Reduced CoE through drive train selection and O&M strategies

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Today’s Slides

- PhD Introduction
- Background & Results of analyses carried out during the PhD
  - Offshore Wind turbine failure rates
  - Difference in reliability between drive train types
  - Availability and O&M Cost Modeling for different drive train types
  - Cost of Energy for different drive train types
- Conclusions

PhD Introduction

Problem Statement: Offshore Wind turbine CoE is too high

Goal Statement: To answer the research question “How can the cost of offshore wind energy be reduced through drivetrain selection and O&M strategies?

To answer the above research question the following steps must be taken:

Step 1: Determine failure rates for different wind turbine types

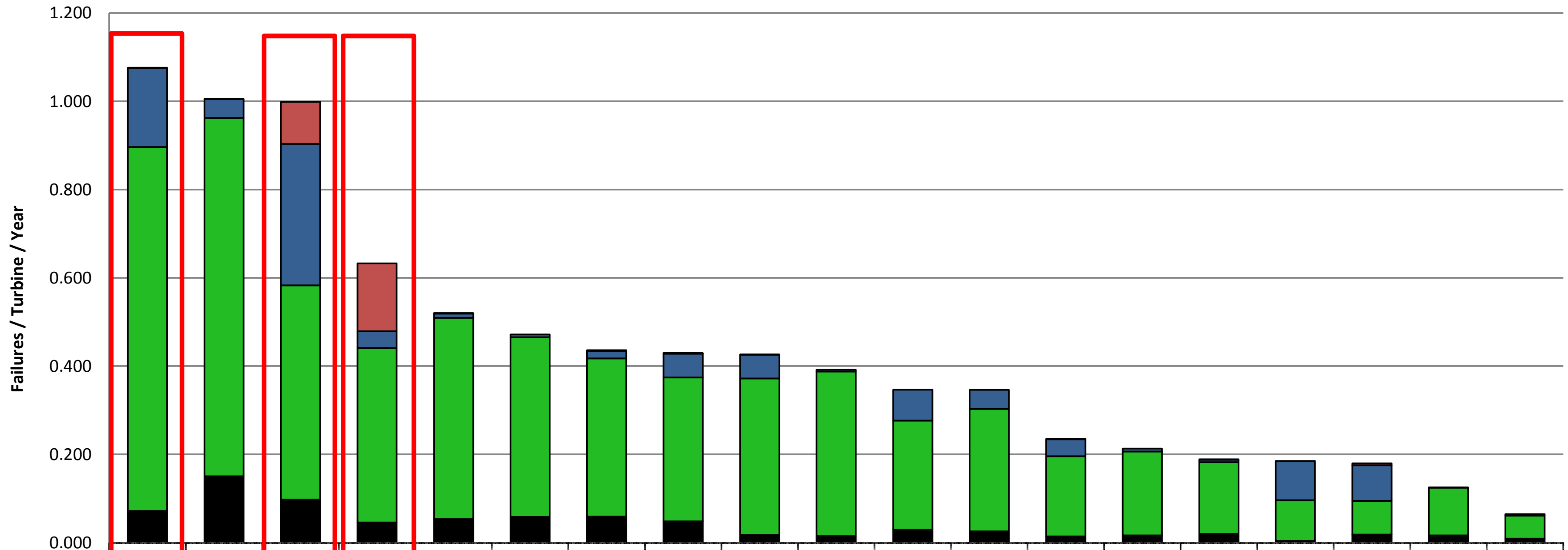
Step 2: Model O&M costs and availability for different wind turbine types

Step 3: Model CoE for each wind turbine type

Step 4: Introduce different O&M strategies to lower CoE

Offshore Wind Turbine Failure Rates

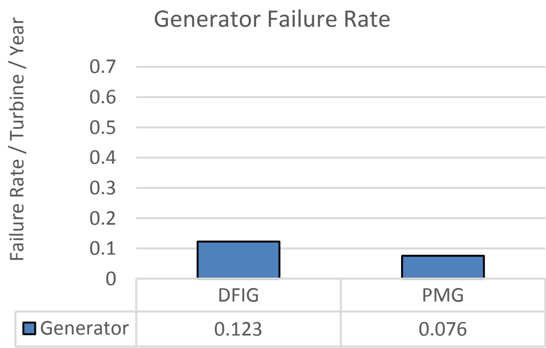
- Based on ~350 offshore turbines
- From Offshore 8 Wind Farms located throughout Europe
- Split into Minor Repair Major Repair and Major Replacement
- Repair times, failure costs, number of technicians required for repair etc.



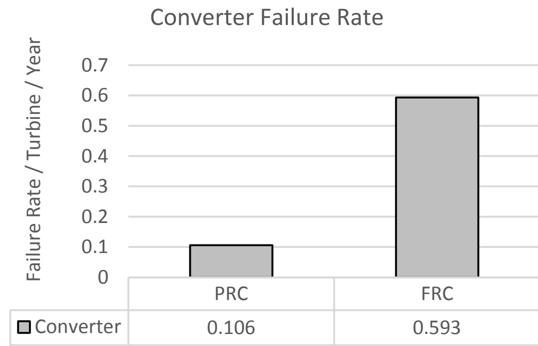
	Pitch / Hyd	Other Components	Generator	Gearbox	Blades	Grease / Oil / Cooling Liq.	Electrical Components	Contactor / Circuit Breaker / Relay	Controls	Safety	Sensors	Pumps/ Motors	Hub	Heaters / Coolers	Yaw System	Tower / Foundation	Power Supply / Converter	Service Items	Transformer
Major Replacement	0.001	0.001	0.095	0.154	0.001	0.000	0.002	0.002	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.005	0.000	0.001
Major Repair	0.179	0.042	0.321	0.038	0.010	0.006	0.016	0.054	0.054	0.004	0.070	0.043	0.038	0.007	0.006	0.089	0.081	0.001	0.003
Minor Repair	0.824	0.812	0.485	0.395	0.456	0.407	0.358	0.326	0.355	0.373	0.247	0.278	0.182	0.190	0.162	0.092	0.076	0.108	0.052
No Cost Data	0.072	0.150	0.098	0.046	0.053	0.058	0.059	0.048	0.018	0.015	0.029	0.025	0.014	0.016	0.020	0.004	0.018	0.016	0.009

