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Research Article

Potential for a circular economy for sustainable large-scale renewable energy systems

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Abstract: The renewable energy industry has been in rapid progression to reduce carbon emissions to net zero by 2050. In this process, we cannot ignore the inevitable and continual decommissioning of a multitude of generation and transmission systems at their end-of-life, leading to a very large mass of waste being produced. With renewable generator lifespans ranging between 20-30 years, there is a limited period to develop a plan to re-introduce materials from these systems into future projects. This paper aims to discuss the status of our renewable energy market and the material available for re-use. This review relies on company and government reports, published work and other sources to establish the material that exists in our solar and wind farms, battery storage and transmission systems, and future changes expected. Then, we collate the options for recycling and the output of these existing recycling processes to separate and reuse the materials collected. There is a significant overlap in material across the generation and transmission networks which could be introduced into the circular economy through mass processing. At present some of this already have proposed uses, but most still goes to landfill, removing them from the circular process we aim to achieve. This research highlights the difficulty in achieving sustainability aspect of the renewable energy industry and some opportunities for introducing all material into the circular economy. This problem is handled for the energy industry and policy makers as well as encouraging those in recycling to take up this challenge.

Keywords: *Circular economy, Renewable energy, Recycling, Sustainability*

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1. INTRODUCTION

We are at a significant turning point in how we support our highly energy-intensive lifestyles and industries. Pressure at the international level for reducing carbon emissions to zero is accelerating the global transition to renewable energy sources but is also being linked to other societal and environmental impacts which are not desirable. These include harm to biodiversity and loss of productive agricultural land when it is allocated to net zero energy resources and infrastructure [1],[2], plus growing amounts of waste from decommissioned renewable energy farms. The International Energy Agency estimates that over just the next twenty years we will need six times the present amount of transition metals mined annually to reach global net-zero carbon emissions by 2050. While some of this may presently be obtained as a by-product of coal mining, that option will be reduced, it is likely that this demand will lead to more mining and more environmental damage.

Recently the Australian Environment Minister blocked a plan to build a wind turbine manufacturing plant on a wetland in Victoria that had been listed in 1982 under the Ramsar convention for internationally important wetlands. The plant would have destroyed 92 hectares of wetlands and impacted the waterbirds and migratory birds that use this location. This site was to be used to assemble offshore windfarm foundations, turbines and towers and create needed support for the growing wind farm industry in Australia. However, another location will need to be found. We cannot create another problem in seeking renewable energy. To manage wastes, it is important to consider the life cycle of material used in renewable energy systems as these will need to be decommissioned and replaced over time. There are options for reuse and recycling in a circular economy, and this can be designed at scale for the large renewable energy farms being constructed. However, these farms exist close to their energy source and hence usually far from manufacturing facilities or industries that may consume the recycled material.

This paper focuses on the effects on waste management and resources from recycling efforts, however does not deal with other economic benefits of such perspectives and processes beyond the economy of less extraction of resources, such as employment in recycling. We present an accounting of the materials used in renewable energy generation and transmission systems. A grounded approach was used to collect information from multiple sources, including data gathered through discussions with different wind farm, solar farm and Battery Energy Storage System (BESS) owners, as well as the NSW Network Operator – Transgrid – who operate the Australian network in New South Wales. From the foundations and structures to the plant and equipment, and everything in between, this paper explores the various components and the raw material that can be found within each sector. Additionally, government and industry reports, media releases, scientific and engineering journals from industry experts confirmed the data and contributed more details.

In this first stage of the research, the key components that make up solar and wind systems, energy storage systems, and transmission systems are considered. By investigating the distinct components and their quantity, we can collate what materials will need to be recycled at the end-of-life of these projects and hence plan for recycling at scale. All systems included in the present work have materials that are common across not only these renewable energy generation and transmission systems, but also industrial, commercial, and residential projects and everything in between. In General Components we discuss the variety of material that exists mostly in the foundations, but also in the collection and transport of electricity from one site to another. Wind farms have large and durable turbines to counteract the forces of the wind whilst still allowing wind energy to effectively produce kinetic energy. This comes with a large number of components that are more difficult to recycle – such as metal alloys and fibreglass composites. Solar farms have even more extensive and complex elements, chemically bonded to produce photovoltaic (PV) cells, further creating a more laborious breakdown of components into multiple raw materials. BESS, like transmission substations, requires a diverse range of functional plant and equipment containing chemically bonded liquids that require meticulous extraction, or single-use material that is essentially disposed of into landfill.

The recycling and re-using components from renewable energy generation and transmission systems requires a depth of knowledge of the materials. It is easy to develop more sustainable systems in the future, however we need to understand what material has already been used, and how it can be added into the circular economy, to repurpose the amount of landfill that will grow exponentially at the end-of-life of these systems. This includes developing new techniques for separation and extraction of material, and often the main components cannot be used without removing all impurities. As the present research explores the present techniques for separation and reuse, this will include options to link the large farms with the recycling industries in a way that does not create major transport issues and reduces the waste disposal of material that is from limited resources. In the next stage we will consider what alternatives exist and so have the basis to balance out the costing between different approaches, both based on scale of farm and type of generation. The examination of the options for recycling will need to consider the existing material used in the farms and how they can be separated, as well as some of the more recent manufacturing techniques.

