An advanced polyurethane resin for wind turbine blades:

Enhanced performance with lower blade cost

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ABSTRACT

A major objective for developing and expanding the use of renewable energies is to focus on technologies and products that also bring societal benefits. While wind power shows significant advantages as a clean energy source, its broader use faces challenges on a cost basis. This paper evaluates new developments in the production of sustainable wind energy based on advances in polyurethane materials, while also noting that a related objective is to reduce wind power cost.

MAKING WIND POWER COMPETITIVE

Covestro is a worldwide manufacturer of high-tech polymer materials for a range of industries, while WINDnovation is a leading designer of rotor blades for multi-megawatt wind turbines. Covestro requested a study to evaluate the potential benefits of using polyurethane (PU) as a laminate matrix in wind turbine blades. Together, the two companies have combined efforts to evaluate new PU materials for advanced uses in various components of wind blades. The goal has been to assess these materials in applications that require greater blade speed and higher output, while also meeting the industry challenge for future, long term development.

A critical objective is to demonstrate the 'workability' of wind power as a cost-effective, sustainable energy source. Reaching this goal requires an integrated approach along the entire value chain, including production, marketing, and monitoring during service. Current research and development ventures point to the renewable property of wind energy as a major component in the worldwide energy market. This objective depends on making wind energy more competitive by reducing elements or streamlining the supply chain – as well as developing approaches to innovate for higher energy output.

The trend toward longer blades has led to new material innovation to meet needs associated with this development. From a material perspective, one essential research focus has been lighter weight blades. In turn, such blades incorporate less raw material, which leads to better product performance.

Another objective is faster, more efficient production, which ultimately relies on shorter infusion and curing times. Combined with minimized cycle time for producing an entire wind blade, the overall result is a reduced use of energy associated with each. Ultimately, this process can lead to better air quality that results from a higher component of renewable energy.

"The trend toward longer blades has led to new material innovation to meet needs associated with this development

In this way, research and development associated with these efforts aligns with a number of **United Nations Sustainable Development** goals (**UN SDGs**), including:

- Affordable clean energy
- Decent work and economic growth
- Industry, innovation and infrastructure
- Sustainable cities and communities
- Responsible consumption and production
- Climate action

The result is a lower levelized cost of energy (LCOE)[1]. That is, if production cost for blades is 10% to 15% less, along with lower weight, and consistent performance is combined with increased length, LCOE could be further reduced.

[1] Levelized cost of energy (LCOE) represents a measure of a power source; it allows comparison of different methods of electricity generation on a consistent basis.

The shape and dimensions of wind turbine blades are determined by the aerodynamic performance required to efficiently extract energy from the wind, and by the strength required to resist forces on the blade. The latter is where a stronger material could play its role.

Figure 1 indicates blade length and mass development over past years.

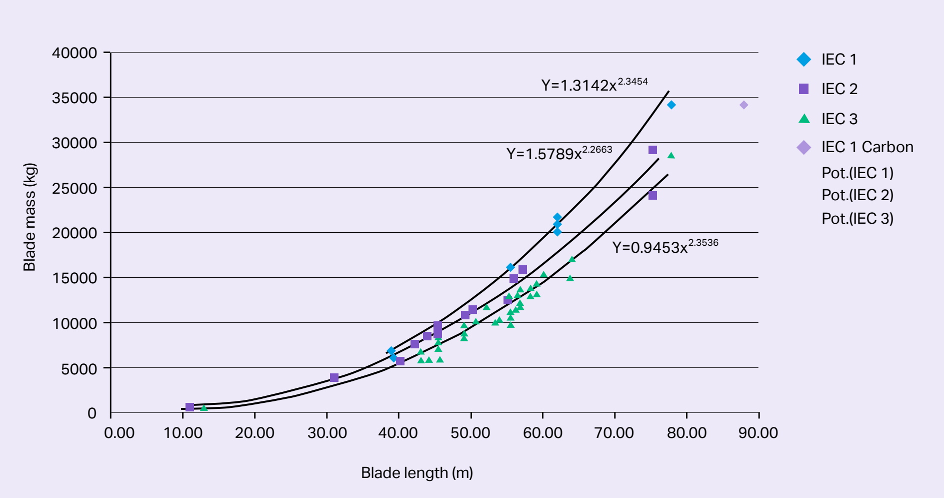

Figure 1. Global trend of blade length and mass (source: WINDnovation).

