CAN O&M SIMULATION TOOLS GUIDE CABLE TOPOLOGY SELECTION?

Nadezda Avanessova, from our Analysis and Insights Team, has finalised her doctorate research, part of which was incorporating cable topology into O&M simulation.

1.1 Why is cable topology design important?

Cable failures are a serious issue for offshore wind farm owners and operators and account for up to 80% of insurance claims across the sector [1], [2]. This, in turn, means that a vast portion of Operation and Maintenance (O&M) cost is attributed to cable failures, repairs and replacements and the revenue losses associated with these events.

Some developers may prefer a string connection for their array cable topology design (Figure 1), others may opt for a ring connection (Figure 2). String connection is cheaper in terms of up-front costs because there are no additional cables but results in higher revenue losses because a failure of one cable can lead to the loss of power output from all turbines on the string. Ring connection is more expensive to build because of the additional cables added for redundancy but reduces the risk of revenue losses in the event of a cable failure. There are other cable connection options but they are not covered by this report.

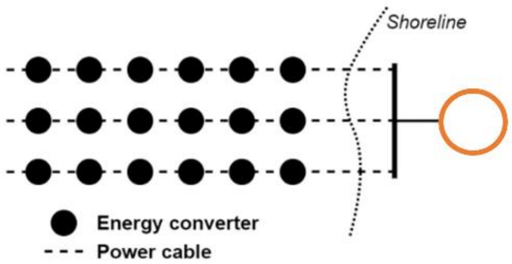

Figure 1: String (radial) connection. Source: [3]

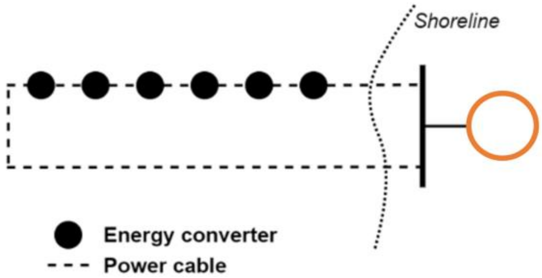

Figure 2: Ring connection. Source: [3]

This report demonstrates how the up-front costs required for inter-array cable redundancy compare with the revenue losses in scenarios without added redundancy. Evaluating the cost of cable failures within a complex cable topology design is challenging, however, the developments in COMPASS achieved via academic research allow for better measurement of the effects of cable failures on power generation.

1.2 How does COMPASS work?

COMPASS (Combined Operations, People, Assets and Systems Simulation) is ORE Catapult's in-house O&M simulation tool built in Python. [4].

COMPASS breaks down the lifetime of a wind farm into one-hour time intervals (known as time steps) and simulates wind farm events and activities at each step. It then outputs a wide range of Key Performance Indicators (KPIs) such as Production Based Availability (PBA), total energy output, number of planned and unplanned visits to the farm, total O&M costs and their breakdown.

In the case of energy transmitting assets, COMPASS models a cable topology design according to the connections between turbines defined by the user. Once all connections have been captured, COMPASS starts the simulation and iterates through one-hour time steps. At each time step it iterates through cables and other assets and checks if any of them have failed and require maintenance. Failure frequency is based on the user input.

When an asset fails, it is removed from the system, COMPASS then checks if there is still a connection between each turbine and the onshore substation. If that connection is missing, COMPASS takes this into consideration and calculates wind turbine KPIs accordingly. Similarly, when an asset gets repaired, it gets added back to the system. This computational logic is demonstrated in Figure 3.