2. RESEARCH METHOD

2.1. Objectives

Renewable energy farms are large scale projects that utilise many components and cover a large area of land. The objective of this research is to support Engineers Australia's vision of continuing to create sustainable materials and products from waste. This will be done by understanding what can be recycled, what has been designed to recycle and what would be difficult to recycle. The work focuses initially on solar and wind farms, as the major sources of energy, through the exploration of the various components of both the generation and transmission side of these projects. The research will aim to break down these components and determine opportunities for improvement in the ecological value. Large projects such as these have a big impact on the environment and this project endeavours to address the environmental concerns that the projects will create once they are decommissioned. The engineering perspective complements the scientific understanding of what can in principle be recycled with the practicalities of how this potential can be realised at scale and in time for the projected growth in renewable generation and storage capacity.

2.2. Assumptions

Technology currently used in renewable energy systems may be redundant by the end-of-life due to the rapidly changing nature of technology or their composite nature. The materials will need to be recycled back into manufacturing or construction projects that are most likely not going to change in the coming decades, that is, procedures that do not require complex technological equipment. Also, up and coming manufacturing techniques proposed for these systems will be considered for the life-cycle benefits and designed with consideration of a circular economy.

Our scope will be restricted to utility-scale assets generally connected to the transmission grid. A significant generation capacity already exists on the distribution grid through customer rooftop solar, and distribution networks are evolving to increase their hosting capacity to enable load balancing in such a complex system. Our assumption will be that the recycling industry that meets the needs of utility-scale assets will also accommodate assets from customer sites; however, the study across different sized farms may suggest there are benefits in different recycling methods, based on scale.

2.3. Collection

To establish the material used in renewable systems we collected reports from industry and government on existing systems, plus research into material usage in the industry. This review covered all publication that related to solar and wind farms and battery storage included in a web search on renewable energy. This review is only to highlight the main components that may be available for recycling and give some options to achieve this. In future research we will access what the available processes for this and the options for reuse of the recycled material. To our knowledge, we have not found any other study either professional or research-based, that looked in detail across the renewable sector at the material used and the processes needed to break down the manufactured components into reusable products. Some existing websites provide an overview of the issues in recycling and the main materials, but these often do not consider the details of extraction to separate materials when recycling. Other work considers details of single types of renewable systems and their recycling, or single materials, but these publications do not present a picture of whole of industry options.

For recycling options, we provide as comprehensive a list as possible from academic and news publications, where the recycling deals with material our research has highlighted as significant components of the waste from this industry, and where the process is already used in industry or at least in small scale trials. Also, we are looking at large wind and solar farms, storage and transmission systems as these provide waste material at scale where there is more opportunity to use more complicated extraction and separation methods and gather most of the waste material as reusable products. When considering smaller system such as roof top solar, the waste can be directed to the plants where the bulk of the material is being handled, rather than creating a separate process.

3. BACKGROUND

3.1. Australia's Status in the Renewable Energy Generation Game

Currently, Australia is developing more wind farms, solar farms and BESS and construction of these assets is unlikely to slow down. For example, the first Capacity Investment Scheme (CIS) auction yielded more than 40GW of project registrations for wind and solar farms which is over 6 times the anticipated 6GW of new power that the CIS was intended to support. This means that there will be hundreds of renewable energy generation systems, and their corresponding transmission systems, that will reach their end-of-life in the next few decades and require repurposing of material to ensure landfill does not increase exponentially as systems are shut down. This growth is to compensate for the staged decommissioning of coal-fire powered generation systems which still provide a significant amount of generation to Australian customers. These non-renewable sites include generators such as Lidell Power Station, now closed, and Eraring Power Station, predicted to close in less than a decade. These systems are generally located in new geographical areas away from the old power stations and this will cause ongoing issues such as altering the geological properties of the land used, as well as the communities in those regions. The lack of research and development into these issues due to an acceleration in the construction of these systems means that planning to reduce the impacts is limited to the availability of human resources and time. One of the most significant issues in the sector is currently the recycling of construction waste. It has been estimated that the most significant contributors to global waste production lies within the construction sector, with over 30% of the waste produced ending up in landfill [3]. To combat this, researchers are developing methods of recycling material into future projects.

