A Multi-State Systems Markov Model for the Reliability Evaluation of Large Scale Offshore Wind Farms considering Network Dependencies

INNOVATIVE TOOLS FOR OFFSHORE WIND AND DC GRIDS

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Content

- Up-to-date Progress
- MSS Reliability modelling Methodology
- Model Description
- System Reliability Evaluation with a Test Case
- Conclusion and Future Work

Up-to-date Progress

[1] G. Abeynayake et al., “Reliability Evaluation of Voltage Source Converters for MVDC Applications,” 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Chengdu, China, 2019, pp. 2566-2570, doi: 10.1109/ISGT-Asia.2019.8881326.

[2] G. Abeynayake, G. Li, J. Liang and N. A. Cutululis, “A Review on MVdc Collection Systems for High-Power Offshore Wind Farms,” 2019 14th Conference on Industrial and Information Systems (ICIIS), Kandy, Sri Lanka, 2019, pp. 407-412, doi: 10.1109/ICIIS47346.2019.9063352.

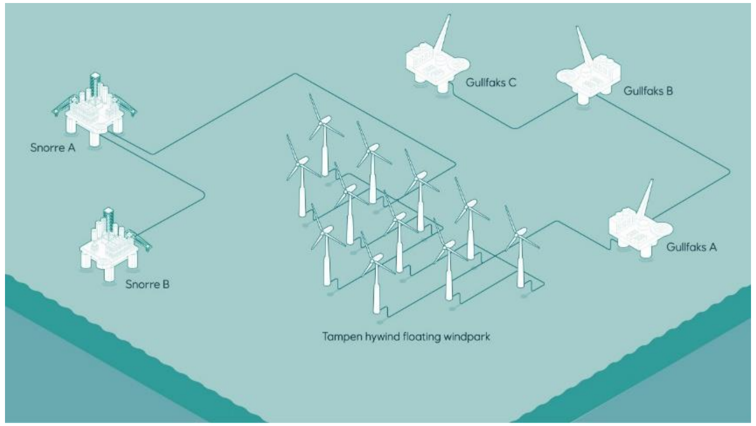
[3] Xiangyu Li, Gayan Abeynayake, Liangzhong Yao, Jun Linag, Fan Cheng, “Recent Development and Prospect of Offshore Wind Power in Europe”, Journal of Global Energy Interconnection, Vol. 2 No. 2, Mar. 2019 DOI: 10.19705/j.cnki.issn2096-5125.2019.02.002

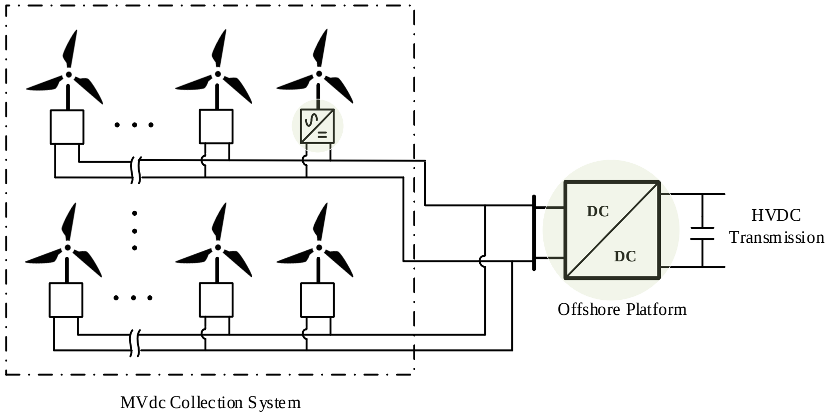
[4] G. Abeynayake, G. Li, et al., “Reliability and Cost-oriented Analysis, Comparison and Selection of Multi-level MVdc Converters”, *IEEE Trans. on Power Delivery,* [Under Review]

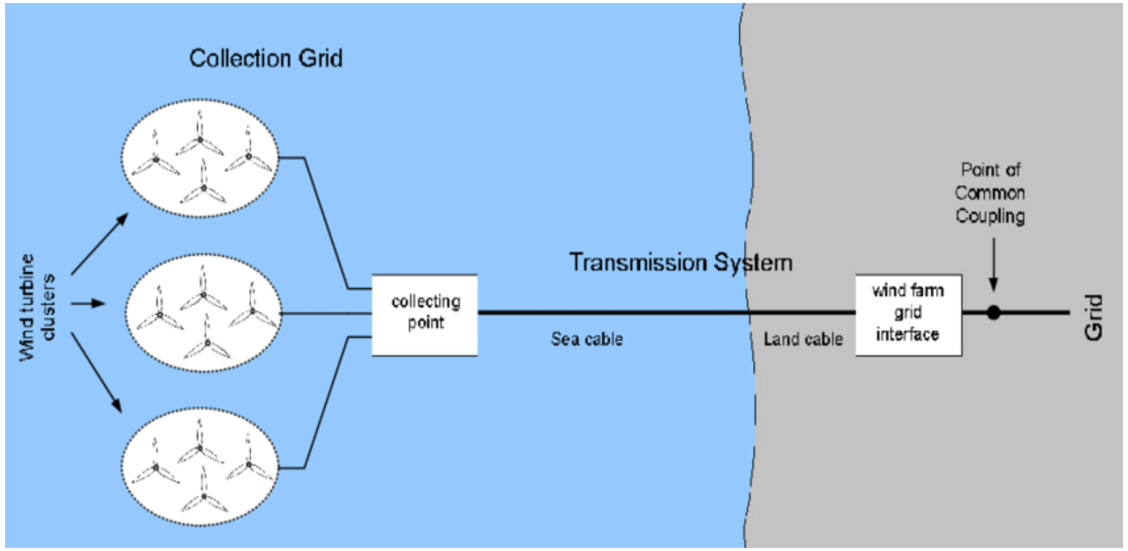
[5] G. Abeynayake, J. Liang, A. Moon, J. Yu, “Analysis and Control of MVDC Demonstration Project in the UK: ANGLE-DC”, Distribution & Utilization, China Academic Journal [Accepted] July 2020

