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Review

Tackling the Circular Economy Challenges—Composites Recycling: Used Tyres, Wind Turbine Blades, and Solar Panels

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Abstract: Transformation of waste into resources is an important part of the circular economy. Nowadays, the recovery of materials in the most effective way is crucial for sustainable development. Composite materials offer great opportunities for product development and high performance in use, but their position in a circular economy system remains challenging, especially in terms of material recovery. Currently, the methods applied for recycling composites are not always effective. The aim of the article is to analyse the most important methods of material recovery from multilateral composites. The manuscript presents three case studies related to the recycling of products manufactured from composites: used tyres, wind turbine blades, and solar panels. It shows the advantages and disadvantages of currently applied methods for multilateral composite utilisation and presents further trends in composite recycling. The results show that increasing volumes of end-of-life composites have led to increased attention from government, industry, and academia.

Keywords: circular economy; composite recycling; multilateral composite; used tyre; wind turbine blade; solar panel

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1. Introduction

Nowadays, the circular economy (CE) is considered a key economic model for many European countries. It was introduced as an economy action plan by the European Commission in 2015 and quickly became a leading initiative [1,2]. However, the concept itself dates to 1966 [3,4]. This model helps to meet the challenge of sustainable development; achieve resource-efficiency; stimulate Europe's boosted global competitiveness, especially through proportion eco-innovation; and generate new jobs [4,5]. One of the areas where new jobs are created is material reusing and recycling.

The concept of the circular economy is based on new approaches to manufacturing and using the goods. In the traditional, so-called linear economy, the following steps are generally implemented: development, consumption (introduction products to the market, growth, maturity, decline), and disposal of materials/products [6,7]. In the circular approach, linear thinking is transformed into loops. The important factor is reusing and recovering materials and products and consequently reducing environmental impact on the environment. For that, additional steps such as waste prevention and management must be added to traditional linear schemes [2]. The transformation of the linear model to circular approaches helps to achieve global sustainability and to minimalise the pressure on natural resources [1,6]. It also helps to create green growth, especially through complementary activities, including eco-innovation and resource efficiency [1,8].

The shift toward a circular economy, promoting the elimination of waste and the continual safe use of natural resources, is required. Material efficiency is a key element of the circular economy to address the challenges of reducing the impacts on the environment and resource deficiency [1,9]. The improvement of material circularity is a basic concept for the circular economy. Reintroduction of the flow of materials should include their economic, environmental, and social effects [1,5,10]. The important element in this case is also the redesign of materials throughout the product life cycle [6,7,11]. The products should be designed by building a closed-loop process and decreasing resource use. At the same time, the persistent use of resources through recycling and reuse instead of landfilling should be promoted [6,10,11].

Nowadays, waste generation is a serious problem [1]. Waste management has become a series of challenges around the world, including reducing the carbon footprint and reducing carbon emissions [10,12]. It is also directly related to soil, water, and air pollution [1,8]. The large amount of waste is mainly related to increased consumption, which in turn is directly related to the growth of the world's population and the linear industrialisation system characterised by a low level of material efficiency [10,13]. The global economy is still under transformation into a circular system. To accelerate this process, technology development as well as educational activities are needed. The important element during education is to stress that the benefits of these changes are not only for the environment, but also for the economy and society [5,10]. One of the most important targets is reducing the consumption of natural resources [10,14]. It is strictly connected with the economic benefit associated with the reduction of cost of the virgin materials and also the decrease in the cost of energy. Due to material recovery, resources can be used many times, and new industries are created that also provide benefits to society. Reduced costs also arise from environmental legislation, taxes, and insurance [5]. This process also helps to build a local community [5]. It is worth stressing that this kind of benefit is usually more evident in countries subjected to rapid industrialization and poor environmental regulations [3,15].

However, it should be noted that not all authors present a positive relationship between economic growth and environmental sustainability [3,16,17]. For example, Kiser stresses that in the circular economy there is a paradox connected with the goal of selling more materials (economic growth) and the use of less resources [16] and Skene [17] affirms that economic growth necessarily creates environmental deterioration, because circles can never deliver growth, unless circles are intended as spirals [17]. Additionally, some problems may be created through modern materials such as biobased polymers that have not been fully investigated and using them as materials for a circular economy may not always be effective [18].

The main aim of the article is based on the conception of the circular economy to analyse the most important methods of material recovery from multilateral composites. The considerations on this topic are supported by three case studies connected with the recycling of multi-material products such as used tyres, wind turbines, and solar panels. The article presents the advantages and disadvantages of currently applied methods for multi-material composite utilisation and presents further trends in composite recycling.

2. Scope of Review

The paper presents a literature review on the challenges of the circular economy and composite recycling, and presents examples of studies that implement used tyres, wind turbines, and solar panels. The Introduction outlines the topic of circular economy to show the proper background for the article. The next chapters present challenges in recycling of multi-material composites and a particular case study for some chosen products that are problematic for recycling and require modern technologies. This article summarises the most promising areas for the development of composite recycling and provides brief conclusions.

