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ON THE SUSTAINABILITY OF WIND ENERGY REGARDING MATERIAL USAGE

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Abstract: *Material sustainability and efficiency in the different phases of the product life-cycle are relevant and necessary perspectives for improving the environmental and economic sustainability of products. Renewable energies need to be sustainable in all the aspects, particularly wind energy which gained the most renewable power capacity around the world in 2011. Sustainable production, maintenance and disposal of wind turbines support sustainability of the energy source. This paper identifies raw materials, auxiliary materials and operating supplies along the life-cycle of wind turbines. Furthermore, an overview of material requirements and potential improvement areas for sustainable material usage is developed and discussed.*
Keywords: *wind energy, sustainability, raw material, material efficiency*

INTRODUCTION

Presently, people consume daily resources and energy more and more. This trend will presumably continue through technical advances and progress that are continuously being made. However, exhaustible raw materials and resources as well as ever-increasing environmental problems illustrate that this attitude is not sustainable long term. When attempting to solve this problem, certain areas are affected, including higher material efficiency, higher system effectiveness or usage of endless resources. Out of several solutions that ensure a sufficient energy supply for the coming generations, the use of renewable energies is a common one. Chief among these renewable energies is wind energy, which was the top added renewable power capacity worldwide in 2011 [1].

Wind energy promises a solution for a environmental friendly and sustainable energy supply. Key facts are:

- Wind is an inexhaustible source of energy.
- The average time for energy amortization is approximately 6 months [2].
- 1 MW wind turbine can provide electricity for an average of 350 households [3, 4, 5].
- Currently, if all needed materials are recovered, over 90% of the wind turbine can be recycled [6].
- There are no CO_2 emissions during running time, without taking into account the maintenance and monitoring.

However, a large amount of material usage in the wind energy sector is needed when producing, constructing, maintaining, and disposing of wind turbines. The total weight amount of material used to produce a wind turbine, including tower, nacelle and blades (foundation not considered), varies depending on size. However, for an average 1.5-2 MW wind turbine model, weight varies between 164 and 334 tonnes [7].

In addition, when regarding the total materials balance of a wind turbine, foundations must be considered as well as the waste materials produced and the materials that become waste in the production processes. This means that the material input of the production processes is higher than *strictly needed for a finished wind turbine. Moreover, operating supplies are needed within the operation phase. These materials, the final product, production waste materials and supplementary waste materials must be disposed of. This affects the overall sustainability and efficiency of a wind turbine life-cycle.*

This paper also provides a brief overview of raw materials, auxiliary materials and operating supplies used in the life-cycle of wind turbines. The focus lies on production, usage and end-of-life material input and output. Some initial approaches regarding sustainable and efficient material usage practices are given.

MATERIAL SUSTAINABILITY AND MATERIAL EFFICIENCY

Material efficiency in production systems describes the ratio between material output and material input, which leads to an ecological characterization of production processes.

A higher material efficiency can be reached by producing more with less material input. In the same way, material efficiency improvement is present in products that allow the fulfilment of the same function with a reduction of used material [8, 9, 10]. Based on these definitions there are two main strategies to apply in order to improve material efficiency. Either the amount of material input brought into the system can be reduced, or a sustainable route of materials or products can be provided.

Measures for each of the strategies are proposed as follows [11]:

Reduction of material input into the system:

- *Material-efficient product design: designing lightweight products;*
- *Decreasing production waste: changes in production processes can allow a better use of resources reducing production waste;*
- *Decreasing maintenance replacements: products design with minimal needs of maintenance replacements;*
- *Increasing Life-cycle performance: using products more intensively, designing products for longer life-cycle or providing means to repair, upgrade or remanufacture products.*

Sustainable disposal route:

- *Material substitution: replacement of the original material by another more sustainable one in terms of energy and end-of-life.*
- *Product designed for re-use: designing products with focus on re-use after their main life-cycle.*
- *Product designed for recycling: designing products with focus on recycling after their life-cycle.*

Focusing on wind energy, the high material input for wind turbine production is apparent. Furthermore, products today are characterized by relatively new materials and supplementary composite materials. While technological progress is rapid in this field, the interest for designing environmental friendly products is growing in the wind energy sector. In regard to the development of the market, it seems that technological leaders in this sector have to address material efficiency from the economic and environmental perspective in order to hold their position [12].

