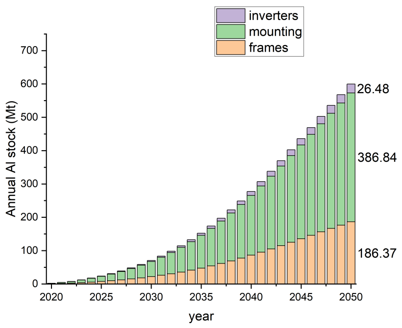
Table 3.2 summarizes the average aluminum CPP of in-use PV systems in 2050 under scenarios. 1 kWp PV system cost 8.02-11.43 kg aluminum in 2050. Mounting systems are the most aluminum-intensive components, with an aluminum usage of 5.13-7.37 kg per kWp. In Combination scenario, the aluminum CPP of newly installed PV systems in 2020 is 16.85 kg/kWp, which drops to 6.70 kg/kWp by 2050, a decrease of 60.2%. This value is 83.5% of the average aluminum CPP for in-use PV systems (8.02 kg/kWp). This demonstrates the reduction in CPP due to technological advancements and the progress of technology iterations.



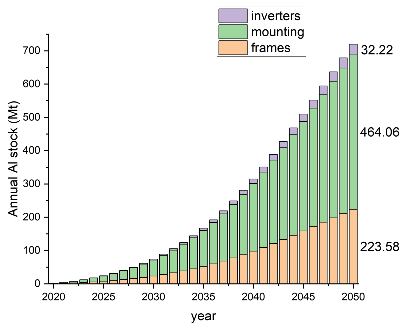
(a) Baseline



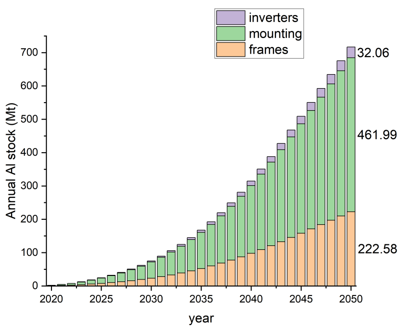
(b) Scenario: Eff LR_7.9%



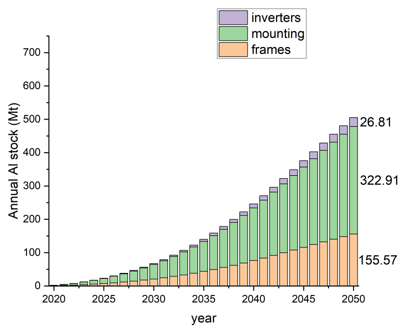
(c) Scenario: Alint LR_5.9%



(d) Scenario: LT+5y



(e) Scenario: Recycle_99%



(f) Combination

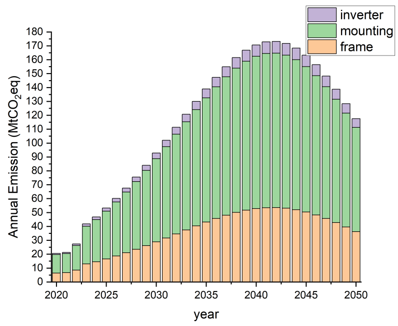
Figure 3.6: Annual aluminum stock under different scenarios.

Table 3.2: Average aluminum CPP of in-use PV systems in 2050

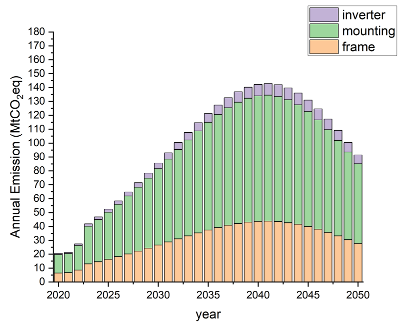
scenario	Al CPP of moudule frames (kg/kWp)	Al CPP of mounting systems (kg/kWp)	Al CPP of inverters (kg/kWp)	Sum (kg/kWp)
Baseline	3.53	7.33	0.51	11.38
Eff LR_7.9%	2.90	6.03	0.51	9.44
Alint LR_5.9%	2.96	6.14	0.42	9.52
LT+5y	3.55	7.37	0.51	11.43
Recycle_99%	3.53	7.33	0.51	11.38
Combination	2.47	5.13	0.43	8.02