Research was conducted in scientific article databases such as ScienceDirect, Scopus, and Google Scholar. It was centred on the term 'circular economy' joined by 'composites recycling'. For the particular case studies, specific terms, such as 'used tyre', 'wind turbine', 'photovoltaic energy', and 'solar panels' were applied.

3. Challenges in the Recycling of Multi-Material Composites

Composites are materials made from two or more constituent materials. It is usually a combination of a matrix and a filler or reinforcement [1,11]. The materials involved have different physical and/or chemical properties [11,12]. The characteristic of the composite material is different from that of the individual components [1,11]. The matrix could be a metal, a ceramic, or a polymeric material [11,19]. The composites were identified long ago, but their wide use is connected with the beginning of the XX century and industrialisation process [11]. Today, their application is becoming more and more popular because of their outstanding properties. The industries where composites are most used are aerospace, automotive, marine, and energy production [11,20]. The main reasons for their application are economic benefits, for example, lightweight composites are able to replace the traditional ones in the automotive industry and can consequently reduce fuel consumption and, at the same time, air pollution [11,21]. The research provided by Chu and Majumdar [22] shows that a 10% reduction in the structural weight of a car could lead to a 6–8% reduction in fuel consumption [22]. The other reason for creating composites is their increased durability [11,23]. The circular economy approach is usually applied to composites as long as the integrity of the product is involved [6]. In the integrity of composites, the integrity of the material has some distinct aspects, such as a long useful life of the product and a lifetime extension through maintenance and repair [6,24]. Nowadays, many composites do not have viable economic ways of recycling [25,26]. The main reasons are that recycling processes tend to break down the composite into its constituting materials, thus losing the specific composite material properties, or the recovered materials have significantly worse properties than virgin and could be used only for so-called down-cycling applications [7,11]. Due to this challenge, the composite material requires a new approach to recycling: novel concepts and technologies [11,27,28], including the design of new composites based on the old [29]. The alternative solution could be also in the design of the recyclable composites, including epoxy resin based, but this kind of material is still in the experimental phase [30]. Currently, biodegradable organic polymers still have limited participation in the market, and creating more advanced composites is a great technological challenge. Nowadays, the rapid development of composites' recycling technologies has led some authors to designate the years 2000–2020s as a composite recycling phase [11]. The main objective of this phase is to change the situation in which most of the composite is buried or incinerated, losing the material in the most effective composites [11]. This approach is coherent with the European Union regulations in this area, including the European Agenda 2030. The circular economy in Europe is one of the key elements in this document. It outlines one of the sustainability goals as increasing waste valuation to 70% by 2020 and developing a circular economy for recycling and reuse.

Today, recycling is a high priority in the world, considering that waste management is supported by the circular economy approach [9]. This approach is based on a waste management hierarchy. This hierarchy is part of the Waste Framework Directive and defines the most effective ways of managing waste [3,5,31]. According to this document, the most effective way is waste prevention, for example, through restricted misuse through anticipation at the source while manufacturing. It is related to the philosophy of zero waste production and, in the case of a large number of products for composites, it is relatively easy to apply [3,5,32]. The next desirable form of waste management is reusing. The product reuse, remanufacturing, or refurbishment is usually more profitable for the environment, because it requires less resources and energy. Very often, it is also more economical than conventional recycling of materials, especially as low-grade raw materials [5,33]. This goal for the composites could be achieved by the long life-time of the products.

The next in the hierarchy are recycling and recovery. The border between recycling and recovery is not always clear, especially when we think about the process of incineration to decompose the waste or using energy [5,31]. Recycling and recovery are both important discussed methods for composite recycling and areas where the most important technologies are being developed. Moreover, a lot of different classifications for recycling methods are used. One of them is divided into three main areas: material recycling (usually crushing, grinding, milling, and/or shredding techniques), thermal recycling (combustion, fluoridised bed, and pyrolysis) and chemical recycling, for example solvolysis by using supercritical water or alcohol or chemical degradation in high concertation acids [11,12,32,34]. The most important advantages and disadvantages for the main recycling areas are summarised in Table 1.

Table 1. Advantages and disadvantages of the main areas of recycling.