Material sustainability can hardly be reduced to the availability and environmental performance of used materials. It is a long term perspective of the availability of needed material in the future and their potential to be recovered. Recycled materials are often related to other, lesser environmental impacts because less energy input is used for processing.

However, the quality and the availability of the materials are essential. Rare materials require more effort to recycle than other materials. In addition, the existing, efficient recycling process must be taken into account, which would result in higher recycling quotas.

When referring to wind energy, we identify some lack of existing industrial recycling options for some parts of the wind turbine, like rotor blades. This is because of the composition of materials which complicates the path to a sustainable solution. There is a solution for the recycling of rotor blades (example: geocycle [13]), but it is still a new solution. Wind park operators are often not aware of it, or try to find other solutions like incineration.

MATERIAL NEEDS IN WIND ENERGY

Primary materials needed for wind turbines include mainly steel, pre-stressed concrete, *magnetic materials, aluminium, copper, wood, epoxy, glass fibre reinforced plastic (GFRP) and carbon-filament reinforced plastic (CFRP). Dividing a wind turbine into four main parts, the figure 1 illustrates the material types involved in each of the parts [14, 15, 16].*

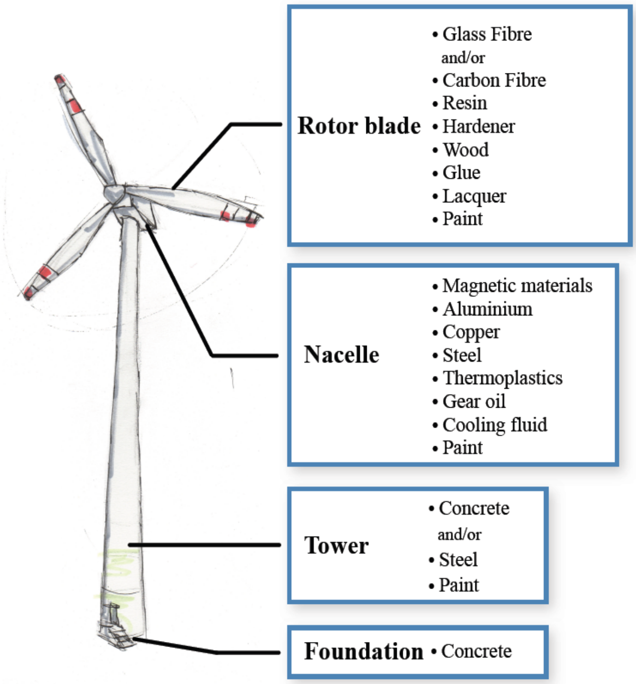

Figure 1 – Materials involved in each part of the final wind turbine [14, 15, 16]

Taking all parts except the foundation into account, the usage of steel is dominant with approximately 89% of total weight present. Furthermore, fibreglass and fibre-reinforced plastics are significant materials in regard to the proportion of weight, the characterization of the industry sector, and especially the costs. Figure 2 illustrates the percentage of other main materials involved in a 1.5 MW wind turbine and its according proportions of weight, excluding the foundation [17].

When regarding the different life-cycle phases, more materials than those directly involved into the wind turbine are needed. From a holistic point of view, further materials are needed in each life-cycle phase as they are used to accomplish related tasks in each phase. The life-cycle phases that must be considered are research, development, production, operation & maintenance, and end-of-life.

