ARRAY CABLE LAYOUT OPTIMISER

TRANSMISSION EXCELLENCE LTD
Lead authors: TARIGE HASSAN AND SEAN KELLY (TX)

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TX Array Layout Optimiser

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1 INTRODUCTION

There are two basic layouts that can be used when designing the power-collector arrays for offshore wind farms – strings and loops. String-based array cable layouts form a 'tree' structure and loop-based structures form closed loops. Please see Figure 1 below (the left image depicts a string-based array cable layout whereas the right image depicts a loop-based array cable layout) –

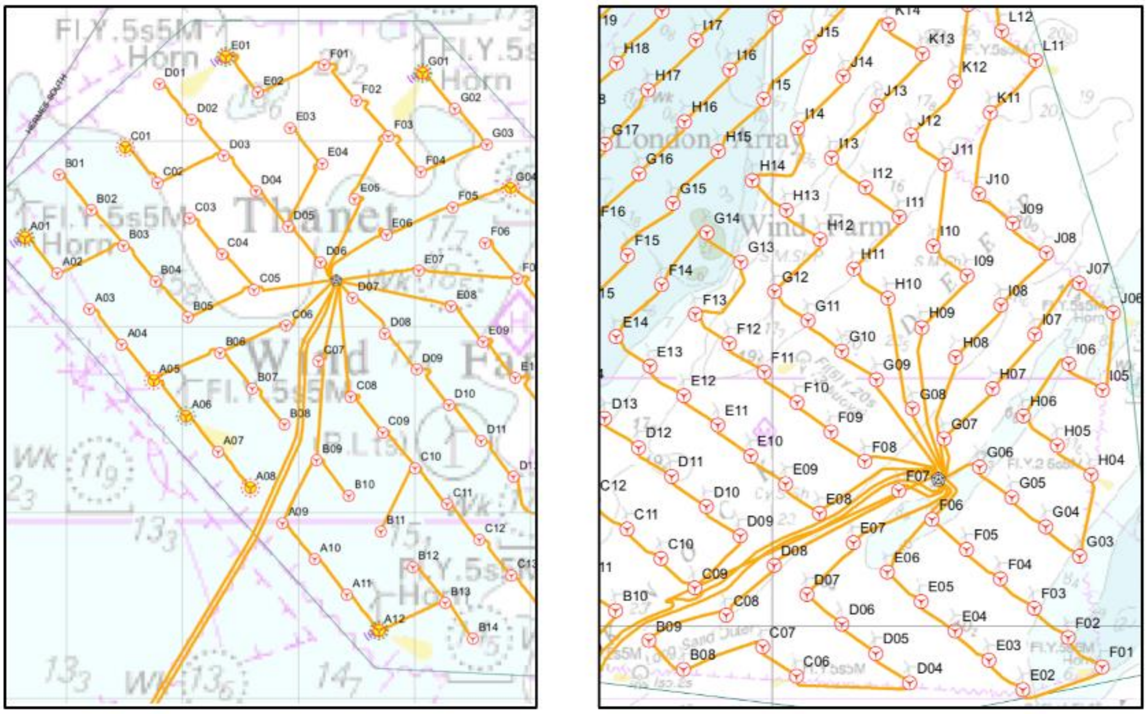

FIGURE 1 - COMPARISON OF STRING AND LOOP WINDFARMS

Both configurations have their own advantages and disadvantages. Loop-based array cable layouts have greater resilience: an array cable fault has a reduced impact on power output – no impact at all at low wind speeds – and no impact on the continuity of auxiliary power supplies for the turbine. The downside is that loops tend to be more expensive since additional cables are required. String-based array cable layouts, in contrast, offer lower capital costs but are less resilient if a fault occurs.

The greater resilience of loop-based array cable layouts is expected to become a larger advantage on future floating offshore windfarms. This is, firstly, because floating windfarms require dynamic cables, which are subject to additional stresses and thus are potentially at greater risk of failure. Secondly, many floating windfarm concepts envisage that turbines may need to be disconnected and towed back to port for major maintenance activities. This could have a severe impact in a string-based array, while the greater resilience of loop-based approaches would help mitigate this impact.