For modern blade designs, stiffness in combination with compressive strength and fatigue characteristics are the design driving parameters. All developments that extend the limits of existing glass/epoxy laminates are welcomed by rotor blade designers and manufacturers.

Over past years, challenges have been identified for the structural design of blades:

- **Slender blades offer very limited internal space to accommodate the blade structure.**
- **Blade mass should be as low as possible (in order to reduce loads and minimize cost).**
- **Long, slender blades often face tip-to-tower clearance problems, indicating the need for high performance glass fiber and carbon fiber as well as sophisticated analysis methods.**

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Wind blades account for

20–25%

of wind turbine cost

RESEARCH AND NEW MATERIALS PROPEL DEVELOPMENT AND PROGRESS

In 2009, based on a grant from the US Department of Energy (US DoE), Covestro began research on an innovative PU solution to allow the wind power industry to move beyond a major challenge for its future development. Given wind power growth trends in China and Europe, this effort clearly holds promise. Wind blades account for 20% to 25% of wind turbine cost, so cost reduction of blades can support reduced LCOE for the wind industry.

Development progress started from PU resin chemistry research, and it extends to PU infusion process development. The first commercial product was introduced in 2019. A significant component of the research associated with this breakthrough was conducted by Covestro and partners in the entire wind energy industry value chain. These included wind turbine and blade manufacturers, a fiberglass supplier, a machine producer and WINDnovation, a blade designer.

A key development in the advance of blade technology is related to the use of the PU resins. Because lightweight design allows for longer rotor blades, essential design requirements can be met with the new resins. WINDnovation initially expressed interest in enhancing blade design by exploiting PU characteristics and advantages. As that work indicated, PU resin is suitable for wind turbine blade manufacture, and it offers blade cost advantages.

For ease in assembly, it also is possible to substitute PU as a replacement for another infusion resin, or consider full design implementation to maximize overall savings. Covestro is currently working with WINDnovation to calculate the full design advantages and options for use of the PU resin.

Figure 2 shows a wind turbine installation at the Datang wind farm in northern China. The 55.2 m wind blade with PU spar cap and shear web has been operating since October 2018. The accompanying graph shows kwh of electricity generated from installation through mid May 2019.