Method	Advantages	Disadvantages
Material recycling	Lack of use of hazardous substances during the process Possibility of processing complex composites (without the separation of particular materials) Usually high energy efficiency	Degradation of material properties Limited possibilities of processing
Thermal recycling	Lack of use of hazardous substances during the process Useful for mixed materials	High cost of proper infrastructure By-products such as environmentally dangerous off-gases
Chemical recycling	The very high holding of material properties	Hazardous materials are used during the process Problems with scalability of most methods Chemical recycling is the least eco-friendly method compared to mechanical and thermal recycling

There are mainly two motivations associated with recycling of multi-material composite waste: the cost of virgin materials production (usually the minimum one of the components) and the environmental problems with utilisation products. It is important to emphasise the utilisation of the value embedded in materials in as high value applications as possible in recycling [5]. The best solution is so-called up-cycling—it is usually achieved by application of recycled material in new areas, sometimes as an additive for high-value products such as vehicles or electronic products [34,35]. However, while up-cycling is the optimal way for recycling, the composites are very often down-cycled, because of the low cost types of solutions. One of the examples is the use of milled composites as admixtures for single-use materials such as concrete [26,32,36,37].

The last place on the waste management hierarchy is disposal [3,31]. This method is clearly not in line with a circular economy approach. Unfortunately, landfilling is still the main method of waste material management for multi-material products. This is mainly due to the complex and high cost of the recycling methods for composites. Another difficulty of recycling composites is the large market [32]. Application in many areas caused problems in controlling and regulation of composites recycling in all areas. Moreover, new areas for the multi-material composites are being developed, including the additive manufacturing market, from composite filaments for FFF/FDM printing to composite liquid resin for SLA/DLP/LCD printing. The statistic shows that globally only ca. 1% of composite waste is recycled [32]. At the same time, there is an opportunity for widespread use, thanks to the diversification of the sources for potential recyclers.

The basic problems related to composites are complex processing; contamination of material, including problems with separation from the waste stream; and the inconsistent supply of recyclable composite products, which restricts long-term business. Conventional recycling techniques are generally not efficient and create additional waste during the process, such as liquefied waste (bases, acids, and surfactants), hazardous gases, and solid waste [38,39]. The mentioned problems are taken into account where circular economy strategies for composites are created. The most popular strategies are [20]:

- Ensuring a long life for products, including their use and reuse through manufacturing high-quality and durable products;
- Extending the lifetime of the products through maintenance, repair, technical upgrading, etc.;
- Product recovery (increasing the number of cycles);
- Structural reuse-retrieving structural elements, preserving the material composition, including reuse of the elements of the product in another context or construction;
- Recycling-recovery of material, including the close of the materials loop.

4. Case Study for Selected Composites

4.1. Used Tyres

Global tyre manufacturing was estimated at 19.25 million tonnes in 2019 and it is growing about 3.4% per year through 2024 [40]. Currently, only 15–20 percent of used tyres are considered for recycling or reuse [41,42]. Furthermore, 70% to 80% of the used tyres are disposed of in landfills [41,42]. This could be potentially harmful to the environment, as could be other materials such as fire hoses in landfills, due to the heavy metal and other pollutant content and risk of the leaching of toxins into groundwater [43,44]. Furthermore, the tyres are not dissolved in organic solvents and therefore are not biodegradable [44,45]. The main advantages of the product, such as resistance to water and temperature, or resistance to mechanical damage, cause problems when tyres become a waste [42,45]. An additional problem is the multi-material composition. Tyres include 45–47% rubber, 21.5–22% carbon black, 16.5–25% steel wires (belts and beads), and 4.5–5.5% textile overlays (polyester cord fabrics, rayon cord fabric nylon cord fabric, and aramid cord fabric) and also other admixtures (antioxidants, antiozonants, sulfur, zinc oxide, etc.) [42,46].

Tyres are processed according to all predicted forms in the waste management hierarchy. Their utilisation includes:

- Reuse and/or export (the used tyre business is quite controversial, for safety reasons; however, according to the Rubber Manufacturers Association (RMA), between 30 and 35 million used tyres are sold annually) [42,43,47];
- Re-treading (used tyre to a new tyre) [42];
- Material recycling including civil engineering and construction applications, environmental rehabilitation projects, and consumer and industrial products. Particular implementations include, i.a., playground equipment, erosion control, and highway crash barriers [43,48,49], or obtaining new constituents such as carbon silica [50,51];
- Energy recovery for co-incineration and cement kilns as well as also pyrolysis [42,43]. It is worth noting that this process usually requires technically demanding equipment and, furthermore, a large amount of CO_2 and SO_2 is released [52];
- Landfilling—many countries limited the possibility of storing used tires, due to the negative environmental impact [43,49] and, in case of fire, the possibility of emission of different poisonous substances such as benzene, xylene, styrene, toluene, etc. [53,54].

According to the waste management hierarchy, reusing or re-treading are the most desirable methods, but it must be stressed that the used tyres lose their characteristics and cannot be reused for their main objective [42,52]. The second possibility, re-treading, also has limitations. It could be used to repair limited worn-out tyres due to initial wear [42,55]. This method also brings economic benefits, including saving resources: about 25% of raw materials and 30% of energy in comparison to the production of new tyre [42,56,57].