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Even with seabed-fixed wind turbines, loop-based array cable layouts are used extensively in Germany and to a reasonable degree in the UK. Based on our analysis of array layout data on the website of 4COffshore [1] we have found that as of May 2020 loop-based array cable layouts were used on 80% of all windfarm projects in Germany and 33% of all windfarm projects in the UK. Table 1 below lists all known loop-based windfarm projects in both countries:

United Kingdom (33%)		
Robin Rigg	London Array	Ormonde
Rampion	Greater Gabbard	Triton Knoll
Humber Gateway	Beatrice	

Germany (80%)		
Sandbank	Baltic 1	Borkum I & II
Butendiek	Baltic 2	Merkur
Veja Mate	Arkona	Alpha Ventus
Albatross	Kaskasi	Nordsee One
Hohe See	Meerwind Sud	Riffgat

TABLE 1 - LIST OF WIND FARMS USING LOOPS IN UK AND GERMANY

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2 OPTIMISER FEATURES

Transmission Excellence has developed software that can be used to optimise the design of a loop-based wind farm collector array. This is unusual: our literature search has shown that, while considerable work has been undertaken on the optimisation of string-based arrays, very little has been undertaken on loop-based arrays.

The optimiser determines the total cost of the cable system by adding:

i. The cable capital expenditure (capex). Different types of cables (i.e. different conductor materials and/or cross-sectional areas) may have different per-km costs and this is considered by the optimiser.

ii. The cost of any crossings – i.e. where two array cables cross each other, or where an array cable crosses an export cable.

iii. The cost of energy lost as heat. Different full-load losses can be entered for different cable sizes, and the optimiser will determine the losses across the full range of possible wind turbine outputs. Each level of wind turbine output is weighted by its probability, and these probabilities are in turn calculated based on a user-input average wind speed, an assumed Weibull distribution for wind speeds, and a user-alterable wind turbine power curve. It is assumed for the loss calculation that in normal operation each loop will be split into two strings.

iv. The lost income due to energy which cannot be collected should a cable fault occur. The optimiser will consider the outcome of every possible cable fault within the array, the likelihood of such faults (the mean time between failures and the mean time to repair are user inputs), and for each such fault it will calculate generation curtailment at every level of wind turbine output, applying probability weights as described in (iii) above.

Other special features of the optimisation software developed by TX include:

i. It determines the optimum set of cable sizes to be used – not just the optimum layout.

ii. Unlike most optimisers, which simply forbid cable crossings, the TX optimiser allows cable crossings but considers their cost as part of the capex. The crossing capex assumed for our validation studies was based on the crossing cable being laid on the seabed and then protected with approximately 1m of rock. Please see Section 7 for more details.

iii. Large wind farms can be automatically divided into multiple clusters, which each cluster served by a separate offshore substation. The location of each offshore substation can either be input by user or the optimum location can be found automatically.

The main limitations of the TX software are as follows:

i. The optimiser assumes that cables run in straight lines between wind turbines. This can result in some cables being considered to have a crossing by the optimiser, even though this crossing could have easily been avoided by a minor re-routing from the assumed straight-line route.

ii. Since export cables (like all cables) are straight lines, and cannot be routed to avoid unnecessary crossings of array cables, the optimiser calculates their cost by multiplying the straight-line distance to a fixed point outside of the wind farm by a fixed factor to allow for the impact of actual routing constraints. Once the optimiser has finished, an realistic export cable route to the edge of the wind farm must be found manually.

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3 COMPUTING TECHNOLOGIES

The optimisation software was initially written in Python because it is a high-level open-source programming language with an English-like syntax and access to a vast range of open-source libraries. However, as the software became more complex and the optimisation became more compute-intensive, the run times became unacceptably long. This required the introduction of a number of technical measures in order to keep run times reasonable:

i. The software was rewritten in Julia. Julia, like Python, is a high-level open-source programming language with an easy-to-read English-like syntax, but it runs faster thanks to Just-in-Time compilation and type declarations [2]. This increased execution speed by a factor of 30-40 relative to Python.

ii. The parallel-processing features of Julia were used to accelerate the program by another factor of 30 when run on TX's 32-core machine.

iii. An improved algorithm for identifying cable crossings, and an improved algorithm that (largely) separated the optimisation of cable routing from the optimisation of cable sizes helped to provide further acceleration, as did pre-calculating commonly computed values and storing these in a lookup table.

iv. The main algorithm used for optimisation is the genetic algorithm, which is described in the following section. Unfortunately, this algorithm is very computation-intensive, so it helps if it can be given a good initial solution guess which is already part of the way towards an optimised design. To do this we used a greedy heuristic[1] method described in the literature [3] to quickly provide a medium-quality starting point for the genetic algorithm. This is discussed in more detail in Section 4.

1 "Greedy heuristic" means that the algorithm decides first to include in its design those cable connections that offer the biggest one-off immediate benefit. It then never goes back on these decisions – even if these early decisions block other later routing decisions that could ultimately have saved more money overall. The main advantage of greedy heuristic algorithms is that they are fast. However in the studies undertaken for this project it was found that for any realistic wind farm layout the genetic algorithm was invariably able to find a better solution. For this reason our use of greedy heuristic algorithms is limited to quickly finding reasonable starting points for the genetic algorithm.