3.5 Global warming potential

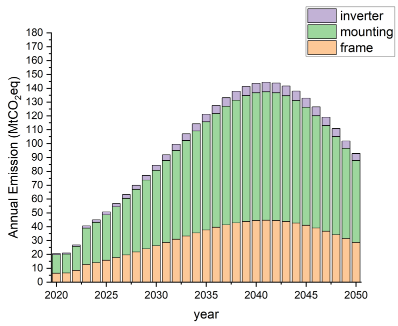
Figure 3.7 shows the results of GWP calculation for scenarios. Due to the rapid decrease in emission intensity resulting from the electrification of aluminum production, the overall GWP has been declining year by year since 2041/2042, even though the aluminum demand for PV systems will continue to grow until 2050. In baseline scenario, the aluminum emissions in PV systems by 2050 are projected to be 117.57 Mt CO_2eq, with 30.8% from component frames, 63.9% from mounting systems, and 5.3% from inverters, which corresponds to the proportion of aluminum demand for each component. The four optimistic scenarios reduce emissions by 22.3% (Eff LR_7.9%), 21.1% (Alint LR_5.9%), 3.0% (LT+5y), and 5.4% (Recycle_99%), respectively. The combined scenarios show a 43.1% reduction in the 2050 annual GWP compared to the baseline. Figure 3.8 illustrates the cumulative aluminum emissions in PV systems across different scenarios. The curve for Eff LR_7.9% scenario shows that increasing PV efficiency has resulted in the largest reduction in greenhouse gas emissions among the four optimistic scenarios (14.6%), while the combination of all four optimistic assumptions achieves a 28.% reduction. Although it is assumed that the emission intensity of primary aluminum will decrease to 2.5 kg CO_2eq/kg by 2050, the cumulative emissions under the baseline scenario are still projected to reach 3534 Mt CO_2eq by 2050, equivalent to 9.5% of global energy-related greenhouse gas emissions in 2023, and even with the most optimistic estimates, the portion remains 6.8% [83]. This indicates that, due to the time required for decarbonizing aluminum production, the large-scale manufacturing of PV systems will inevitably result in significant greenhouse gas emissions.



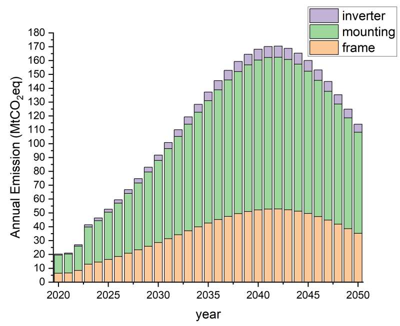
(a) Baseline



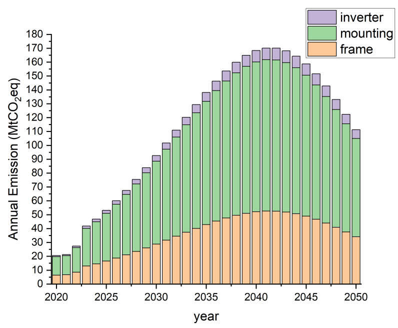
(b) Scenario: Eff LR_7.9%



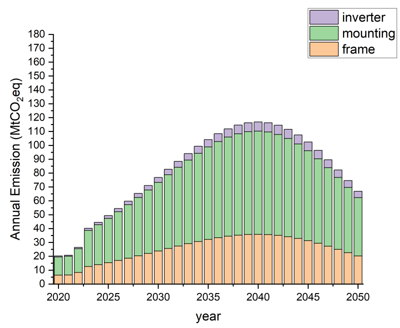
(c) Scenario: Alint LR_5.9%



(d) Scenario: LT+5y



(e) Scenario: Recycle_99%



(f) Combination

Figure 3.7: Annual Global Warming Potential under different scenarios.

