

Article

Pro-Environmental Solutions in Architecture—The Problem of Decommissioned Wind Blades

Aleksandra Śledzik ¹ and Marzena Banach ^{2,*} ¹ Institute of Building Engineering, Poznan University of Technology, 61-131 Poznan, Poland; aleksandra.sledzik@student.put.poznan.pl² Institute of Architecture and Physical Planning, Poznan University of Technology, 61-131 Poznan, Poland

* Correspondence: marzena.banach@put.poznan.pl

Abstract: Since the 1990s, Polish energy companies have been using new technologies to build wind farms, consisting of large devices. Over the years, the power and the size of installations have increased, and it continues to do so. In Poland, as well as in other countries, a problem with the post-use management of wind turbine blades has appeared. The recycling of wind turbine blades has remained challenging hitherto. The utilization of many different materials and changes in the dimensions cause multi-material waste. Since there are no economically viable recycling technologies available for such large-scale composite products, other treatment strategies for disposed WTBs have to be considered. This study explores the repurposing of WTBs as a pro-environmental alternative approach from a technological and architectural point of view. For this purpose, the study is guided by an analysis of wind turbine locations in reference to the impending need for waste management of wind blades in Poland. Well-profiled blades help transfer a large portion of wind energy to turbine rotors, which is why their construction is a challenge when it comes to designing new objects or elements thereof from decommissioned blades. They have a continuous curvature, where both the cross-section and thickness change, which is why, in the design of architectural or engineering objects, they are cut into smaller parts. This solution makes it possible to optimize the load-bearing properties of individual segments, ensuring a more stable system. Smaller elements also provide greater freedom in shaping architectural forms, which is associated with better control of the final effect from the aesthetic side. The potential of repurposing WTBs is shown, for example, in the design concept for the Archery Centre in Poznan (Poland).



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1. Introduction

In contemporary urban planning, sustainable development consists, to a large extent, of aspects that aim to use pro-environmental solutions in the development of cities. The recycled materials have been used in architecture more and more, although it is associated with a number of different problems, such as availability, price, responsibility, impact on the design process, and sustainability [1]. The blades of a wind turbine are the most difficult parts of the device to recycle. Due to their exposure to wind forces and atmospheric factors, these elements must meet high durability requirements. This property is obtained by combining different materials into conglomerates. For this reason, their potential post-use separation is extremely difficult (energy- and time-consuming). Additionally, in the process of obtaining smaller elements from blades, it is necessary to take into account the dust emitted during cutting of fibre-reinforced polymers (FRPs, most often glass, carbon, aramid,

and basalt), which poses a health risk. However, processes for the recovery of raw materials by subjecting polymers to chemical processes (as granulates) and pyrolysis (reuse of fibres for the production of adhesives and concrete) are still under development.

The first step toward the reuse of recycled materials is to recover as much raw materials as possible from exploited objects or buildings. In the case of wind turbine blades, the complication arising in the recovery process concerns disassembly and division into elements that are easier to transport. The blades of a wind turbine are the most difficult parts of the device to recycle. Due to their exposure to wind forces and atmospheric factors, these elements must meet high durability requirements. This property is obtained by combining different materials into conglomerates. For this reason, their potential post-use separation is extremely difficult (energy- and time-consuming). Additionally, in the process of obtaining smaller elements from blades, it is necessary to take into account the dust emitted during the cutting of fibre-reinforced polymers (FRPs, most often glass, carbon, aramid and basalt), which poses a health risk. However, processes for the recovery of raw materials by subjecting polymers to chemical processes (as granulates) and pyrolysis (reuse of fibres for the production of adhesives and concrete) are still in the initial phase of development. There are many examples of the successful use of reused and recycled materials, for example, in both public and residential buildings; however, most examples concern such materials as brick, wood, or steel. Objects connected with renewable energy sources are quite different in their specific composition, and so they require a certain approach. One of the difficulties associated with using reused or salvaged materials, as opposed to recycled materials (or materials manufactured from waste), is availability. The problem is finding appropriate materials at the right time [1]. Since many wind turbines (for example, in Germany) have reached their expiration date, the problem of disposal has appeared, while an abundance of material has become available for processing, opening up the search for new solutions in architecture.

Increasing attention has been paid to the recycling and reuse of thermoset composite materials for wind turbine blades. The current recycling technology needs to be much further developed so that commercial production can be achieved at a lower expense. In addition, new environmentally friendly blade materials should be designed using for example recyclable thermoplastic resin, which would make wind a truly clean energy source, for example, by eliminating or at least reducing the problem of disposal used turbines [2].

2. State of the Art

2.1. *The Problem of Ageing of Wind Blades and Their Post-Consumer Development*

A renewable energy utility can be decommissioned for a variety of reasons. These may include a reduction in the general resource in the material sense, depletion of the useful resource despite a certain part of the general resource being preserved, operating expenditures exceeding the value considered to be economic, or a decrease in operational efficiency below the value achieved by another facility. Currently, it is estimated that 60 to 90% of used WTBs (depending on the source) can be recycled [3]. Turbine blades are exposed to constant contact with all substances contained in the air, which can cause damage to the blade surface. These include rainwater (in all forms, including snow and hail), pollution (suspended dust), and extremely sharp sand grains. However, prepared composite wind turbine blades have a service life of 20 to 25 years. During this period, the blades are damaged due to the impact of their environment, resulting in delamination between different layers of the blades. This separation of adjacent plies is a common failure process, based on the low through-thickness strength of the laminates. The activity of a wind turbine is influenced not only by the quality of materials and the structure of the

turbine components but also, among other things, by the conditions in which the installation will operate. To characterize them, measurements of meteorological and environmental parameters are taken, including the temperature, relative humidity, and atmospheric air pressure at the height of the nacelle as well as the speed and direction of flowing air masses. Regarding the aspects of wind turbine blade wear, three basic types of gradual change in composite properties can be seen: (a) mechanical degradation (as a result of long-term permanent/variable/impact loads); (b) physical degradation; and (c) chemical degradation. These processes can and often do occur simultaneously, accelerating the process of wear [4].