Evident through the observations of remote communities in Australia's Northern Territory and their distance from more populated areas, Thai et al., [4], have developed a feasibility study to introduce a hydrogen energy solution and limit the barriers affecting remote communities Mathur et al., [5], has recognised the economic and environmental impacts that solar panel removals are creating. The volume of waste in conjunction with a lack of clear guidelines at a national level to collect, transport and dispose of solar panels has limited the ability of local governments in decreasing landfill. Solar Energy Systems in Northern Australia are also exploring methods of transitioning towards a circular economy and proposing ways to limit up to 145,000t of solar panels being decommissioned by 2030 [6]. To limit this amount of material at the end of these projects, the Waste Management hierarchy shown in Fig. 1 aims to minimise landfill by re-using materials found across different renewable energy generation systems before considering recycling and recovery strategies or ultimately disposing them. This work does not deal with waste prevention strategies.

Figure 1. Waste management hierarchy as per The European Union's 2008/98/EC directive.

Solar and wind farms generating electricity at high capacities require various components to operate, as well as substations and transmission lines to transmit the electricity to customers. To combat the intermittency of these new generators connecting to the grid, energy storage systems are being introduced to store and dispense load during off-peak and on-peak hours as well as limit the strain on network. All the material being used to construct and operate these systems will eventually end up in landfill, making these "green" systems lose their environmentally sustainable value. To put things into perspective, Figs. 2-4 present the current number of operational sites and generative capacities of solar, wind and battery systems in Australia, as well as their generative capacities by 2030.

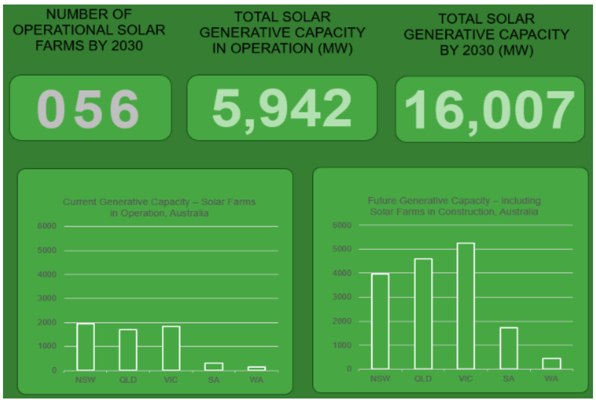

Figure 2. Operational solar farms and generative capacities by 2030 in Australia.

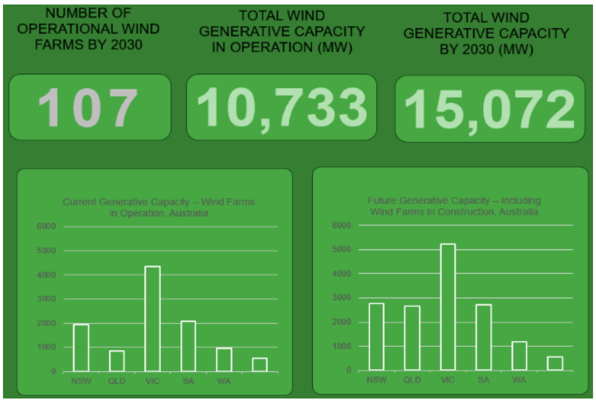

Figure 3. Operational wind farms and generative capacities by 2030 in Australia.

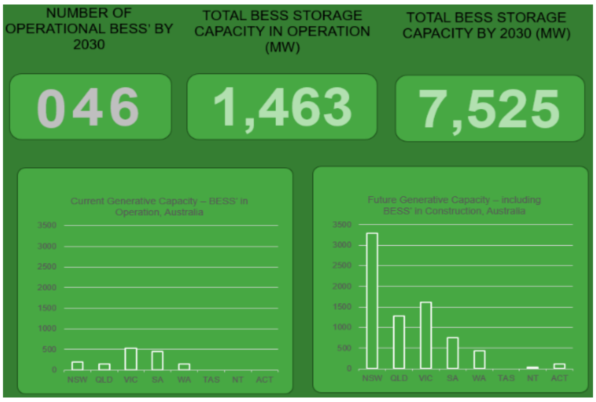

Figure 4. Operational Battery Energy Storage Systems (BESS) and generative capacities by 2030 in Australia.

Overall, the generative capacity of solar farms in Australia triples once the systems currently in construction are producing electricity, with the more populated states developing more than twice their amount of generation in the next five years. Wind farms show a slower progression in comparison to solar farms, with a generative capacity increasing only by 50% by 2030, however, equate to the total capacity of solar farms. The BESS are the newest technology on the market, representing the lowest generative capacity, but are set to have the most rapid increase across renewable energy in Australia, due to the country's reliance on storage systems to balance the renewable energy generation.

3.2. General Components

Much of the civil and electrical material used to build high voltage electrical generation systems and transmission networks are common across all types of facilities. Foundations made of concrete and reinforced with steel bars; steelwork to produce rigid structures; backfill, gravel and sand to dissipate electrical currents during faults; underground cables to transport power locally; and overhead wire to transmit power to the grid account for a substantial mass of the material.