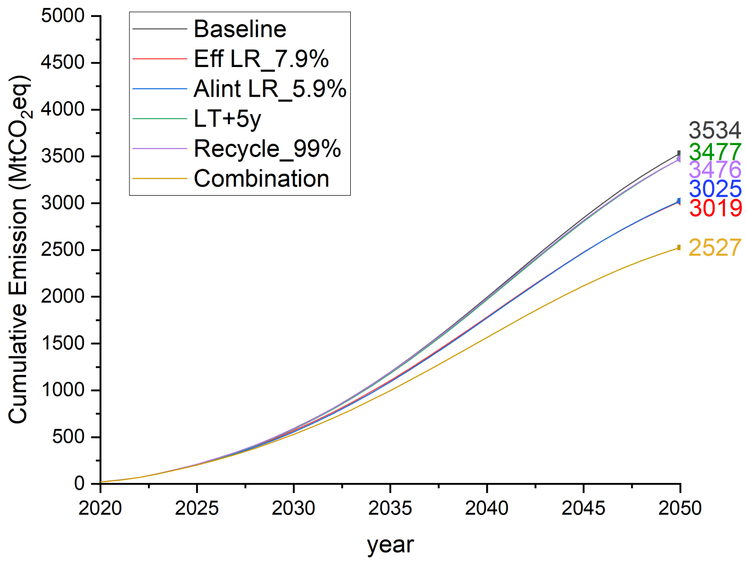


Figure 3.8: Cumulative global warming potential of scenarios (primary Al: 9.31 kg CO_2eq/kg, secondary Al: 0.849 kg CO_2eq/kg).

Chapter 4

General Discussion

4.1 Significance of key factors

The installed capacity of PV systems is the most decisive factor affecting the demand for aluminum in PV systems, while the emission intensity of aluminum production plays a crucial role in determining the environmental impact associated with aluminum use. This study's projections are based on two critical assumptions: the board electrification scenario and the below 2°C scenario. The former provides the basis for assumptions regarding PV installation capacity from 2020 to 2050, while the latter underpins assumptions about the emission intensity of primary and secondary aluminum production. These assumptions are critical as they significantly influence the results.

4.1.1 Impact of photovoltaic installed capacity on aluminum demand

My findings demonstrate that improvements in PV efficiency, component material intensity, component lifetime, and recycling rates could collectively reduce global aluminum demand for PV systems by 31.6%. However, the impact of PV installed capacity on aluminum demand is far more significant. In the board electrification scenario, where all energy-required sectors including sectors like transportation and heating, which currently reliant on fossil fuels, are electrified, Bogdanov et al.[3] estimated a PV installation of 63.4 TW by 2050. Excluding these fuels-required sectors, they estimated a PV installation of 22.0 TWp by 2050, with an annual installation rate of 1.4 TWp [84]. This represents a 65.3% reduction in PV capacity compared to the large-scale electrification scenario, leading to a proportional reduction in aluminum demand. This decrease far exceeds the combined potential reduction from the four factors discussed in this study.

Given the critical importance of PV capacity, this study did not create scenarios to analyze its sensitivity. This is because its impact on the results is too significant, potentially overshadowing the discussion of other factors in the study. Furthermore, reducing PV capacity is not a viable strategy for decreasing aluminum demand in PV systems. In the context of global energy transitions, reducing PV capacity would necessitate other power generation technologies to fill the gap, leading to increased material consumption and greenhouse gas emissions in other sectors.

4.1.2 Impact of emission intensity of aluminum production on total GWP

Regarding the emission intensity of aluminum production, previous studies have provided varying calculations. Ding et al. [31] conducted a life cycle assessment of aluminum production in China, estimating the emission intensity of primary and secondary aluminum at 14.5 kg CO_2eq/kg and 0.93 kg CO_2eq/kg, respectively. The emission intensity for primary aluminum in their study is 56% higher than the 9.31 kg CO_2eq/kg used in this study. In fact, a significant portion of global primary aluminum production is concentrated in China, which accounted for 41,666 kilotons out of the global production of 70,581 kilotons in 2023, representing 59% [28].

When substituting the emission intensity with 14.5 kg CO_2eq/kg in 2020, linearly decreasing to 2.5 kg CO_2eq/kg in 2050, and the secondary aluminum emission intensity with 0.93 kg CO_2eq/kg in 2020, linearly decreasing to 0.5 kg CO_2eq/kg in 2050, the cumulative GWP in each scenario significantly increases, as shown in Figure 4.1. Comparing these results with the original findings (Figure 3.8), it is evident that the emissions in baseline scenario of the original results are comparable to those in combination scenario after adjusting the emission intensities. Both assumptions lead to the same emission intensity level by 2050, yet the mere adoption of alternative initial emission intensity data has a greater impact on the results than all the factors discussed in this study, underscoring the decisive influence of aluminum production's emission intensity on the overall GWP.

