Public Report

Project: RENE 042

VB (Virtual Blade) Wind Power - Sub-Project 1

Better Wind. By Design.

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June 12, 2015

Notes

*1) VB Wind technology is **confidential information** at this point in time. Hence this report outlines the project in general detail and explains the technology in terms of its proven benefits. Additional information is available from GTRenergy upon confirmation of serious intent and the signing of a non-disclosure agreement.*

2) This report was produced with support from Natural Resources Canada.
Its contents do not necessarily reflect the opinions of the Government of Canada.

Executive Summary The VB (Virtual Blade) Wind Power Project (RENE 042) was intended to address the technical risks associated with moving VB Wind technology from the lab into the field, through the completion of a 5kW field trial and a preliminary 65kW VB design. The initial scope was scaled up during the course of the project to include the design of a 100kW VB wind turbine as the true capabilities of this unique wind turbine blade configuration became more clearly understood.

The technical objectives of the project may be summarized as follows:

- **To confirm that an 8 - 12% increase in energy production can be achieved in the field**
- **To quantify and characterize the observed reduction in noise and vibration**
- **To increase the knowledge base regarding VB technology and related testing methods**
- **To identify further R&D needs before the technology can proceed to a full scale demonstration.**

GTRenergy is pleased to report that a 16% increase in energy production was achieved in the field, which was well above expectations, with a 5dB(A) reduction in noise emissions. The knowledge base was substantially improved through the design and testing of the 5kW VB turbine, and the design and first level optimization of the 100kW VB blades. It should be noted that the new VB blades are compatible with traditional wind turbine hubs, enabling widespread commercialization. However the design is still in the preliminary stages and several additional R&D needs were identified, in order to optimize performance, minimize cost and weight, and mitigate the associated risks before installation.

Achievement of the project objectives led to a clear "go" recommendation to proceed with a 100kW VB pilot scale test. This critical next phase will accelerate commercialization, as was intended at the outset of the project. External validation comes from a Tehachapi, CA based wind farm that has already expressed interest in providing a 100kW VB test site, prior to retrofitting 250 of their Vestas V17 wind turbines that have failing blades. In this case the expected performance gains are actually in the range of 24% since the new VB blades will enable a concurrent upgrade to a more efficient variable speed Permanent Magnet Generator (PMG). It should also be noted that GTRenergy has obtained confirmation from an established wind turbine blade manufacturer that the 100kW VB blades can be made cost effectively with existing methods and materials.

The next steps are to address the identified areas of further R&D, then implement the 100 kW VB pilot scale test. Results will be reported according to IEC and AWEA standards, similar to the current project, to confirm the expected 24% increase in performance. GTRenergy is currently seeking a partner to provide funding for the next project and share the benefits, in order that VB Wind technology can realize its full potential to contribute to Canada's Cleantech economy. GTRenergy also wishes to take this opportunity to thank NRCan for its tremendous support of the current project, which would not have been otherwise possible.

Wind Industry Overview Wind is one of the fastest growing sources of renewable energy in the world. Canada set the pace in 2014 with 37 new wind energy projects totalling 1,871 MW, providing a 23.9% increase in the installed base which now stands at 9694 MW. This represents about 4% of the nation's demand for electricity, or enough power for over 2 million homes (1). Last year's rapid growth put Canada on par with the USA, where 4.4% of the electricity is produced from wind (2).

Unfortunately these numbers still fall short of the goals established by both countries. Prime Minister Harper has committed Canada to reducing GHGs by 17 per cent below 2005 levels by 2020, and this can only be achieved with substantial growth in renewable sources of energy. However, some academics are stating that this is not enough, claiming that all of the nation's electricity could and should come from renewable sources by 2035 (3). The US Department of Energy (DOE) has actually issued some direct goals for wind energy; 10% by 2020, 20% by 2030, and 35% 2050 (4). It is widely accepted that these goals may, in fact, become more aggressive during the "Road to Paris", i.e. in preparation for the United Nations World Climate Summit in Paris scheduled for December, 2015.