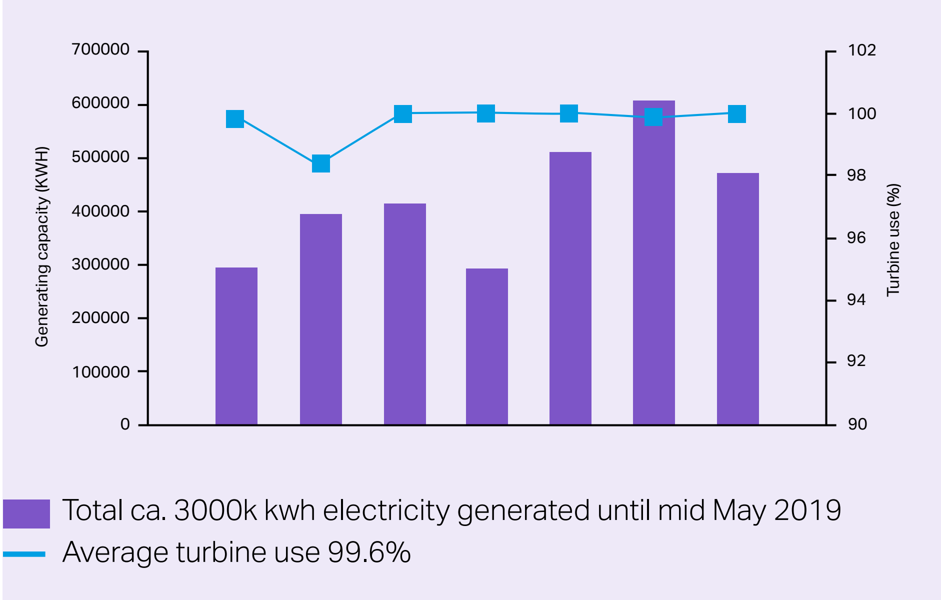


Figure 2. This wind turbine with its PU wind blade continues to run well while experiencing high use.

AGILE DESIGNABILITY AND ITS ADVANTAGES

The new PU resin offers advantages in terms of fast infusion and fast curing performance in production of the very large-fiber composites used in blades. The initial viscosity of PU resin is very low, which brings the advantage of fast infusion during wind blade production. Figure 3 shows the viscosity of PU resin is only 58 mPa.s at 25°C, which is significantly lower than that of conventional epoxy infusion resin.

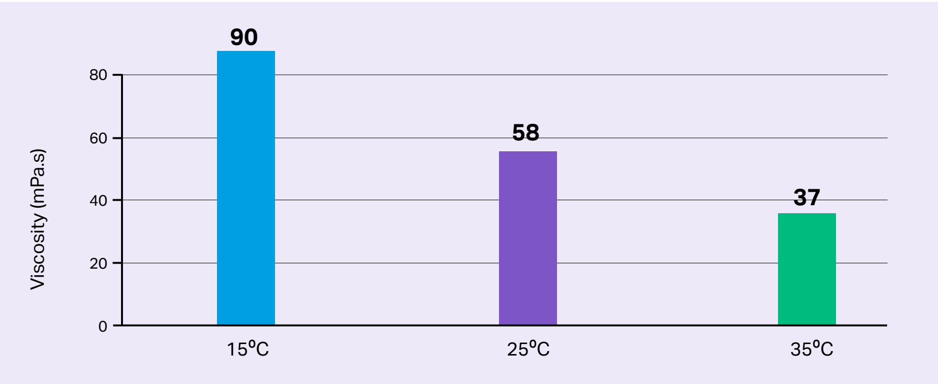


Figure 3. Initial viscosity at different temperatures.

Under the same conditions, polyurethane resin has better flow characteristics than epoxy resin due to its low viscosity, which can result in greater infusion speed. Figure 4 shows the viscosity of PU is below 600 mPa.s in 140 minutes at 25°C after mixing, which is suitable for large wind blade production. Particularly at the beginning of 90 minutes, the viscosity of polyurethane remains below 300 mPa.s, which means PU will be infused much faster than conventional epoxy infusion resin during wind blade production.

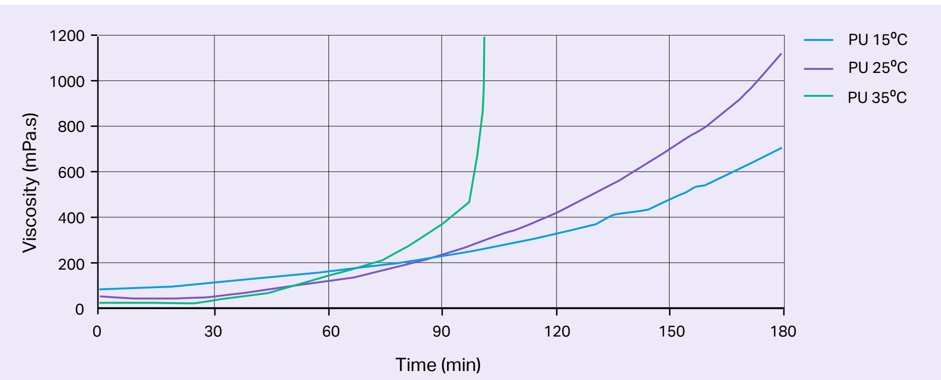


Figure 4. Viscosity curves at different temperatures.