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4 OPTIMISATION ALGORITHM

The genetic algorithm [5] [6] [7] was selected as the main optimisation algorithm. A wide range of optimisation algorithms exist, and the genetic algorithm was preferred over the alternatives because:

i. It is flexible (with some other methods adding new features would be very complex).
ii. It is well documented in the literature.
iii. It scales well, working on very large wind farms with hundreds of turbines.
iv. No special software or mathematical skills are required for its use.

This choice is not unusual: a literature review of published algorithms for windfarm cable routing undertaken in 2019 [8] concluded that the genetic algorithm is the most popular:

i. 34% of published papers used the genetic algorithm.
ii. 25% used binary (or mixed integer) linear programming.
iii. 19% used heuristic methods (for fast medium-quality results).
iv. 8% used particle swarm optimisation.
v. The remaining 14% used a wide range of other algorithms, none with a popularity above 4%: mixed integer quadratic programming, mixed integer non-linear programming, ant colony optimisation and simulated annealing. Our own literature review revealed even more esoteric algorithms, including the Bat Navigation algorithm and the Harmony Search algorithm.

The genetic algorithm draws its inspiration from the evolution of organisms, with the array cable layouts being represented as “chromosomes” – a series of numbers that encodes how the wind turbines are connected to each other. A group of chromosomes – referred to as a “population” – is initially input. In our case this initial population comes from a fast heuristic method, as is described further below. Chromosomes are then randomly selected from the population and “bred” with each other to produce child chromosomes that contain a mix of their parents’ number-sequences. Some of these child chromosomes are then subject to random mutation.

The mutation algorithms used are outlined below. Whenever a chromosome is to be mutated one of these algorithms is selected at random:

i. Two random elements in the chromosome (representing two wind turbines) are swapped.
ii. A section within the chromosome between two randomly selected locations is reversed.
iii. A section between two randomly selected locations in the chromosome is moved by a randomly selected offset.
iv. A random number of turbines is donated from one loop and received by another loop.
v. A loop of sufficient length is split into two separate loops.

The chromosomes in the population with high “fitness” (i.e. a low total cost for the collector arrays they represent) are passed on to the next generation without further breeding or mutations. Chromosomes with high or medium fitness can breed to produce the next generation, and some of these offspring may also be mutated. The chromosomes in the population with the lowest fitness (i.e. high total cost) are not allowed to breed and become extinct. This process is repeated over multiple generations of breeding and mutations in order to keep improving the genetic fitness (i.e. to keep reducing the total cost). The process eventually halts when a certain number of generations have passed without any improvements in the best genetic fitness found.

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Please see Figure 2 below showing the genetic algorithm's concept:

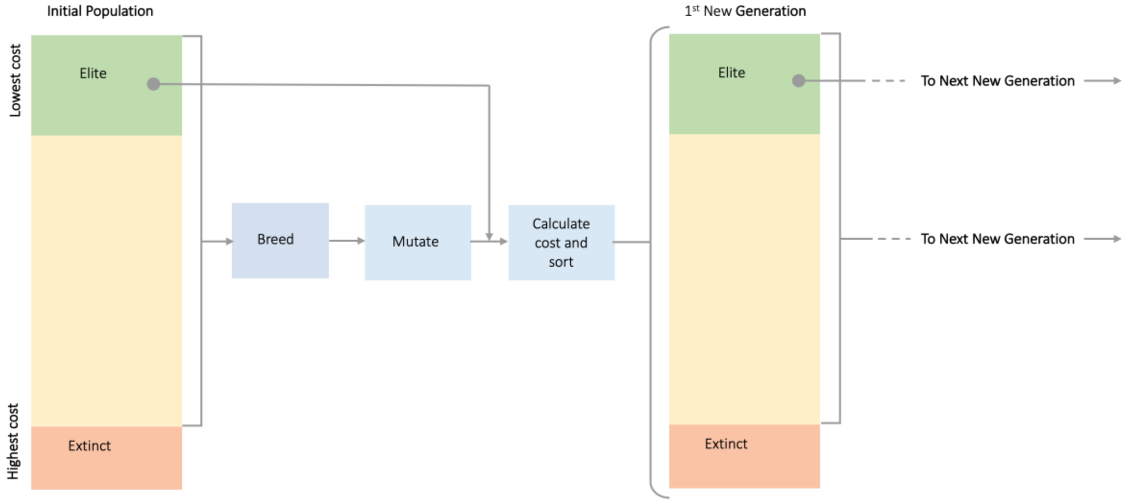

FIGURE 2 – GENETIC ALGORITHM

As noted in Section 3 above, a greedy heuristic method is used to provide the genetic algorithm with a medium-quality initial population. This heuristic method works by dividing the windfarm into "clusters" - segments radiating out from the substation in the centre, with each cluster containing the same number of turbines (except the last such cluster, which may have fewer). The Clarke and Wright savings algorithm [4] is then used to arrange all of the turbines in each cluster into a loop. Please see Figure 2 below –