The components most susceptible to damage include the main gearbox with the generator (gears, bearings, shafts, and intermediate clutches), turbines with their angle adjustment mechanism, and the turbine tower (foundation and tower connections). The most frequent forms of damage are those affecting the rotating elements and blades, which are usually caused by long-term exposure to load, material fatigue, and manufacturing defects. Other examples include corrosion, damage from lightning strike, and collisions with birds. These pose additional problems [5]. However, the difficulty of processing the blades prevents complete recycling. Their disposal (e.g., pyrolysis or grinding) is an energy-intensive and expensive process. Incineration of blades can be associated with formation of dangerous by-products, while about 60% of post-incineration material remains as scrap. The cheapest but also most controversial way is to bury used blades in landfills, which is a completely unacceptable practice. Unfortunately, this solution is the most commonly used. It is estimated that by 2050, the waste from wind turbines in the world will amount to approximately 40 million tons. In 2024 in Germany, for example, several thousand blades had been decommissioned and they must be disposed. The process of dismantling has already begun, and the composite blades from the turbines are being resold to markets in Eastern and Southeastern Europe and Latin America, among others. The high costs of dismantling and transport (which requires, among other things, specialist equipment and certified companies) have contributed to the creation of so-called “wind turbine graveyards” in many places around the world, where unwanted and expensive-to-recycle turbine blades are buried (e.g., the USA). In response to such phenomena, similar practices have been banned in some countries (e.g., Germany, Austria, the Netherlands, and Finland). In the case of reuse, there is also a transportation challenge. It is difficult to carry long, wide blades around turns, through narrow passages, and beneath overhead obstructions on roads and railways. This circumstance generally forces a limit to be imposed on the length of blades that can be transported over roadways (in the USA, for example, it is between 53.0 m and 62.0 m), depending on the design characteristics of the blade (the amount of precurve and type of airfoils used) [6]. Unfortunately, the problem of dismantled wind turbines concerns not only worn-out installations but also the ones that have ceased to be profitable after the end of government funding (e.g., Alpha Venus—the first German offshore wind farm in the North Sea, consisting of 12 towers with turbines 155 m high, which was supposed to operate at least until 2035—is currently closed). Such situations will slowly contribute to the increase in the number of dismantled wind installations and to the problem of their management.

There have been calls for a ban on landfill disposal of old wind turbines by 2025 directed at EU countries. This recommendation was made by organizations promoting RESs (Renewable Energy Sources), along with calls for ‘re-powering’. Old wind turbines that were assembled in large numbers in the 1990s are becoming worn out and must be replaced with new ones. The old turbines will be dismantled and decommissioned. Technologies, forms, and methods of disposal became a problem for which solutions need to be found relatively quickly [7].

The phase of post-consumer management is a stimulus for the creation of new facilities that contribute to minimizing the negative impact on the environment. In comparison to earlier products. More and more manufacturers are therefore announcing the introduction on the market of blades whose recycling would be possible to a much greater extent. However, when it comes to the blades already exploited, there are ideas for converting them into raw material for the production of cement, developing a widely practicable method of processing blades into pellets and slabs, using blades in the construction of transmission towers, incorporating them into acoustic screens on highways, or using them for concrete reinforcement. One solution is the use of blades in road construction as a reinforcement for embankments and slopes [8]. Other solutions propose the use of long raw fibres as reinforcing elements for the construction of buildings or the use of chopped fibres either for bonding with resins or as batches of components for thermoplastic and sealing materials [9,10]. Experiments were conducted on fragments of blades shredded into straw-like pieces of epoxy–glass composite. By mixing this material with resins and shredded wood, wood-based tiles and beams were obtained. Other studies introduced ways to obtain a durable material that could be used in construction, e.g., as slabs for laying ceilings, by combining shredded polyester–glass fibres with concrete. Moreover, solutions such as using small parts of blades (Figure 1) to build bridges or small architectural elements have proven effective [11]. In light of all types of environmental impacts, post-consumer waste management practices that does not require materials to be incinerated without energy recovery or landfilled as waste, are the most advantageous solution [3].

Well-profiled blades help transfer a large portion of wind energy to turbine rotors, which is why their construction makes it challenging to design new objects or elements of them. They have a continuous curvature, where both the cross-section and the thickness change; for this reason, in the design of architectural or engineering objects, they are cut into smaller parts. This solution makes it possible to optimize the load-bearing properties of individual segments, ensuring a more stable system. Smaller elements also provide greater freedom in shaping architectural forms, which is associated with greater control of the final effect from the aesthetic side. The structure itself is another issue, as it consists of various types of materials. Due to the rather complex structure of wind turbine blades, in order to be able to use them fully, it is necessary to conduct initial tests. It is important to assess the condition of the blades after the end of their service, on the basis of which a decision can be made to use the whole or undamaged (non-delaminating) parts of it [5]. The recycling of wind turbine blades still remains challenging. The utilization of many different materials as well as the rapid change in dimensions and thus blade designs lead to multi-material waste. According to Prof. Miśkiewicz from Gdańsk University of Technology (Poland), there are currently no systematic types of wind turbine blades. Therefore, each of them is an independent structure and can have different applications; hence, attempts were made to develop a methodology for dealing with these elements [5].

In a study by Deeney P. et al. [12], an AHP (Analytical Hierarchy Process) and Promethee study was conducted to assess sustainability indicators for several waste management methods applicable to wind blades. The presented solutions included landfilling, incineration, co-processing (processing of alternative fuels allowing simultaneous energy and material recovery of waste), furniture manufacture, and bridge construction. The indicators were grouped according to three aspects of sustainable development: the economy, society, and the environment. The results of the AHP index, for each of the above methods, are between zero and one, where a higher score indicates a more sustainable alternative. The index results for Promethee may be positive or negative, with a higher number indicating a more sustainable result. By this analytical method, landfilling was found to be the least environmentally friendly alternative in all three aspects. The best indicators were

for the reuse of blades in furniture manufacture and bridge construction [12]. Another review highlighted some of the current challenges of repurposing blades into a second service life in other structures as an alternative to disposal. A Design Atlas with 47 blade product concepts, screened for their usability, was mentioned as a resource of overcoming the challenges of reuse. Basing on this ranking, three scenarios were developed in the study, with the goal of maximizing utilization of the blade [13]. However, the literature still emphasizes that recycling carbon/glass fibre-reinforced composite-based WTBs is not convenient. Due to their complicated nature and extremely harmful side effects, which may result in severe health and environmental issues, various hybrid recycling technologies are still not very popular [14].

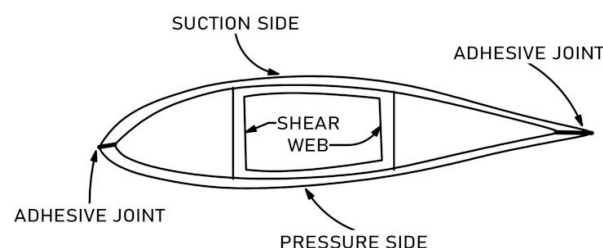


Figure 1. A sketch showing the construction of a wind blade.

2.2. Onshore Wind Farms and Construction of a Wind Blade

In Poland and other countries where the power engineering sector consists mainly of power plants and combined heat and power plants using hard coal and lignite, a different energy model is currently being introduced—a model based on sustainability and renewable energy sources (RESs).

The vast majority of installations are onshore installations, which is gradually changing. As a standard, the wind turbine consists of a foundation, a tower, a nacelle with a gearbox, a generator and control systems, and rotor blades [7].