While these objectives are indeed worthy, they may not be achievable unless wind energy becomes more competitive with other sources of electricity. This is consistent with the NRCan ecoENERGY Innovation Initiative (ecoEII) objective stated at the outset of the project, which was to support energy technology innovation to produce and use energy in a cleaner and more efficient way. Recognizing the importance of renewable energy technologies to this objective, the ecoEII call for proposals included, as part of its scope, research and development (R&D) up to and including field trials to assist in the accelerated commercialization of renewable energy innovations such as VB Wind technology. The US DOE has echoed this objective by stating that continuing declines in wind power costs are needed to improve market competition with other electricity sources and achieve the wind energy goals as stated above. This is, in fact, one of the key messages in the US DOE's recently published "Wind Vision" document (4).

To that end, it is important to note that the most significant result of this project was a confirmed 16% increase in wind turbine efficiency with VB Wind technology. This will have a substantial impact on the wind industry because it has the potential to significantly increase wind farm profitability, to the extent that many currently unfeasible sites will become economically viable. **The net effect will be an increase in the competitiveness of wind energy.**

References

1. Canadian Wind Energy Association (CANWEA)

2. American Wind Energy Association (AWEA)

3. Globe & Mail, "Complete shift to renewable energy within Canada's reach, academics say" March 18, 2015

4. US Department of Energy, "Wind Vision: A New Era for Wind Power in the United States"

Project Intent and Technical Objectives It is important to note that the current project was preceded by extensive testing at NRC's 9m x 9m wind tunnel in Ottawa, using a 5kW Fortis Montana wind turbine that had been retrofitted with VB blades.

The results of that testing may be summarized as follows:

- **Performance increased by 12.8% after the turbine was retrofitted with VB blades**
- **Testing was performed into the Reynolds Number (Re) independent range to confirm that VB Wind technology was scalable to larger blades**
- **Further field testing was recommended, based on an optimized blade configuration and control algorithm**

With that in mind, the VB Wind Power Project was intended to address the technical risks associated with moving the technology from the lab into the field, through the completion of a 5kW field trial and a preliminary 65kW VB design. This initial scope was scaled up during the course of the project to include the design of a 100kW VB wind turbine as the true capabilities of the unique blade configuration became more clearly understood.

The following four technical objectives were identified at the outset of the project:

- **To confirm that an 8 - 12% increase in energy production can be achieved in the field**
- **To quantify and characterize the observed reduction in noise and vibration**
- **To increase the knowledge base regarding VB technology and related testing methods**
- **To identify further R&D needs before the technology can proceed to a full scale demonstration**

Project Summary

R&D Performed The R&D began with a re-design of the 5kW VB retrofit so that it would be suitable for field testing. The most significant area to be addressed was the tail design, which had to be modified to accommodate the increased yaw torque produced by VB blades, as observed during the testing at NRC. The modified tail design was then tested at the University of Waterloo wind facility to ensure that it would operate correctly in the field.

Other aspects of the re-design included a nacelle for weather protection, power conversion equipment for connection to the grid, and the associated load control algorithm. However it is important to note that the VB blade configuration remained exactly as tested at NRC, to allow for validation of the field test results.

Once the re-design was complete the necessary components were built, staged and tested prior to shipment to the Wind Energy Institute of Canada (WEICan) for field testing. The 5kW VB wind turbine was then installed along with a meteorological (MET) mast to measure wind speed, wind direction and other environmental conditions. The installation was followed by a commissioning period to ensure that the test turbine, the associated instrumentation and the data loggers were functioning correctly before the test began.

The 5kW VB test turbine was commissioned on December 1, 2014 and tested through to March 28, 2015. It is important to note that the site layout and the test procedures were closely controlled to comply with the international IEC 61400-12 and AWEA 9.1-2009 standards, with reference to IEC 61400-11. This allowed the WEICan test results to be compared with baseline results for the OEM turbine that were obtained by Intertek, based on the same IEC standards. The results of this comparison may be summarized as follows:

- ***A 16% increase in annual energy production (AEP) associated with VB Wind technology,*** **which was significantly above the project objective of 8 – 12%**
- ***A 5dB(A) reduction in noise emissions***

Further R&D included the design of 100kW VB blades to be used for a commercial demonstration of the technology. The first step in this process was the adaptation of an existing Blade Element Momentum (BEM) model to incorporate the unique aspects of VB blades and accurately predict VB wind turbine performance. In this case the underlying software was WT-Perf, obtained from the US National Renewable Energy Lab (NREL) and subsequently modified with their assistance. The accuracy of the adapted code was then validated against the 5kW wind tunnel test results from NRC, to ensure that it could reasonably predict the performance of the modified 100kW VB blades.

