Institution: University of Sheffield		
Unit of Assessment: B-12 Engineering		
Title of case study: Driving Siemens Gamesa's offshore wind turbines		
Period when the underpinning research was undertaken: 2009–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Zi-Qiang Zhu	Professor (RAE/Siemens Research Chair)	1989–present
Period when the claimed impact occurred: August 2013–July 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Sheffield's research into permanent magnet direct-drive generator technology is incorporated in all 1,049 of Siemens Gamesa's direct-drive offshore wind turbines operating globally, which account for 23% of worldwide offshore wind grid-connected capacity and £3.5bn total turnover. The step-change improvements in power density and reliability developed through Sheffield's research has led to five successive generations of turbines with increasing power output from 6MW (installed in 2014) to the most recent 14MW model which received its first orders in 2020. The associated reduction in levelised cost of energy from £157 to £39 per MWh has enabled the world's first zero-subsidy offshore wind farm.

2. Underpinning research (indicative maximum 500 words)

Early wind turbine generators used a gearbox, but as these proved to be the least reliable part of the drivetrain, Siemens sought a gearless (direct-drive) solution where the generator is directly connected to the turbine shaft. In 2009, Siemens commissioned the prototype for a 3MW onshore permanent magnetic direct drive (PMDD) generator. This experience demonstrated that for offshore application, where the reliability and uptime of generators are critical, the integration of a direct drive generator into the turbine itself would require new technology. This led them to call on Sheffield's expertise in the design of permanent magnet generators to help them develop a PMDD solution in-house.

Recognising the Electrical Machines and Drives (EMD) Research Group (led by Professor Zhu) as a global leader in the design and control of novel high torque/power density and high efficiency permanent magnet machines and drives, the Sheffield-Siemens Wind Power Research Centre (now the Sheffield Siemens-Gamesa Renewable Energy (S^2GRE) Research Centre) was established in December 2009. With Zhu as Academic Director, its role was to support the commercialisation of PMDD generators for the offshore wind power market. The overall objective was to reduce the Levelised Cost of Energy (LCoE) by increasing Annual Energy Production (AEP) while reducing Capital and Operational Expenditure (CAPEX and OPEX).

The initial focus was reducing vibration induced wear in the generator, which shortens useful life and increases OPEX using the EMD group's research into **magnet shaping and skewing [R1].** [Text removed for publication]

Subsequently, the group focused **increasing output power while minimising overall generator size at no additional cost,** to meet the challenges of reducing CAPEX whilst simultaneously increasing AEP. This was achieved through a series of distinct research steps:

[Text removed for publication].

This culminated in May 2020 with their launch of the world's largest capacity turbine with a 222 meter rotor diameter producing output of 14MW.

3. References to the research (indicative maximum of six references)

University of Sheffield staff and students in **bold**

R1. **Chu, W. Q.,** & **Zhu, Z. Q.** (2013). Reduction of On-Load Torque Ripples in Permanent Magnet Synchronous Machines by Improved Skewing. *IEEE Transactions on Magnetics, 49*(7), 3822–3825. https://doi.org/10.1109/tmag.2013.2247381. Cited by 26.

R2. **Zhu, Z. Q.,** & **Leong, J. H.** (2012). Analysis and Mitigation of Torsional Vibration of PM Brushless AC/DC Drives With Direct Torque Controller. *IEEE Transactions on Industry Applications, 48*(4), 1296–1306. https://doi.org/10.1109/tia.2012.2199452. Cited by 41.

R3. **Hu, Y., Odavic, M.,** & **Zhu, Z. Q.** (2016). DC Bus Voltage Pulsation Suppression of the Permanent Magnet Synchronous Generator With Asymmetries Accounting for Torque Ripple. *IEEE Transactions on Energy Conversion, 31*(3), 1080–1089. https://doi.org/10.1109/tec.2016.2553127. Cited by 3.

R4. **Thomas, A. S., Zhu, Z. Q.,** & **Wu, L. J.** (2012). Novel Modular-Rotor Switched-Flux Permanent Magnet Machines. *IEEE Transactions on Industry Applications, 48(*6), 2249–2258. https://doi.org/10.1109/tia.2012.2226860. Cited by 21.

R5. **Li, Y., Zhu, Z. Q., Wu, X.,** Thomas, A. S., & Wu, Z. (2019). Comparative Study of Modular Dual 3-Phase Permanent Magnet Machines With Overlapping/Non-overlapping Windings. *IEEE Transactions on Industry Applications, 55*(4), 3566–3576. https://doi.org/10.1109/tia.2019.2908138. Cited by 3.