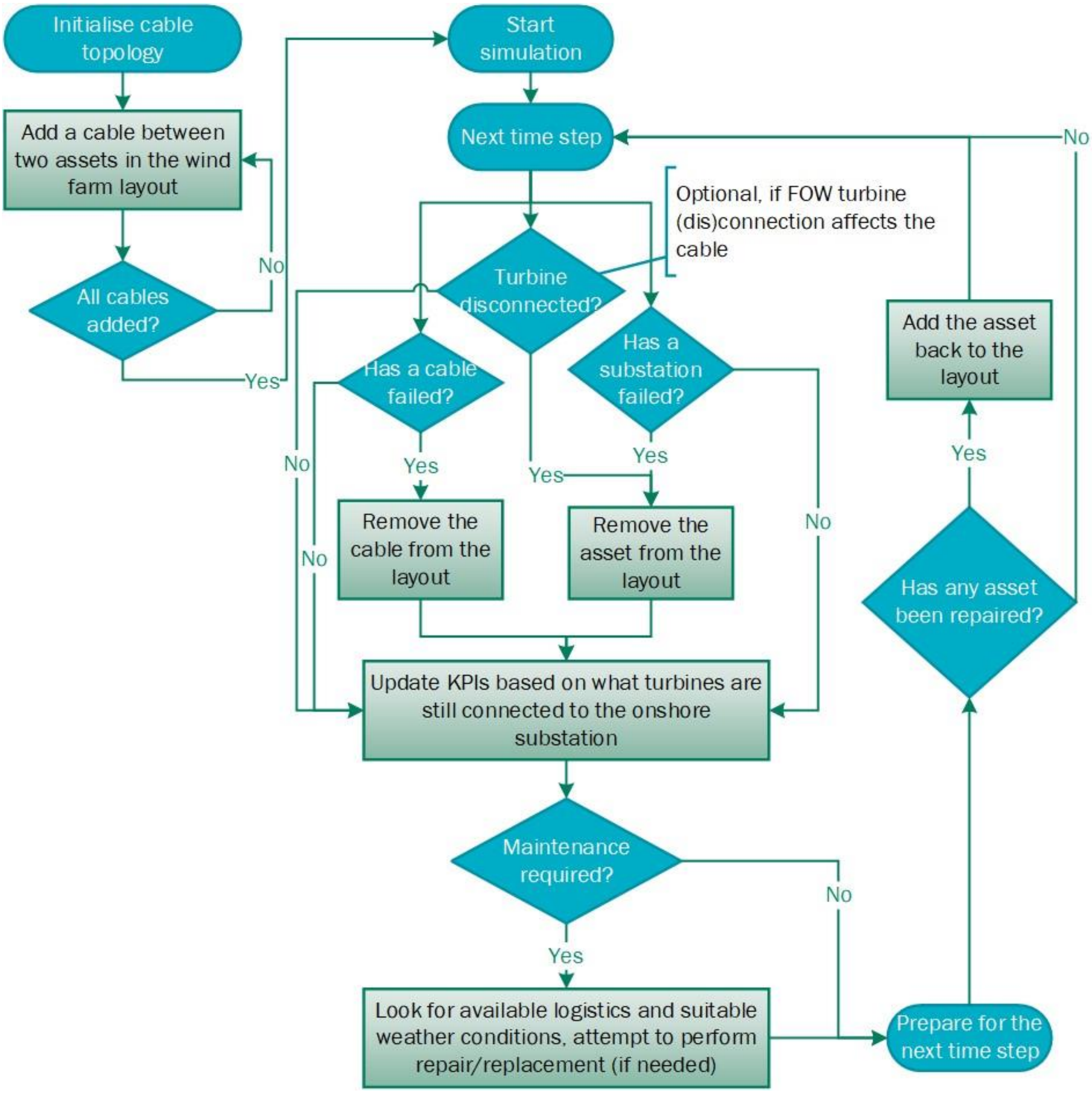

Figure 3: Computational logic in COMPASS for capturing cable failures and their impact on KPIs

1.3 Case study assumptions

Four cable topology designs were generated for comparison and are shown in the images below. Figure 4 and Figure 5 represent Design 1 and 2 respectively with 40 cables each, without any added redundancy. In both designs cables are connected in a string connection, but strings are shorter in the second design than in the first. Each modelled wind farm consists of 40 wind turbines, 15 MW each and 2 substations.