The curing behavior of the polyurethane resin offers additional advantages. Almost complete curing is possible in less than 4 h at 80°C, and pre-curing time can be even shorter, potentially saving valuable processing time.

Key benefits of PU resin

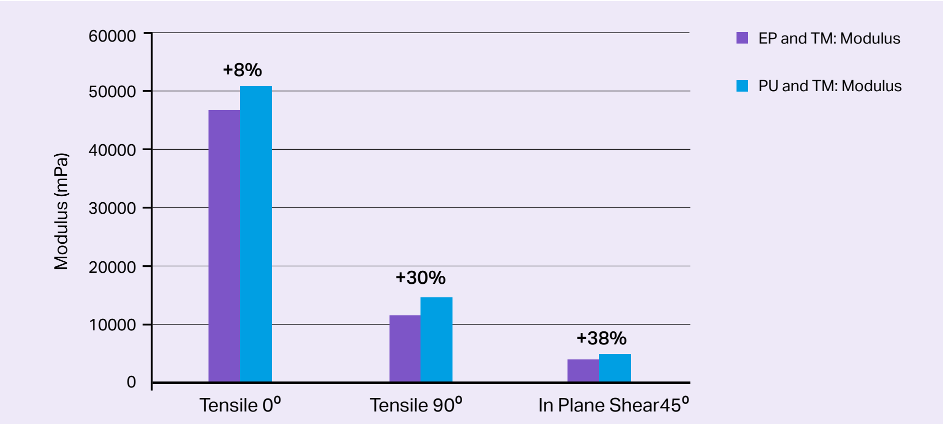
- Low viscosity
- Faster infusion
- Shorter curing and pre-curing time

"PU will be infused much faster than conventional epoxy infusion resin during wind blade production

SUMMARY OF PROPERTY EVALUATIONS

Several blade properties were evaluated as part of a benchmark study conducted by WINDnovation[2]. These evaluations were based on the SR552-2 rotor blade design.

Material Data. PU-based composite in combination with the PU infusion process leads to higher fiber matrix ratios, potentially offering superior mechanical properties compared to conventional epoxy-based composite, where there is potential to reduce blade mass (Figure 5). Analyses based on two scenarios were conducted by WINDnovation: (a) 1-to-1 replacement of resin without any form of optimization, and (b) structure optimization by the use of mechanical property advantages associated with the use of PU.



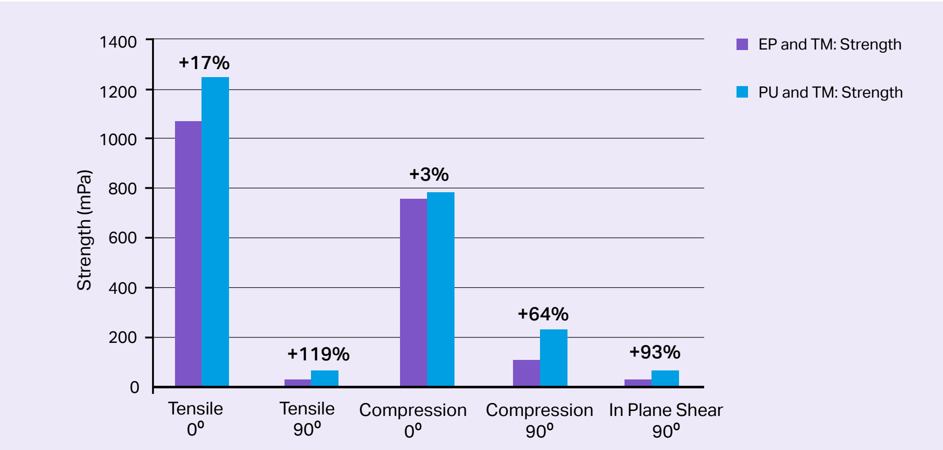


Figure 5. Mechanical property comparisons. (EP: epoxy resin PU: polyurethane resin TM: TM fiberglass from CPIC.)