R6. **Maraví-Nieto, J.,** Azar, Z., Thomas, A. S., & **Zhu, Z. Q.** (2019). Utilisation of grain-oriented electrical steel in permanent magnet fractional-slot modular machines. *The Journal of Engineering, 2019*(17), 3682–3686. https://doi.org/10.1049/joe.2018.8171. Cited by 1.

4. Details of the impact (indicative maximum 750 words)

SGRE is the global leader in offshore wind power generation with greater than 70% market share **[S1]**.

Impact on SGRE

SGRE credits Sheffield as having had significant impact on its strategy and innovation capacity by enabling it to reduce risk in developing new technologies and increasing their ambition by creating excellent modelling and simulation techniques that allow every aspect [Text removed for publication] to be tested and validated **[S2]**. This has enabled SGRE to develop more speculative concepts, increase "right-first-time" designs, and bring products to market faster **[S2]**. This has allowed SGRE to deliver greater changes in capability between models, provide evidence to convince clients to adopt new technology, enabling them to maintain their leading position in mature and newer offshore wind generation markets **[S2]**. The Head of Drive Train Design at SGRE stated, "*Sheffield has made a major contribution to Siemens achieving its key* *target of zero-subsidy offshore wind, and brought wind power to the point where it must be taken seriously because it's competitive with every other energy type*" **[S2]**. In terms of commercial impact, the underpinning research has been incorporated into every one of SGRE's offshore wind PMDD generators. From 2015 to 2020 the company has launched to market a series of models, enabled by Sheffield's research, increasing in output from 7MW to 14MW - see Table 1 **[S2]**.

From 2014-2020 a combined total of 1,049 of SGRE PMDD generators (Table 1) are operational worldwide **[S2]**, producing approximately 6.8GW **[S2]** representing 23% of total global installed offshore wind energy capacity **[S3 p44]** and in 2019 SGRE accounted for 62% of European new grid-connected capacity **[S4 p23]**. SGRE currently has a backlog of orders for over 1,000 generators, mostly from new markets in North America and Asia **[S2]**.

SGRE Head of Drive Train Design states, ***"In total, the turbines developed with Sheffield have generated turnover of GBP3.5bn for the company from the offshore sector, facilitated by having a market leading turbine enabled by the direct drive generator technology"* [S2].**

SGRE have outlined Sheffield's contributions as: **[S2]**

- Reduced the number of moving parts with high failure rates and maintenance requirements by 50%, significantly lowering maintenance and repair costs.
- [Text removed for publication] facilitating longer turbine life and reduced maintenance and repair costs **[R1, R2] [S5a]**.
- [Text removed for publication]. This enabled efficiency gains within viable manufacturing limits, boosting capacity of the current manufactured models from 6MW to 8MW (Table 1) with no increase in physical envelope, or in manufacturing or installation costs.
- [Text removed for publication] delivering a 20% saving in production costs.
- Developed proprietary co-simulation software to identify performance gains and cost savings in the design process.
- [Text removed for publication]

Wider impact

Both installation and operational costs contribute towards the LCoE. High LCoE has, until recently, been a barrier to adoption. Whilst SGRE cannot quantify the specific contribution of individual technology developments, they do state that Sheffield's research has *"undoubtedly played a significant role in reducing the installed cost per Megawatt of an SGRE wind turbine, and consequently the overall reduction in LCoE"* **[S2]**. The LCoE on SGRE projects has fallen from £157 per MWh in Hornsea Project 1 (began development 2014) to £39/MWh in Hollandse Kust Zuid 3&4 (tender awarded 2019) **[S2]**. Improvements in generator technology driven by Sheffield's research has undoubtedly helped reduce the global weighted average LCoE for offshore wind from $183/MWh in 2014 to $115/MWh in 2019 **[S6]**.

The cost effectiveness of PMDD generators made possible the **world's first zero-subsidy offshore wind farm**, marking a significant turning point in offshore wind power generation. In June 2020, Vattenfall (a leading European energy company) took the final investment decision for the world's first subsidy-free offshore wind farm, confirming they will install 140 SG11.0-200DD turbines on the Hollandse Kust Zuid project in the Netherlands **[S7a]**. The Offshore Wind

Development Project Manager at Vattenfall stated that because they had "*successfully established partnerships with suppliers in recent years, we can optimally apply the latest technological innovations in our projects – even before they are available in the market*" **[S7b]**. The Hollandse Kust Zuid Permit Development Manager at Vattenfall confirmed, "*This turbine* [SG11.0-200DD] *offers many benefits for both the project and the environment. The most important benefits of this turbine are a 30% increase in energy output and reduced ecological impact. We would not have achieved this without intensive cooperation between Vattenfall and Siemens Gamesa*" **[S7b]**. SGRE confirmed that by using the 11MW turbine meant, "*fewer turbines are needed to generate the same amount of energy. This will reduce installation, operations and maintenance costs and thereby contribute to further reductions in Levelized Cost of Energy for offshore wind. Furthermore, it significantly reduces the environmental impact of installation and operation of the wind farm*" **[S7c]**.