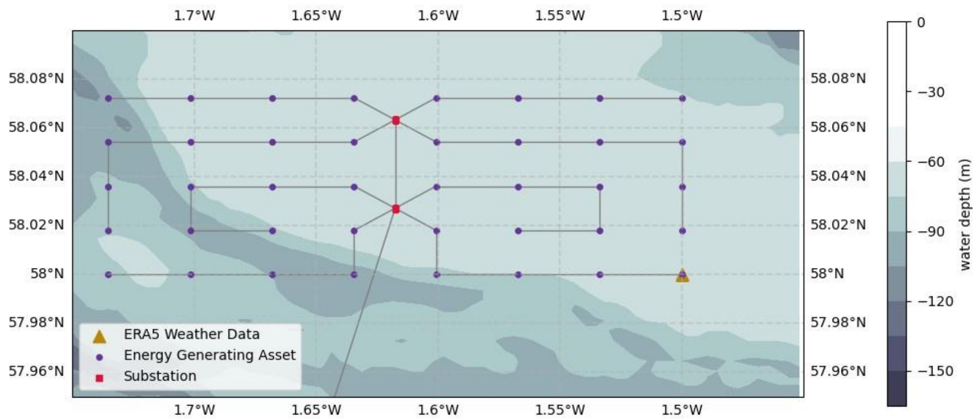

Figure 4: Wind farm layout where 40 turbines are connected in a string (radial) connection forming 8 strings representing Design 1

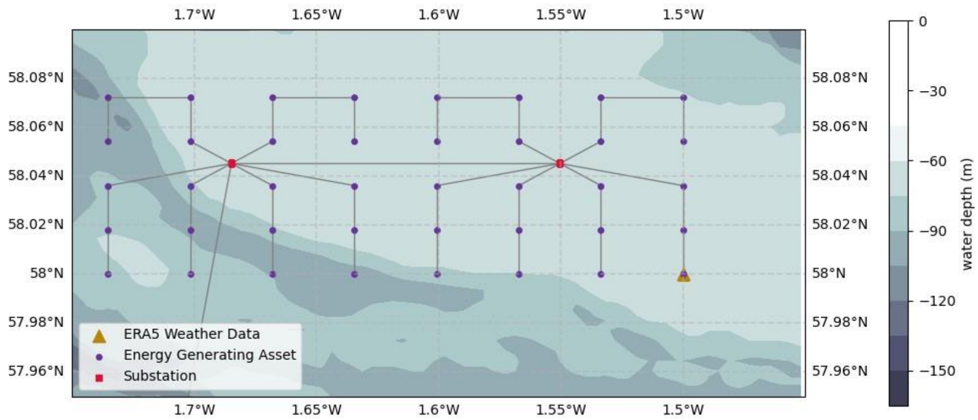

Figure 5: Wind farm layout where 40 turbines are connected in a string (radial) connection forming 12 strings representing Design 2

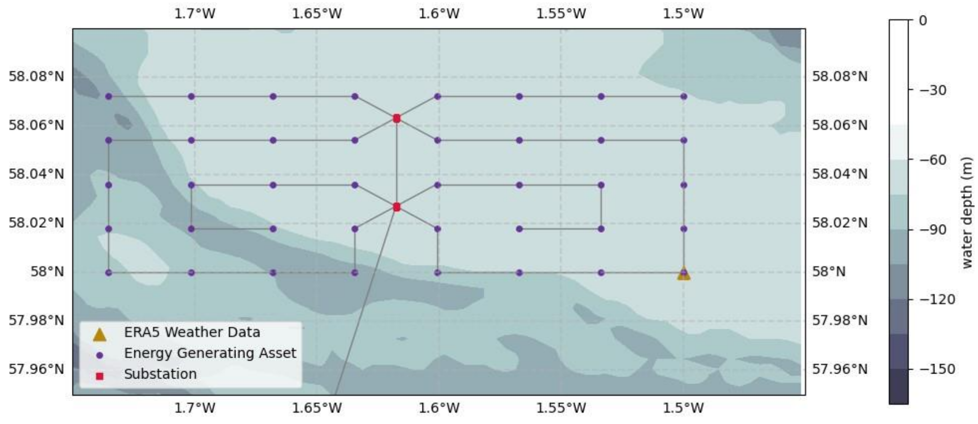

Figure 6: Wind farm layout where 40 turbines are connected in a combination of a string and a ring connection representing Design 3