3.2.1. Foundations

Bou Melhem and Tam suggests that concrete accounts for up to 80% of construction and demolition waste, equating to approximately 22.5 million tonnes in Australia alone [6]. However, waste does not suggest the material is without value, rather, a resource is dependent on the value it is given. A comprehensive study on CO_2 associated with concrete has resulted in a sustainable solution that could eliminate the amount of concrete being disposed of, and instead it can be recycled onto future projects. Wind farms, specifically, use a large amount of concrete per farm, with most projects requiring batching plants to provide a sufficient supply. The size of the turbines and distance between these large structures accounts for a significant amount of concrete production during the building of the system, and hence will result in that same mass being disposed of in the decommissioning stages of these farms. Gravel and sand make up another significant portion of the foundations of these systems, with Mehsas et al., [8], explaining the need to recycle both these materials. Gravel and sand are the most common types of fills used in substations and industrial sized generation systems, and have always been readily available through the constant establishment of new mines. The same two materials are major components in concrete foundations and although the ratios are continually configured to suit the properties required to strengthen foundations, the general materials used remain the same. To filter the combination of fill that has been imported for these systems, the simple process of sifting the mixture through different sized mesh screens is the most efficient method. To minimise earth potential, these materials are laid as the top layer of transmission systems and are therefore the easiest layers to remove. Most of the cost to complete these works will be reflective of the expense to hire bulk earthwork machinery as this involves the physical process of shaking the sand off the gravel.

A concerning issue that has impacted the social, environmental, and political climate is the limited supply of gravel and sand that can be mined for future use [9]. It is essential to resource alternative sources of supply to avoid completely diminishing the natural deposits of aggregates and a solution may be to recycle these aggregates into future foundational concepts [8]. Rather than mining these materials, Mehsas et al. [8] have developed recycled aggregate concrete (RAC) of high quality and durability, which recycles these materials into concrete for future use. Based on the experimental results of the study, recycled gravel, and sand, as opposed to newly mined material, was used as replacements of up to 60% of recycled materials, improving the mechanical compressive strength.

3.2.2. Structures

Steel is consistently used in different components of each renewable energy system including control panels and racks, as well as structures supporting solar panels, wind turbine towers, battery racks in generation systems; along with a range of components on the transmission side, such as transmission line towers, control panels and racks, and structures supporting high voltage switchgear. From 1950 to

2006, there has been a significant increase in the production of steel, from 187Mt to 1,299Mt [10]. As one of the most recycled metals, a process has already been determined to reuse this material, however only 40% of steel currently produced comes from recycled scraps [11]. From the foundations to the structures, to the high voltage equipment and transmission cables, steel can be found in different forms. Although a significant mass of material is found in easily locatable areas, extracting steel from some sources may prove difficult.

Foundations are strengthened by rebars, which are un-processed raw metal and although this raw metal can easily be reformed into other products, this may be a source that requires a significant amount of effort to retrieve the steel. The concrete covered steel makes it especially tiresome to extract, as jackhammering the surrounding hardened concrete may prove tedious and difficult. Steelwork in open air such as structural steel supporting equipment or transmission towers, however, can be easily dismantled and prepared for recycling. Once the material has been retrieved, steel can undergo the process of using an Electric Arc Furnace (EAF). EAF is the theoretical process of converting pure scrap metals into new products by re-melting 100% of the steel to produce material at either the same, higher, or lower grade, depending on the metallurgy and process of the original material [12]. This restricts the mass of material which can potentially be recycled from different systems to just pure steel that has not been treated. Alternatively, manufacturers can reverse the effects of galvanising on the steel by undergoing additional steps to chemically remove the galvanising layer before it can be melted down in the EAF process.

Chemically removing the galvanising layer from steel proves to be another difficulty faced in the recycling of this material. To prolong the life of the material and limit the diminishment and corrosion it is subjected to, steelwork placed in the natural harsh climate conditions of the Australian environment require a protective layer. Further, steel is treated with this galvannealed layer to increase its weldability, workability, and corrosion resistance properties [13]. As manufacturers require raw, untreated steel to produce material and equipment, recycling galvanised steelwork must undergo the additional process for re-use. This chemical stripping of the galvannealed layers creates a by-product, steel slag, through the Electric Arc Furnace (EAF) process, providing another material that will need to be recycled [14]. Theoretically, the processes to recycle steel is one of the simplest methods in developing a circular economy, particularly through the creation of rebar in concrete and sections used in structures. Rebar used in foundations, and steelwork used on structures, are vital in developing strong foundations to uphold heavy structures and equipment that withstand heavy loads over a long period of time. Further, high value engineering steels require further processes to develop the material to the definitive specifications – like how steel is originally manufactured. However, efficiencies cannot not be made to explore prototypes to recycle this material due to a limited amount of steelwork currently being decommissioned and disposed of in a short amount of time [12]. The extended use of steelwork to support high voltage equipment in switchyards and towers supporting transmission lines that have not yet been decommissioned is a testament to the strength and durability of steel that was produced over the last century. As technology evolves or is damaged, high voltage equipment and conductor is replaced with no consideration being made to recycle the steel supporting these assets, even if they don’t appear to have physical deformities [12].