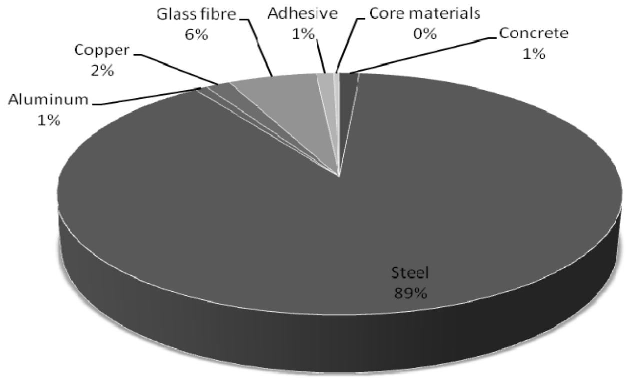

Figure 2 – Distribution of raw materials in wind turbines without foundations (1.5 MW) [17]

Intense material usage is found in production, operation (due to maintenance) and end-of-life phases. Moreover, the weight, variability and costs of materials in research and development phases are insignificant when compared with materials involved in the other phases [6]. The remaining parts of this chapter will focus on material needs for production and operation; the challenges of today with be illustrated accordingly. Based on the discussion, considerations of disposal routes for production and maintenance waste and for the wind turbine itself will follow.

Production

In the production processes, raw materials are more or less directly involved in the wind turbine production. Furthermore, there are auxiliary materials that are not part of the final product, but are needed within the production processes. In regard to three main parts, namely tower, nacelle and blades, raw materials and auxiliary materials are presented in the following subchapters.

¤ ***Tower***

Commonly available materials used to construct towers of wind turbines are steel and concrete. There are different structures of the tower within the wind power market; the most common tower is made of tubular steel structures and represents about 85% of the wind turbines around the world. [15, 18] Table 1 shows a comparison between the material needs for a 100 m height tower of tubular steel tower and the pre-stressed concrete with their foundation material needed for on-shore wind turbines:

Table 1 – Comparison of material needs between Steel and Concrete tower [19]

	Steel Tower		Concrete Tower	
Total weight per part	tonnes	%	tonnes	%
Tower	295	13	1.817	65
Foundations	1.911	87	1.077	35
Total tonnes	2.206		2.894	
Total weight per material	tonnes	%	tonnes	%
Steel	339	15	100	3
Concrete	1.867	85	2.794	97
Total tonnes	2.206		2.894	

Assuming that the tower can be 100% recycled, and the foundations only 60%, we see a huge loss of material for steel towers. Until now, there have been no figures summing up the lost material of the foundation. However, the advantage of concrete is that this material will be available in future without conflicting with other known technologies. Steel might become critical if its growing worldwide demand increases the cost. On the other hand, the recycling of steel is an established process and through melting it, it can be used for new steel parts as well. Concrete can be recycled as construction material but cannot be used for the construction of new wind turbines. Therefore, we find a downcycling of concrete, and the material flow never goes back into the turbine.

¤ ***Nacelle***

The nacelle contains most of the electric equipment of the turbine and therefore contains the most metals by weight. The casing is either made of cast iron, thermoplastics, or glass fibre reinforced plastic. The electric equipment composes of cast iron (generator, drive, etc.), aluminium, copper and other metals that are considered critical within the European Union [20]. Mass per weight varies according to different manufacturers. Most precious metals are located in the nacelle. Most parts inside the nacelle can be refurbished as well. The casing is made of similar material to the rotor blades, and can enter the same recycling process.