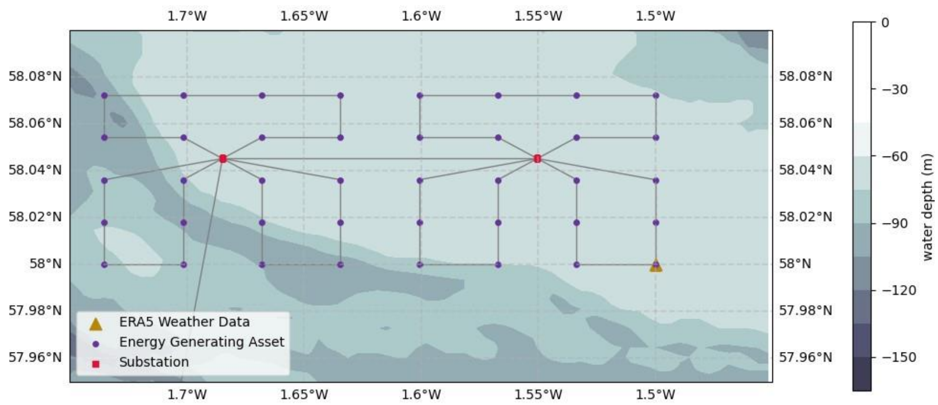

Figure 7: Wind farm layout where 40 turbines are connected in a ring connection representing Design 4.

The following assumptions were made in O&M simulations using these four designs:

- Power curve for 15 MW turbines was based on NREL [5].
- Power losses through the cables are neglected.
- Four failure rate options were considered: 0.006, 0.012, 0.015 and 0.018 failures per cable per year. The lowest value is estimated based on the average transmission cable failure rate reported in [6] and assuming a cable length of 2 km. Other values are added for the sensitivity analysis.
- Wind turbine, substructure and offshore substation failures are neglected. Export cable failures are neglected in all cases apart from the cable connecting the two substations, its failure rate is the same as that of other cables.
- Cable failure leads to a complete cable outage (i.e. no amount of electrical energy can transfer through that cable until it is fully replaced).
- The cable replacement process takes 48 hours (from the arrival of the cable laying vessel at the site)

- The table below shows the assumptions related to the cable laying vessel used during repair and replacement campaigns.

Table 1: Cable laying vessel assumptions.

Parameter	Value
Port	Fraserburgh, Scotland
Significant wave height limit during transit	5 m
Significant wave height limit during maintenance	2 m
Speed	20 knots
Mobilisation time	10 days

1.4 Results

1.4.1 Production Based Availability

Figure 8 provides the average PBA values resulting from simulating the wind farm in COMPASS with the four designs. As expected, PBA reduces much faster with an increase in failure rate in less redundant designs. Design 1, with long strings, resulted in the lowest PBA values and the steepest PBA reduction with failure rate increase. As expected, this is followed by Design 2, 3 and 4. Increase in failure rate affects Design 3 and 4 significantly less than Design 1 and 2.

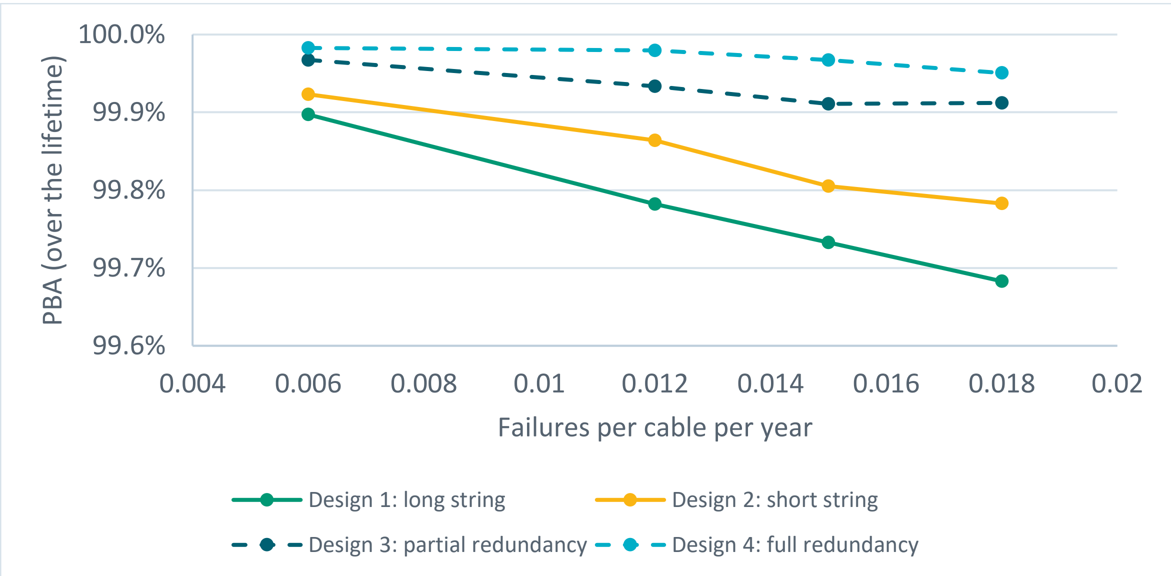

Figure 8: PBA over the entire lifetime of a wind farm resulting from each cable topology design and four failure rate options.