In May 2020, SGRE launched to market its latest 14MW offshore wind turbine model (SG 14-222 DD). This model offers a lifetime avoidance of ~1.4Mt of CO_2 emissions per machine compared to coal-fired power generation, and represents a 25% increase in AEP compared to its predecessor model. Within a month of launch, SGRE has secured conditional orders from the USA **[S8a]**, Taiwan **[S8b]**, and the UK **[S8c]**.

*Table 1: Key dates and unit numbers for individual models **[S2]**.*

Model	Nominal Power (MW)	1st ordered	Serial Production	1st installed	Units installed
SG14-222DD	14	-	-	-	-
SG11.0-200DD	11	04/19	2022	-	1
SG8.0-167DD	8	01/18	2019	2020	40
SWT-7.0-154	7	10/15	2017	2018	518
SWT-6.0-154	6	07/12	2014	2014	491

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Siemens Gamesa Renewable Energy Annual Report 2019. Confirms over 70% share of the total market volume installed (page 23). (Accessed 16th July 2020). https://bit.ly/3bTxMDv

S2. Confidential testimonial from the Head of Drive Train Design at Siemens Gamesa Renewable Energy (2020). Corroborates a) economic impact to Siemens Gamesa, b) critical role of the various strands of Sheffield's research is reducing offshore-generated energy cost, c) Sheffield technology incorporated in 1049 operational turbines (models and numbers), d) technical challenges overcome by Sheffield's research, and e) order backlog and new markets.

S3. Global Wind Energy Council - Global Wind Report 2019. Reports total global installed offshore wind capacity of 29,136 MW in 2019 (page 44). (Accessed 17th June 2020). https://gwec.net/global-wind-report-2019/

S4. Wind Europe - Offshore Wind in Europe Key trends and statistics 2019. Reports SGRE connected 62% of all the new grid-connected capacity in 2019 (page 23). (Accessed 17th June 2020). http://bit.ly/3rQATBw

S5. Combined source: SGRE patents with Sheffield researchers as named inventors (Accessed 4th Feb 2021).

a) **Chen, J.** & **Zhu, Z.Q.**, 2012. A synchronous permanent magnet machine. Siemens AG. 2525479B1. (Granted 2019). http://bit.ly/3czvw39
b) **Li, Y.,** Thomas, A. & Zhu**, Z.Q.**, 2018. *Segmented stator electrical machine*. Siemens Gamesa Renewable Energy A/S. EP3560075A1. (Pending) http://bit.ly/2OrVeyM

S6. International Renewable Energy Agency (IRENA) Renewable Power Generation Costs in 2019 report (page 75 Fig 4.1). Reports calculated global weighted-average LCoE for offshore wind. (Accessed 23rd Oct 2020). https://bit.ly/38Dbwvt

S7. Combined source: Vattenfall and SGRE press releases confirming 140 SGRE 11 MW turbines in the world's first zero subsidy wind farm. (Accessed 4th Feb 2021).

a) Vattenfall confirms final contracts awarded for 140 SGRE 11MW turbines (July 2020). http://bit.ly/3rRrSZ1
b) Vattenfall highlights the importance of Siemens Gamesa technology (April 2019). https://vattenfall-hollandsekust.nl/en/blog/2019/04/18/energy-transition/
c) Siemens Gamesa confirmed 140 11MW turbines to be deployed (November 2019). https://bit.ly/3cD328E

S8. Combined source: SGRE press releases confirming conditional orders for the SG 14-222 DD turbine in USA, Taiwan and UK projects. (Accessed 16th July 2020).

a) USA - Dominion Energy's 2.6 GW Coastal Virginia Offshore Wind project (May 2020) https://bit.ly/3cD2U9a
b) Taiwan - Hai Long consortium's 300 MW Hai Long 2 project (May 2020). https://bit.ly/3voQsT8
c) UK - innogy SE's 1.4 GW Sofia Offshore Wind Farm (June 2020). https://bit.ly/30MAgNy