3.2.3. Overhead conductor

Overhead conductor is used to transport high voltages of electricity over varying distances – long distances, for the transmission of electricity on a national scale, and shorter distances within renewable energy systems. As it accounts for a significant bulk of material in the transmission and renewable energy systems, it is required to be recycled during the end-of-life stages. The fatigue on the conductor caused by the stress and environmental factors determines the general lifespan of the material. The cross-sectional area of a typical Aluminium Cable Steel Reinforced (ACSR) conductor –comprises aluminium strands wrapped around a composite steel core.

Typically, tonnes of conductor would be decommissioned and re-drummed on site, then sent internationally to undergo a process which allows components to be broken down for recycling. A mobile recycling prototype developed by Germany's ZECK GmbH has been adapted and recreated by NSW Network Operator, Transgrid, to pilot the decommissioning of overhead conduct in New South Wales (NSW), Australia. The ZECK Aluminium/Steel Separator (ZAS) is used to break down general overhead conductor into its various components in preparation for recycling and re-use of its different elements. The original design efficiently sorts scraps of ACSR conductor to increase the sustainability whilst concurrently reducing emissions. After being decommissioned in the field, conductors are fed into the machine under tension which removes aluminium material on the outer layer and consequently cuts the material into pieces 30-70mm in length. This material is then sent to scrap metal dealers or smelters for re-production into new products. As the remaining undamaged steel core leaves the machine, it is wound onto a cable drum and sent for recycling. Aluminium and steel serve many purposes in the construction industry. Steel can be melted down into other structures as mentioned above.

3.2.4. Underground cables

Underground cables require more protection from the local environment than overhead cables, and submarine cables even more so, and they have correspondingly more complex internal construction. The range of underground cable sizes, compositions, rated operating loads and specified conditions make it difficult to explore the varying options to recycle them, as well as determine their design lives [15]. However, the general composition of a cable is copper cores surrounded by insulating polyvinyl chloride (PVC) and paper layers. The decomposition involves multiple stages so numerous researchers have explored new processes. They have yet to determine which products the waste will be best suited for in terms of recycling. Chemically manipulated material that produce semi-conductive components of cable prove to be difficult in breaking down into raw material, further financially and physically adding to the recycling stages for re-use. Both low voltage and high voltage cables contain PVC and copper for insulating and earthing properties. Recycling these materials will alleviate the mining of copper from copper ore, and production of virgin PVC. This will reduce the environmental impacts through the reduction of landfill, energy and water usage, and emissions to environment [16].

The cables used in electricity generation and transmission make up only a fraction of the uses of cable in the world, as they are also used in transportation, construction, communication, and other consumer goods. To understand where cable material can be recycled, it is necessary to understand the major categories and formations that cables come in, material the cables are made of, and how much raw material can be extracted from the cable, as well as the cost effectiveness of breaking down each cable. The generic structure of cable consists of conductive metal cores such as copper or aluminium, thermoplastic and thermoset insulation, auxiliary elements to protect the cable and guarantee its longevity, and an outer sheath to protect them from the elements. Blinova and Godovcin [16] noted that the composition of different cables are annealed copper and PVC insulator, with others using more complex combinations that involve layers of different insulating materials wrapped around singular cores. The complexity of the cable determines the process which the cable will be dismantled, with the simple cables requiring as little energy as mechanical treatment, or more complex combinations requiring chemical processes.

The current process to recycle the copper sheath out of cables is to strip back the insulating PVC layer, which goes to landfill, and collect the copper sheath layer for recycling. Due to the time and cost exceeding the value of the copper within the core, or cores, the copper surrounded by the tight insulating layer of PVC is normally disposed of into landfill.

3.3. Wind Farm Generation Systems

The deployment of turbines, both on-shore and off-shore, connected to make an internal network of electricity generation, is accelerating [17]. Dependent on the climate and operation of these turbines, the lifespan of these assets range between 20-30 years [18]. In Australia specifically, wind farms range from

34.5 MW to 420 MW, and although the different sized farms use varying material based on their geographical location, most of the material and design concepts are uniform. A typical wind farm produces energy at the turbine through the blades, transports this kinetic energy to the power conversion system in the nacelle, from where the electricity generated will travel through underground cables to the substation. In some cases, larger wind farms will own multiple substations and an internal overhead transmission line will transport electricity to the closest connection point on the existing grid. To understand the weight of material that will contribute to the waste that will be created during the decommissioning process, a breakdown of the components needs to be made. One of smaller wind turbines, the Vestas V47, details the various components in a typical wind turbine, and although it produces only 660 kW of power, it is a general representation of a typical structure used in Australia. The structure can be dissected into several components and further classified into 2 main material categories, metals: base frames, main shaft, and mechanical components; and fiberglass: blade and blade hub.