[6] Gayan Abeynayake, Tom Van Acker, Dirk Van Hertem, Jun Liang, “Reliability Assessment of Large-Scale Offshore Wind Farms including its Collector System”, [in progress for submission]

Requirement of Reliability







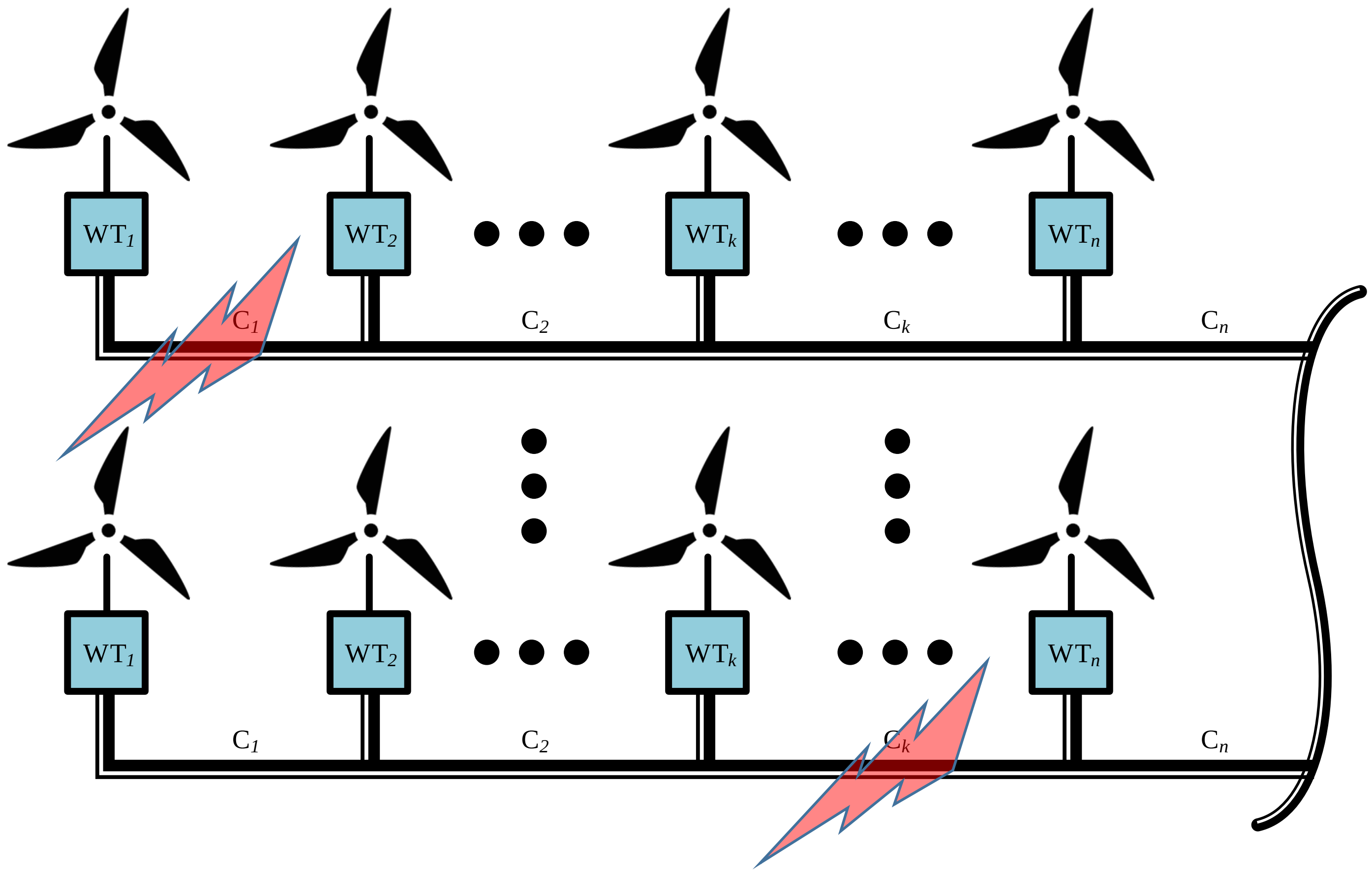
- **wind farm developers for making planning decisions**
- **wind farm operators for reliability-oriented maintenance planning**

Collaboration

- This work has been conducted in collaboration with Dr. Tom Van Acker, KU Leuven, Belgium.
- Special thanks to Dr. Hakan Ergun and our Professors.