> For mass reduction, the blade structure would need to be adjusted according to the new strength properties

[2] Source: Doc. No. 00220-00, Covestro PU Benchmark Study

Structural Configuration. The design PU-1on1 (1-to-1 replacement of resin without any form of optimization) has the same structural configuration as the original blade SR552-2, with the exception that PU resin is substituted for EP resin throughout the entire blade. The result is a blade design with lower efforts, less deflection, better fatigue properties and increased stability. For mass reduction, the blade structure would need to be adjusted according to the new strength properties. This is for design PU-opt (structure optimization by the use of PU mechanical property advantages), mainly by reducing the layers of the spar cap and by adjusting the layup at the root, in order to maintain a valid comparison.

Figure 6 shows the layer distribution along the blade.

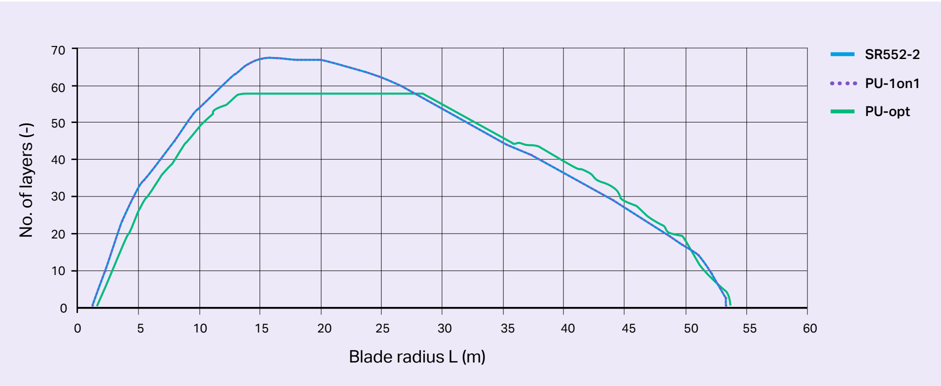


Figure 6. Distribution of spar cap layers.

Blade Weight. Calculations show blade weight can initially be reduced by 1.1% as a result of direct resin substitution, while maintaining necessary strength. Figure 7 shows blade weight can be reduced up to 5.0% with the PU-opt blade design.

Description			SR552-2	PU-1on1	PU-opt
UD spar cap, TEUD	Spar cap mass	(kg)	5074.7	4913.7	4700.0
	Mass difference	(kg)	-	-161.0	-374.7
	Mass difference	(%)	-	-3.2%	-7.6%
Laminate (Shell, Root)	Laminate mass	(kg)	4502.1	4565.4	4354.0
	Mass difference	(kg)	-	+63.3	-148.1
	Mass difference	(%)	-	+1.4%	-3.2%
Blade (including other components)	Mass	(kg)	11179.1	11058.8	10621.9
	Mass difference	(kg)	-	-120.3	-557.2
	Mass difference	(%)	-	-1.1%	-5.0%

Figure 7. Comparison of potential weight reduction.

> Blade weight can be reduced up to 5.0% with the PU-opt blade design.

Blade Deflection. With increasing blade length at a given power rating, blade deflection becomes more crucial. This key design parameter is necessary to avoid collision between blade tips and the tower. Figure 8 compares values when using higher fiber matrix ratios (FMRs). With PU as a matrix, deflection in design PU-1on1 is considerably reduced by 2.1%. The resulting deflection of the optimized design PU-opt is maintained, and it is similar to the original SR552-2, with a difference of just -0.03%.