One of the most promising alternatives seems to be material recycling. Currently, the material recycling of tyre products is still very low, due to many problems related to the processing of used tyres, especially multicomponent construction [43,58]. The particular techniques in material recycling could have different forms, but the main steps are usually the same. The first step is to collect the products and then sort them [43,53]. The sorting process is usually connected with pre-treating and de-beading (removing of steel elements from tyre). Steel wire received in this step could have application as a reinforcement for building products or as a raw material for the production of virgin steel [48]. Next, the used tyres are cut and crushed or dissolved. The most often applied techniques of mechanical processing are cutting, shredding, and granulating or sieving [43,59]. The rubber obtained in this step could be fragmented, granulated, and thermal treated depending on its future application, such as manufacturing tracks for athletics, insulation in buildings, matting surface, surfaces for playgrounds, marine non-slip surfaces, etc. [42,60]. The other possibility is obtaining, through a mechanical grinding process, rubber particles of various sizes, steel, and textile waste as a mixed fraction. Irrespective of the fractions obtained, the grinding process is energy-consuming and causes high noise emission. In the case of rubber-based products such as used tyres it is additionally complicated because of the high elastic properties of the rubber [43,53]. To improve this process, a low temperature may be applied, which makes the rubber brittle and much easier to crush [43,53,59]. Using the temperature below the glass transition temperature of rubber significantly reduces energy consumption for mechanical grinding, prevents fire and explosion hazard, and allows for production of a finely dispersed rubber powder with a particle size of up to 100 microns with elimination of environmental pollution [53,61]. The main disadvantage of using low temperature is the increase in cost [43,53]. The multi-material composition of tyres causes difficulties both in the tyre recycling process and in using the components. Some components such as rubber and steel can be relatively easy recovered and find applications, for example, in the concrete industry [62,63]. Others, for example, textile cord, have limited possibilities for use after recovery [61,64,65]. The problem of reusing textile fibres in the recycling of car tyres has not yet been sufficiently explored [43]. It was tested as a reinforcement material for the production of polypropylene composites and used for the production of bumpers for cars or different building materials [43].

The other possibility of using used tyres is energy recovery, including pyrolysis, gasification, and hydrothermal liquefaction [42,66]. It allows waste tyres to be turned into energy in the form of fuels (most often gasoline and diesel) but usually is connected to the loss of materials. Recently, waste tyre pyrolysis technology has become more and more popular and is including waste management strategies in different areas [42]. Energy recovery technologies could also be an option for the accumulated stocks of waste tyres, especially in the case where material recycling is not effective, because of partial environmental degradation. The thermal process could help dissolve the problem of about 100 million tons of waste tyres that require recycling or safe disposal, which is against circular economy goals [53].

All presented methods could be complementary to each other. They bring benefits, but they also have some limitations—Table 2. Most of the methods of utilisation also require some future development work.

Table 2. The most popular methods of waste utilisation applied for used tyres.

Method	Advantages	Disadvantages	Perspectives	Source
Reuse and re-treading	Require the limited deployment of additional energy and resources, economically profitable	Possible only for selected products, limited worn-out. Because of the safety issue at high speed, re-treaded tyres are not used in automobile applications.	The more durable materials, longer life cycle	[42,53,57]
Material recycling	Many techniques are possible to apply in the process. Possibility of recovering material or particular components.	Not all recovered materials are reused as upcycled products.	Increasing the efficiency, the methods for application advanced solutions, such as processing in low temperature.	[42,43]
Energy recovery	The cement industry uses tyres as a source of energy, making it a cost-effective way to meet its high-temperature requirements.	The incineration of tyres is technically demanding as far as the machine equipment is concerned and, additionally, a large amount of CO_2 and SO_2 is released. Pyrolysis needs more development before it can be scaled up to an industrial level; it requires costly infrastructure. During the process, only energy, but not the raw material, is recovered.	The final products of pyrolysis can replace non-renewable fossil fuels.	[42,53,57]
Landfilling	In short, the cheapest solution.	Material and energy are lost. Not coherent with requirements of the circular economy.	Forbidden by many countries, including EU.	[42,43]

4.2. Wind Turbine Blades

The wind industry is ranked as one of the fastest growing energy sources. Currently, about 2.5 million tons of composite materials are in use in the world wind energy sector [67,68]. They are applied, i.a., to wind turbine blades. Estimates show that an expected lifetime for turbine blades is about 20–25 years, which means about 14,000 blades will need to be recycled by 2023 [69,70]. As the first major wave of composite wind turbines were installed in the 1990s, their life expectancy will end in the decade of 2020s [11,67]. Because of that, the challenge of recycling wind turbine blades has become an important topic [67,71].