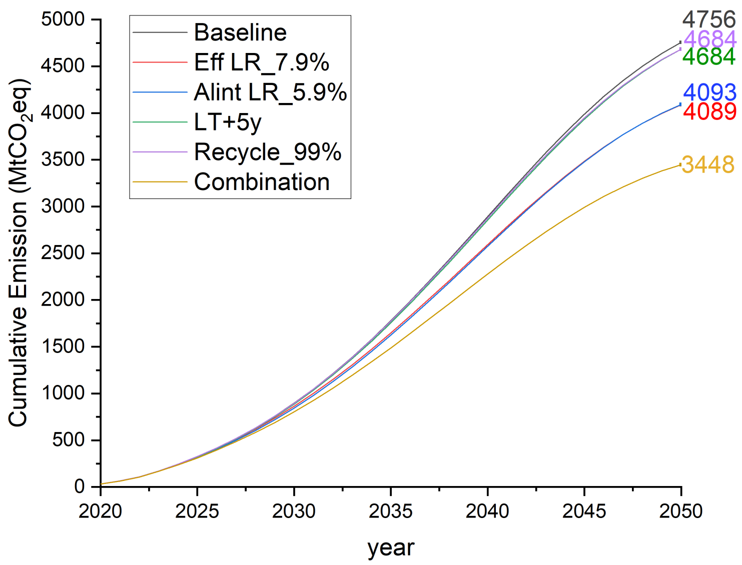


Figure 4.1: Cumulative Global Warming potential of scenarios with initial emission intensity changed (primary Al: 14.5 kg CO_2eq/kg, secondary Al: 0.93 kg CO_2eq/kg)

4.1.3 Challenges and implications for aluminum decarbonization

This study assumes that under the below 2°C scenario, the emission intensity of primary aluminum will decrease to 2.5 kg CO_2eq/kg by 2050. This is an ambitious target, implying the elimination of electricity-related emissions within less than 30 years—a significant challenge for primary aluminum producers. It also entails a 50% direct emission reduction and further reductions in emissions from raw materials and auxiliary processes [27]. Achieving this would be a major challenge for all participants in the aluminum value chain. The extent to which future emission intensities can meet these targets, and the shape of the reduction curve, will both influence the environmental impact of aluminum used in PV systems.

Reducing the emission intensity of aluminum production is a crucial focus for the entire aluminum industry. The decarbonization pathway for aluminum production faces many complex and unique challenges, influenced by numerous factors. In regions heavily reliant on fossil fuels, aluminum production is predominantly powered by self-generated electricity. According to IAI data, 97% of electricity in Asia (excluding China) is self-generated [28]. Following the B2DS emission pathway, capital investment required for electricity decarbonization over the next 30 years is estimated to range between $0.5 trillion and $1.5 trillion [27].

In terms of CCUS (Carbon Capture, Utilization, and Storage) deployment, the relatively low concentration of CO_2 emitted from electrolysis cells during aluminum smelting (500-15,000 ppm) poses additional challenges, as well as the costs associated with redesigning, retrofitting, and implementing electrolysis cells [27]. For thermal processes such as alumina production, decarbonization progress depends on the development and deployment of green hydrogen technology. In summary, the decarbonization pathway for aluminum is influenced by multiple industries and factors, making predictions about changes in the emission intensity of aluminum production a topic worthy of further exploration.

4.2 Circular economy potential of aluminum in photovoltaic systems

One of aluminum's unique advantages is its ability to be infinitely recycled without any loss of performance, making it an ideal material for a circular economy [85]. This characteristic is particularly significant in building a circular PV industry. As discussed earlier, there are two primary pathways for recycling aluminum components: re-melting them into new aluminum ingots or refurbishing and reprocessing them into new components. The latter option is more energy-efficient and has a lower emissions profile since it avoids the energy-intensive re-melting process [41]. However, it also requires more stringent collection and sorting of EoL components.