A preliminary VB design was developed using NREL's S819/820/821 "thick" airfoil family for 100kW blades, and modelled with the adapted BEM code to determine its performance and load characteristics. The blade was then combined with a suitable high speed Permanent Magnet Generator (PMG) and other components to develop a complete 100kW retrofit for existing wind turbines such as the Windmatic 15s/17s or Vestas V17. A preliminary technical assessment was completed by Frontier Power Systems to confirm the feasibility of the proposed retrofit design.

The 100kW VB blade design was then optimized using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) software provided by project partner Autodesk. Use of these tools confirmed that the VB design could indeed be implemented with NREL's S805A/806A/807 "thin" family of airfoils while still maintaining the required structural integrity, thereby reducing the overall mass of the blades without impacting performance.

Challenges Encountered A few major challenges were encountered during the course of this R&D, as summarized below:

Baseline Tests Operational problems and equipment issues presented challenges for the baseline tests that were envisioned at the outset of the project. However it was subsequently discovered that the required IEC 61400 baseline performance and acoustic data was readily available online. This development allowed the project to be completed successfully without having to resolve the aforementioned challenges. In addition, the extra time available allowed for further optimization of the 100kW VB blade design, to enhance performance and reduce weight while maintaining the required structural integrity.

CFD Modeling The unique aspects of the VB blade design presented some initial challenges for CFD modelling with tools such as OpenFOAM, which tended to over-predict drag and delay the stall point. As a result the wind tunnel was used more extensively than planned to determine the lift and drag characteristics of each blade section. The experimentally obtained data was then used as input for the adapted BEM model. However the situation changed when GTRenergy became an Autodesk Cleantech partner during the course of the project. Autodesk provided access to CFD and FEA tools that were indeed capable of modelling the VB configuration. A fortunate aspect of these circumstances was that the CFD results could ultimately be validated against the wind tunnel results for greater certainty.

Final Results The final results can be most clearly presented in relation to the project objectives, as follows:

Objective 1 *To confirm that an 8 - 12% increase in energy production can be achieved in the field.*

The project results actually confirmed a **16% increase in AEP,** which exceeded the original project objective of 8 – 12%, with reference to the following sources:

Configuration	Source	Report No.	AEP (kWh)*	% Increase
OEM	Intertek	1001460CRT-003	9,114	
VB Modified	WEICan	5025-001	10,578	16.06%

**AEP-Extrapolated based on AWEA standards (6 m/s and reference air density (1.225 kg/m3))*

The results are significant because increased energy production from wind was the key objective for this project, consistent with the ecoEII objective to support energy technology innovation to produce energy in a cleaner and more efficient way. The magnitude of the increase at 16% will have a substantial impact on the wind industry because it will significantly increase wind farm profitability, to the extent that many currently unfeasible sites will become economically viable.

Objective 2 *To quantify and characterize the observed reduction in noise and vibration.*

The following table presents a summary of the results and confirms the aforementioned **5dB(A) reduction in acoustic noise**.

Configuration	Source	Report No.	Noise (dB(A))*	Reduction (dB(A))
OEM	Intertek	1001460CRT-003	49.8**	
VB Modified	WEICan	5025-002	44.8	5.0

** AWEA Rated Sound Level ** Calculated from IEC 61400-11 results*

The results are significant because reducing noise is a critical design objective for all wind turbines. It should be noted that reducing acoustic noise while simultaneously increasing performance is extremely difficult to achieve, but that is indeed the case with VB wind technology.

Objective 3 *To increase the knowledge base regarding VB technology and related testing methods.*

GTRenergy completed several reports to document the systematic discovery of, and subsequent increase in, knowledge related to VB Wind technology, thereby increasing the knowledge base and achieving objective 3.

This result is significant because it led to the filing of three additional US Provisional Patent applications, providing prior filing dates for subsequent non-provisional applications. It will also aid in the dissemination of knowledge related to VB Wind technology, once the IP related confidentiality concerns have been cleared. Further information is available from GTRenergy upon confirmation of serious intent and the signing of a non-disclosure agreement.

Objective 4 *To identify further R&D needs before the technology can proceed to a full scale demonstration.*

GTRenergy and partners completed several additional reports and analyses to identify further R&D needs before VB Wind technology can proceed to a full scale demonstration, thereby achieving objective 4. These generally include a more extensive performance analysis, enhanced CFD and FEA modelling, aero-structural optimization, and further third party validation. Addressing these R&D needs will improve the design, assist in planning for the demonstration, and mitigate the associated risk.