A wide variety of materials are used in the construction of wind turbine blades [67,72]. This is because of the high requirements for the material, such as high stiffness and resistance to strong gusts of wind, icing, and lightning. The material composition is usually based on [69,72]:

- Fibre reinforcement (glass, carbon, aramid, or basalt)—43%;
- Resin, polymer matrix: thermosets such as epoxy, polyester, vinyl esters, polyurethane, or thermoplastics—24%;
- Core materials, usually sandwich core: balsa wood or foams such as polyvinyl PVC, PET—20%;
- Adhesives—9%;
- Coatings, usually PE and PUR—4%;
- In some cases, also other materials, for example: metals copper wiring, steel bolts.

An additional problem for the recycling is that the used composite is dependent on a particular producer, and some parts of the turbine blade can be composed of different compositions [67,72,73].

Nowadays, many recycling methods are being tested for the wind turbine blades. We may classify them as [67,74]:

- Mechanical, including grinding powders and recovery fibres; the powdered products could be used as cement kiln;
- Chemical—solvolysis and high voltage pulse fragmentation (material recovery, but limited to laboratory scale);
- Thermal, i.a., incrimination (energy recovery) and pyrolysis classical as well as by using microwaves (energy recovery and part of materials) and fluidised bed (energy recovery);
- Mixed methods, such as using microorganisms for degradation composites. However, although the method of using bacteria for materials recycling purposes is interesting, their usage is limited even at laboratory scale;
- Landfilling, that is not recommended and prohibited by law in many countries.

The prevention of waste is, according to the waste management hierarchy, the preferred method to apply. In case of wind blade turbines, it can be applied as a mass reduction during the design resulting in less material to recycle [68,69]. The other possibility is to use the blades for as long as possible before waste treatment is needed. In this case, the importance of routine maintenance and repair is paramount. Regular monitoring could produce many useful data and help to increase the useful life of the blade [68,75,76]. The other challenge is re-using an existing part of the blade for a different application than the original. For that, only a few possibilities have been tested, usually in down-cycling applications, such as [69,74–77]: reusing the blades for playgrounds or small architecture (city furniture), as an element of building structures, e.g., bicycle shelters and elements of bridges or walkways. It is worth mentioning that this solution depends on the blade's condition. Additionally, after using the blade for other applications, it will not be possible to reuse it as a blade again [69].

The next option in the waste management hierarchy is recycling and recovery. This is achieved by mechanical, thermal, chemical, and mixed methods [67,74]. Mechanical recycling involves the use of crushing, grinding, milling, and/or shredding techniques to reduce the size of elements to powder and fibrous fractions [26]. The powder is usually is used as a filler or, less frequently, as reinforcement or as fuel for thermal waste processes. Implementations are also very often related to downcycling, because after this process the mechanical properties of the material are reduced, especially stiffness and strength, and there are also the cheapest virgin fillers (calcium carbonate, silica) [74,75]. The process itself usually has three stages [77–79]. In the first stage, the blades of wind turbines are cut into components with dimensions that facilitate transport. The second stage is connected with fragmentation to a certain size. If the material contains metal, slow cutting or crushers reducing the material size from 50 mm to 100 mm shall be used. If the material is solid without metal content, high-speed mills are used to crush the material to sizes of 50 µm to 10 mm. At this stage, the resin is separated from the fibres. The third step is to classify where larger fibre elements are separated from the filler and polymer matrix. This is done with the help of hydrocyclones or sieves [78,79]. One modern technology is the area of material recycling using high-voltage pulsed fragmentation. It is an electromechanical process that effectively separates the matrix from the fibres using electricity [79,80]. Only short fibres are recovered in this process. Obtaining high-quality fibres requires a high level of energy. Compared to mechanical grinding, the obtained fibres have a better quality, longer length, and higher purity [79,80]. The main challenge of this type of recycling is to find potential applications for the fragmented composite fraction. Most of them are used in down-cycling applications such as a filler for concrete composites or other materials, but new possibilities are also being investigated [69]. One of the most interesting uses of this waste is as a base to a filament dedicated for 3D printing [81].

The material can be also recovered by chemical methods, especially solvolysis. In this process, solvents (water, alcohol, acid) are used to break the matrix bonds at usually elevated temperatures (300–650 °C) and under high pressures. This method can be defined as a chemical treatment with using a solvent to degrade the resin [82]. This method is mainly used for composites with carbon fibres because this kind of fibre is not dissolved by solutions, while glass fibres degrade [74,81]. Carbon fibre materials recovered in this process have similar strength (even 90% of properties comparison with virgin fibres). The other parts of composites, such as resins, are combusted for energy recovery. Currently, solvolysis is used only on a laboratory scale, but considering the fact that the recovery material is much cheaper and the manufacturing of virgin carbon fibres emits 10 times higher greenhouse emissions than that of steel manufacturing, the technology has potential for wider applications [12,83]. Solvolysis can be carried out in many ways due to the wide range of solvents, temperatures, pressures, and reaction catalysts available. Water is most commonly used as a solvent. Other solvents are ethanol, methanol, propanol, and acetone, and their mixtures with water. Additionally, some admixtures and catalysts are used during the process; some of them can adversely affect the fibres and the environment. In addition, the remaining particles of the fibre catalyst on the surface of the fibre impair its resin adhesion, which is disadvantageous when recycling the recovered material [32,74,84]. The main disadvantages of this method are the high price of the equipment, especially reactors that can withstand high temperatures and pressures, the corrosions that occur when sub- and supercritical conditions are used, and the fact that it is not always efficient enough. Additionally, the mostly acidic solutions can be dangerous in terms of safety and environment [84,85].