4.2.1 Importance of recycling policies and collection efficiency

Circular economy policies that improve scrap collection and alloy sorting are crucial for preserving aluminum's value (and the significant energy invested in its initial production) at the end of a product's life [27]. The collection rates for new and internal scrap (waste generated during various production and manufacturing processes before the final product is made) are very high, with minimal loss after collection. However, the quality of aluminum scrap collected at the end of a product's life varies depending on the alloy composition and the degree of sorting. The IAI advocates that producers, consumers, and waste management participants bear responsibility for ensuring that materials are returned to the system at the end of their life cycle. Those involved in designing metals and converting them into products are also responsible for creating applications that facilitate easy and effective separation, collection, and sorting of aluminum components, thereby preserving the metal's value and its alloy integrity [27].

4.2.2 Attempts on modeling a circular photovoltaic system

Currently, due to the lack of a mature recycling stream and processing line for discarded PV modules, this study only considers the re-melting pathway. However, establishing a resource-efficient, circular PV system requires the reuse of PV components. In fact, incorporating the refurbishment and direct recycling of PV components would add complexity to the model. Specifically, both the material flow of components and the aluminum flow would follow an extra circular pathway, necessitating a reevaluation of the efficiency, material intensity, lifetime, and recycling rates of second-hand components. The reusability of EoL components depends on their condition and duration. Moreover, depending on the degradation, different EoL components may require varying amounts of additional materials during refurbishment. These factors imply that incorporating the refurbishment and reuse of PV components requires more detailed assumptions and a more realistic model.

Khalifa et al. [41] have attempted to address this complexity. They provided a dynamic material flow analysis model for PV systems in the United States, quantifying the cradle-to-cradle material flows and inventories for utility-scale crystalline silicon PV systems through 2100. In their model, they considered the refurbishment of discarded modules, assuming that 50% of the generation capacity loss could be restored and reused. These secondary components were assumed to have a shorter lifetime (15 years) while maintaining the same efficiency and material intensity. In this model, all PV components could only be reused once, with no consideration of tertiary components. Their results showed that module reuse had a limited impact on reducing cumulative waste generation. Even if 70% of decommissioned modules were reused, and half of these were refurbished to recover half of the efficiency loss, only 5 million tons of waste would be avoided by 2100. The impact on aluminum demand and emissions, however, requires further exploration.

4.2.3 Economic and technical barriers to photovoltaic component reuse

Reusing PV components presents many challenges. Currently, neither the reuse of EoL components nor the recycling of their materials is economically viable [43, 86]. In fact, besides the two recycling pathways, there are two other ways to handle EoL components: landfilling and storage. Due to the relatively high cost of recycling, landfilling remains the most common option [43]. Moreover, most recovered components are simply crushed and sorted before being sent to the mature metals industry for refinement and further use [41]. The lack of proper sorting leads to high-value alloy scrap being contaminated by lower-value waste, which also reduces the feasibility of reusing discarded materials.

EoL components must undergo quality inspection before they can be refurbished and re-enter the reuse cycle [87]. A study conducted in the United States on 100,000 large-scale PV systems found that PV modules have a significantly lower failure rate compared to other system components such as inverters and breakers [88]. This might indicate that only a small proportion of modules would qualify for refurbishment [89, 90]. Furthermore, the efficiency and safety of second-hand PV modules remain uncertain. Currently, there is no comprehensive screening system or standards, leading to a lack of confidence in deploying second-hand modules and stifling their potential economic benefits at scale. Additionally, social factors, such as customer attitudes, play a significant role. Consumer perceptions of second-hand components greatly influence their market value in secondary markets, which in turn affects manufacturers' decisions [86].

Recycling PV modules is a complex and costly process due to the need to separate different materials [43]. Additionally, the rapid development of PV technology and the frequent updates of products further diminish the potential economic benefits of refurbishing old PV modules [86]. In contrast, mounting systems are less affected by these factors. As long as they are recycled according to alloy types and meet standards, EoL mounting systems can be refurbished into second-hand components or reprocessed to produce new products with different specifications. Furthermore, mounting system parts are easier to disassemble, making recycling costs lower. It is foreseeable that the reuse of mounting systems is an area with significant potential for both economic and environmental benefits.