This mass of wind turbines will produce tonnes of material which will need to be disposed of at the end-of-life phase, leading the Clean Energy Council to develop a plan to prevent most wind turbines ending up in landfill. Desktop studies have shown that between 85-94% of a wind turbine, including steel, aluminium, copper and cast iron, can be dismantled, and recycled in Australia, accounting for a significant portion of material. The remaining 6-15% is the material of blade, made up of fibreglass composites. The carbon fibre and fibreglass are yet to be reused and by 2034, an estimated 15,000t will be created from the decommissioning of wind farms. Consequently, 4,000t may be produced each year after from the decommissioning of other wind farms.

Mechanical components in wind turbines such as the fasteners, gears, and other steel components, like many other mechanical components in other equipment, are primarily steel to alleviate the rate of diminishment in harsh climate conditions. Though these may be minute in comparison to the mass of steel in the base frame and main shaft components, collectively, they account for a significant weight of material. As mentioned above, steel has a variety of uses in a circular economy and can be melted down for re-use. To improve the stiffness, tensile and compressive strength of material and allow them to withstand harsh winds [19], blades are currently primarily made up of fibreglass pieces and are injected with resin [20]. The approximate composition of the blade is typically 93% polymer composite reinforced with glass or carbon fibres, 2% PVC, 2% balsa wood, and the remaining 3% metal paint and putty [21]. Due to the multiple chemical changes made to Fibre Reinforced Polymer (FRP) and the specificity of the designs for constructions to suit applications, these materials are made with no intention of recovery or reuse once they reach the end-of-life [22]. This makes it a difficult material to recycle due to the strength of the material significantly decreasing when the fibres are shattered, as well as the issue that it is no longer a raw material, rather, a composite. With a low-viscous resin flowing and wetting the fibres, the chemical properties of the fibreglass are more irreversible, and the material requires chemical manipulation to return it to the basic raw materials. There are still a range of issues relating to the three main methods of recycling – mechanical, thermal, and chemical – including risks of surface defects, fibre length, equipment costs, and process suitability according to the composition of the blade composites: all providing financial and physical obstacles in recycling turbine blades [23].

Fibreglass has an array of products that can potentially re-use the recycled material. Mechanical methods of recycling can shred and use the material to produce alternatives to standard cement [19] and replace raw materials as fillers, however, increase the cure time due to boron in the composites [21]. It has also been tested and successfully constructed into prototypes such as toys, bridges, and new wind turbine blades [23]. Thermal solutions to extract material through pyrolysis involve losing 50% of the material properties, however, they can produce organic liquid fuel, pyrolytic gas or oil or composites reinforced by short, recycled fibre [24]. Danish Company, ReFiber, successfully re-used the recovered glass using this method, however, due to economic restrictions of high investment and processing cost, and limited commercial applications, the company ceased operation in 2007 [25]. Another more laborious method is to chemically extract the resin from the fibreglass, as well as solvolysis to create fuel gas [24], which is also being explored to make reinforced industrial products though not as economically viable at present. Chemical methods prove to be more dangerous in comparison to mechanical and thermal recycling and are less desirable due to the technologically complex process.

3.4. Solar Farm Generation Systems

The most common renewable energy generator is solar powered technology due to its ease of constructability and the minimalistic geographical requirements. It is estimated that these farms are retired with a 25-year life span [26]. However, the high volume of material required to produce these systems leads to a mass of material requiring a home at the end-of-life of the farms. Modern designs integrating materials from old panels have suggested that the continual use of solar panels to produce electricity as a method of solar generation will exist in the future. Present issues across all stages limit the sustainability of this system, including prior to the systems being energised and producing electricity, the production of modules to be installed on solar farms, and the construction. The development of high efficiency solar modules incorporates the processing, cleaning, and manufacturing of quartz with other components at very high heat, followed by combining this quartz with multiple materials. These processes cannot be complete without using fossil fuels on large scales, and typically in single locations, therefore create significant emissions.

The six layers of a solar panel provide over 25 years of life when subjected to extreme temperature, humidity, wind and ultraviolet radiation variations, and include the solar photovoltaic cells, toughened glass, extruded aluminium frames, Ethylene Vinyl Acetate (EVA) film layers, polymer rear-back-sheets and junction boxes containing diodes and connectors, as shown in Figure 5. According to the Institute for Sustainable Futures, the most common photovoltaic (PV) panel uses the crystalline-silicon (c-SI) structure, and the material mass composition is typically made up of approximately 76% glass, 10% plastic polymer, 8% aluminium, 5% silicon, 1% copper, and < 0.1% silver and other metals [27]. Although there are a range of materials that form a PV panel, some layers, such as the aluminium frames and back sheets, are made of pure material that can be recycled efficiently [28,29]. However, the extraction methods for other materials have been more expensive than the value of their outputs.