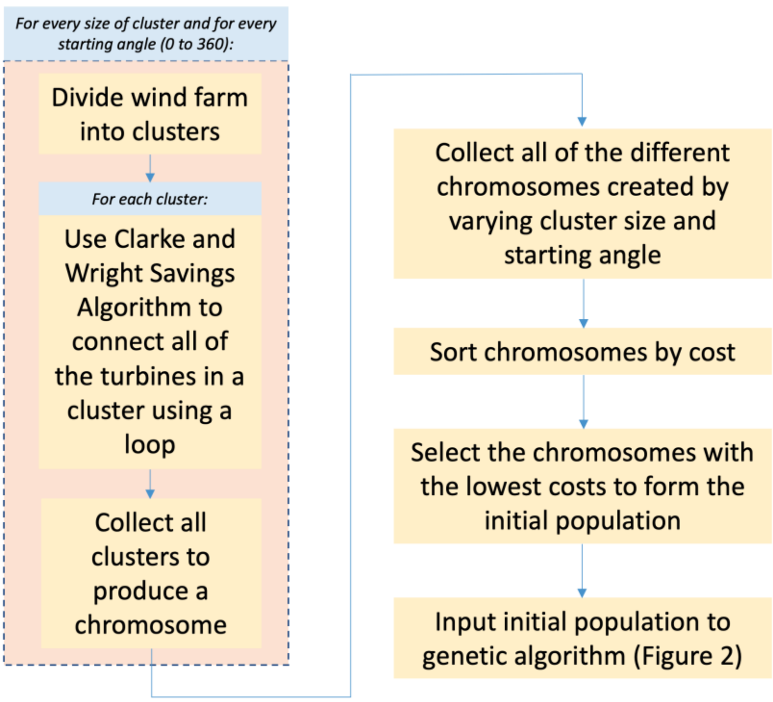

FIGURE 3 - GREEDY HEURISTIC ALGORITHM

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5 VERIFICATION

The genetic algorithm relies on a random number generator to decide which chromosomes breed, which are mutated, and how the breeding and mutation operations are undertaken. There is no certainty that it will find the optimum design. This means that it is impossible to verify our implementation of the algorithm by showing that it produces a "known correct" optimum design when given certain inputs.

Because of this, the verification process needs to be more complex. We have chosen a multi-stage approach:

i. The function that calculates the cost[2] associated with a chromosome is not dependant on random numbers. Hence this function can be tested in isolation (a "unit test") by feeding it test chromosomes for which the correct cost values have been independently calculated using a spreadsheet. This is discussed in more detail in Section 5.1.

ii. Once the cost calculation has been verified, the operation of the genetic algorithm can be verified by checking that the costs of the best chromosomes in the population fall as the algorithm runs for many generations.

iii. This shows that the genetic algorithm works in theory – but it does not prove that the results it produces are good enough to be useful on real windfarm projects (a downside of the genetic algorithm is that it gives no indication of how close to optimality its results are). To show that the results are practically useful, therefore, we have compared them to actual array cable designs on in-service windfarms. Examples of applying the array cable layout optimiser to in-service offshore windfarms are demonstrated in Sections 5.2, 5.3 and 5.4.

5.1 Unit testing of cost function

The unit testing stage involves inputting to the cost calculation function a range of simple windfarm designs for which the capex, curtailment and losses can be calculated analytically. Hence, errors in the code can be detected which would be very difficult to recognise on bigger windfarms.

Losses, curtailment, and capex costs are calculated via an Excel spreadsheet and/or manually and compared with the losses, curtailment and capex costs calculated by the cost calculation function. The cost calculation function, which is called by the genetic algorithm and elsewhere in the code, represents a substantial proportion of the code written, since in addition to calculating the cost of the cables, it must also:

i. Split loops into strings to calculate losses in their normal operating configuration.
ii. Consider the curtailment that would result following every possible cable fault.
iii. Calculate both losses and curtailments at all possible load levels, weighting each load level by its probability.
iv. Identify all cable crossings, adding an extra cost where these occur.