¤ ***Rotor Blades***

The blades used in commercial wind turbines are mostly made of glass fibre, mixed with smaller amounts of more expensive but stronger carbon fibre. A switch to more carbon fibre due to bigger rotor blades is being addressed, which will have a higher stress load with a more reasonable weight. While the broad usage of composite materials is still relatively new in the industry in general, smaller wind turbines manufacturers have started to study the possibility of other solutions. One such solution is the usage of thermoplastics composites for the production of rotor blades [21]. Researchers are also looking at the appropriateness of this solution. Delft University Wind Energy Research Institute [22] is paying close attention to the study of composite properties, and has already developed a one meter demonstrator. Furthermore, the research project GreenBlade is currently trying to produce glass fibre-reinforced propylene (Twintex®) thermoplastic blades for 6 kW and 15 kW. GreenBlade is developing a 12.6 meter long thermoplastic composite demonstrator blade. The possibility of recycling the whole blade at the end of its life-cycle as well as manufacturing waste and cuts-off [23] can be identified as the main advantages when using this material. However, it is not clear yet if these solutions are suitable for larger and commercial rotor blades.

Nowadays, most manufacturers produce rotor blades with GFRP through a vacuum infusion process called Vacuum Assisted Resin Transfer Moulding (VARTM), while others produce with prepreg (pre-impregnated) technology. Prepreg presents a Fibre-Reinforced Polymer (FRP) reinforcement that is pre-impregnated with a resin. Its usage in the airplane construction industry and in the production of rotor blades has many advantages. It is the optimal solution of glass fibre and resin proportion, with very little unnecessary material used, and the quality and conformity of the final product are improved greatly. However, using prepregs requires higher material costs as well as the need of special storage conditions. [24, 25] The data presented in Figure 3 is based on the production of rotor blades with GFRP through a VARTM process. The amount of raw materials needed to produce one rotor blade, including manufacturing waste, is considered, as well as auxiliary materials that are used to complete the production process. The VARTM process is mainly operated manually and raises the usage of auxiliary materials to up to fifty different materials.

Although the length of rotor blades varies in mass and material, a 40 meter long finished rotor blade made through VARTM process contains mainly GFRP or glass fibre. The total weight of the final product is around 7 tons of materials. The approximated material weight distribution is as follows in Figure 3 [16].

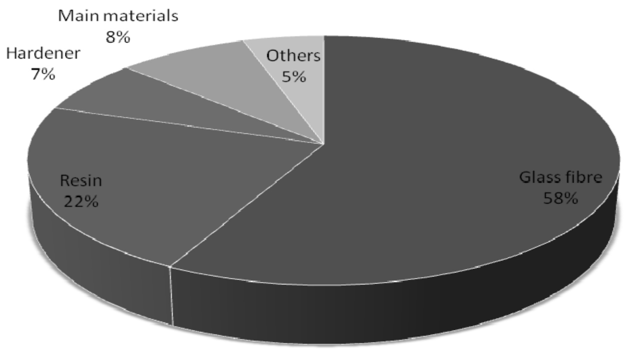

Figure 3 – Material distribution in a 40 meters and 7 tons rotor blade [16]

Many different materials are found in the waste generated by the production of 180 rotor blades during one year using the VARTM process. This waste includes production waste, packaging waste, maintenance waste and administration waste of the offices. This amounts to the entire amount of waste related to the production plant and their related activities.

The total amount of materials to dispose of is more than 800 tons. In this case, every rotor blade induces an additional material usage of more than 4 tons compared to the 7 tons of the final product [16]. The distribution of different waste material types is presented in the following Figure 4.

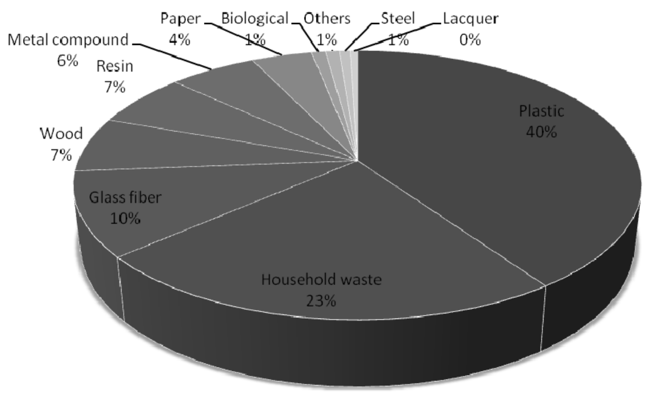

Figure 4 – Waste generated to produce 180 rotor blades [16]