The next group of methods according to the waste management hierarchy are the methods related to thermal recovery. In the case of wind turbine blades, between material recycling and thermal recovery is pyrolysis, because in this case it allows for partial material recycling. The pyrolysis process is based on the thermal degradation of materials in the absence of oxygen [86,87]. These reactions are very complex and consist of many stages. It produces char, such as carbonized solid fuel, oil, and gas. [86–88]. The particular products depend, i.a., on the pyrolysis temperature. Because of that, this process can be divided according to some classifications. One of the most popular is according to the temperature used [86,87]. The majority of pyrolysis processes are conducted at high temperatures between 300 °C and 1000 °C with operating temperatures that can reach 3000 °C, but the process could be also made in lower temperature or with using microwaves [86,87]. In the case of wing turbines, the decomposition of the pyrolysis occurs at temperatures ranging from 450 °C to 600 °C, depending on the atmosphere resins and the used atmosphere [69,74]. The other division could be made according to time of reaction: fast or conventional (slow) pyrolysis [89,90]. Fast pyrolysis is usually employed to maximise the liquid product and as a result slow pyrolysis maximises the solid product [90].

During the pyrolysis of wind blade turbines, the matrix is degraded and forms gases and oil fractions that could be recovered but are usually burned. Fibres are recyclable, but during this process they significantly lose their mechanical properties, for example, the tensile strength of carbon fibres is reduced from 4% to 85%, and of glass fibres from 52% to 64% [69,88]. It is worth adding that estimations show this method is currently cost effective for recycling carbon fibres. There are several variants of pyrolysis. One variant that has been tested for wind turbine blades is microwave pyrolysis (microwave heating in an inert atmosphere). It allows the material to heat up in its entire volume, because thermal transfer is very fast [74,79]. It supports a very rapid increase in temperature throughout the volume. This method can reduce energy consumption compared to other pyrolysis variants. It can be used for the recovery of carbon fibre and glass fibre composites. By-products include syngas (later combusted for electricity and heat recovery) and char (recycled as fertilizer) [74,79]. Another form of pyrolysis that has been tested is fluidised bed pyrolysis. It involves passing the size-reduced composite through a bed of sand, fluidised by a stream of hot air [74,79]. This method was tested for carbon fibres, and the results show that the surface of the fibres are more damaged compared to traditional pyrolysis.

Other thermal method applied to wind turbine blades is incrementation. The material can also be burned as a source of energy or co-burned with other products. The used composites have a high fuel value. However, combustion can lead to the production of harmful organic and inorganic compounds such as HCL, NOx, SOx, CO, CO_2, F_2, CF_2, H_2S, HF, HCN, as well as harmful dioxins and furans, as well as toxic ashes and slags [79,89]. Their quantity varies widely, depending on the combustion conditions and the type of composite. Furthermore, approximately 60% of the material after burning must be stored or recycled, as even the polymer matrix does not completely burn [79,89,91]. The challenge in incineration is the high glass fibre content, which prevents an effective burning of the parts and creates relatively large amounts of remaining ashes, which are usually landfilled [69]. In the case of co-burning in a cement kiln, where the waste material is additionally mixed with other recovered solid fuels, the high content of glass fibre is desired [89,90]. If the composite waste contains type E glass fibre, it consists of aluminosicates, borosilisates, resins, and sometimes calcium carbonate. In this process, organic resin burns up, providing thermal energy, and fiberglass mineral components are a raw material for the production of clinker cement. Calcium carbonate calcines into calcium oxide. The resulting clinker process is ground to form cement. The amount of boron can adversely affect the early hardness of cement. Co-production of composites reduces CO_2 emissions in cement production to 16%. This method, compared to incineration, leaves no waste [89,91].

In terms of thermal recovery methods, gasification also has an important place. It still requires development work; however, it is being evaluated as a high potential technology for the recycling of wind turbine blades [67,68]. The temperature of gasification is usually higher than in the case of incrementation and pyrolysis [68,89], but it is also more tolerant of contamination as well as differences in the waste compositions [67,68]. Taking into consideration significant differences in particular composition of wind turbine bladed made by different producer, it has the potential to be a universal method. The most important products retrieved in this process are energy and potential precursor chemicals. There is also the possibility of recovering some fibres in this process, but they are usually of much lower quality than those of the solvolysis or pyrolysis process [67,68].