Investing in wind turbines is an expensive undertaking, and they also have their “lifespan” [15]. It is worth mentioning that in renewable energy not only the method of production (i.e., electricity) but also the production, transport, use, and disposal or recycling of the device ought to be ecological. This latter stage seems to be the most serious problem in the wind energy industry at present.

It is estimated that by 2050, wind turbine waste worldwide will reach about 40 million tons. Currently, about 85–90% of the total mass of blades can be recycled. One of the difficulties is the requirement of durability, achieved through complex connections of various composite materials, which makes complete recycling problematic. Rotor blades are a conglomerate of synthetic plastics and fibres (glass or carbon), which are hard to separate or crush. Their disposal (including pyrolysis and grinding) is an energy-intensive and expensive process. Incineration of blades, in turn, can be associated with the formation of risky by-products, with about 60% of the material remaining as scrap after combustion. It should be added that some recycling technologies are not yet available on an industrial scale, hence the probable attempts at non-ecological solutions.

The most common way of dealing with wind turbine blades is to shred the blades, combust the organic matrix, and reuse the remaining short fibres as fillers. Although this approach does not multiply costs, it leads to drastic downcycling of the fibres, blocking the reuse of the organic components in new materials [5]. There are a few different dismantling procedures, such as modular dismantling, folding blasting, collapse blasting, hydraulic ram demolition, and wrecking ball demolition. In preparation for dismantling, lubricants and other hazardous substances are removed from open and closed systems. The modular dismantling method is used for structures that were built using the same

method of construction. Large numbers of modules or lattice tower sections demand special equipment (a crane), which is costly and time-consuming. However, this solution is quite safe for the environment (low emissions) and does not require much space for the procedure. If modular dismantling is not possible, the tower can be cut into transportable modules, although sawing technology is also quite expensive [16]. Since all the methods require a great deal of money and time, reverse logistics (RL) can be proposed. It is a process of managing the flow of products, components, and materials from the point of use back to a point of disposition (e.g., reuse, remanufacturing, recycling, incineration, or disposal), which, in the case of wind turbines, might still appear as most convenient [17]. One American company, for instance, crushes and grinds decommissioned blades using a diamond-coated wire. This helps avoid splinters that occur when sawing. This process yields so-called “fillets” (10–45 fillets from one blade), which can be used as benches if they are additionally equipped.

There are three main recycling technologies under research investigation aimed at carbon footprint reduction and a closed-loop economy. First ones are thermal and chemical methods, which are being tested to determine where most of the organic material (as monomeric or oligomeric components) is recoverable. This is due to direct reuse in new materials or as carbon units for synthesis of new basic chemicals.

The most troublesome elements of wind turbines in the context of recycling are their wind blades. Due to the fact that they are exposed to inclement weather conditions (e.g., hurricanes) and diverse forces of nature operating in various directions, they must be constructed in such a way as to prevent their easy destruction. They are made of thermosetting composites; steel; copper; and fibre-reinforced polymers (FRPs), most often with glass, carbon, aramid and basalt fibres. Usually, this fibreglass is the main building block and gives the blade high durability and strength. The designed blade must have appropriate aerodynamic parameters, low weight, sufficient rigidity (also due to vibrations), durability (life cycle minimum 20 years), and low noise generation as well as resistance to ice, dirt, and atmospheric discharges [18]. Wind turbine blades often reach lengths of several dozen metres. They are transported to the assembly site in their entirety, as their production technology does not make it feasible to break them down into parts. Blade spans vary (e.g., the blades of one of the wind turbines in the port of Rotterdam are 107 m long, and a single turbine weighs about 55 tones).

It is hard to assume a priori constant properties of elements, which, even if they have the same standard dimensions, structure, and installation conditions, will nevertheless have a different range of wear or damage. It should be noted that the Polish provisions of the Waste Act do not yet include blades as a special type of waste. According to the regulation of the Minister of Climate on the waste catalogue, blades can be classified as plastic or glass fibre waste, depending on the dominant material. In Germany, however, blades are classified as hazardous waste, which, in turn, prevents their storage. Elements dismantled so that they can be reused, e.g., in engineering or architectural structures, should be tested to determine the current material properties, based on which it would be possible to decide on their purpose in the project (structural element, facade element, detail, etc.) or their useful form. That is why it is also important to assess their appropriate load-bearing capacity and stiffness, as well as the feasibility of bridge spans built from recycled composite wind turbine blades. In order to improve the implementation of recycling technologies, this aspect should be included in the blade production strategy, ensuring more attentive design (including the choice of materials). Such approach is encouraged by, among others, the provisions of the European Directive on Life Cycle Assessment [19] and Directive on Waste [20]. An additional issue is safety, which can be measured by the global safety factor. It can be presented as a product of partial factors representing different

independent factors significantly affecting the reliability of the tested element and which can be calculated from the strength condition [21].

2.3. Analysis of the Presence of the Largest Wind Power Plants and Turbine Types in Poland Between 1991 and 2015

Natural conditions in Poland are conducive to introducing wind energy because the winds are at an appropriate intensity in one-third of the country's surface (similar to conditions in Denmark or Germany—countries with large wind farms). The best regions are the coastal belt and the central part of the country. The so-called class I wind energy resources include Pomerania and the north-eastern edges of the Suwałki region. The wind speed (at a height of $H = 50$ m above the Earth's surface) reaches up to 7 m/s there, which means a large energy potential from wind, as the profitability of such an investment starts from a minimum of 5 m/s. The efficiency of a wind turbine depends, however, not only on the wind speed at the place of its operation but also on the stability of the desired wind conditions [22]. During the year, wind speed varies in individual periods, with the most favourable period occurring from November to March. Unfortunately, this time period coincides with the period of the highest demand for energy in Poland. This variability of wind conditions has a significant impact on the efficiency of wind installations, as well as on their level of reliability. A much better direction of wind energy development is slowly beginning to be seen in offshore installations, associated with the length of the coastline and a significant area of the territorial sea. The first wind turbine was installed in 1991 in the place where the most favourable wind conditions prevail (Lisewo, near Żarnowiec) [23,24]. Furthermore, currently Poland has one of the best technical potentials for the development of offshore wind energy in the Baltic Sea.

Table 1 (authors' list based on [23–26]) lists the onshore wind power plants built in Poland between 1991 and 2001 with total capacity above 95 kW [25,26]. At the time, they were the largest power plants in the country. They were created about 21–31 years before the compilation of the list (2022).

Table 1. List of onshore wind farms in Poland with total capacity of over 95 kW.