1.4.2 Revenue losses

PBA, weather data and electricity price can then be used collectively to estimate the revenue losses. Using ERA5 weather reanalysis data and the turbine power curve, total possible energy production per year was calculated to be 3,387,000 MWh [5], [7]. Revenue losses were then calculated using this value, PBA results from Figure 8. Discount rates were varied between 1% and 10% for the sensitivity analysis. Electricity price was assumed to be 60£/kWh, which is lower than what is currently seen in the market but it is in line with future projections. The volatility of the electricity price is not considered in this study but it can also make an impact on the selection of an optimal cable topology design. Higher electricity price would result in higher revenue losses in all cases.

As expected according to the PBA results, revenue losses are the highest when there is no additional cable that would add redundancy to the system. Figure 9 demonstrates how revenue losses vary under different discount rate conditions. As the discount rate gets higher, the difference between the revenue losses under different design conditions narrows down.

When the failure rate increases, the gap between the costs increases even further, this is demonstrated in Figure 10, where the failure rate per cable per year is 0.18 compared to 0.06 used in Figure 9.

Revenue loss estimates cannot be used to guide the selection of the optimal cable design alone. Another factor to consider is the price of additional cables added for redundancy. In Design 1, 2, 3, and 4 there are 40, 40, 42 and 46 array cables respectively. That translates into two additional cables in Design 3 and six additional cables in Design 4.

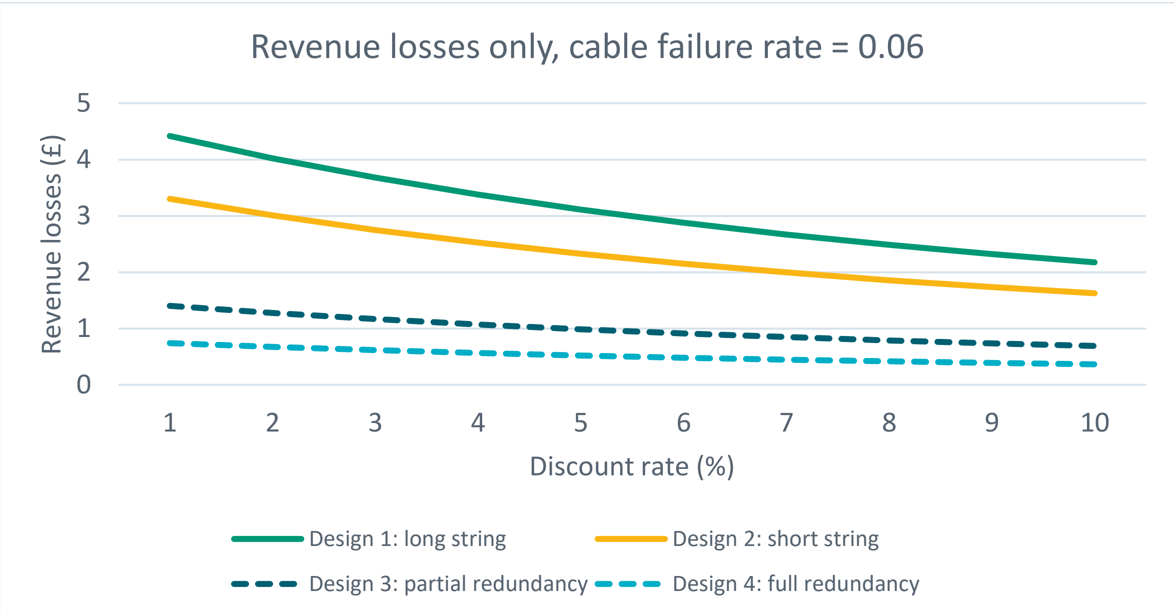

Figure 9: Revenue losses resulting from four designs under different discount rate conditions, assuming the rate of 0.06 failures per cable per year.