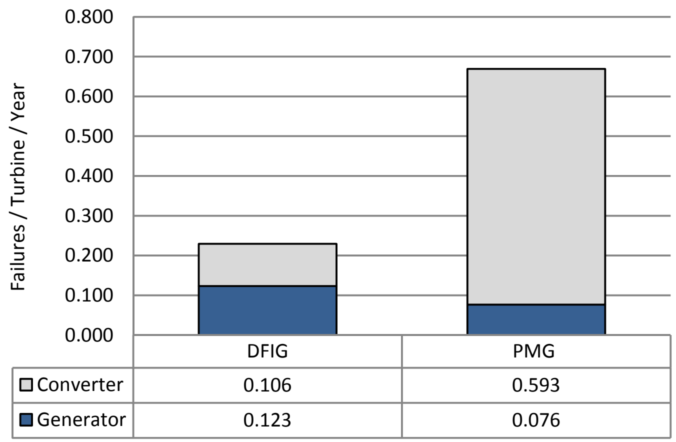
Failure Rates from Different Turbine types

- Over 1800 DFIGs over 5 years (3391 Turbine Years of Data)
- 400 PMG FRCs over 3 years (511 Turbine Years of Data)
- Same turbine type different (Mk version so same turbine except for drivetrain)



Failure rates combined for over all configuration failure rate

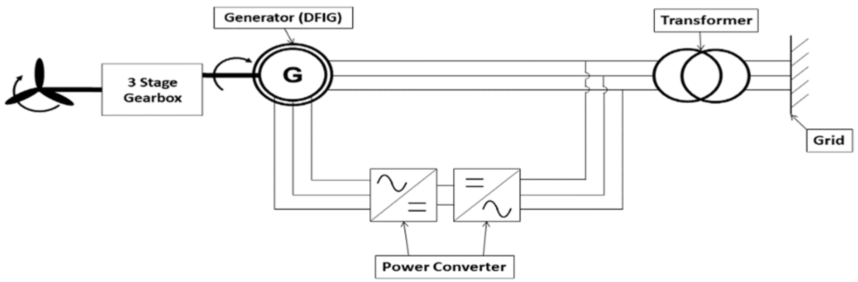




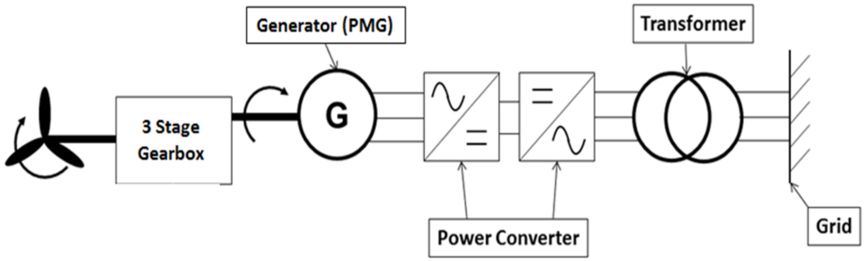
Different Drive train Types

Interested in 4 different offshore turbine types, differentiated by their drive train:

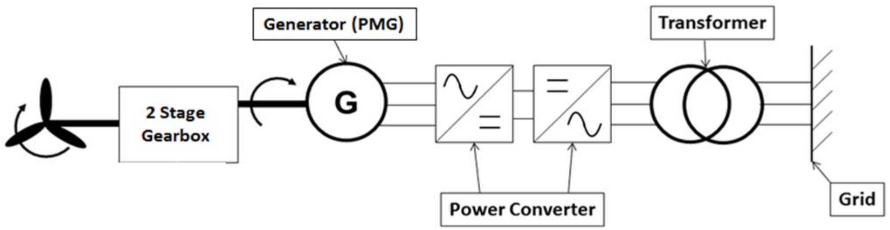
Turbine Type 1: 3 Stage, DFIG, PRC



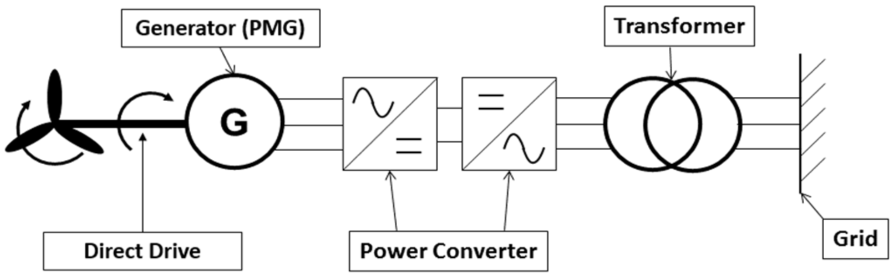
Turbine Type 2: 3 Stage, PMG, FRC



Turbine Type 3: 2 Stage, PMG, FRC

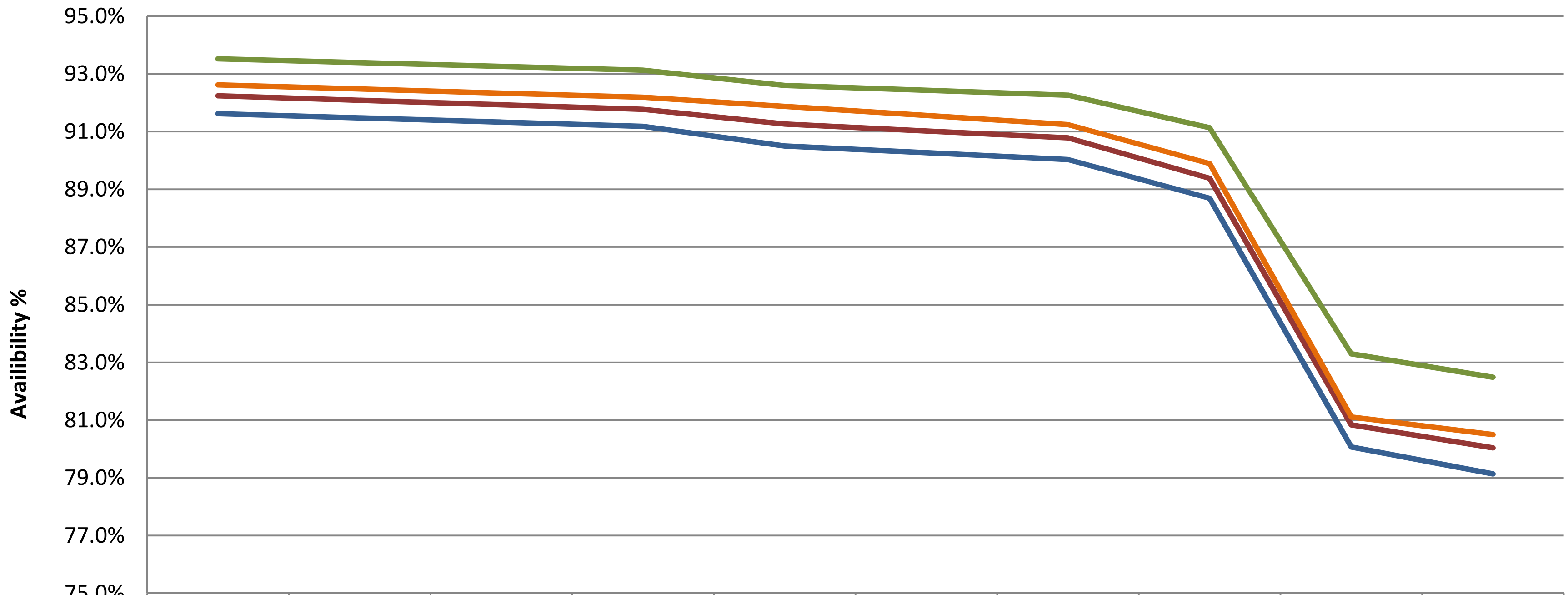


Turbine Type 4: DD, PMG, FRC



Availability of Different Turbine Types

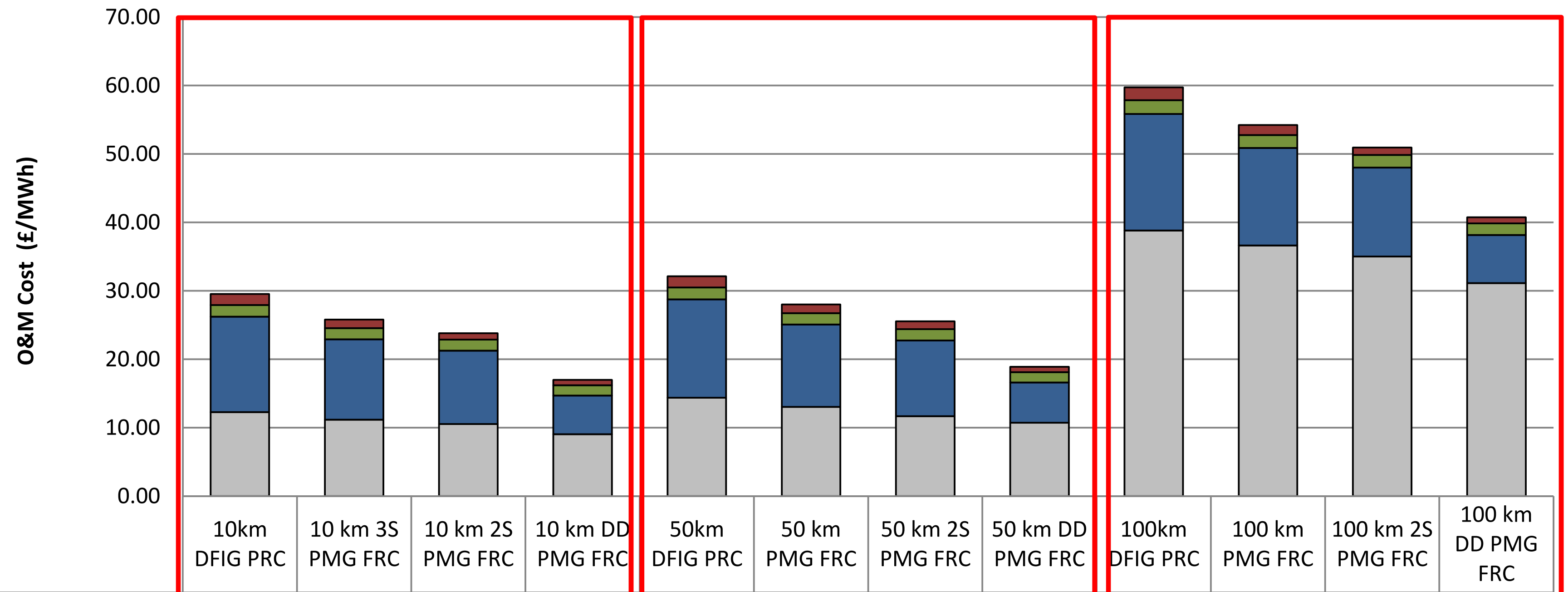
- Availability of turbine types and distance from shore
- Based on empirical and simulated operational data + AM02 Availability Model
- 3 stage PMG has a higher failure rate but higher availability than DFIG
- DD has the highest availability across all sites because of less requirement for jack up vessel



	10km	20km	30km	40km	50km	60km	70km	80km	90km	100km
DFIG PRC	91.6%	91.5%	91.3%	91.2%	90.5%	90.3%	90.0%	88.7%	80.1%	79.1%
3S PMG FRC	92.2%	92.1%	91.9%	91.8%	91.3%	91.0%	90.8%	89.4%	80.8%	80.0%
2S PMG FRC	92.6%	92.5%	92.3%	92.2%	91.9%	91.6%	91.2%	89.9%	81.1%	80.5%
DD PMG FRC	93.5%	93.4%	93.3%	93.1%	92.6%	92.4%	92.3%	91.1%	83.3%	82.5%

O&M costs of Different Turbine Types

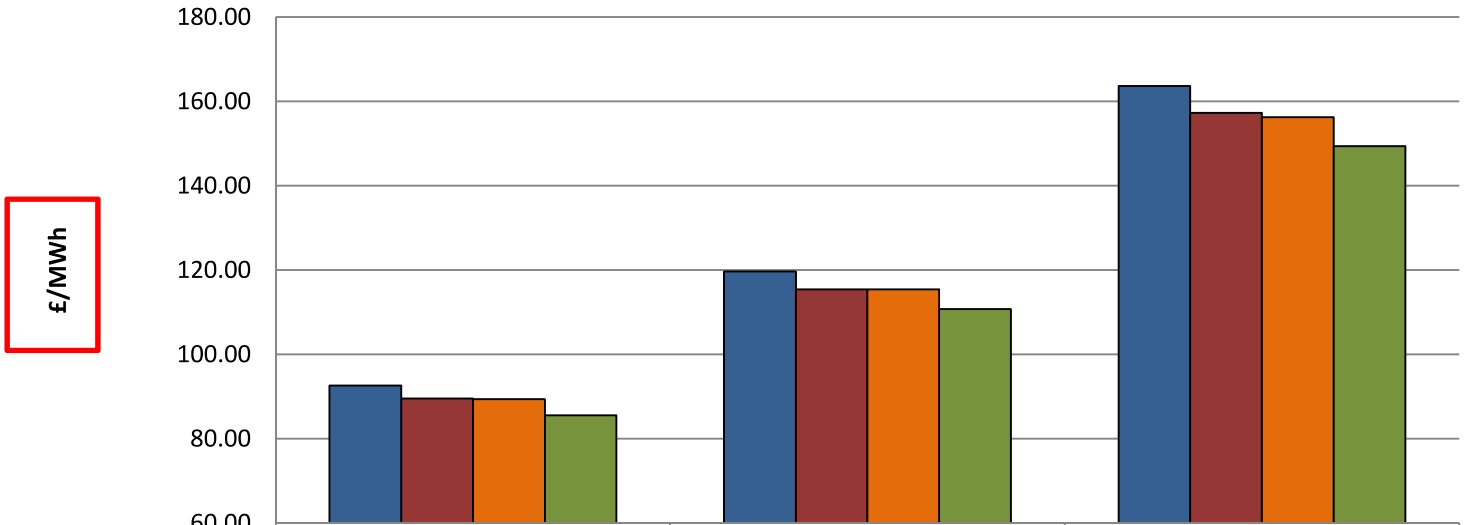
- O&M costs / MWh across 3 distance from shore
- DD has lowest O&M cost overall, DFIG has highest
- O&M costs at 50km ~45% lost production, 45% transport costs, 5% staff and 5% repair costs
- Jump in lost production costs at 100km