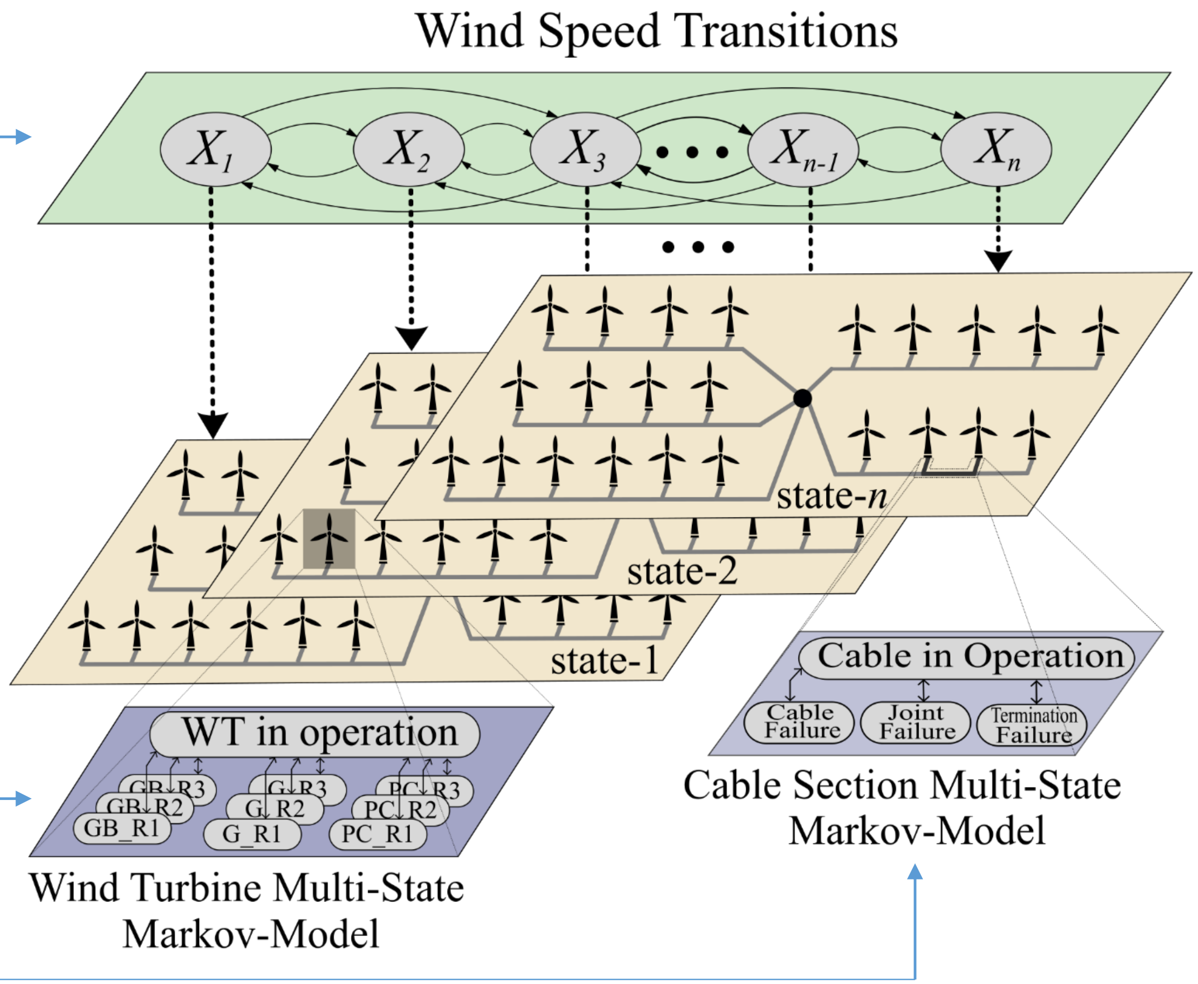
Research Gap

- Compared to WT failure rates, collection system cable failure rates are LOWER
- However, due to higher repair time it cannot simply be neglected.
- **The proposed method based on Universal Generating Function combined with continuous time Markov Chain model is used to answer this question!**



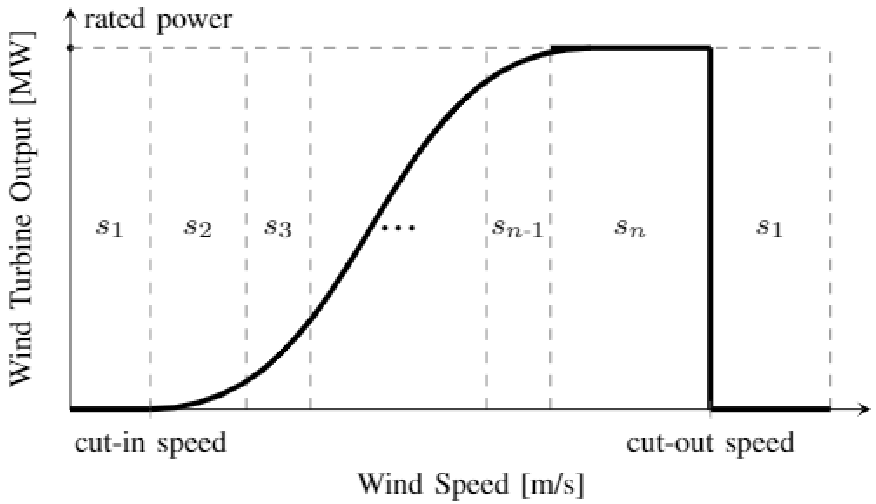
Model Overview

1. Wind Speed Model
2. Wind Turbine Model
3. Cable Model



Methodology

1. Calculation of wind turbine power output for the given wind speed data [1],[2]
2. Calculation of optimal number of clusters using the a suitable data clustering algorithm. (ex. Jenks clustering method)
3. Calculation of power output transitions rates between each state and state probabilities



WIND TURBINE OUTPUT CLUSTERING FOR EIGHT CLUSTERS INCLUDING THEIR CENTER, STATE PROBABILITIES AND TRANSITION RATES

Cl.	Center [MW]	State Prob.	Transition Rates [1/yr] 1	2	3	4	5	6	7	8
1	0.0	0.111220	0.0	4706.64	26.9979	8.99931	0.0	0.0	8.99931	26.9979
2	0.187	0.191447	2739.58	0.0	3769.53	120.249	10.4564	0.0	5.2282	0.0
3	0.655	0.139921	21.4607	5229.27	0.0	5601.26	221.761	21.4607	14.3072	0.0
4	1.224	0.110248	0.0	136.187	7372.24	0.0	7217.9	326.848	108.949	9.07912
5	1.818	0.092120	0.0	21.7332	152.132	9030.14	0.0	7726.15	1075.79	108.666
6	2.361	0.056386	0.0	0.0	0.0	407.922	12929.3	0.0	11687.8	248.3
7	3.099	0.088451	11.2944	0.0	33.8832	90.3552	1174.62	7476.89	0.0	7431.71
8	3.600	0.210207	14.2376	0.0	0.0	9.49173	33.2211	61.6962	3141.76	0.0