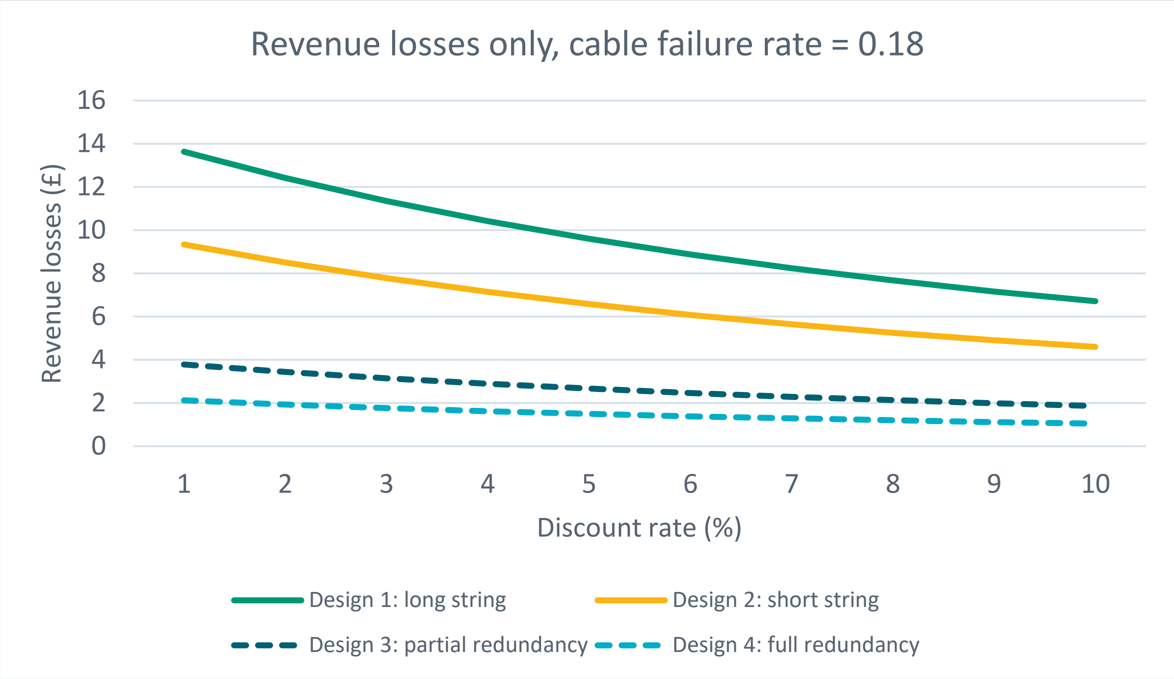

Figure 10: Revenue losses resulting from four designs under different discount rate conditions, assuming the rate of 0.18 failures per cable per year

1.4.3 Additional cable costs

Additional cable costs (those added to make up ring connections for redundancy), two cables in Design 3 and six cables in Design 4 were calculated assuming the cost per cable is £700,000/km. The costs were then combined with the revenue losses calculated previously. The results are demonstrated in the Figures below.

Despite the lowest revenue losses, Design 4 resulted in the highest cost overall among the considered designs, because of the up-front costs associated with six cables added for redundancy. In the case of high failure rate (equal to 0.18), Design 1 with long strings performs the poorest when the discount rate is below 5%.

Design 1 with long strings and Design 2 with short strings , which uses short strings without any additional redundancy are the most cost-effective in scenarios when the failure rate per cable per year is equal to 0.06, unless the discount rate is below 2% which is highly unlikely.

When failure rates increase, Design 2 (short strings) and Design 3 (partial redundancy) become more cost-effective than other designs. Design 2 is optimal when the failure rate is lower and Design 3 is optimal when the failure rate is the highest. For failure rates between 0.12 and 0.18 the choice of an optimal design would depend on the discount rate.