Location	Power of the Power Plant	Turbine Type	Turbine Quantity	Blade Quantity	Impeller Diameter	Blade Length	Year of Commissioning
Lisewo near Żarnowiec (#)	150	NTK-150/25	1	3	24.6	11.5	1991
Swarzewo near Puck	95	DANmark	1	3	NO DATA	NO DATA	1991
Rytro near Nowy Sącz	160	EW-160	1	3	22	10	1992
Wrocki near Toruń	160	EW-160	1	3	22	10	1995–1997
Kwilcz near Poznań	160		1	3		10	
Zawoja near Bielsko Biała	160		1	3		10	
Będkowo near Wrocław	160		1	3		10	
Słup near Legnica	160		1	3		10	
Starbienino near Łębork	250	N29/250	1	3	29.7	13.4	1997
Rembertów near Tarczyn	250	LW-250	1	3	NO DATA	NO DATA	1997
Swarzewo near Puck	$2 \times 600 = 1200$	TW-600	2	6	43	20	1997
Cisowo near Darłowo	$5 \times 132 = 660$	SEEWIND 25/132	5	15	22	10	1999
Nowogard	225	V29-225	1	3	29	13	1999
Wróblak Szlachecki	$2 \times 160 = 320$	EW-160	2	6	22	10	2000
			SUM:	60	AVR:	11.6	

in Pomeranian Voivodeship.

The analysis was divided into categories such as location, total capacity of the power plant, type and number of turbines used, number of blades, rotor diameter, blade length and year of commissioning.

The total number blades from the list is 60. The weighted average length of the blades used is also given, taking into account their individual length and the number of turbines on which they occur. This value was estimated at 11.6 m [24].

Table 1 contains a list of onshore wind farms in Poland with a total capacity of over 95 kW built in 1991–2000 (authors’ list based on [23–26] and other local sources).

Table 2 (authors’ list compiled on the basis of [25–27]) contains a list of onshore wind power plants in Poland with a total capacity above 5 MW built in 2001–2015 [26]. The timeframes included in both Tables 1 and 2 represent the earliest periods when the wind blades could be decommissioned. Additionally, over the entire period up to present, the development of wind technology in the country has progressed, and so more power plants have been built [27]. However, they are so new that they do not significantly affect the subject of the study. Table 2 was compiled on the basis of Flag (2012), Jastrzębska (2017), Tytko (2010), and other local sources [25–27].

Table 2. List of onshore wind farms in Poland with a total capacity of over 5 MW.

Item.	Location	Power of Power Plant [MW]	Turbine Type	Blade Quantity	Impeller Diameter [m]	Blade Length [m]	Year of Commissioning	Blade Quantity
1	Barzowice	5	Vestas V-52 850	6	18	52	25	2001
2	Cisowo/Energia Eco/EEZ	18	Vestas V80/2000	9	27	80	39	2002
3	Zagórze	30	Vestas V80/2000	15	45	80	39	2008
4	Lisewo I & II	10.8	Enercon E40/600	14	42	40	ND	2005/2007
			Enercon E48/800	3	9	48	22.8	
5	Tymień	50	Vestas V80/2000	25	75	80	39	2006
6	Gnieźdźewo near Puck	22	Gamesa G87/2000	11	33	87	42.5	2006
7	Kisielice	77.5	GE Energy 1.5 Enercon E82E2	47	141	77	37.5	2007, 2011, 2014
8	Jagniątkowo Lake Ostrowo	30.6	Vestas V90/2000	17	51	90	44	2007
9	Kamieńsk	30	Enercon E-70 E-4	15	45	71	32.8	2007
10	Malbork (Sztum)	18	GE Wind Energy 1.5 sl	12	36	77	ND	2008
11	Łebcz I near Puck	4	Enercon E-48/800	4	12	48	22.8	2007
12	Łebcz II near Puck	4	Vestas V80/2000	4	12	80	39	2008
13	Zajązkowo	48	Vestas V80/2000	24	72	80	39	2008
14	Karścino–Mołtowo	90	Vestas V90/3000	17	51	90	44	2008
15	Krzęcin	14	Gamesa G90/2000	7	21	90	44	2008
16	Darżyno	12	Enecon E-82/2000	6	18	82	41	2008
17	Śniatowo	32	Vestas V90/2000	16	48	90	44	2008
18	Inowrocław	32	Vestas V90/2000	16	48	90	44	2008
19	Hnatkowice-Orzechowice near Przemyśl	12	Gamesa G87-2MW	6	18	87	42.5	2009
20	Łęki Dukielskie	10	Repower MM92/2050	5	15	92.5	45.2	2009
21	Suwałki	41	Siemens SWT-2.3-93	18	54	93	45	2009
22	Tychowo	50	Nordex N90/2500	20	60	90	43.8	2009
23	Margonin	120	Gamesa G90/2000	60	180	90	44	2010
24	Karnice	31	Siemens SWT-2.3-101	13	39	101	49	2010
25	Karcino	51	Vestas V90/3000	17	51	90	44	2010
26	Wind Farm Piecki near Suwałki	32	Gamesa G90/2000	16	48	90	44	2011
27	Tychowo	35	Siemens SWT-2.3-93 Nordex	20+15	105	90. 93	45	2011
28	Lipniki	30	Repower MM92	15	45	92.5	45.2	2011
29	Wind Farm Łukaszów	34	Vestas V90/2000	17	51	90	44	2011–XII
30	Wind Farm Modlikowice	24	Vestas V90/2000	12	36	90	44	2011–XII
31	Pelplin	48	Gamesa G90/2000	24	72	90	44	2012
32	Taciewo	30	Gamesa G90/2000	15	45	90	44	2012
33	Pagów	51	Vestas V112/3000	17	51	112	54.7	2012
34	Wind Farm Nowy Tomyśl	5	Fuhrländer FL-2500	2	6	100	ND	2012

Table 2. Cont.

Item.	Location	Power of Power Plant [MW]	Turbine Type	Blade Quantity	Impeller Diameter [m]	Blade Length [m]	Year of Commissioning	Blade Quantity
35	Wind Farm Krobia	33	Acciona Windpoer 3000	11	33	116	56.7	2012
36	Wind Farm Golice	38	Gamesa G90/2000	19	57	85	44	2012
37	Wind Farm Górzycza	28	Starke Wind Polska	14	42	ND	ND	2012
38	Taczalin	45.1	Repower MM92/2050	22	66	92.5	45.2	2013
39	Darłowo	250	General Electric	100	300	103	ND	
		Phase I 80						2011
		Phase II 95						2012
		Phase III 75						-
40	Marszewo	82	Vestas V80 & V90	41	123	80/90	39/44	2013
41	Pawłowo	79.5	Acciona AW 82/1500	53	159	82	40	2013
42	Itża	54	Vestas V90/2000	27	81	90	44	2014
43	Skurpie near Działdowo	43.7	Siemens SWT-2.3-108	19	57	108	53	2015
44	Oprzędów	5.1	Gamesa G58 & Vestas V66	4	12	58/66	28.3/32	2015
45	Michów–Abramów	51.2	Vestas V112/3200	16	48	112	54.7	2015
				SUM:	2658	AVR:	42.1	

The analysis was performed for the same categories as in Table 1. The total number of blades in the list was 2658. The weighted average length of the blades used, calculated according to the same principles as for Table 1, was estimated at 42.1 m.