[1] "Offshore wind data," Library Catalog: Ørsted.com. [Online]. Available: https://orsted.com/en/our-business/offshore-wind/wind-data
[2] "Manufacturer datasheet-Siemens SWT-3.6-120" [Onlien]. Available: https://www.thewindpower.net/turbine_en_79_siemens_swt-3.6-120.php

Methodology

4. Add component failure and repair rates of each wind turbine and cable section to the model [3],[4]

TABLE II
RELIABILITY OF WIND TURBINE SUB-ASSEMBLIES

Sub-Assembly	Corr. Maintenance	λ_f [1/yr]	μ_f [1/hr]
Gearbox (b)	Minor (r_1)	0.059	0.0132
	Major (r_2)	0.042	0.0361
	Repl. (r_3)	0.432	0.0752
Generator (g)	Minor (r_1)	0.007	0.1695
	Major (r_2)	0.024	0.3704
	Repl. (r_3)	0.437	0.0625
Converter (c)	Minor (r_1)	0.077	0.0158
	Major (r_2)	0.338	0.0443
	Repl. (r_3)	0.538	0.0515

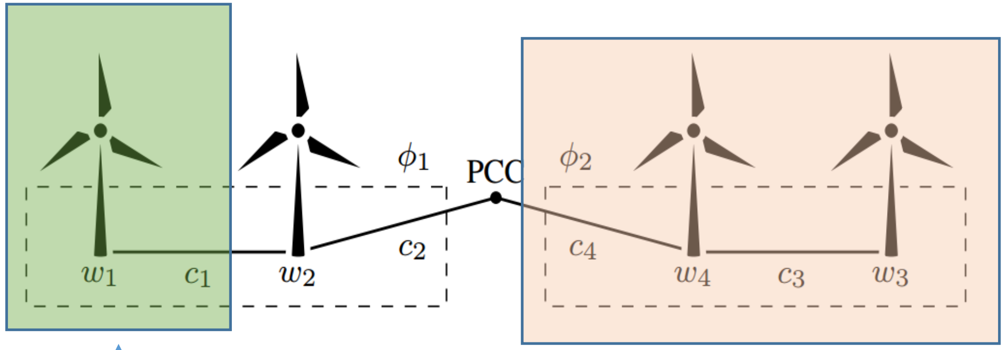
TABLE III
RELIABILITY OF THE CABLE SYSTEM

Diameter	Cable		Cable Termination	
	λ [1/yr/km]	μ [1/hr]	λ [1/yr]	μ [1/hr]
150/240 mm^2	7.43e-3	6.94e-4	1.68e-3	9.26e-4
500 mm^2	9.45e-3	6.94e-4	1.68e-3	9.26e-4

5. Define the network with set of sources (WTs) and edges (cables) with their state-transitions
6. Use of the Universal Generation Function technique to calculate state probabilities for different power output states of OWF collection system.

[3] J. Carroll, A. McDonald, and D. McMillan, "Reliability comparison of wind turbines with DFIG and PMG drive trains," *IEEE Transactions on Energy Conversion*, vol. 30, no. 2, pp. 663–670, 2015.
[4] B. W. Tuinema, "Reliability of transmission networks: Impact of EHV underground cables a interaction of offshore-onshore networks," Ph.D. dissertation, TU Delft, 2017.

UGF Technique



$$f^{\mathrm{c1,w1}}(\gamma) = \min(v_{c_1}, v_{w_1}) \qquad f^{c_{3,4},w_{3,4}}(\gamma) = \min(v_{c_4}, v_{w_4} + \min(v_{c_3}, v_{w_3}))$$

UGF for individual WT and Cable

$$\omega_w(z) = 0.3z^{0\,\mathrm{MW}} + 0.7z^{2\,\mathrm{MW}}, \quad \forall w \in \mathcal{W},$$
$$\omega_c(z) = 0.1z^{0\,\mathrm{MW}} + 0.9z^{4\,\mathrm{MW}}, \quad \forall c \in \mathcal{C}.$$