Oakville Innovation Award *It should also be noted that GTRenergy was a recipient of the 2014 Oakville Innovation Award.*

While not associated with any particular project objective, it is significant because the awards were created to recognize those companies in Oakville that have developed exceptional products or services that exhibit leading edge research and development. A selection panel comprised of experts in the fields of engineering, technology, finance, academia and R&D reviewed all submissions and five Oakville businesses were selected to be awarded for their outstanding contributions in the fields of technology and engineering. The Oakville Innovation Awards were sponsored by Siemens, a global wind turbine manufacturer, and PricewaterhouseCoopers (PwC), the largest professional services firm in the world.

Benefits The following benefits were envisioned at the outset of the project, listed here along with their status at the end of the project.

Confirm Performance & De-risk Further Development

Beneficiary ***GTRenergy***
Status ***Achieved***

This benefit has been achieved. The final VB test results, i.e. a 16% increase in performance and a 5dB(A) reduction in noise emissions, were actually better than anticipated, putting GTRenergy in a stronger than expected position to move forward with the 100kW field trial and enhancing the market value potential. Further, the increased knowledge base and identification of R&D needs before proceeding serve to de-risk future development.

Gain Further Expertise with VB Wind Technology

Beneficiary ***GTRenergy & WEICAN***
Status ***Achieved***

This benefit has been achieved for both beneficiaries, based on the substantial transfer of related knowledge to WEICan during the course of the project. This more favourably positions WEICan to host and manage a potential full scale demonstration with a VB retrofitted Vestas V47 or Enercon E48, after the proposed 100kW field trial, and it may evolve into some early commercialization opportunities with PEI Energy Corp to retrofit their V47 turbines. WEICan also collected relative humidity information during the 5kW VB test, enabling them to participate in the development of IEC standards that may include this parameter in the calculation of site air average air density.

Increased Financial Return for Existing Canadian Wind Farms

Beneficiary ***Canada***
Status ***Not Yet Achieved***

This benefit was not expected to be achieved until the technology is successful in reaching the market. However the better than anticipated test results increase the likelihood of its achievement since wind farm operators will realize a 16% increase in revenue and the 5dB(A) lower noise levels will increase community acceptance.

Improved Economics for Proposed Canadian Wind Farms

Beneficiary ***Canada***
Status ***Not Yet Achieved***

Similar to above, this benefit was not expected to be achieved until the technology is successful in reaching the market. In this case the 16% increase in revenue will reduce the payback period associated with the capital investment required for a wind farm. Further, the 5dB(A) lower noise levels will most likely reduce setback requirements and improve community acceptance. These factors, when combined, would push many previously unprofitable sites into viable range, thereby increasing the amount of electricity from wind and contributing to Canada's renewable energy objectives.

Economic Growth & New Jobs for Canada

Beneficiary ***Canada***
Status ***Not Yet Achieved***

Commercialization of VB Wind technology will lead to the realization of economic growth and new jobs for Canada, through the sale of VB components and related services provided to the wind farms. Blades for the domestic market and certain regions of the USA may be economically produced in Canada, but blades for other markets may be more advantageously produced closer to the actual installation site due to the high cost of transportation. However there are strategic opportunities to manufacture and export other high margin components such as controllers and software, because they are critical to the performance of a VB wind turbine and easily transportable. This sustainable business model will ultimately lead to greater growth in Canada's Cleantech economy as profits are used for the further development of enhanced wind energy technologies.

Reduced Greenhouse Gas (GHG) Emissions

Beneficiary ***Canada***
Status ***Not Yet Achieved***

While not explicitly mentioned at the beginning of the project, it is important to note that once commercialized, VB Wind technology will make a greater contribution to the reduction of GHG emissions than traditional wind turbines.

The impact may be quantified by using a reference turbine such as an Enercon E-82 2MW with a nominal capacity factor of 35%, to reflect the average of commercial scale retrofits and new installs that may range from 800 kW to 4 MW over the next 20 years. This turbine, when equipped with traditional wind turbine blades, would produce 6,132 MWh/yr, replacing an equal 6,132 MWh/yr that is currently being generated by fossil fuel generators. There are various numbers available, but a reasonable estimate is that each kWh of electricity produced from fossil fuels generates 227g of carbon dioxide in Canada (source: Veritec Consulting) or 995g of CO_2 in other parts of the world (source: UK Office of Science & Technology).