	10km DFIG PRC	10 km 3S PMG FRC	10 km 2S PMG FRC	10 km DD PMG FRC	50km DFIG PRC	50 km PMG FRC	50 km 2S PMG FRC	50 km DD PMG FRC	100km DFIG PRC	100 km PMG FRC	100 km 2S PMG FRC	100 km DD PMG FRC
Repair Costs (£)	1.61	1.26	0.94	0.79	1.65	1.26	1.15	0.80	1.88	1.46	1.08	0.89
Staff Costs (£)	1.71	1.63	1.6	1.49	1.74	1.65	1.65	1.5	2.01	1.9	1.85	1.71
Transport Costs (£)	13.95	11.75	10.73	5.66	14.37	12.05	11.06	5.88	17.03	14.24	13	7.02
Lost Production Costs (£)	12.26	11.16	10.53	9.04	14.37	13.03	11.68	10.72	38.81	36.63	35	31.13

CoE for Different Turbine Types

- Total CoE for each drive train shown at all 3 distances from shore
- CoE includes: Turbine costs, O&M costs, BoP costs, Other capital costs
- CoE increases as wind farms move further from shore (Wind Speed Assump.)
- DD has the lowest, DFIG has the highest



	10km	50km	100km
3 Stage DFIG PRC	92.58	119.64	163.63
3 Stage PMG FRC	89.53	115.41	157.27
2 Stage PMG FRC	89.38	115.42	156.25
DD PMG FRC	85.52	110.74	149.38

Conclusion

- Pitch/Hydraulic has the highest failure rate offshore

- DFIG PRC has a lower failure rate than PMG FRC

- DD PMG FRC has highest availability, lowest O&M cost and Lowest Overall CoE out of the four drivetrain types analysed

Remaining PhD Work:

- Vessel analysis to be completed

- Mothership analysis to be completed

- Thesis write Up to be completed

Questions

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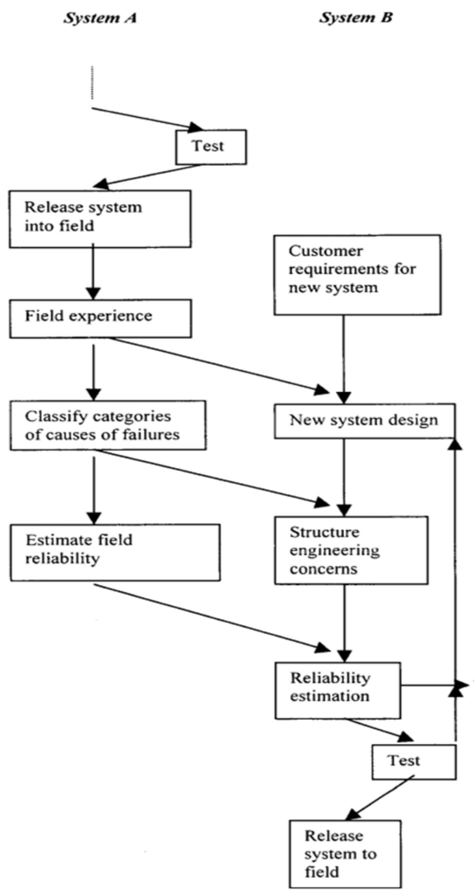
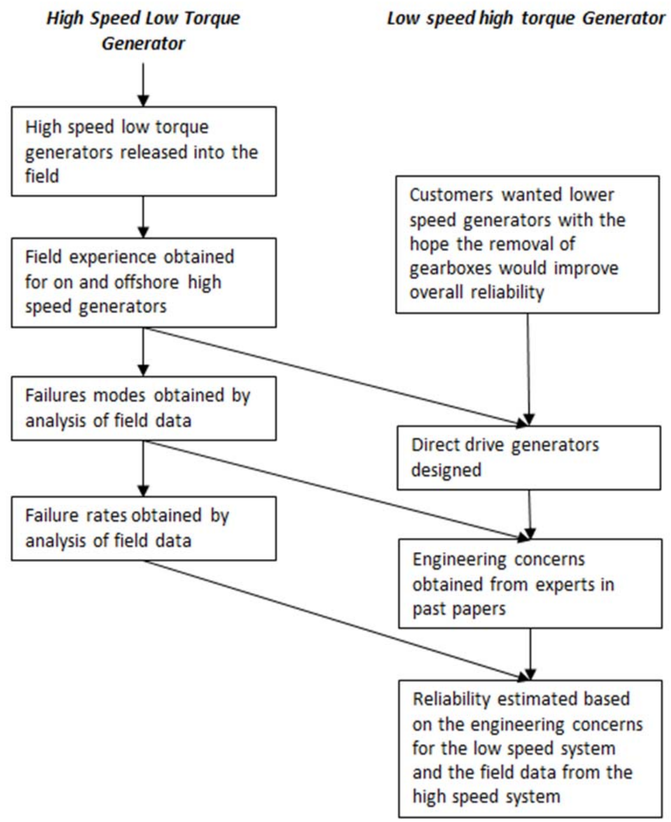
Back-up Slides