The last option in the hierarchy of waste management is landfilling. Many countries have a regulation that limits this kind of possibility, and the other requires high taxes for this kind of waste [74]. The disposal causes the loss of material and energy used to produce a wind turbine blade and it is inconsistent with a circular economy policy.

Despite the large number of recycling technologies for wind turbine blades presented so far, there is a lack of one leading technology. They all have advantages and disadvantages—the most important are summarized in Table 3.

Table 3. The most popular methods of waste utilization are applied to wind turbines.

Method	Advantages	Disadvantages	Perspectives	Source
Gasification (Fluidised Bed)	Highly flexible process—different composites. Recovery of energy and potential precursor chemicals. High efficiency of heat transfer.	Most of the material is lost or low-quality material is recovered. Lack of industrial application; only prototype solution. Process-related with emissions of potentially toxic elements.	Technology modifications —increasing the quality of recovered material.	[68–70,79–81,85,88,89,91]
Solvolysis	Recovery of clean fibres in their full length. Recovery of resin which can be re-used.	Not operated on an industrial scale because of low efficiency. Catalysts are used during the process, some of them can adversely affect fibres and the environment. Lack of industrial application; only prototype solution. High energy consumption due to the high-temperature and high pressure.	Increasing the efficiency of this method.	[68–70,79–81]

Table 3. *Cont.*

Method	Advantages	Disadvantages	Perspectives	Source
High Voltage Pulse Fragmentation	Easily scalable—possible usage for large amounts of waste. Low investment required.	Lack of industrial application; only prototype solution. Heavily decreased modulus of glass fibres.	Recommended method for the current stock of wind turbine blades	[68–70]
Pyrolysis	Very efficient and possibly applied on a large scale.	Low-cost efficiency. Low quality of recycled materials. Up to 40% material waste.	Development of efficiency. New methods for using material waste from this process.	[68–70,79–81,84,85,88,89,91]
Mechanical Grinding	Efficient and high throughput rates.	Decreased mechanical properties of the powder comparison with virgin composites. Application is usually in down-cycled products.	New applications for recycled materials.	[68–70]
Co-Processing	Highly efficient, fast, and scalable. Large quantities can be processed; the method is quite flexible (changes in matrix material). No ash left over.	Loss of material. Additional energy is needed for this process (high processing temperatures are required). Pollutants and particulate matter emissions.	Strictly connected with the cement industry.	[68–70,79–81,85,88,89,91]
Landfilling	In short, the cheapest solution.	Material and energy are lost. Not coherent with requirements of the circular economy.	Some EU countries have banned the disposal of composite blades in landfills.	[67,91]

4.3. Solar Panels

Solar panels are also multimaterial products that are very popular. Estimates indicate that there will be almost 80 million tons of solar waste projected by 2050 [92,93]. Market trends show that increased production of solar panels is expected in the coming decades. The operating lifetime for the solar panel is maximum 30 years [92,93]. The problems with their recycling will be increasing year by year and new effective methods for their recycling will be required.

The solar panel may have varied composition depending on the producer, but usually the final product includes silicon solar cells, metal frames, glass sheets, wires, and polymers (Poly (methyl methacrylate), PMMA), also known as acrylic glass or plexiglass). It means that the ingredients of the final composition are the following materials [94,95]: glass, plastic (PMMA, EVA, and others), silicon, and metal, including aluminium. Broadly, it is possible to divide the solar panels into three generations [94]:

- Crystalline silicon that is based on mainly monocrystalline or multi-crystalline silicon;
- Thin film, where main ingredients are amorphous silicon, cadmium telluride, copper indium gallium selenide;
- Concentrator photovoltaics and emerging technologies, such as concentrator photovoltaics solar panels, dye-sensitised solar panels, organic solar panels, and hybrid panels.

This diversity makes it as a very demanding product from the point of view recycling it. Because of that, various waste management strategies are applied in the case of solar panels [94,95].

The main motivation for the development of solar panel recycling is the slight amount of rare element that is included in products. The most popular methods for solar panel recycling are [96,97]:

- Physical/mechanical, such as physical separation or mechanical crushing;
- Thermal treatment;
- Chemical treatment by using, i.a., organic solvents for the recovery of rare elements;
- Landfilling, which is especially challenging for solar panels because they include heavy metals and because of that, should not be dumped in landfills.

The most desirable form of waste management according the waste management hierarchy is reuse. In the case of solar panels, a form of solar cell recovery is possible [96–98]. However applying this method in practice has significant limitations, i.a., localisation of the solar cell [99,100]. Currently, there is only one widely applied method in this area: the replacement of components, which extends the life cycle of the product [94].