On the basis of the analysis, we developed Figure 2, which presents the locations of the largest listed power plants in Poland.

One of the companies involved in the recycling of wind turbine blades in Poland is Anmet. In cooperation with a team from the Department of Roads and Bridges of Rzeszów University of Technology, concepts of a footbridge over the Szprotawa River (2021), made of two dismantled wind propellers and used for pedestrian and bicycle traffic, were created. The span between the supports is 16.4 m, and the width of the footbridge is 4.3 m. This is the first building of this type in the country. The propeller from the wind power plant is the supporting element of the structure [28].

This form of waste treatment is called upcycling. The difference between recycling and upcycling is that the latter results in high-quality utility products with greater value than the raw materials used to make them. This is the opposite of downcycling, i.e., producing things less valuable than the raw materials used. The construction of the footbridge is in accordance with the idea of circular economy, and its construction has been patented.

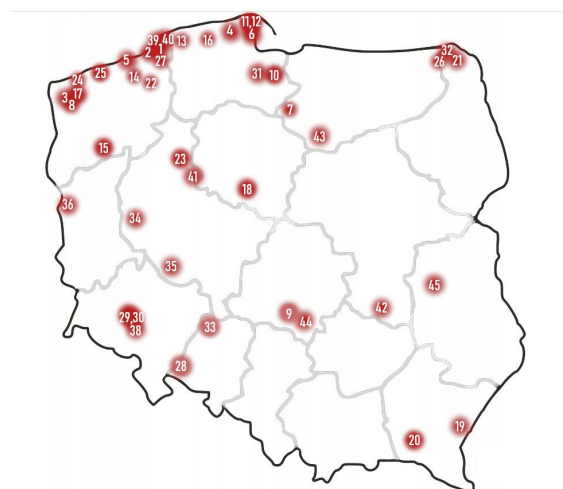


Figure 2. Map showing the locations of the largest power plants in Poland from Table 2.

According to the concept, the span must include at least one wind turbine blade, which acts as the main girder to which ribs are attached; to them, in turn, a light platform with a railing is attached. Ultimately, a girder built of two composite blades was designed, and to combine them, flanges were used [29].

- Bridge in Cork, Ireland

On a 23-km route (under construction) in Cork (Ireland), there was a bridge concept developed based on worn out wind turbine blades. It was created as part of the Re-Wind research project. Laser scanning technology assisted in the analysis of the blade geometry; additionally, a number of studies were carried out on aspects including blade strength and element joining. The five-metre structure is made up of two processed LM13.4 wind blades from Nordex N29 turbines that were handed over to the project. Between two sections of propellers of about 8.5 m length, a platform was built, fixed to the blades at an appropriate height [29,30]. It is worth noting that the concepts developed in the project allow construction of footbridges with a span up to 15 m and a platform width of up to 6 m [29].

- Other concepts developed within the Re-Wind project

As part of the project, catalogues have been developed that contain a set of concepts for wind blade reuse. This material can be recycled in a multitude of methods, most of which are based on the idea of upcycling. The study presents concepts such as pedestrian/bicycle bridges (two- and multi-girder, tow, suspended), poles, fences, acoustic barriers, small architecture (seats, shelters), cattle partitions, reservoirs, and grain warehouses, as well as stands, embankments, breakwaters, skate parks, foundation piles, barriers, pontoons, and facades. The possibility of using wind blades for production of aggregate or fillings or as a 3D printing material (Figure 3) was also mentioned.

A different project was carried out in Mexico, where buildings near the Gulf of Mexico are exposed to strong hurricanes and flooding. So for this area a concept of building affordable housing (using wind turbine blades) was developed. The focus was on the use of large FRP (fibre-reinforced polymer) elements. This solution can be used in both new and renovated housing projects. The concept was based on dividing the prototype of a 100 m long blade in such a way as to show the use of its individual segments in housing [31].



Figure 3. Footbridge in Szprotawa: flanges connecting two wind blades.

Scientists are constantly working on improving available technologies or finding new, less energy-intensive ones. In addition, alternative technologies for reusing wind energy composites are being developed. Options include mechanical recycling, solvolysis, and pyrolysis, which will ultimately provide the industry with additional solutions for wind turbine decommissioning. Thermal recycling technologies have been evolved, in which the key point is to degrade the organic parts of composite materials and transform them into molecular form as gas, liquid, or remaining solids. Another method uses plasma technology to form micrometric fibres out of shredded wind turbine blades. Importantly, during the process, no toxic combustion gases or degradation products of the matrix resin were formed. Thus, only environmentally friendly microfibres were created during the plasma process. The most common recycling method is the mechanical method. The first step normally involves jaw cutters, which are tools for sectioning blades and can handle large sizes and volumes of composite materials. There also exist different crushers, mills, shredders, or grinders for all kinds of wind turbine blades. The resulting material can be used either for production of new plastic parts or as fillers in the building industry. Mechanical recycling can only be an intermediate step and must be followed by thermal or chemical recycling processes to close the recycling loop and to make wind turbine blade production sustainable. American scientists, in the process of pyrolysis under the influence of high temperature, decompose the composite material, separating the organic material from the inorganic glass fibres, thus obtaining a material that is burned to generate energy. Unfortunately, this is a long and energy-consuming process. The Danes, on the other hand, are repurposing propeller blades as small architectural elements such as benches, bus stops, bicycle shelters, or garden furniture. Scientists from Rzeszów University of Technology (Poland) have proposed using blades in bridge construction to make load-bearing elements of footbridges. For example, a group of scientists from Białystok University of Technology (Poland), led by Prof. Broniewicz, is developing systems of road acoustic screens using composite elements of wind turbine blades. Their research includes conceptual and experimental studies on a full scale, and numerical studies with FEM. These attempts were undertaken due to the massive problems associated with the disposal of wind turbine blades that have gone out of use or are being replaced with more efficient technical solutions (re-powering). The average life cycle of wind blades implies that after 2035, approximately 225 thousand tons of used blades should be dismantled [5]. Therefore, reuse of WTBs has a wide range of possibilities.

3. Research Methodology

The conducted studies included analyses of the largest onshore wind power plants present in Poland in the years 1991–2015 and the characteristics of the most common types of them in Poland, followed by a description of the current state of knowledge on the topic of reuse of wind turbines all over the world. There were also conclusions drawn from the existing literature. This paper indicates one of the solutions to the research problem as well as an assessment of the design implemented in this project.