2. Offshore Failure Rates of Wind Turbines and Their Subassemblies (Adjustment for 2 Stage and DD PMG FRC)

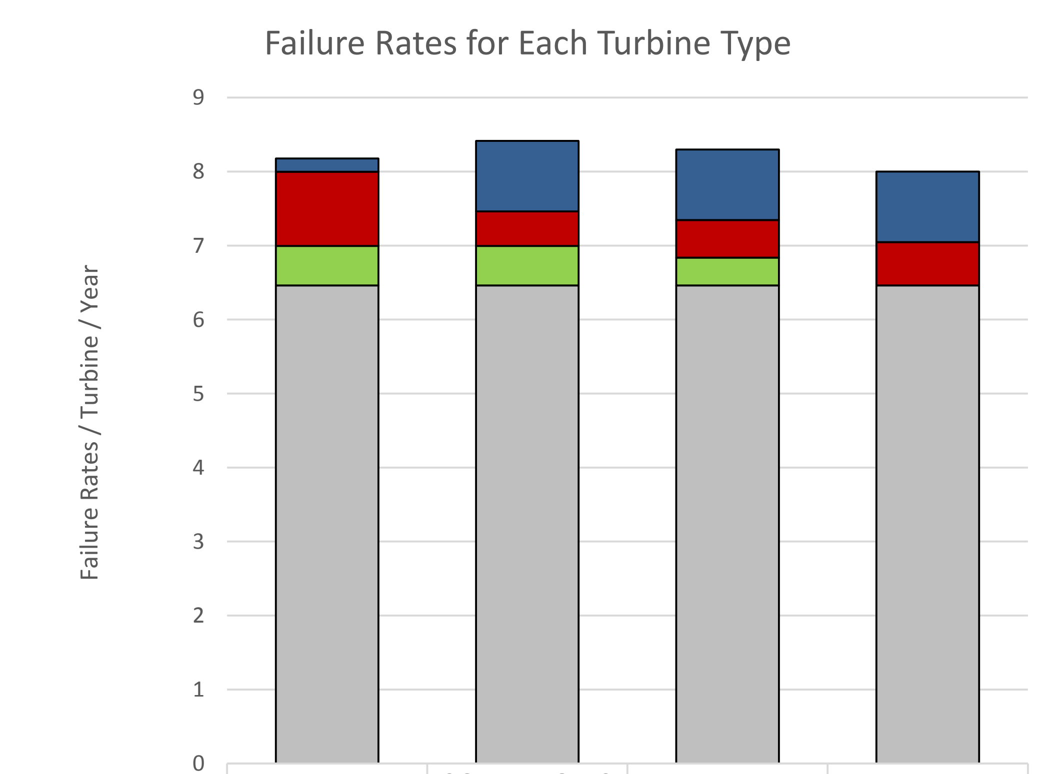
- Adjusted from 3 Stage PMG FRC Offshore Failure Rates
- FRC failure rates assumed the same
- Gearbox failure rates adjusted based on an FMEA paper by Tavner et al.
- Generator failure rates adjusted based on reliability enhancement modelling and methodology (REMM)





2. Offshore Failure Rates of Wind Turbines and Their Subassemblies (Overall failure rates for each turbine type)

- DD PFG FRC has the lowest failure rate
- 3 Stage PMG FRC has the highest
- FRC has highest failure rate
- Deeper analysis (table) needed for O&M modelling

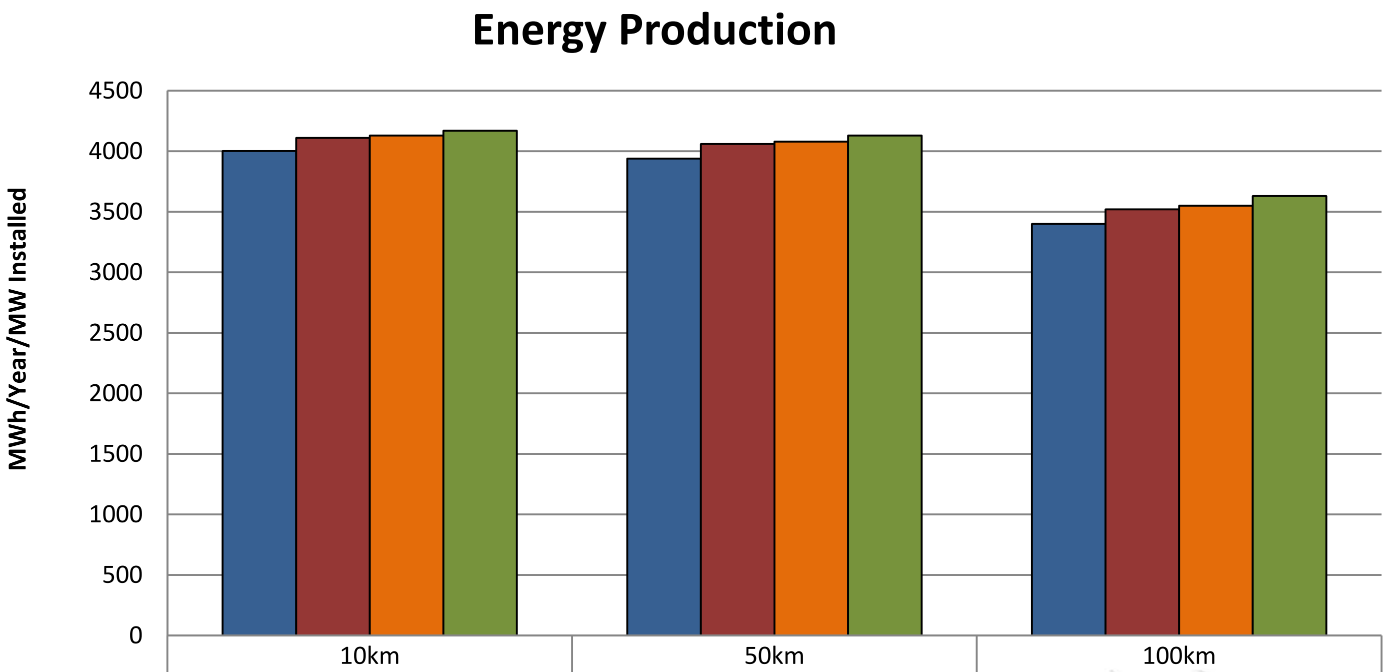


	3 Stage DFIG PRC	3 Stage PMG FRC PRC	2 Stage PMG FRC	DD PMG FRC
Converter	0.18	0.953	0.953	0.953
Generator	1.003	0.468	0.507	0.585
Gearbox	0.533	0.533	0.377	0
Rest of Turbine	6.461	6.461	6.461	6.461

		3 Stage DFIG PRC	3 Stage PMG FRC PRC	2 Stage PMG FRC	DD PMG FRC
Gearbox	Major Replacement	0.059	0.059	0.042	
	Major Repair	0.042	0.042	0.03	
	Minor Repair	0.432	0.432	0.305	
Generator	Major Replacement	0.109	0.007	0.008	0.009
	Major Repair	0.356	0.024	0.026	0.03
	Minor Repair	0.538	0.437	0.473	0.546
Power Converter	Major Replacement	0.006	0.077	0.077	0.077
	Major Repair	0.09	0.338	0.338	0.338
	Minor Repair	0.084	0.538	0.538	0.538
Rest of Turbine	Major Replacement	5.764	5.764	5.764	5.764
	Major Repair	0.686	0.686	0.686	0.686
	Minor Repair	0.011	0.011	0.011	0.011