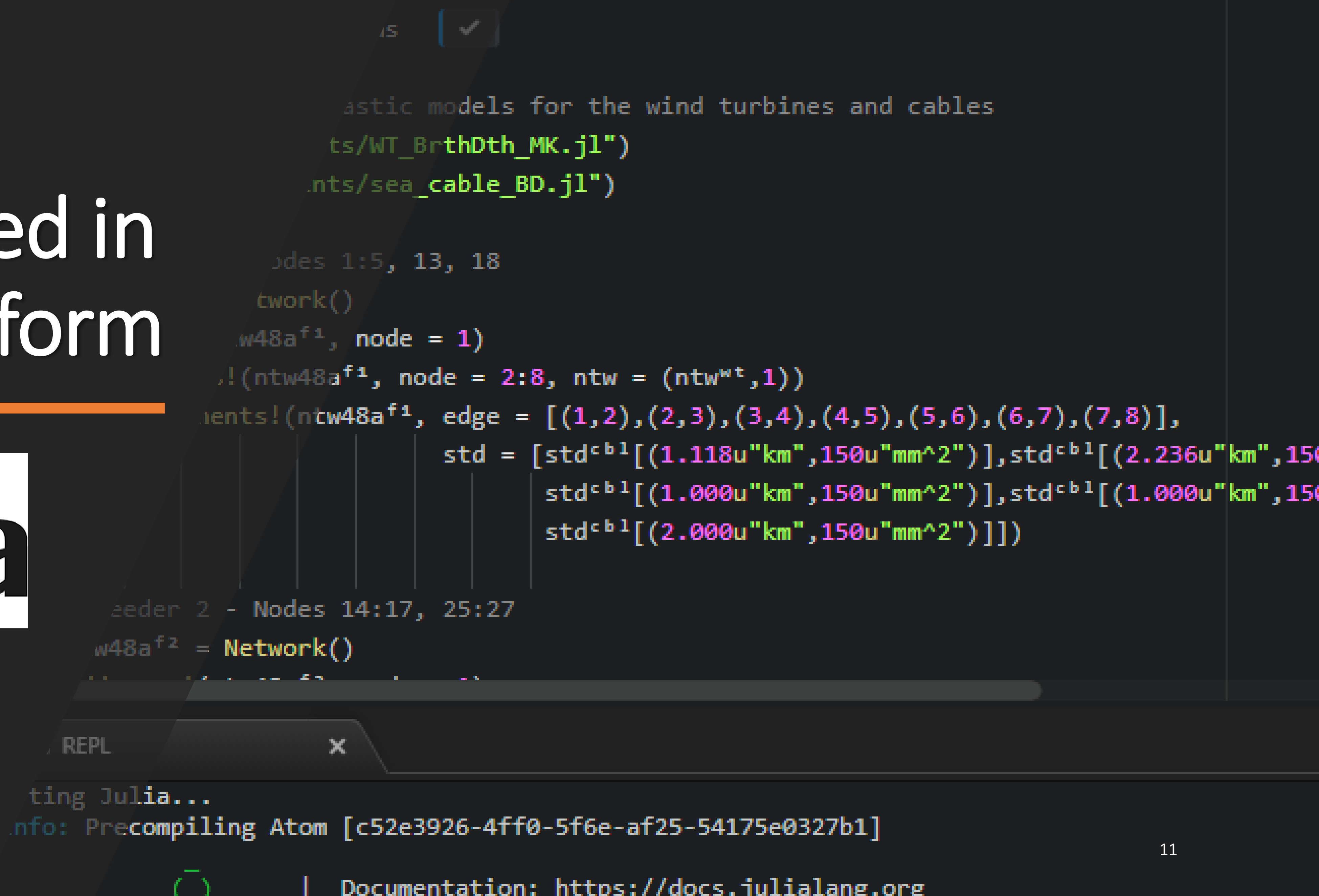
Down State ($0.1z^{0\,\mathrm{MW}}$) **Up State** ($0.9z^{4\,\mathrm{MW}}$)

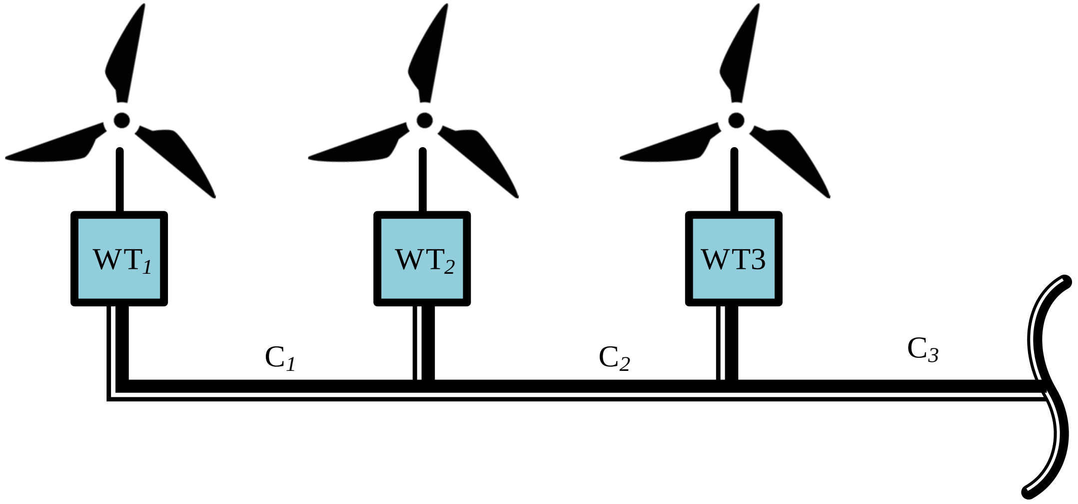
Structure Function for Two Strings $f^{\mathrm{str}}(\gamma) = \min(v_{c_2}, v_{w_2} + \min(v_{c_1}, v_{w_1})) + \min(v_{c_4}, v_{w_4} + \min(v_{c_3}, v_{w_3}))$

Generalized UGF [5] for a radial OWF network $\Omega_u([\omega_e(z)]_{e\in\mathcal{E}}) = \sum_{\gamma\in\Gamma} f^{\mathrm{prb}}(\gamma)\cdot z^{f^{\mathrm{str}}(\gamma)}$

[5] A. Lisnianski, I. Frenkel, and Y. Ding, “Multi-state system reliability analysis and optimization for engineers and industrial managers”, Springer Science & Business Media, 2010.