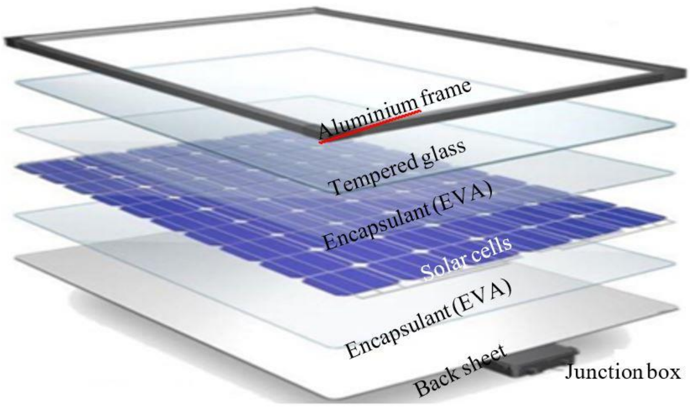

Figure 5. Layers of a solar photovoltaic cell.

Companies are starting to see the potential returns of recycling solar panels. Through manual, thermal, and chemical processes, nearly 100% of the panels can be theoretically recycled with the aluminium, silicon, copper, silver, and glass recovered and re-used in the manufacturing of new products [28]. Due to the delicate nature of the fibreglass and the fact it cannot be recycled if fractured, only the glass can be reused, whilst the remaining material is often burned in cement ovens. To decrease the human labour of decomposing the panels to their individual materials, robots are used to extract the glass, silicon, plastics, copper, and silver – to allow these raw materials to be re-used for new panels. This method, however, may prove to be unsustainable due to the rapid development of technology and potential phase out of current photovoltaic technology.

Europe has invested in the development of their first solar panel recycling plant in France. The plant currently only recycles the glass and aluminium frames; however, these materials make up a significant portion of the panels, making it a notable advancement in sustainability in the industry. Australia has also developed a method to recycle 100% of end-of-life PV modules and all associated materials recovered from the solar farms, breaking down the inverters, cables, optimisers, and mounting structures into the raw materials [28]. This method has shown the availability of resources to decompose the panels into raw materials such as high-grade aluminium, high grade silica dust, copper, PVC, and silver.

3.5. Battery Energy Storage Systems (BESS)

Battery Energy Storage Systems (BESS) are being increasingly integrated to alleviate the instability in the network produced by the influx of power from the new renewable generators. Although they are primarily storage systems, they also function as independent generators for the transmission grid during when environmentally dependent generators are not generating. The expected lifetime of these storage systems reflects their capacity and operation [29], with batteries estimated to reach up to 20 years [30]. BESS are quite similar to substations, where most of the equipment connecting, controlling and protecting the generation/storage source – batteries – are high voltage switchgear, relay devices, and cables. All the physical control equipment such as the Battery Management Systems (BMS) and the Power Conversion Systems (PCS) are made up of storage racks with relays, connected by cables and wires to allow systems to communicate with each other. Relays and racks will be discussed further in the “Transmission Line and Substation System” section. The equipment unique to a BESS is the Battery Cells/Modules which utilise different types of batteries based on the energy density, cycle life, and other performance characteristics. The different chemistries of battery include the commonly used Lithium Ion (Li-Ion), and the less commonly used Lead-Acid (PbA), Sodium-Sulphur (Na-S), Flow Batteries, and Zinc Bromine Cerium-Zinc. As these batteries are chemical compounds, a lot more challenges are present in recycling due to their compound chemical compositions.

Currently, much like household and vehicle batteries, the batteries used by BESS utilise chemicals and plastics. Li-Ion batteries are the most common cell types, used not only for industrial energy storage systems, but also electric vehicles, with a demand of nearly 250 GWh in 2020 and a predicted increase of a multiple of 10 by 2030. Only 10% of Li-Ion batteries in Australia were recycled in comparison to the 99% of Lead-Acid alternatives as a consequence of the expensive nature of the extraction process. Due to limited resource availability, all Lithium batteries collected in Australia are shipped overseas or stored in warehouses or scrapyards, creating issues of fire risks and potential environmental contamination. To combat the issue of harmful chemicals going to landfill and negatively affecting the environment, Sweden’s Northvolt announced their production of the first lithium-ion battery cell featuring a nickel manganese-cobalt (NMC) cathode using metals recovered through the recycling of battery waste. This is another system which has allowed the re-use of technology into the same, slightly more developed technology. However, this method of recycling may prove unsustainable due to the development of new technology.

3.6. Transmission Line and Substation Systems

High voltage equipment responsible for monitoring and transmitting electricity from generators to the grid require expensive and unsustainable material to function. Across the protection, metering, control and operation of the switchyard, equipment such as insulators, surge arrestors, voltage and current transformers, circuit breakers, disconnectors, transformers, busbars, and post insulators are made of different individual recyclable components which have yet to be explored. The functionality and the timely operation of each piece of equipment will determine the service life of each asset and it is therefore difficult to estimate the life span of each item. Many mechanical components within each piece of equipment may prove difficult to explore, with no effective recycling scheme developed due to the intricacy of the design of the equipment, as well as the cost savings failing to compensate the labour to complete the decomposition [31].