3. Offshore Availability and O&M costs of Different Wind Turbine Types (Energy Production for each turbine type)

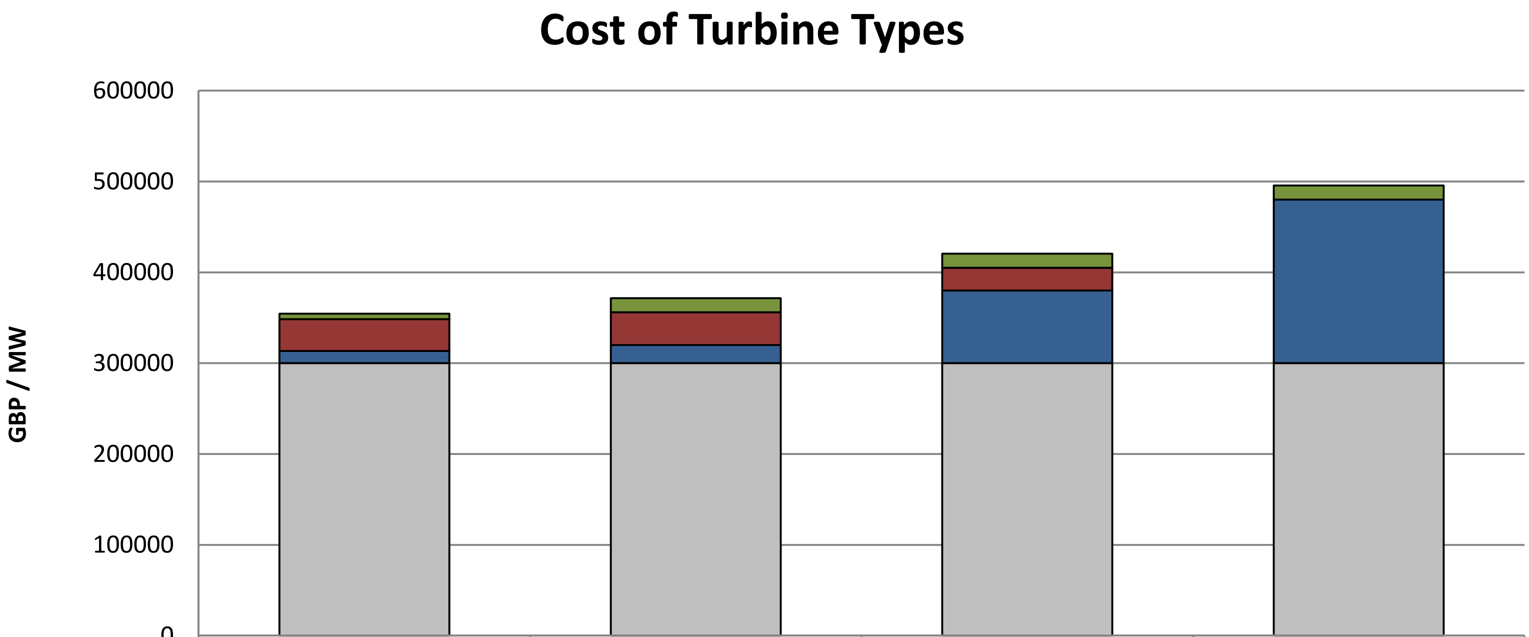
- Energy production per MW installed
- Empirical Power Curves used for 3 stage turbines
- Adjusted for two stage and DD based on Polinders work
- Fino wind data used across all sites
- DD has most energy production because of power curve and higher availability



	10km	50km	100km
3 Stage DFIG PRC	4002	3940	3400
3 Stage PMG FRC	4110	4060	3520
2 Stage PMG FRC	4130	4080	3550
DD PMG FRC	4170	4130	3630

4. CoE Modeling for Each Drive Train Type (Turbine Costs)

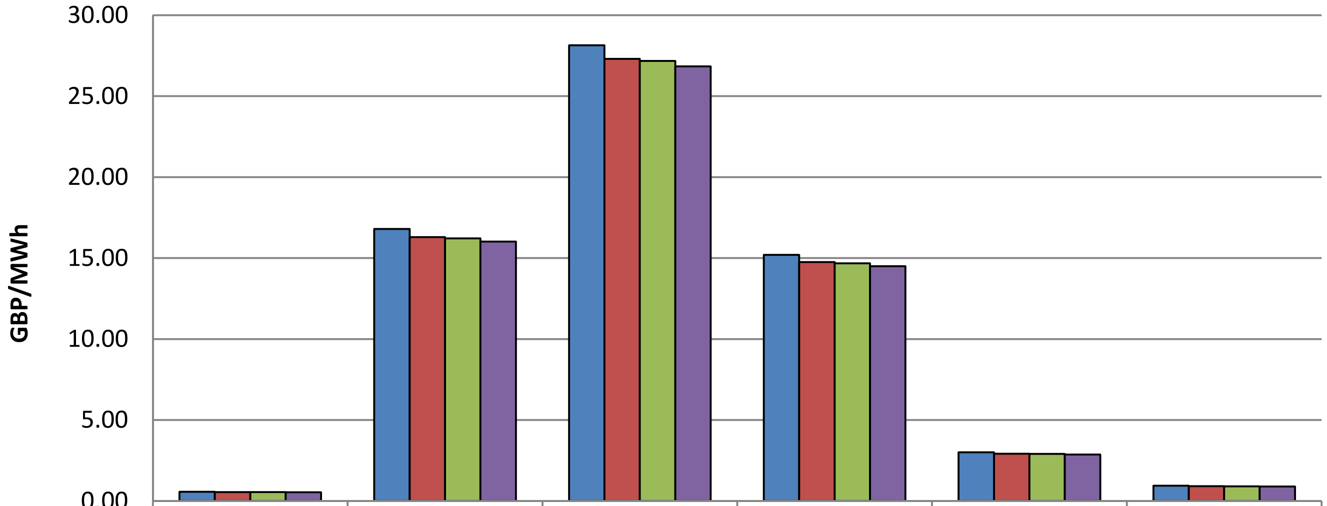
- GBP/MW
- 3 stage configurations came from industrial partner
- 2 stage and DD generator cost adjustments were based on Polinder’s work
- Generator is the biggest cost differentiator



	3 Stage DFIG PRC	3 Stage PMG FRC	2 Stage PMG FRC	DD PMG FRC
Converter	6000	15500	15500	15500
Gearbox	35000	36000	25000	0
Generator	13500	20000	80000	180000
Rest of Turbine	300000	300000	300000	300000