Blade	Deflection	Difference
(-)	(M)	(%)
SR552-2	9.162	-
PU-1on1	8.968	-2.1%
PU-opt	9.160	-0.03%

Figure 8. Deflection comparison.

Static Moment. With reduced blade weight, static moment also decreases, as Figure 9 indicates. While the weight optimized design PU-opt achieves a static moment reduction of 2.54%, the design PU-1on1 already shows a static moment reduction of 1.76%, only by substituting the resin. A reduction in static moment has the positive effect that fatigue loads on the turbine are reduced, and the operational life of certain components can be prolonged.

Blade	Deflection	Difference
(-)	(kg.m)	(%)
SR552-2	1.89E+05	-
PU-1on1	1.86E+05	-1.71%
PU-opt	1.84E+05	-2.54%

Figure 9. Static moment comparison.

Interfiber Failure (IFF). IFF can be one of the most critical failure cases in a rotor blade design. In Figure 10, the maximum overall IFF efforts are shown for all blade components for each design. The higher stiffness of the spar cap leads to a redistribution of load in the blade and therefore to a significantly reduced IFF effort in every component of design PU-1on1.

The significant reduction in IFF efforts, with the optimized design PU-opt, represent a positive result and thus increase the safety margins considerably. Instead of 0.98, the efforts could be reduced to 0.87, a reduction of 11.2%, indicating even further optimization potential.

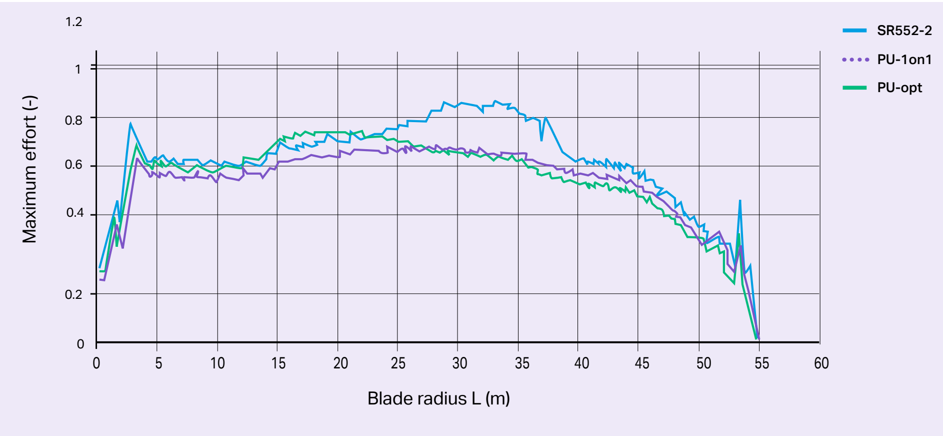


Figure 10. Maximum overall IFF efforts.

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Using PU solutions for rotor blade design helps reduce instances of interfiber failure by as much as

11.2%

CONCLUSIONS

When substituting each standard laminate ply by a PU/TM ply in a 1:1 scenario (design PU-1on1), blade weight decreased slightly. As a result, IFF and deflection safety margins improved considerably. The effect on the fatigue analysis was quite small, and it cannot be evaluated, as fatigue test data for the PU/TM material were not available.

Carrying out an optimization of the design PU-1on1, which leads to design PU-opt, the PU reduced material use for the entire blade considerably at 5.0%. A very important result (particularly for large wind turbines) is the fact that this mass reduction leads to a reduction in fatigue loads. Again, this allows designers not only to further reduce blade mass, but also the mass of other wind turbine components (especially the hub) in proportion. Additionally, a reduction in the number of layers enables a faster and easier infusion process.

In summary, the optimization of the SR552-2 according to the capabilities of the PU material was performed successfully, and it resulted in a lighter blade.