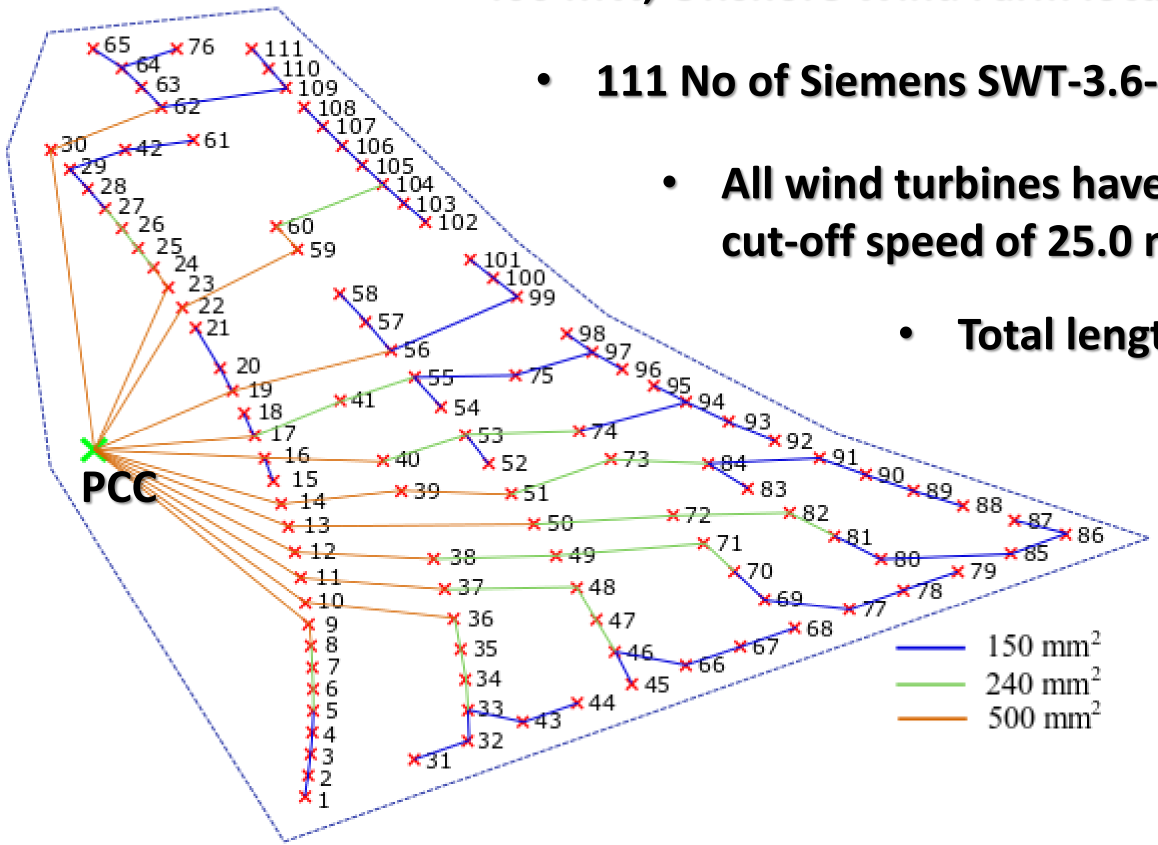
Tool Developed in Julia Platform





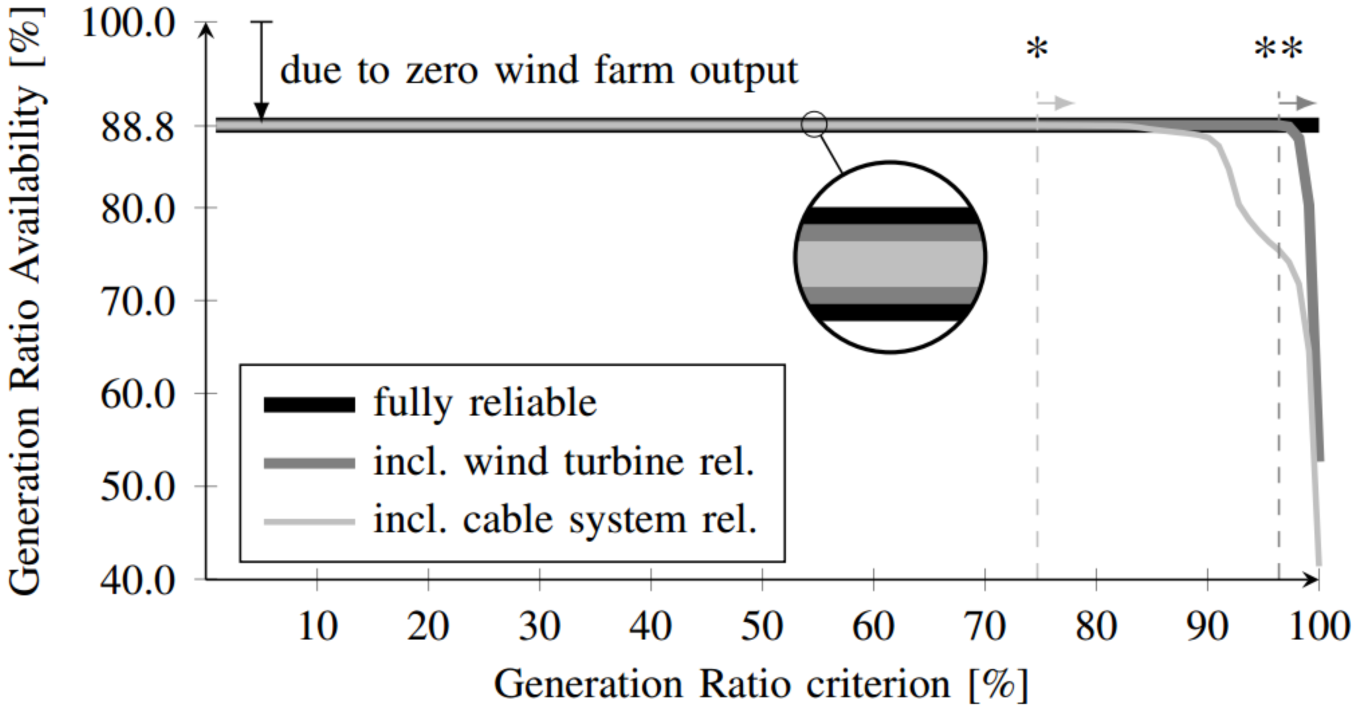
Case Study

Case Study – Anholt Offshore Wind Farm



- 400 MW, Offshore Wind Farm located between Djursland and Anholt island in Denmark
  - 111 No of Siemens SWT-3.6-120 wind turbines with a rated power of 3.6 MW
    - All wind turbines have a cut-in speed of 3.5 m/s, rated speed of 14.0 m/s, and cut-off speed of 25.0 m/s.
      - Total length of 177 km inter-array cable network