These numbers can be used to determine that installing an Enercon E-82 with traditional blades would reduce annual GHG emissions by 1,392 tonnes of CO_2 in Canada, or as much as 6,101 tonnes of CO_2 in other parts of the world. It follows that the incremental annual benefit associated with a VB Wind retrofit would be 16% of those amounts, i.e. 223 tonnes of CO_2 in Canada or as much as 976 tonnes of CO_2 elsewhere, resulting in new totals of 1615 and 7077 tonnes of CO_2, respectively. A similar analysis can be used to determine that the VB Wind retrofit would also save an incremental 14.93 tonnes of sulphur dioxide and 4.03 tonnes of nitrogen oxides per year in most parts of the world, based on 15.2g of SO_2 and 4.1g of NO_x released for each kWh produced by fossil fuel equipment (source: UK Office of Science & Technology).

Conclusions and Recommendations It is evident from the preceding sections that all project objectives have been achieved, the knowledge base regarding VB wind technology has been substantially increased, and there is a clear path for further R&D before subsequent scale-ups.

Hence the fundamental conclusion that can be drawn from the project, and therefore the recommended next step, is a "go" decision to immediately proceed with a 100kW VB pilot scale demonstration site. Further, based on knowledge and market intelligence gained throughout the course of the project, it may be concluded that this would be best implemented on a Vestas V17 in order to accelerate commercialization of the technology. External validation comes from a Tehachapi, CA based wind farm that has already expressed interest in providing a 100kW VB test site, prior to retrofitting 250 of their Vestas V17 wind turbines that have failing blades.

In this case the expected performance gains are actually in the range of 24% since the new VB blades will enable a concurrent upgrade to a more efficient variable speed Permanent Magnet Generator (PMG). It should also be noted that GTRenergy has obtained confirmation from an established wind turbine blade manufacturer that the 100kW VB blades can be made cost effectively with existing methods and materials.

Expected Results The power curves in Figure 1 depict the expected performance of a Vestas V17 with a 100kW VB retrofit, relative to that of an unmodified Vestas V17.

The two solid lines indicate performance at a reduced air density of 1.06 Kg/m^3 as would be typical of a mountainous region such as Tehachapi, CA. It should be noted that the OEM version of the turbine could only be adapted for various altitudes by manually changing the pitch angle at time of installation. The 100kW VB retrofit, on the other hand, may be adapted by simply changing the maximum rpm in the control algorithm. This makes it much more suitable for installations from sea level to mountain top with very little impact on overall performance.

Figure 1 also includes the Annual Energy Production or AEP numbers for both turbines at a particular site in Tehachapi, CA. It may be seen that the increase associated with the 100kW VB retrofit is a very significant 24.1%. As previously noted, this reflects the combined benefits of the VB blades (~16%) and the upgrade to a more efficient Permanent Magnet Generator (~8%), which is in turn made possible by the variable speed characteristics of the new VB blades.