BoS Costs Further Analysis

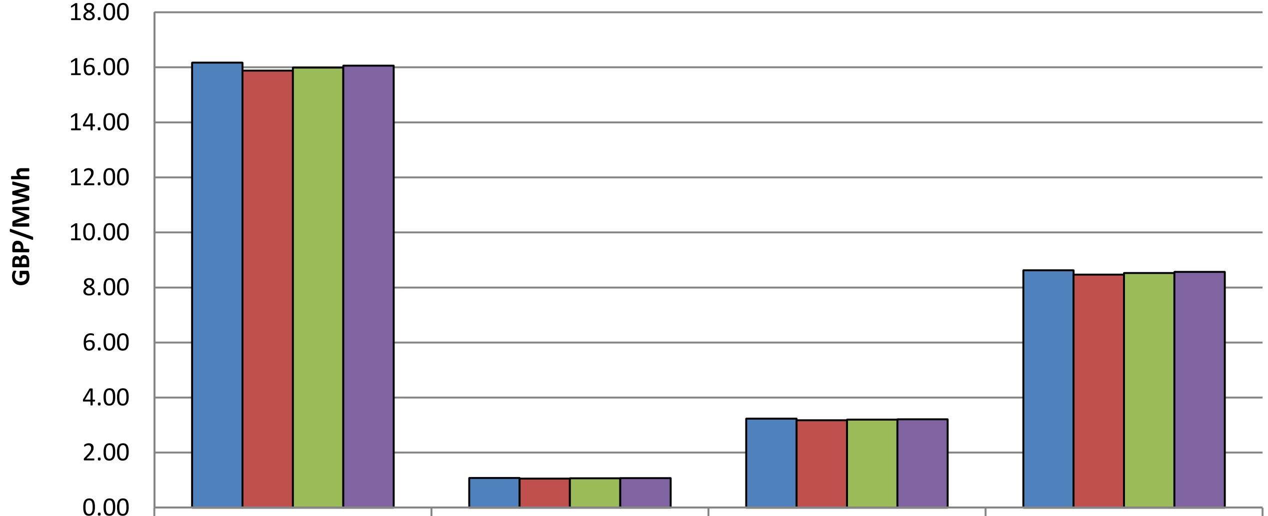
- BoS costs for 50km offshore
- Includes port and staging, foundation, ….
- Electrical Infrastructure is the highest cost followed by … (Same across all distances from shore
- Same absolute cost across all turbine types but different cost / MWh



	Port and Staging	Substructure and Foundation	Electrical Infrastructure	Assembly and Installation	Development, Engineering & Management	Commisioning
3 Stage DFIG PRC	0.57	16.80	28.14	15.20	3.01	0.94
3 Stage PMG FRC	0.55	16.30	27.31	14.75	2.92	0.91
2 Stage PMG FRC	0.55	16.22	27.17	14.68	2.90	0.90
DD PMG FRC	0.54	16.02	26.84	14.50	2.87	0.89

Other Capital Costs

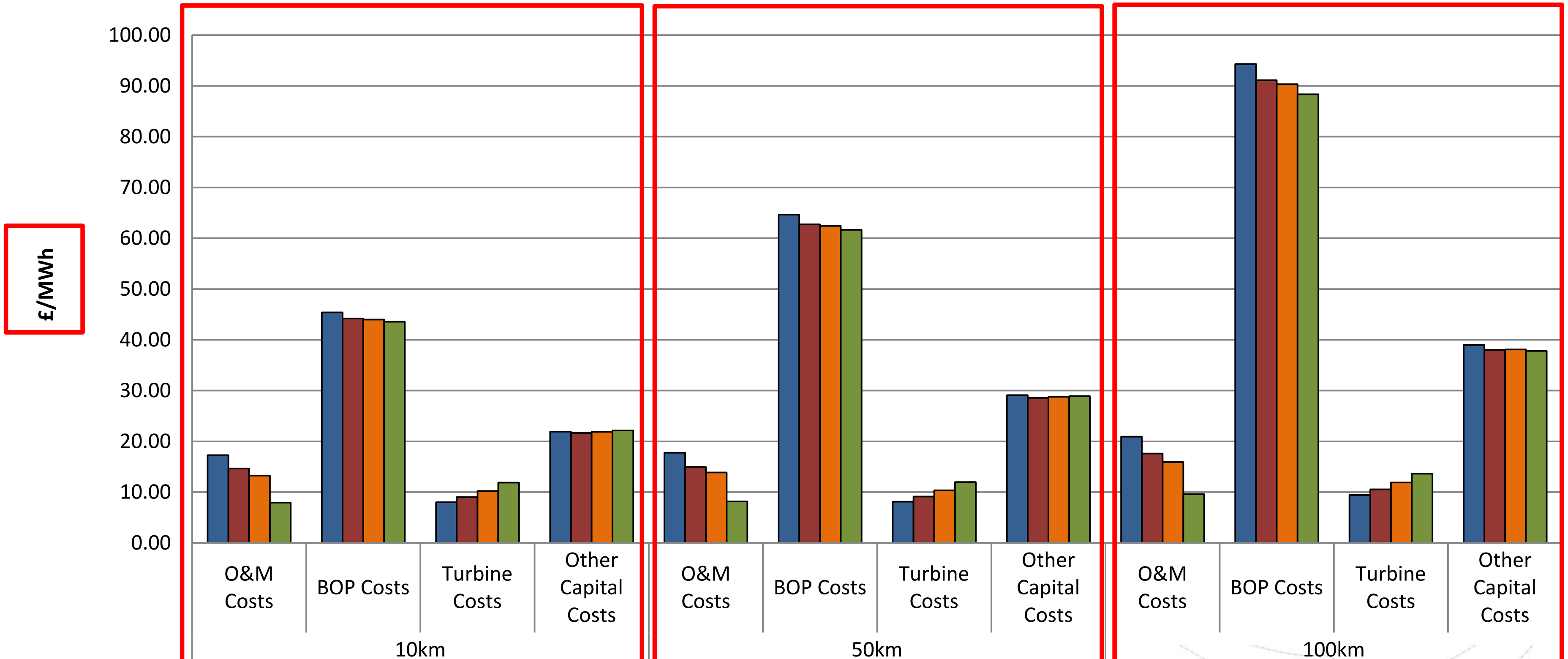
- Other Capital costs for 50km offshore
- Includes contingency, insurance etc.
- Contingency and the cost of finance are the highest cost
- Calculated as a % of overall capital costs