Case Study - GRA



- **Generation Ration Availability (GRA) is an index used to assess the availability of OWFs under stochastic nature of wind speed and component failures[6]**

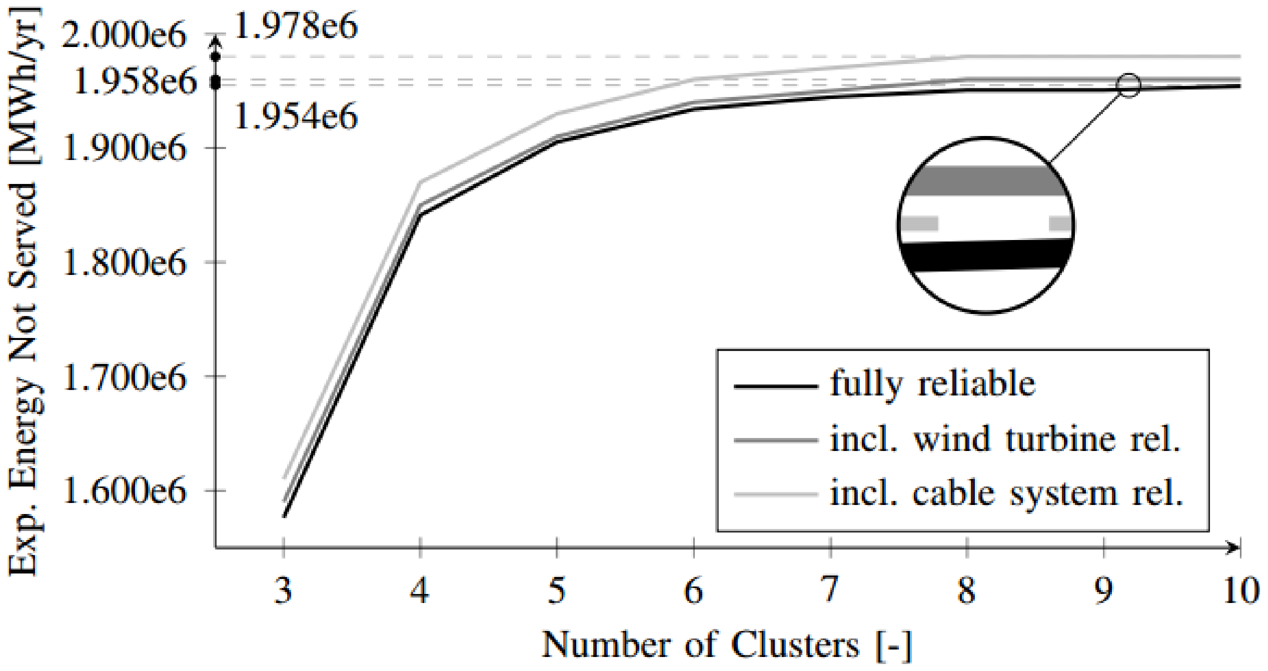
$$\mathrm{GRA}(\mathrm{GRc}) = \sum_{i \in \mathcal{I}\,:\,\mathrm{cnd}_i} \mathrm{GRc} \cdot \omega^{\mathrm{ntw}}.p_i,$$

$$\mathrm{cnd}_i = \omega^{\mathrm{ntw}}.v_i \geq \mathrm{GRc} \cdot \max(\omega^{\mathrm{ntw}}.v)$$

- For a GRc of 95.0 %, the GRA is reduced to 76.3 % (-12.0 %) when considering the collector system reliability.
- The impact of collector system reliability starts from a significantly lower GRc compared to the wind turbine reliability: 74.7 % * and 96.4 % **, respectively

[6] M. Zhao, Z. Chen and F. Blaabjerg, "Generation Ratio Availability Assessment of Electrical Systems for Offshore Wind Farms," in IEEE Trans. on Energy Convers., pp. 755-763, Sept. 2007

Case Study - EENS

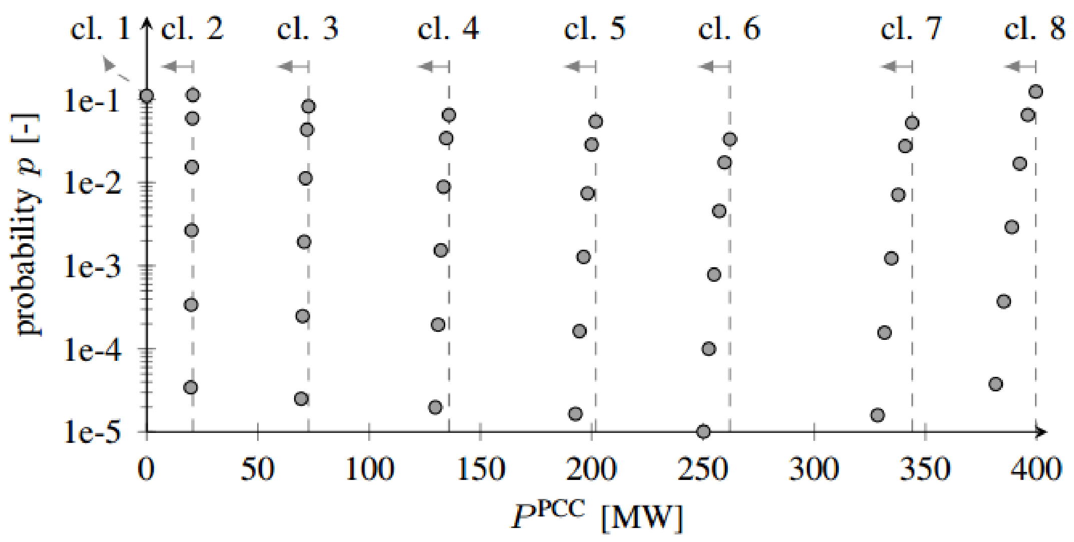


$$EENS = 8760 \cdot \sum_{i \in \mathcal{I}} \omega^{pcc}.p_i \cdot (\max(\omega^{pcc}.v) - \omega^{pcc}.v_i)$$