The motive for the study was the gradually increasing problem of decommissioned wind turbine blades management in the world. This served as a premise to demonstrate the scale of the problem within the borders of Poland and to attempt to seek a solution. In light of the above, the objective of this article is to analyse the presence of the largest wind power plants in the country and to explore the possibilities of using worn turbine blades in architecture and construction, as well as to present one such possibility in the design section. Two research hypotheses were assumed in the paper:

- The development of wind energy in Poland since the 1990s will force the necessity of post-consumer management of wind turbine blades in the near future;

- One of the solutions for the management of decommissioned wind turbine blades, is their reuse in architecture and the construction industry, which, at the same time, contributes to extending their life cycle.

In the first hypothesis, a quantitative comparison was made against the adopted criteria, based on a review of existing data and documents. The relationship of the collected data with the previously identified research problem was analysed. As for the second hypothesis, the study was based on a case study and, to a lesser extent, on observations and interviews.

Considering the schemes of reusing wind turbine blades in architecture and civil engineering, one can see the implementation of sustainable development. This direction certainly promotes economically viable solutions, thanks to savings on materials. There is no cost of extraction or processing (preparation for use), as would be incurred in the case of natural resources. Furthermore, cutting into smaller elements (for convenient transport/handling in reuse) without the chemical or thermal processing necessary in other cases is more effective. The method of reusing blades is also pro-environmental, as it implements the postulate of abandoning the use of natural resources. It is also a solution that is less burdensome for the environment in terms of the emission of harmful substances into the atmosphere (compared to the chemical/thermal recycling procedure). Additionally, the life cycle of the elements is extended, making it possible to avoid the generation and storage of waste, which is also a step toward a closed-loop economy. Additionally, the life cycle of the elements is extended, making it possible to avoid the generation and storage of waste, which is also a step toward a closed-loop economy.

4. Discussion of Results

Analysis of Tables 1 and 2 show the location and power capacity of the turbines along with the quantities of turbines and blades that might be reused. This analysis leads to the observation that a significant increase in the installed capacity of power plants has occurred since 2006. The first power plants were built in 1991, i.e., 33 years prior to 2024. In light of the fact that the blades used for the construction of parts of Polish wind farms, mainly until 2010, had been previously used abroad for many years [32], the technical lifetime of these blades should not be counted from the moment of their installation in Poland.

Table 3 summarizes the blades used in the design with new functions assigned to them. Information about the location of the elements in the design and the total number of blades used is also included. To estimate quantities of materials replaced by wind blades a set of data has been presented (Table 4). According to different types of material: reinforced concrete, architectural type concrete, GFRC, cellular concrete, item designation and element location in the design have been given. As a result the estimated number of blades used have been recognised.

Assuming, to simplify matters, the execution of the designed elements with reinforced concrete and concrete technology, has been estimated that the use of wind blades provides in the design replacement of 331 m³ of reinforced concrete and 42.5 m³ of architectural concrete, cellular, and GFRC combined.

The concepts present examples of planes in which blades ought to be cut and the possibility of joining the fragments with other elements (Figure 4). The objective of the project was not to develop solutions in technical terms but to present the concept. Figure 5 shows all blade elements of the design brief as they would appear in the planned installation.

Table 3. List of wind blades used in the presented design.

Blade Type	Characteristic Data	Item Designation	Element Location in the Design	Number of Blades Used
Vestas V-90/2 MW	blade length: 44 m largest profile chord: 3.9 m	roof girder	above the audience of archery tracks	1
SEEWIND 25/132	blade length: 10 m	roof girder	in the dance hall	12
Vestas V-80/2 MW	blade length: 39 m blade weight: 6500 kg largest profile chord: 3.5 m	retaining wall	around archery tracks	31 whole + 65 fragments 7.5 m long from the top of the blade
		supports	under the footbridge and roof from the south	
		sun shades	facade of the archery hall and the front building	
		partition wall	locker rooms	
		green walls	at the acrobatic hall, with open-air shooting tracks, north facade of the front building	
		plant containers	grounds	
		seats	grounds	
		climbing walls	grounds	
		retention tanks	below ground level	

Table 4. Estimated quantities of materials replaced by wind blades: reinforced concrete, architectural-type concrete, GFRC, cellular concrete (table developed by author).

Material	Item Designation	Adopted Reference Dimensional Material Consumption	Volume [m ³]
reinforced concrete	retaining wall	thickness 40 cm	268.8
	supports	diameter 40 cm	12.3
	roof girder of 26 m span	cross-section 25 × 40 cm	7.8
	roof girder of 13 m span	cross-section 30 × 90 cm	14.0
	climbing wall posts	Diameter ≥ 10 cm	0.3
	green wall frame posts	diameter 20 cm	11.8
	retention tanks	1.5 m ³ by 12 m ³ capacity	16.0
		TOTAL	331.0
concrete architectural, GFRC, cellular, etc.	plant containers	0.08 m ³ /item	1.2
	openwork facade slabs	0.02 m ³ for each 1 m ² of surface	13.2
	seats	0.04 m ³ /pc	0.9
	partition wall	thickness 10 cm	27.2
		TOTAL	42.5

Overview of Examples of Reuse of Wind Blades in Architecture and Engineering Structures

According to the concept of a closed cycle, it seems reasonable to consider the possibility of obtaining fibres from blades (separating the composite into parts) to strengthen concrete mix as a dispersed reinforcement. Then, a material can be obtained that is much more resistant to compression and tension, which facilitates the free shaping of architectural forms (bridges, footbridges, tunnels, etc.) while maintaining good load-bearing parameters. When designing or building bridges with wind turbines, it is necessary to take into account the variability of the strength properties of turbine elements due to wear and damage during operation. Hence, in order to use them safely, it is necessary to carry out strength tests that will show whether, which, and how many parts are suitable for reuse. Regardless,

however, the development of a calculation model is a safe verification of how the designed bridge structure (with specific loads) can work in reality.