Plastic materials represent the highest waste stream (40%), followed by normal household waste (23%). GFRP represents only 10%, mainly cut-offs. The plastics are part of the VARTM production process as the resin must infuse in a vacuum with the fibre layers. For the VARTM process to run correctly, plastic auxiliary materials like vacuum foil, plastic hose, perforated foil, green mesh, resin channel, fleece stripes, and many different types of adhesive foil are needed. Most of these materials are then removed after the process is finished and become plastic waste. As these materials are needed within the production process, the waste can only be minimised by changing the process itself.

Operation and Maintenance

The operation phase is the longest phase within the life-cycle. When considering current off-shore wind turbines, it must be remembered that 20 years of operations have been the basis for reliability engineering of main components of wind turbines. From a technical perspective, a complete maintenance-free operation of a wind turbine is not possible, due to the state of the art. Depending on the particular maintenance strategy, divided mainly into reactive and preventive ones, maintenance actions and the according material flows must be considered throughout the operation phase. Preventive maintenance with respective time intervals, also known as periodic maintenance, is the most common of such strategies in the wind energy sector. This strategy consists mainly of two actions, inspection/service and troubleshooting. Ongoing support for the rising usage of condition monitoring systems to measure crucial technical parameter does not change the general necessity for both actions. Rather, it aims at rescheduling the periodic intervals and lowering the amount of troubleshooting missions. Analyzing the material usage in the operation phase can then be detailed according to those actions.

In general, inspection and service is a yearly maintenance action, where crucial parameters of the components of wind turbines are observed, as prescribed by checklists [26]. Basic technical services like lubricating tribological systems, changing carbon brushes of the generator or replacing filters are some examples, often done during inspection and service. Related material *flows include mainly operating materials, whereas the refilling of wear-out reservoirs as well as replacements for related waste must be considered. Aside from that, auxiliaries that are needed to execute different actions must be disposed of.*

Besides the regularly planned inspections and services, technical failures of wind turbines can lead to extraordinary troubleshooting missions [26]. The range of particular actions that have to be executed is wide. This is also reflected by the related material flows, i.e. normal operating materials that could be needed, as well as more complex components in the electrical or mechanical systems. Normally replacements are performed on an item level, such as pumps, electrical controller, etc. Depending on the values of the components, replaced components are either disposed of or refurbished. In case of unlikely replacements of the big main components like main gear, blades or converter within the planned operating period, total aggregates are replaced and usually refurbished later on.

End-of-life

The end-of-life of products and materials is a necessary factor to study, in order to achieve a sustainable approach that allows and ensures the use of future products from the material perspective. When regarding the total percentage of material related to wind turbines that are theoretically reused or recycled, the development seems to point in the right direction. The entire wind turbine can theoretically be more than 90 % by mass [6] recycled on the material level, without taking into account periphery materials involved in electrical networks or the wind turbine foundations. This is due to the differences between on-shore and off-shore installations.

However, the 10% of industrial wind turbine material that cannot be recycled equals at least 15 tonnes of material. The practical recycling degree of the main materials used in a wind turbine is shown in Table 2.

In Table 2, some assumptions have been formulated to achieve these recycling quotes. One of these assumptions is that rotor blades or GFPR are recycled or used in a cement plant as a raw material to produce cement. This is a solution that has been developed in North Germany to provide a sustainable dismantle option for the end-of-life of rotor blades, as this method avoids any kind of waste and reduces the CO_2 emissions of the cement plant [13].