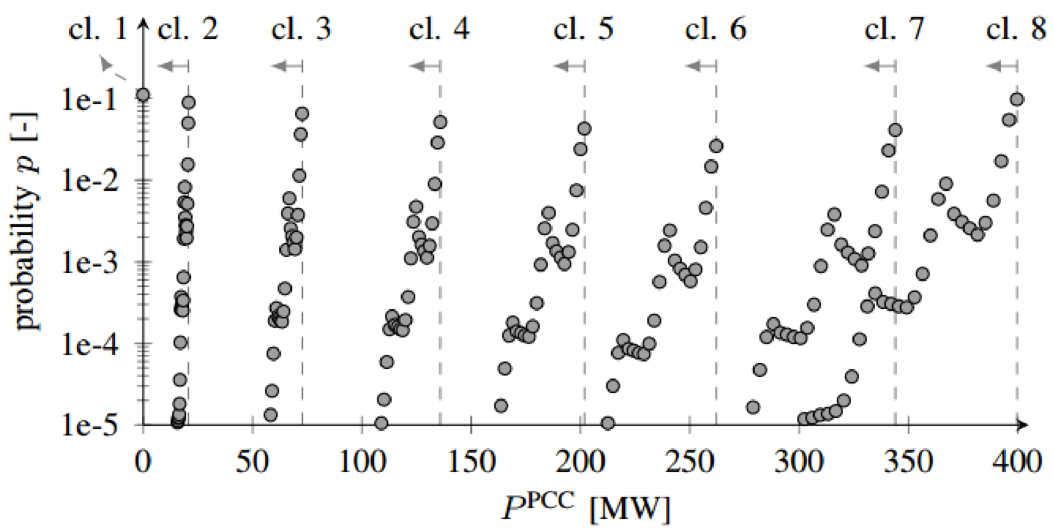
- At least 8 clusters are required to accurately represent the Anholt wind speed data
- Not including the cable network will result in EENS error of 19.89 GWh/yr (1.0 %) which account for 24.05M$ miscalculation over the operating life (20yrs) of the OWF. *

* With a discount rate of 5% and average Danish wholesale electricity price of 36.57 $/MWh

Case Study – Probability Distribution



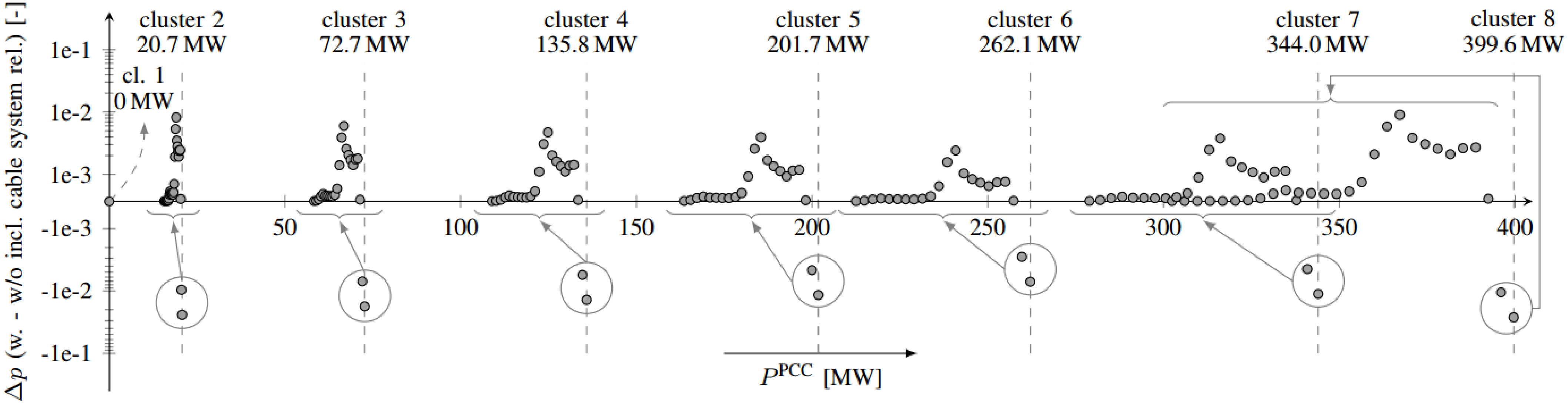
(a) without cable network



(b) with cable network

1) The average power output for a specific cluster is reduced
2) The output variance within a specific cluster is increased

Case Study – Probability Distribution



Difference of the probability distributions between the scenario with. cable system reliability and with. cable system reliability.

Conclusions

- The proposed method includes reliabilities of cable sections which has higher repair time
- The case studies demonstrate the requirement to include the cable network reliability in the reliability analysis of large offshore wind farm.

Future Work

A. Observe the impact of wake-effect on Reliability evaluation of Offshore collection systems considering the network.
B. Reliability oriented dc-Wind Turbine topology selection based on mission-profile and physics-of-failure.

Thank You !

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