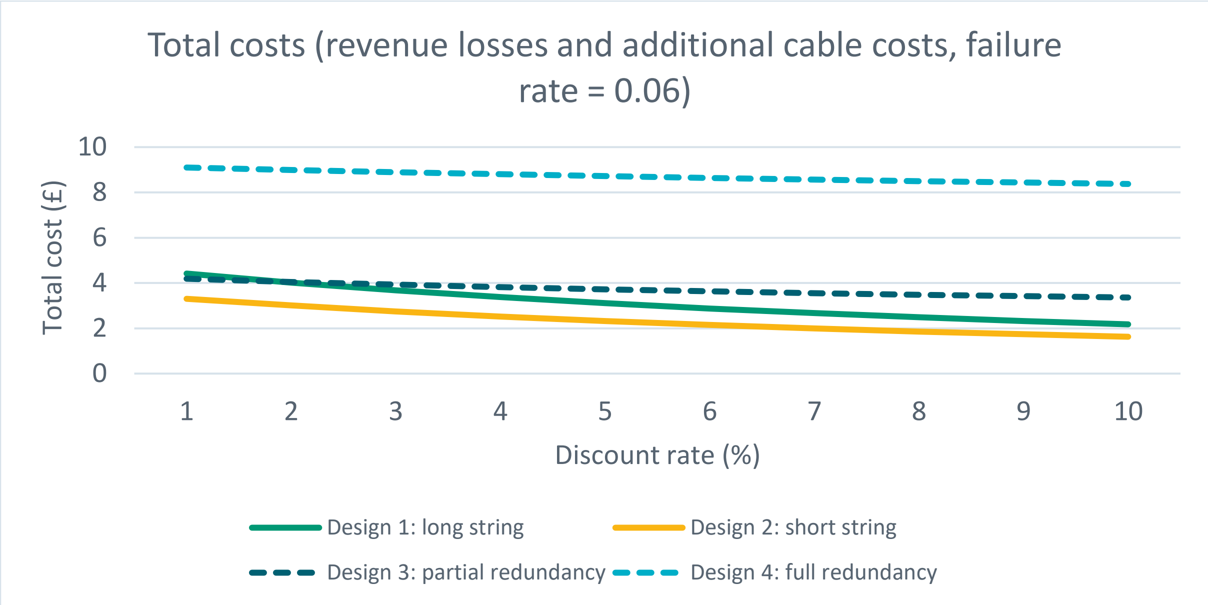

Figure 11: Total costs including revenue losses and additional cable costs under different design conditions assuming the failure rate of 0.06.

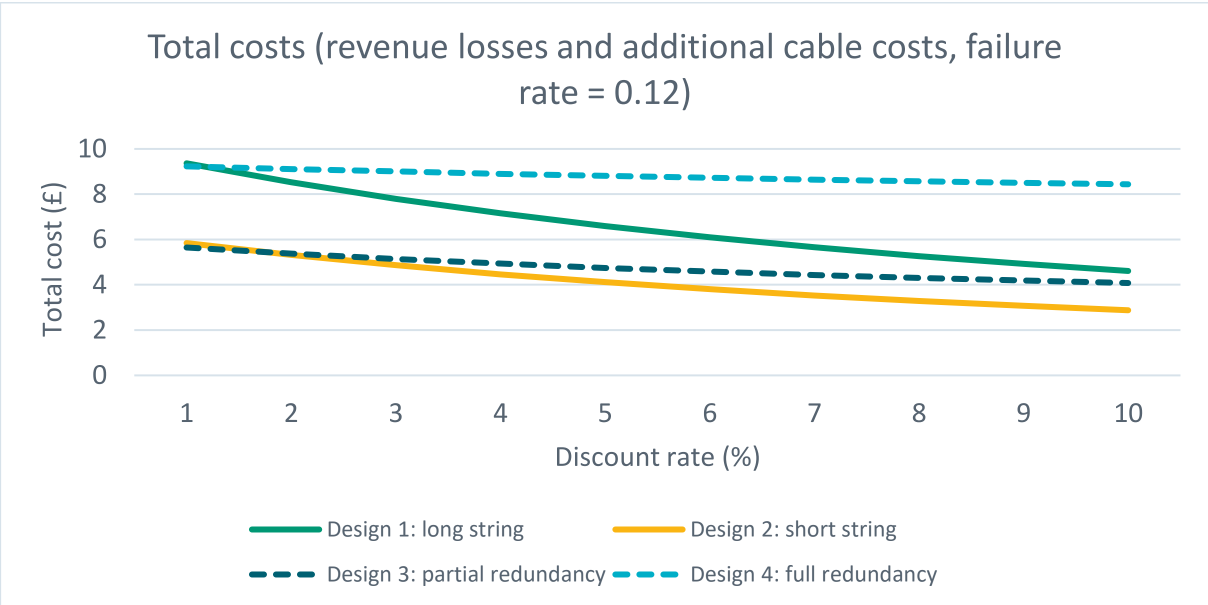

Figure 12: Total costs including revenue losses and additional cable costs under different design conditions assuming the failure rate of 0.12.