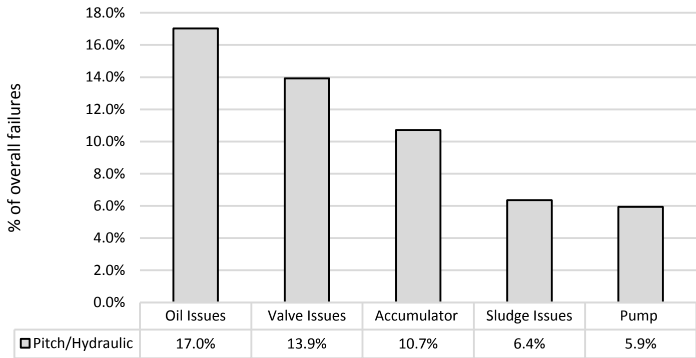
	Contingency (15% of total capital costs)	Insurance during construction (1%)	Decomisioning (3%)	Construction finance factor (8%)
3 Stage DFIG PRC	16.17	1.08	3.23	8.62
3 Stage PMG FRC	15.88	1.06	3.18	8.47
2 Stage PMG FRC	15.99	1.07	3.20	8.53
DD PMG FRC	16.06	1.07	3.21	8.56

4. CoE Modeling for Each Drive train type (CoE Contributors)

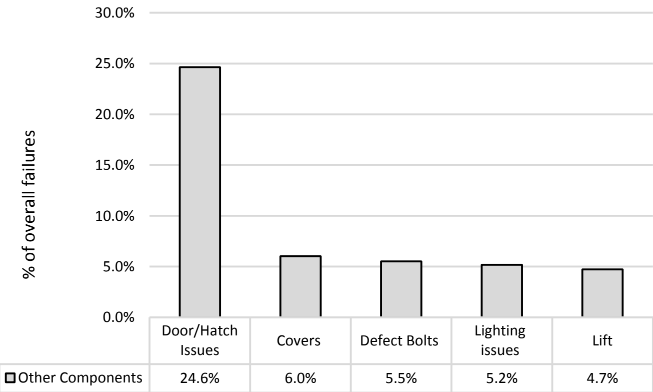
- Shows contributions towards CoE for sites 10km, 50km and 100km offshore
- BoP = Substructure and foundation, Electrical Infrastructure, Assembly and Installation, Developing engineering and management, Commissioning, Port and Staging
- Other capital costs = Insurance, decommissioning, contingency, construction finance factor
- DFIG 50km, O&M ~15%, BoS costs 54%, Turbine Costs ~7%, other capital costs ~24%



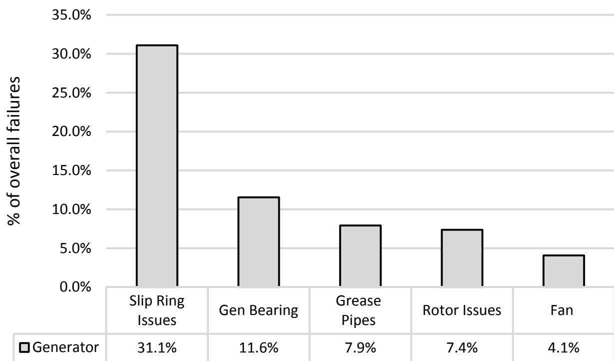
	10km O&M Costs	10km BOP Costs	10km Turbine Costs	10km Other Capital Costs	50km O&M Costs	50km BOP Costs	50km Turbine Costs	50km Other Capital Costs	100km O&M Costs	100km BOP Costs	100km Turbine Costs	100km Other Capital Costs
3 Stage DFIG PRC	17.27	45.40	8.01	21.90	17.76	64.65	8.13	29.10	20.92	94.31	9.43	38.97
3 Stage PMG FRC	14.64	44.21	9.03	21.66	14.96	62.73	9.14	28.58	17.60	91.10	10.54	38.03
2 Stage PMG FRC	13.27	43.99	10.23	21.89	13.86	62.43	10.35	28.78	15.93	90.33	11.90	38.10
DD PMG FRC	7.94	43.57	11.87	22.15	8.18	61.67	11.98	28.90	9.62	88.34	13.63	37.80



	Oil Issues	Valve Issues	Accumulator	Sludge Issues	Pump
Pitch/Hydraulic	17.0%	13.9%	10.7%	6.4%	5.9%



	Door/Hatch Issues	Covers	Defect Bolts	Lighting issues	Lift
Other Components	24.6%	6.0%	5.5%	5.2%	4.7%



	Slip Ring Issues	Gen Bearing	Grease Pipes	Rotor Issues	Fan
Generator	31.1%	11.6%	7.9%	7.4%	4.1%

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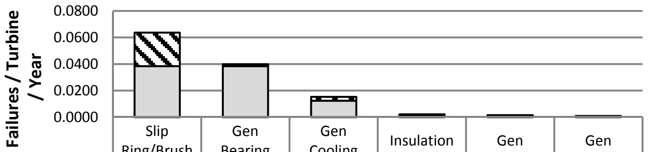
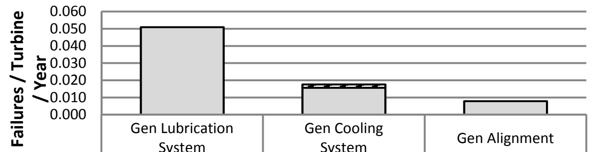
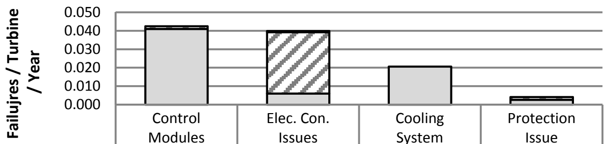


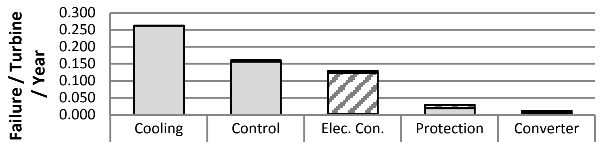
	Slip Ring/Brush Issue	Gen Bearing Issue	Gen Cooling System	Insulation Issue	Gen Encoder	Gen Allignment
Major Rep.	0.0000	0.0003	0.0000	0.0018	0.0000	0.0000
Major Repair	0.0254	0.0012	0.0029	0.0003	0.0000	0.0000
Minor Repair	0.0383	0.0383	0.0124	0.0000	0.0015	0.0009



	Gen Lubrication System	Gen Cooling System	Gen Alignment
Major Repair	0.000	0.002	0.000
Minor Repair	0.051	0.016	0.008



	Control Modules	Elec. Con. Issues	Cooling System	Protection Issue
Major Rep.	0.000	0.001	0.000	0.000
Major Repair	0.001	0.033	0.000	0.001
Minor Repair	0.041	0.006	0.021	0.003



	Cooling system	Control Modules	Elec. Con. Issues	Protection Issues	Converter Rep.
Major Rep.	0.000	0.000	0.006	0.000	0.008
Major Repair	0.000	0.004	0.121	0.010	0.004
Minor Repair	0.262	0.157	0.002	0.020	0.000