Table 2 – Practical recycling degree of main materials [6]

Material	Practical Recycling Quote %
Aluminium	100
Copper	97
GFPR(Glass Fibre Reinforced Plastic)	100
Cast iron	98
Steel	100
Concrete	60

Cement plants recycle the rotor blades on a material level due to the GFRP being included into the clinker formation. Another solution available is the incineration of the rotor blades outside of a cement kiln. This is associated with a high ash content of an average 50% of the ash input. Not only this, but the energy needed to shred the rotor blades into smaller pieces must be taken into account as well. For the cement solution, rotor blades must be shredded to a maximum particle size of 30 mm, whereas in the incineration solution the maximum size must be 500 mm. The energy needed in each of these cases is different, and an exhaustive analysis of energy needs will help to support or refuse the sustainability of the cement solution.

Table 3 – Economic comparison of disposal rotor blades possibilities

	Incineration solution	Cement solution
Costs pro tonne	550€	650 €
Treatment costs (shred)	Yes	Yes
Logistic costs	Yes	Yes
Dismantle costs	No	No
Total costs pro wind turbine (6,5 tonnes rotor blades)	10.725 €	12.675 €

From an economic perspective, Table 3 represents an economic comparison between the cement solution and the normal incineration solution. This *comparison is for 3 rotor blades (each 40 long and 6.5 t weight) that must be transported a total of 250 km. In this comparison, logistics and treatment costs are included, but dismantle costs to remove the rotor blades from the wind turbine are not.*

There is a price difference between both solutions, which is greater when disposing of larger rotor blades, or a big amount of rotor blades. The complex pre-treatment is the main reason for using the rotor blades in the cement solution. The need to shred the rotor blades into smaller pieces requires special machinery and more intensive energy use. In order to achieve the best environmental friendly solution, a proper footprint analysis is needed that takes into account the energy, CO_2 emissions and material use. As of the present, the incineration solution is still the most reasonable from a business perspective, as it has lower related costs. Currently, no regulation in Europe determines which party has the responsibility to recycle rotor blades.

Other than the rotor blades, we have not identified efforts that will recycle the entire wind turbine foundation in the future. Rather, discussions with experts have rather shown that the recycling of foundation concrete can be as little as 60 %. Additionally, there is no concrete decommissioning plan for the steel foundations used in the wind parks in the North Sea, and there are also discussions about new "artificial reefs".

CONCLUSIONS

In this paper, we wished to highlight the current awareness of material sustainability for renewable energy derived from wind. Currently, regulations for this sector are lacking, and some issues must still be taken into account. No fully sustainable solution has found at this point. The non-regulated fate of a foundation during its wind turbine decommissioning is a prime example of this problem. Removing all parts of the foundation after the use phase of the wind turbine in both installations, on-shore and off-shore, is still an open question. However, off-shore wind turbines might be more interesting in this case.

Also, the production waste during the costly rotor blade manufacturing can be reduced by making the process more efficient. To sum up, wind energy is a sustainable energy supply. However, for future progress we must keep the materials involved in each of the life-cycle phases in mind, and must provide a sustainable end-of-life for each of these materials. Based on this, further research must focus on designing wind turbines for disassembling and recycling under consideration of more economic studies regarding the entire wind turbine disposal.

REFERENCES

[1] Renewables 2012, Global Status Report 2012, www.ren21.net, 2013-01-10.

[2] Zimmerman, T.: Parameterized tool for site specific LCAs of wind energy converters, The International Journal of Life Cycle Assessment, 6(2012), 1-12.

[3] Wind Energy America: FAQs, www.windenergyamerica.com/faqs.html, 2013-03-14.

[4] Energy and Environmental Affairs: Wind Energy: Facts, www.mass.gov/eea/energy-utilities-clean-tech/renewable-energy/wind/wind-energy-facts.html#c, 2013-03-14.

[5] Trade Wind Energy: FAQ, www.tradewindenergy.com/windlibrary_sub.aspx?id=136, 2013-03-14.