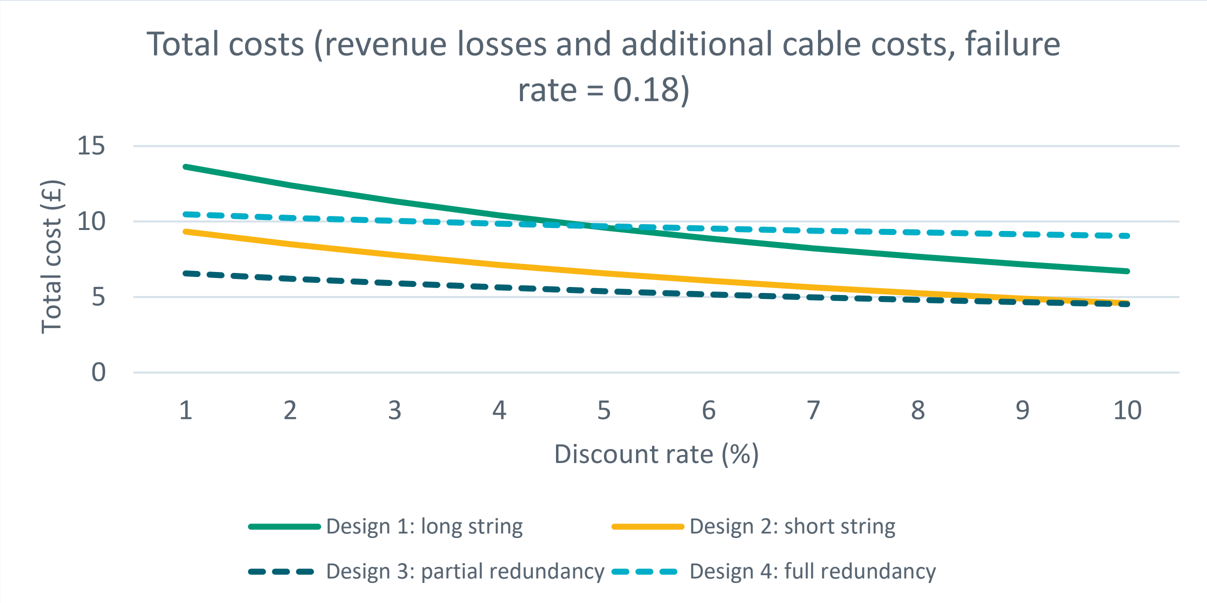

Figure 13: Total costs including revenue losses and additional cable costs under different design conditions assuming the failure rate of 0.18.

1.5 Conclusion

This analysis has shown how O&M simulation tools such as COMPASS can effectively be used for estimating PBA and the resulting revenue losses, comparing different cable topologies and analysing the impact of increasing the cable failure rate on the difference between the designs.

This analysis was based on a specific case of a hypothetical wind farm. Four hypothetical cable topology design options were considered. It is clear shorter cable strings can reduce the revenue losses and COMPASS has proven to be effective for assessing these savings quantitatively.

It has been shown that the choice of an optimal cable topology design can depend on the failure rate of the cable and the discount rate. It was shown in this hypothetical case that the design with short string connections is the most optimal one when the failure rate is low. When the failure rate is high, it was observed that partial redundancy can offer a cost advantage over a string connection. Additionally, reductions in revenue losses in the design with full redundancy do not compensate for the up-front costs required to add the redundant cables.

It is recognised that many other assumptions such as repair duration, cable laying vessel mobilisation time, cable cost and especially electricity price can all affect the preference of one cable topology design over the other. There is a lot of uncertainty in these variables. This work varied only failure rates and the discount rates however future sensitivity analyses can include more variables.

2 REFERENCES

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