The transmission system connects all the generation systems to the different distribution networks. It is highly critical that this system is therefore secure, to protect the multitude of generators, vast transmission grid and extensive customer network receiving electricity. To manage and protect the assets within the systems, relays and communication systems in racks and panels connect the various pieces of equipment to ensure that issues are alarmed and inspected as soon as reasonably practicable, and isolated or connected to the grid safely. Panels and internal digital systems are sheltered from the external environment and have a longer service life than the equipment situated outdoors. Therefore, the state of the panels and associated equipment connecting the internal systems will be far more immaculate than those subject to weather conditions. This means that if technology does not change with time, relays and panels can be transferred into new substations, and re-used for future projects. However, due to relays, fuses, cables, wires, and other functional components being used until failure, the material is generally disposed as repurposing it would be more expensive and less efficient. Common high voltage equipment typically found in substations encompasses a variety of apparatus including transformers (step-up/step-down, auxiliary, automatic, current, voltage), disconnectors, circuit breakers, and surge arrestors. The majority of this old but current technology includes mineral-oil insulating fluids – some containing Polychlorinated Biphenyls (PCBs), or gas (SF6) insulated materials, and currently all go to landfill through qualified disposal companies during the decommissioning of the high voltage switchyards. Substations servicing distribution networks are unlikely to be decommissioned due to the growing population remaining in areas which have already been developed, in addition to sprawling into more regional areas. This means that equipment is less likely to be removed, rather, replaced in the event of equipment failure. High toxicity levels seen in PCBs negatively affect ecosystems and living organisms and have demonstrated major issues when determining the method of disposal at the decommissioning stages [32]. Due to the depletion of metal from environmental conditions, and aged oil affecting the durability of the material it comes into contact with, it is difficult to return material to its original state without diminishing physical properties, specifically its strength. The cost to dispose of contaminated products is already costly, without considering efforts to recycle material, and therefore the only known results are re-using equipment that has not yet reached its end-of-life, or has been tested for damage and other issues, on future switchyards.

The transmission line structures supporting overhead conductor, and connecting substations to other substations, come in three main forms: steel, concrete, and treated and untreated wood structures. Steel fittings and glass or polymer insulators form part of this system and are required to connect the adjacent structures to form the lines. As mentioned above there is opportunity to include steel and concrete into a circular economy. Although Australian Standard *"AS 2209 – Timber Poles for Overhead Lines"* specifies only Class 1 and 2 species of timber be used for wood poles, as opposed to the full range of Classes 1 to 4, timber wood poles are becoming less common due to their lack of durability and inability to withstand the harsh Australian climate. Natural disasters and fauna interactions decay the material at a rapid rate in comparison to the newer steel and concrete structures, especially untreated wood, although this, can be re-used or recycled in various scenarios outside of construction. Treated wood, on the other hand, poses additional risk to recycling due to additives in the material, therefore limiting the potential of re-using the material in a circular economy.

Polymer insulators in substations and on transmission lines have been introduced to alleviate the potential damage caused by porcelain/ceramic or glass insulators at failure, however, they have a relatively shorter life in comparison to the ceramic counterparts, with an estimated 20-year life span [33]. To increase the mechanical strength of polymer insulators, some systems continue to utilise porcelain or fibreglass cores [34]. Therefore, polymer, porcelain and glass must all be considered for recycle and re-use. Zimmermann and Zattera [31] produced a method to recycle and reuse the waste produced from ceramic insulators into thermoplastic composites and hybrid composites.

4. CONCLUSION

To provide a more sustainable renewable energy industry, it is critical to provide options to produce a circular economy. Renewable energy generators have often led to a decline in sustainable practices in the use of resources. This can be countered now with a focus on the re-use and recycling of the mass of material at the end-of-life for these systems. From a study of reports of the materials and composites used in construction of renewable energy components, and verification of this analysis with industry professionals from each sector, we have collected a full range of the types of components used and through further research we are identifying what can be realistically extracted on mass. With the substantial recycling opportunities developed globally, there remain many possibilities to rectify the mining of a limited supply of natural resources and move towards a cyclic economy. Understanding the current availability of material in renewable energy components and length of time before these assets reach the end-of-life will provide a timeline for opportunities of recycling and re-use to be explored and improved. Furthermore, by considering all renewable resources in the one study we can consider more economies of scale in extraction and resale. The next step is a comprehensive study to quantify the amount of material available for re-use and develop a provision to introduce specific materials into the circular economy and catalogue the remaining materials. This will provide an idea of the scale of each type of waste and hence the more feasible recycling methods of those available. The optimal recycling may vary between different sizes of renewable energy farms where the optimal process depends on the economy of scale of each technology considered.

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