APPENDIX

Certification

DNV-GL (an abbreviation of the company Det Norske Veritas–Germanischer Lloyd) is a global quality assurance and risk management company, leading international industry standards for the safety, reliability and performance of wind turbines.

The Covestro polyurethane resin system (Desmodur 44CP20 Baydur 78BD085) has been approved and certified by DNV-GL that the products comply with the “GL rules for classification and construction II – Materials and welding part 2 – non-metallic materials” for application as laminating resin for construction of laminates made of fiber-reinforced plastics.

For the wind energy industry, and specifically for wind turbine and wind turbine blade manufacturers, the DNV-GL certification provides an initial indication of appropriate properties and performance of the Covestro polyurethane resin for use as a matrix resin for manufacturing wind turbine blades.

DNV·GL

TYPE APPROVAL CERTIFICATE

Certificate No:
TAK0000054
Revision No:
1

This is to certify:
That the Polyurethane (PUR) Systems

with type designation(s)
Baydur 78BD085

Issued to
Covestro Polymers (China) Company Limited
Shanghai, China

is found to comply with
GL Rules for Classification and Construction II - Materials and Welding Part 2 - Non-metallic Materials

Application :
Laminating resin for construction of laminates made of fibre reinforced plastics.

Issued at **Hamburg** on **2017-02-22**

This Certificate is valid until **2022-02-21**.
DNV GL local station: **Hamburg Materials & Welding**

Approval Engineer: **Guido Michalek**

for **DNV GL**
Digitally Signed By: Lohmann, Thorsten
Location: DNV GL Hamburg, Germany
Signing Date: 2017-02-28

Thorsten Lohmann
Head of Section

This Certificate is subject to terms and conditions overleaf. Any significant change in design or construction may render this Certificate invalid.
The validity date relates to the Type Approval Certificate and not to the approval of equipment/systems installed.

Form code: TA 251 Revision: 2016-12 www.dnvgl.com Page 1 of 2

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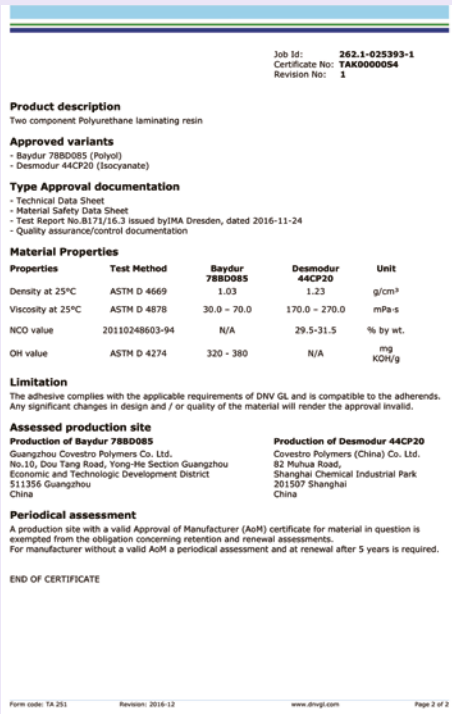


Job Id: **262.1-025393-1**
Certificate No: **TAK0000054**
Revision No: **1**

Product description
Two component Polyurethane laminating resin

Approved variants
- Baydur 78BD085 (Polyol)
- Desmodur 44CP20 (Isocyanate)

Type Approval documentation
- Technical Data Sheet
- Material Safety Data Sheet
- Test Report No.B171/16.3 issued byIMA Dresden, dated 2016-11-24
- Quality assurance/control documentation

Material Properties

Properties	Test Method	Baydur 78BD085	Desmodur 44CP20	Unit
Density at 25°C	ASTM D 4669	1.03	1.23	g/cm³
Viscosity at 25°C	ASTM D 4878	30.0 – 70.0	170.0 – 270.0	mPa·s
NCO value	20110248603-94	N/A	29.5-31.5	% by wt.
OH value	ASTM D 4274	320 - 380	N/A	mg KOH/g

Limitation
The adhesive complies with the applicable requirements of DNV GL and is compatible to the adherends. Any significant changes in design and / or quality of the material will render the approval invalid.