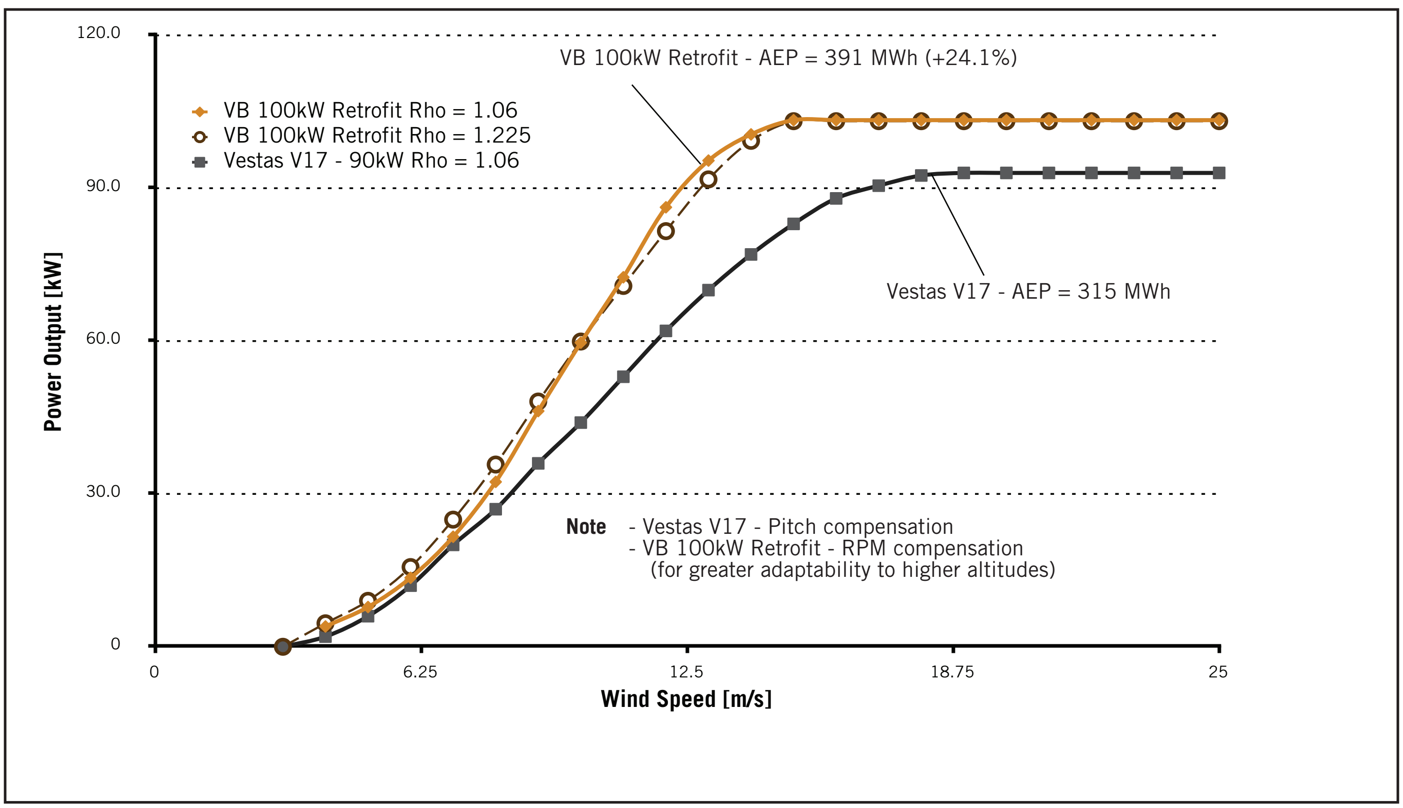

Figure 1: Vestas V17 / 100kW VB Retrofit - Estimated Power Curves

Implementation plan GTRenergy has identified the following next steps, based on the recommendation to proceed with a 100kW VB pilot scale test on a Vestas V17 platform.

- **Final aero-structural optimization for the 100kW VB blade design.**
- **Final selection and/or design of other retrofit components such as the high speed Permanent Magnet Generator (PMG) and auxiliary brake.**
- **Final load and structural analysis with a Vestas V17 tower and nacelle (third party validation).**
- **Characterize PMG and develop converter load control table.**
- **Develop integrated control algorithm, combining Vestas V17 operational and safety requirements with converter load control table.**
- **Install and commission VB retrofitted Vestas V17 wind turbine.**
- **Design and implement IEC 61400 tests for performance and acoustics.**
- **Complete successful VB 100kW pilot scale test and report accordingly.**
- **Update 100kW VB retrofit design, if necessary, before commercialization.**

Commercialization The 5 year commercialization plan for VB Wind technology may be summarized as follows:

Year	*Key Milestones*
2016	Pilot Scale (100kW) Demonstration
2017 – 2018	100kW VB Retrofit Installations – USA Develop Commercial Scale VB Design
2019 – 2020	100kW VB Retrofit Installations – Europe Commercial Scale Demonstration - Vestas V47(660kW) or Enercon E48 (800kW)
2021	Scale-up Retrofit Installations – Global License VB Technology to GE, Vestas, Enercon, etc. for New Turbines - Global

Figure 2: VB Wind - 5 Year Commercialization Plan

Further Information VB Wind technology is **confidential information** at this point in time. Hence this report outlines the project in general detail and explains the technology in terms of its proven benefits. Additional information is available from GTRenergy upon confirmation of serious intent and the signing of a non-disclosure agreement.

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