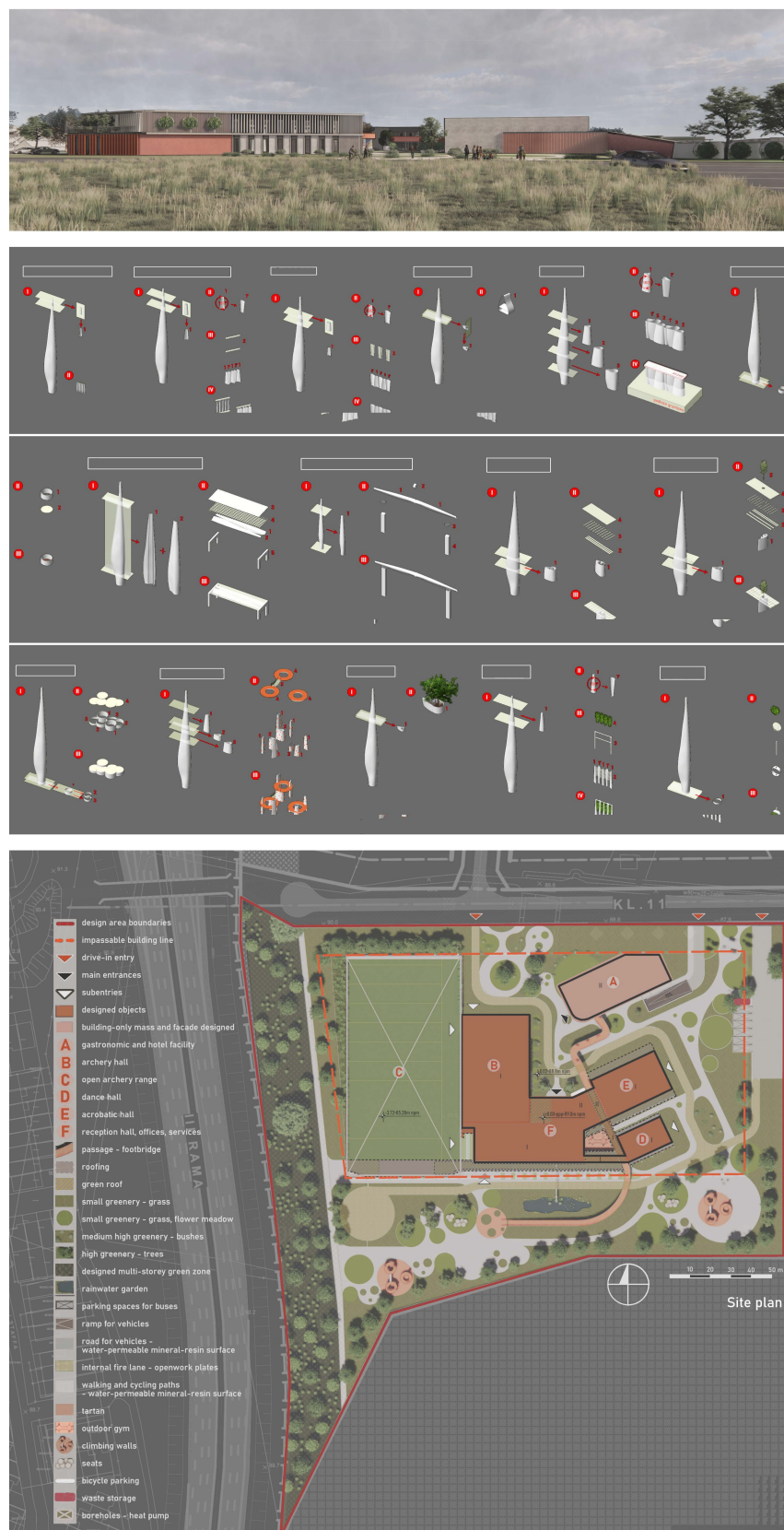


Figure 4. Bird's-eye view of the design brief; wind blade elements are marked in red.

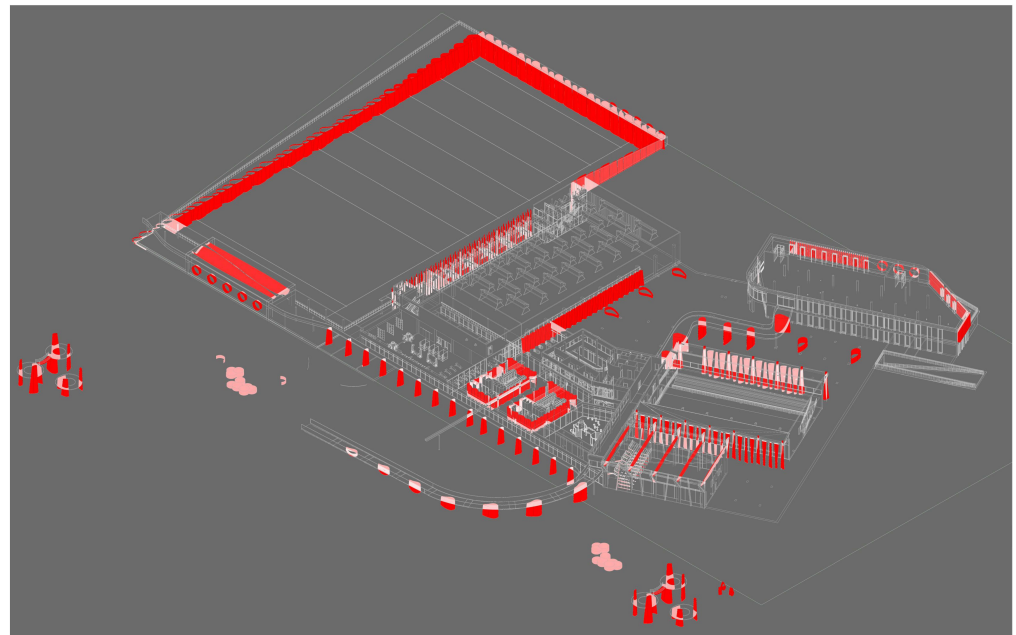


Figure 5. Bird's-eye view of the design brief; wind blade elements are marked in red.

A building or an object needs to be considered in terms of its entire life cycle. This cycle extends from the sourcing of the raw materials through to the reuse or disposal of the building or object and its parts. This solution has the potential to prevent future problems with RES waste disposal through reuse. The compiled conclusions and information indicate that some of the blades in the country will soon finish their service, and this waste will have to be managed. Problematic issues include not only their number and dimensions, but also, among others, their construction, which is currently the greatest challenge in the pro-environmental management of decommissioned WT installations. The location of wind farms in Poland will have an impact on the demand for recycling services, largely due to transport and financial reasons. The developed map in Figure 2 shows that the installations listed are located mainly in the northern part of the country, which coincides with the extremely favourable energy zone of the country.

On the other hand, the analysis of cases of wind blade reuse in architecture and construction shows that there are many possibilities for blade recycling in these industries. The realizations prove the actual use of these power plant elements in response to the need for post-consumer management. Concepts, in turn, effectively demonstrate the ingenuity and creativity of designers in the context of this relatively new challenge.

In light of the conducted research and the resulting conclusions, appropriate design decisions were taken. First of all, elements from worn-out wind blades were introduced into the concept with new functions. The idea of reusing the blades in the project is supposed to be not only pro-environmental but also educational. The exhibited elements can point out the issue of post-consumer blade management and various possibilities of their use in architecture and construction, as, among others, presented in the design of the Archery Club in Poznań. Elements that were designed from worn-out WTBs were introduced into it. At the place of dismantling from the turbine, the blade, depending on its later purpose and transport possibilities, can be subjected to preliminary cutting into smaller fragments.