The next possibility is material recycling. This method is most commonly used in the case of solar panels, and mechanical and chemical methods for this type of composites are especially intensively developed [101,102]. Mechanical recycling is connected with separation and the next cutting, milling, or gridding of the material. It is usually made in separate fractions, but it could be applied for some layers together (Figure 1). The next material could be used as a filler for a type of composites, including building products [102]. The process of shredding the material could be also the first step to chemical recycling where the silicon and precious metals can be recovered from solar panels [97,103].

Figure 1. Solar panel after material recycling.

The more challenging methods for material recycling are chemical and thermal methods. Most of the methods allow recovery of metals, including aluminium and glass, as well as some rare elements, such as Cd and Te [104,105]. During the process, polymers are melted, dissolved, or burned [106,107]. The different solvents are used for recovery of different types of elements or compounds [97,103]. They are often selected according to the particular solar panel, because all technology is hard to standardise. In many cases only the most valuable rare elements are recovered, and the rest of the material is lost via incineration of the material. Additionally, some of the thermal methods are connected with hazardous by-product emission [108]. It is worth to add that typical thermal methods such as pyrolysis or gasification, used other composite waste such as used tyres or wing turbine blades, are not so prevalent and used only in local scale. In the case of solar panels the thermal methods are usually only a part of the process for the chosen components.

Landfilling is the less desirable option, especially in the case of solar panels. The material and energy loss and additionally potential problems with leaching elements from composites could occur [96,97]. This method is potentially hazardous to the environment as well as indirectly to human health. It is also inconsistent with the circular economy approach and regulations provided in many countries where the solar panel itself is treated as hazardous waste and requires special procedures for utilization [109].

The pro and contra of the most popular methods for recycling solar panels are summarised in Table 4.

Table 4. The most popular methods of waste utilisation applied for solar panels.

Method	Advantages	Disadvantages	Perspectives	Source
Physical/mechanical	Relatively easy to apply and to scale-up. Possibilities of separation between different components.	Most of the application in the up-cycling area. Some of the rare elements are lost.	New areas for applications.	[96–102]
Thermal treatment	Possibility to recover some rare elements.	Some methods produce hazardous by-products. Many technologies are still in prototype phase and do not have full efficiency.	Increasing the efficiency of technology.	[95–106]
Chemical treatment	Possibility to recover some rare elements.	Many technologies are still in prototype phase and do not have full efficiency.	Modifications of technology and more efficient methods.	[96–102]
Landfilling	In the short-term, the cheapest solution.	Material and energy are lost. Not coherent with requirements of the circular economy. Leaching of hazardous elements during storage.	Low restriction.	[96,97]

Nowadays, in the area of solar panels, new solutions are implemented, the most important being replacement of silicon crystals by perovskite solar cells [92]. Perovskite solar cells are made of metal crystals, usually lead; however the new research shows that it is possible to also use other nontoxic metals like tin or germanium for their production [92,110]. This method could be a breakthrough in the solar panel area, but requires further research work [92,110].

5. Development of Composites Recycling

The provided analysis clearly shows that the recycling of the multi-material advanced products is a real challenge. It requires the development of new technologies and the improvement of existing ones. Other important challenges are proper law regulations and building social consciousness about the influence of this waste on the environment and social health. Regulatory issues become more and more important, because the shown product starts to be a problem on a global scale, not only for national or local economies [109].

The main goals for the developing techniques mentioned above are high effectiveness and high quality—producing higher quality recycled materials and improving resource efficiency—and at the same time limiting the influence on the environment. Selected case studies show that there is no single ideal solution, but there are a lot of options for particular areas and products. The technologies presented have different properties, advantages, disadvantages, and technology-readiness levels. Additionally, they are dedicated to different material compositions. However, the differences between them are useful for distinguishing the most effective and help to create benchmarks that can be copied for other types of composites.

6. Conclusions

Composite materials offer great opportunities for product development and high performance in use, but their position in a circular economy system remains challenging. The recycling of the composites is still an immature area. A new solution dedicated to new products is urgently needed. The increased use and proportionally increasing volume of end-of-life materials have led to increased attention from government, industry, and academia. The crucial requirements for the launch of new composite products on the market should indicate an effective method of waste management and recycling process of a particular product. These requirements should also be an important element for national and international research projects.

The composites recycling market offers significant potential. A lot of presented technologies are still required to be optimized to produce higher quality recycled materials or improve efficiency. The presented technologies for the three case studies have different properties, advantages, disadvantages, and different perspectives, but in the case some of them there are significant similarities. As the particular case studies of products show, there are a lot of possibilities for the recycling of even complicated, multi-material products, but not all are effective or economically justified. The policy of circular economy stresses the problem of depleted resources; to be in line with this trend we must design the product thinking about its end-of-life. Unfortunately, this approach is used very rarely in practice. Most often, solutions are created ad hoc when the problems start to be serious and potentially hazardous for the environment on a large scale.

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