Chapter 5

Conclusion

This research introduces a photovoltaic material flow model to track the flow of aluminum and associated environmental impacts in the global PV systems from 2020 to 2050, under the broad electrification scenario. The circulation of aluminum has been taken into account in the model. The aluminum flow and greenhouse gas emissions from the module frame, mounting system, and inverter are calculated and discussed separately. This model applied a wide range of PV-specific parameters and aluminum production parameters. Multi-scenario analysis is used to reveal the impact of several factors on aluminum demand. The results and discussions could provide answers to research questions proposed in section 1.5.

Question a) By 2050, what will be the global aluminum demand for PV systems?

In baseline scenario, the cumulative aluminum demand of global PV systems until 2050 is 830.98 Mt. The demand in mounting structure, frame and inverter accounts for 63.9%, 30.8% and 5.3%. The average annual aluminum demand is projected as 55.74 Mt in 2050, with recycled secondary aluminum meeting 19.5% of this demand. The total aluminum stock until 2050 is 716.63 Mt, with module frames, mounting structures, and inverters accounting for 31.0%, 64.5%, and 4.5%, respectively. The annual aluminum demand curve shows a trend that secondary aluminum will take over primary aluminum in material supply of new PV systems in next decades after 2050.

Question b) What factors influence aluminum demand in PV systems?

According to the research model, factors influencing aluminum demand in PV systems include PV deployment capacity, component market mix, PV efficiency, aluminum intensity of components, component lifetime, and aluminum recycling rate. Among these, aluminum demand in PV systems is most sensitive to PV deployment capacity, varying proportionally with changes in deployment capacity. The aluminum consumption per unit capacity or area varies across different components, and some components, such as mounting structures made of stainless steel, do not consume aluminum. Therefore, changes in the market mix can significantly impact the global aluminum demand for PV systems. Given a fixed target capacity, PV efficiency determines the total installed PV area. Reducing the PV system area not only decreases land use but also reduces the number of modules and the layout area of the installation system, thereby reducing overall aluminum consumption. Lower aluminum intensity in components means less aluminum is required for the same PV system capacity. A longer component lifetime means that components, and the aluminum contained within them, remain in use for an extended period, thus reducing the demand for new components and aluminum. The aluminum recycling rate determines the supply of secondary aluminum, which, in turn, affects the demand for primary aluminum.

Question c) What is the potential for reducing aluminum demand in PV systems?

This study provides four options for conserving aluminum resources in PV systems: increasing LR of PV efficiency, increasing LR of components' aluminum intensity, extending components lifetime, and increasing aluminum recycling rates. We found that accelerating the growth of PV efficiency and reducing material intensity have the most significant impact on reducing aluminum demand. By increasing the LR of PV efficiency from 3.4% to 7.9%, the cumulative aluminum demand reduces by 15.9%. In Alint LR_5.9% scenario, the LR for aluminum intensity increases from 2.6% to 5.9%, leading to a 15.5% reduction. In contrast, extending the lifetime of PV components has a minimal effect, with only 4.1% reduction led by extension of lifetime by 5 years. While increasing the aluminum recycling rate (from 75% in 2050 changed to 99% in 2050)enhances the production of secondary aluminum by 28.9%, its impact on reducing primary aluminum demand is limited to 7.0%. Combining all four options could reduce cumulative aluminum demand by 31.6% and cumulative emissions by 28.5% by 2050. Achieving these reductions requires all four parameters develop at the expected rates. It is also important to note that the PV capacity is a more direct and significant factor affecting aluminum demand in PV systems, while the projected GWP largely depend on assumptions about emission intensity of aluminum production.

Question d) What are the greenhouse gas emissions of producing the aluminum needed in PV systems?

In the projection of greenhouse gas emission, the aluminum used associated with cumulatively 3534 Mt CO_2eq within 2020-2050, equivalent to 9.5% of global energy-related greenhouse gas emissions in 2023. In combination scenario, the reduction of aluminum demand reduces the cumulative emissions by 28.5% (2527 Mt CO_2eq). If aluminum production can not decarbonized on schedule, the GWP will be even greater. The global PV systems have the potential to establish a closed-loop aluminum recycling system if with accurately sorted and recycled, given that the aluminum used in PV systems have similar functions and are similar types of alloys. The recycle of aluminum and aluminum components offers substantial emission mitigation potential.

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