Safety precautions (including dust protection) must be observed while cutting. Then, depending on the purpose of the blade, it can be subjected to adequate tests (e.g., strength), or, in the place of its further processing, accurate cutting, grinding, finishing, etc., can be performed. The use of fibre-reinforced polymer composites (PCs) in the production of structural elements requires the determination of the strength reserve adapted to the level

of expected durability and operational safety. Similarly high resilience and reliability are expected from composites used in wind energy. Due to the high fibre content, turbine blades have a very high strength-to-weight ratio and excellent load-bearing capacity and efficiency. Each of the elements presented in the design was obtained as a result of proper cutting of the blade crosswise or lengthwise. These elements were a retaining wall, plant containers, footbridge supports, footbridge supports with space for greenery, movable sunshades (brise soleil type), fixed sunshades (brise soleil type), roof girders (inside the building's dance hall), roof girders (in the open-space archery range auditorium), green walls (both vertical and circular), partition walls, climbing walls, step stools, single seats, and retention reservoirs.

In addition, it is recommended that all elements exposed to moisture should be covered with a waterproofing agent, and elements that, as intended, require close adhesion to each other should be properly joined (e.g., with screw connections). Each element intended to perform a structural function should be designed by the constructor and should be preceded by tests for strength. This is due to the fact that dismantled wind blades may uncontrollably lose their characteristics in their primary operation. The stability of elements that need to be fixed in the ground or recessed in the ground, i.e., supports, retaining walls, and climbing walls, is ensured by appropriate depth of penetration of the element into the ground.

Attention should also be paid to the possible necessity of including band drainage in the retaining wall. In places where the underground floor falls below the ground level footbridge, supports should be positioned on the ceiling and poles of this floor. Sunshades and partition walls are designed to be attached to the frame and then to the ceilings.

The idea of proposing solutions for wind blades in the project was to consider the problem of their recycling. When developing the concepts, similar implementations were considered, assuming that strength requirements were met on the basis of prior tests. Therefore, this paper presents examples of reuse of wind blades as an architectural aesthetic.

5. Conclusions

Since the 1990s, there has been a development of wind energy in Poland, which resulted in the construction of more and more wind power plants over time. As this phenomenon progressed, the overall dimensions of the wind blades used also increased.

Potential wind turbine blade waste from 2018 to 2050 is expected to increase significantly. Referring to the year 2024, the following estimates are projected for 2050: China (40% of the world's total), year 2024—20,000 tons, year 2050—850,000 tons; Europe (25% of the world's total), year 2024—70,000 tons, year 2050—480,000 tons; USA (15% of the world's total), year 2024—2000 tons, year 2050—300,000 tons.

The issue of post-consumer management inspires the creation of new objects that are less burdensome to the environment. For now, new ideas are emerging to process them into a raw material for cement production, which could be used to create acoustic screens, transmission towers or concrete reinforcement. The aim is to develop a common method of producing plates or granules from blades. One solution indicates the potential of using blades as slope reinforcement. Still another indicates the usefulness of long raw fibres as reinforcing elements for building structures, or chopped fibres for combining with resins or as inputs into thermoplastic and sealing materials. Scientists are also working on the use of crushed blade fragments in the form of epoxy—glass straw, so that after combining this material with resins and crushed wood, wood-based tiles can be obtained.

However, direct solutions are also implemented, such as building bridges from blades or small architectural elements (bus stops, benches, tables and playground equipment). Another interesting proposal is the one by the design studio Superuse Studios, which

transformed the gondola (the upper part of a wind turbine) into a small but fully functional house. Despite the variety of recycling methods, in the case of wind turbines, the cheapest, most energy-efficient, and least burdensome solution for the environment (no need to burn plastics, no waste) still seems to be repurposing. As the number and size of wind turbines grow, so does the demand for new materials that provide better mechanical properties. The increased length of the blades leads to greater stresses and, consequently, faster material fatigue. The possibilities and complexity of recycling processes will depend on used technology and respect for the circular economy. It seems reasonable to search for innovative technological solutions that will ensure effortless recovery of the component materials while maintaining durability, strength, lightness of the elements, and low environmental impact. As presented, there are many ways of utilizing recycled and reused materials in architecture. The discussed parts of wind turbines hold many aesthetic and design possibilities, which give an unique solutions in architecture in the form of structural and facade elements, interior design and small architecture.

The future of reuse and recycling of wind turbine blades lies in the properties of the materials and the structure of these objects. Hence, the development of research on wind turbines should take into account, on the one hand, work on lightweight but durable (and longer-lasting) materials that, nonetheless, according to the principle of closed circulation, could be quickly recovered and extracted with low energy input. On the other hand, it also seems important to direct research work on the possibility of modular construction of wind turbines. This would ensure easy assembly and disassembly, without the use of complicated chemical processes, as well as less troublesome transport both before and after operation. Such a construction would also facilitate implementation in other architectural projects, within the framework of reuse.

The development of new materials in this context is most important because both lifetime extension and an easier separation of matrix resin and fibres for recycling processes can be achieved. Therefore, new coating materials were studied, that provide optimized anti-corrosion properties. These materials are based on polyurethanes or interpenetrating networks between polyurethanes and epoxides and can contain constrained viscoelastic layers within multilayer coatings. There is also a self-regenerating solution, which means polymers, that can be used as components in matrix resins of wind turbine blades [5].

The recently introduced concept of the circular economy (often defined as a closed-loop economy) allows waste to be treated as a source of raw materials to maintain added value for as long as possible and to eliminate waste. In a closed-loop economy, recycled FRP composite elements are one of the basic production materials. Reusing blades is directly related to the idea of a closed-loop economy. Not only is their life cycle extended, their strengths are also used to a greater extent. The period of their use, in accordance with the new purpose, may provide additional time for searching and for improving other methods of post-use management [33]. In bridge applications, they can perfectly meet the requirements of sustainable development in the use of waste, while simultaneously leading to a reduction in costs of building bridges from FRP composites. Minimizing the negative impact of bridge structures on the environment, while also allowing for the extension of the service life (i.e., reuse) of wind turbine blades, fits very well in the current trends of sustainable development and the circular economy.

This paper presented a conceptual Archery Center design with secondary sports functions in Poznań (Poland). The possibilities of repurposing of wind turbine blades in different forms has been presented. It should be emphasized that such solutions can contribute to increasing society's awareness of recycling (mainly reuse), waste management, circular economy.

The above-mentioned example shows that architecture and construction provide a wide range of possibilities for implementing solutions in the field of sustainable development, the needs of modern world and the implementation of used WTBs in the architectural concept, demonstrated the potential of these materials.

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