[6] Pehlken, A., García Sánchez, R., Marx Gómez, J.,: How critical is Wind Energy?, Hanse Studies-Institute for Advanced Study, 8(2013)

[7] Hau, E.: Windkraftanlagen, Springer, Heidelberg, 2008.

[8] Allwood, J. M., Ashby, M. F., Gutowski, T. G., Worrell, E.: Material efficiency: A white paper, Journal of Resources, Conservation and Recycling, 55(2011), 362-381.

[9] Worrell, E., Faaij, a. P. C., Phylipsen, G. J. M., Blok, K.: An approach for analysing the potential for material efficiency improvement, Journal of Resources, Conservation and Recycling, 13(1995), 215-232.

[10] Söderholm, P., Tilton, J. E.: Material efficiency: An economic perspective, Journal of Resources, Conservation and Recycling, 61(2012), 75-82.

[11] Lewandowski, M., García Sánchez, R.: Prospects for Raising Awareness in Material Efficiency: Context-Sensitive Support for Technicians and Engineers Using ICT, Hanse Studies-Institute for Advanced Study, 8(2013).

[12] Islam, M. R., Mekhilef, S., Saidur, R. : Progress and recent trends of wind energy technology, Renewable and Sustainable Energy Reviews, 21(2013), 456-468.

[13] Schmidl, E., Hinrichs, S. :Geocycle Provides Sustainable Recycling of Rotor Blades in Cement Plant, DEWI Magazin, (2010)36, 6-14.
[14] Jacobson, M. Z., Delucchi, M.: Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials, Journal of Energy Policy, 39(2011), 1154–1169.
[15] Feito-Boirac, A., Vronsky, T., Vuillaume, A.: Recycling Wind Turbines Outlook and Technologies, EWEA (2011).
[16] García Sánchez, R.: Material Flow Assessment of Rotor Blade Production for Windturbines, Master Thesis Universität Bremen, June 2011.
[17] Energy Efficiency and renewable Energy: 20% Wind Energy by 2030, www.nrel.gov/docs/fy08osti/41869.pdf, 2013-03-04.
[18] AcelorMittal: Winds of Change, www.arcelormittal.com/fce/repository/fce/Brochures/EN_UpdateFCE_Nov12.pdf, 2013-03-04.
[19] Rodeja, J.: Sustainability of towers for wind turbines, pure.ltu.se/portal/sv/studentthesis/sustainability-assessment-of-towers-for-wind-turbines(47ac14e1-2231-4b00-becd-6cf5b1d46883).html, 2013-03-04.
[20] European Commission, Report of the Ad-hoc Working Group on defining critical raw materials, /ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf, Brussels, 2010.
[21] Gardiner, G.: Wind Blade Manufacturing, Part II: Are thermoplastic composites the future, www.compositesworld.com/articles/wind-blade-manufacturing-part-ii-are-thermoplastic-composites-the-future, 2011-02-17.
[22] Bersee, H., Teuweb, J., Rasool, S.: Thermoplastic Composite Rotor Blades, dww.wmc.eu/pdf/3c-05%20TUD-DPCS-DWW2010.pdf, 2012-08-22.
[23] ÉireComposites: Wind Energy, www.eirecomposites.com/wind-energy-composites-materials-manufacturing-and-prototyping.html, 2012-09-13.
[24] Lavender CE.: Guide to Prepregs, www.lavender-ce.com/wp-content/uploads/guide-to-prepregs.pdf, 2013-03-04.
[25] Philip, T.R., Winkel, T., Reinhart, G.: Enhaced production control for prepeg manufacturing, Forty Sixth CIRP Conference on Manufacturing Systems 2013, Procedia CIRP 7 (2013) 467-472.
[26] van Bussel, G.J.W.; Henderson, A.R. (2001): State of the Art and Technology Trends for Offshore Wind Energy. Operation and Maintenance Issues. Delft University of Technology., www.offshorewindenergy.org/ca-owee/indexpages/downloads/Brussels01_O&M.pdf, 2013-07-05.

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