Assessed production site

Production of Baydur 78BD085
Guangzhou Covestro Polymers Co. Ltd.
No.10, Dou Tang Road, Yong-He Section Guangzhou
Economic and Technologic Development District
511356 Guangzhou
China

Production of Desmodur 44CP20
Covestro Polymers (China) Co. Ltd.
82 Muhua Road,
Shanghai Chemical Industrial Park
201507 Shanghai
China

Periodical assessment
A production site with a valid Approval of Manufacturer (AoM) certificate for material in question is exempted from the obligation concerning retention and renewal assessments.
For manufacturer without a valid AoM a periodical assessment and at renewal after 5 years is required.

END OF CERTIFICATE

Form code: TA 251 Revision: 2016-12 www.dnvgl.com Page 2 of 2

Wind blade test and certification

The 55.2 m wind blade for 2MW wind turbine with PU spar cap and shear web has passed static and fatigue tests at China General Certification Center (CGC). This blade was designed by WINDnovation, and blade design was certified by DEWI.

鉴衡认证

中国认可 国际互认 检测 TESTING CNAS L5687

2015010415Z

科思创聚合物（中国）有限公司

WB552-2.0-PU 型风轮叶片

固有频率测试与静力试验检测报告

报告编号	CGC-B-FNc-2017-062 A/0
合同编号	CGC201746131003
样品编号	SR2.0-WB113-PU-17-001
文件级别	客户酌处

北京鉴衡认证中心

2017 年 6 月

鉴衡认证

中国认可 国际互认 检测 TESTING CNAS L5687

2015010415Z

科思创聚合物（中国）有限公司

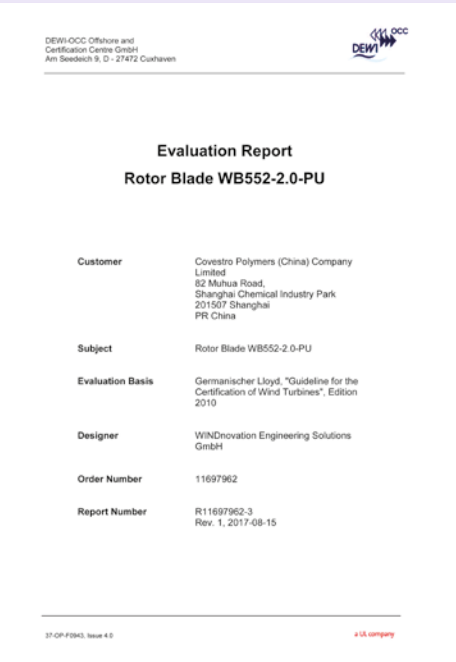
WB552-2.0-PU 型风轮叶片

疲劳试验（双方向）检测报告

报告编号	CGC-B-FNc-2017-074 A/0
合同编号	CGC201746131003
样品编号	SR2.0-WB113-PU-17-001
文件级别	客户酌处

北京鉴衡认证中心

2017 年 10 月



DEWI-OCC Offshore and
Certification Centre GmbH
Am Seedeich 9, D - 27472 Cuxhaven

Evaluation Report

Rotor Blade WB552-2.0-PU

Customer	Covestro Polymers (China) Company Limited 82 Muhua Road, Shanghai Chemical Industry Park 201507 Shanghai PR China
Subject	Rotor Blade WB552-2.0-PU
Evaluation Basis	Germanischer Lloyd, "Guideline for the Certification of Wind Turbines", Edition 2010
Designer	WINDnovation Engineering Solutions GmbH
Order Number	11697962
Report Number	R11697962-3 Rev. 1, 2017-08-15

37-OP-F0943, Issue 4.0

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