The unit testing process was automated so that these unit tests could be repeated easily whenever a change was made to the fitness calculation function.

[2] i.e. the total cost: cable capex + crossing capex + capitalised losses + capitalised curtailment

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5.2 Rampion

The first windfarm chosen to test the optimiser was Rampion [9]. Rampion was chosen because –

i. It is a relatively new windfarm (commissioned in 2018). Although we are not sure whether an optimiser was used in its design, its recent date suggests it was likely that some form of optimisation technique would probably have been applied.

ii. The windfarm is large with 116 wind turbines- so it is not "easy" to optimise.

iii. Data was available on the cross-sectional area of the array cables.

Data for the positions of the wind turbines and the offshore substation platform, along with the cable layout, was taken from the public website of KIS-ORCA [10] (an information service for the fishing industry), while data for cable sizes was obtained from [11]. Parameters used by the optimiser were as set out in Section 7. No attempts were made to find the parameters that might have been used by the original designers.

Please see Figure 4 which shows what we call the "as built" design for Rampion. It comprises:

i. The actual cable layout for Rampion, as given by the KIS-ORCA website [1].

ii. The two cable sizes actually used on Rampion: 33kV cables with either 150mm^2 copper conductors or 400mm^2 copper conductors. [11]

iii. For each cable in the array the choice between 150mm^2 and 400mm^2 is made in favour of the cheaper 150mm^2 unless the higher rating of 400mm^2 cable is required to allow the windfarm to operate at full load. We know from [11] that four of the cables shown below as 150mm^2 are in fact 400mm^2 (but not which cables) – but this represents a cost difference of less than £0.4m, so we feel justified in referring to Figure 4 as the "as-built" design.

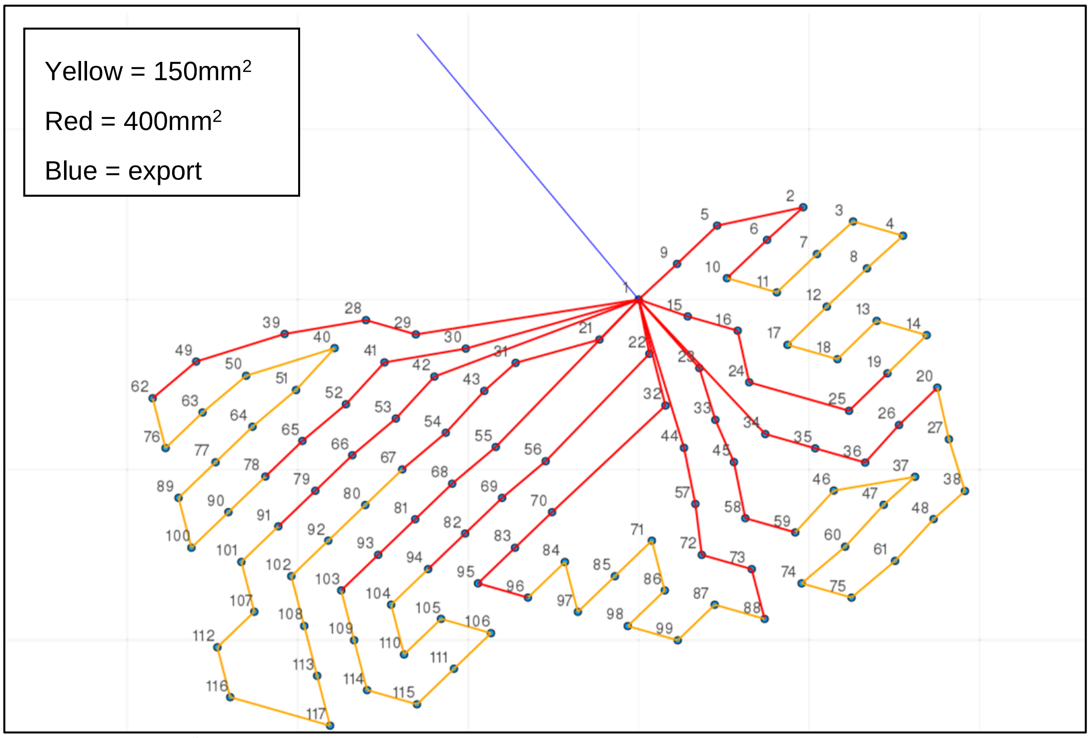

FIGURE 4 - RAMPION "AS-BUILT" DESIGN

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Figure 5 below shows the optimized array layout that results when we apply our optimiser to Rampion and restrict it to using the same cable types as are used in the "as-built" project.

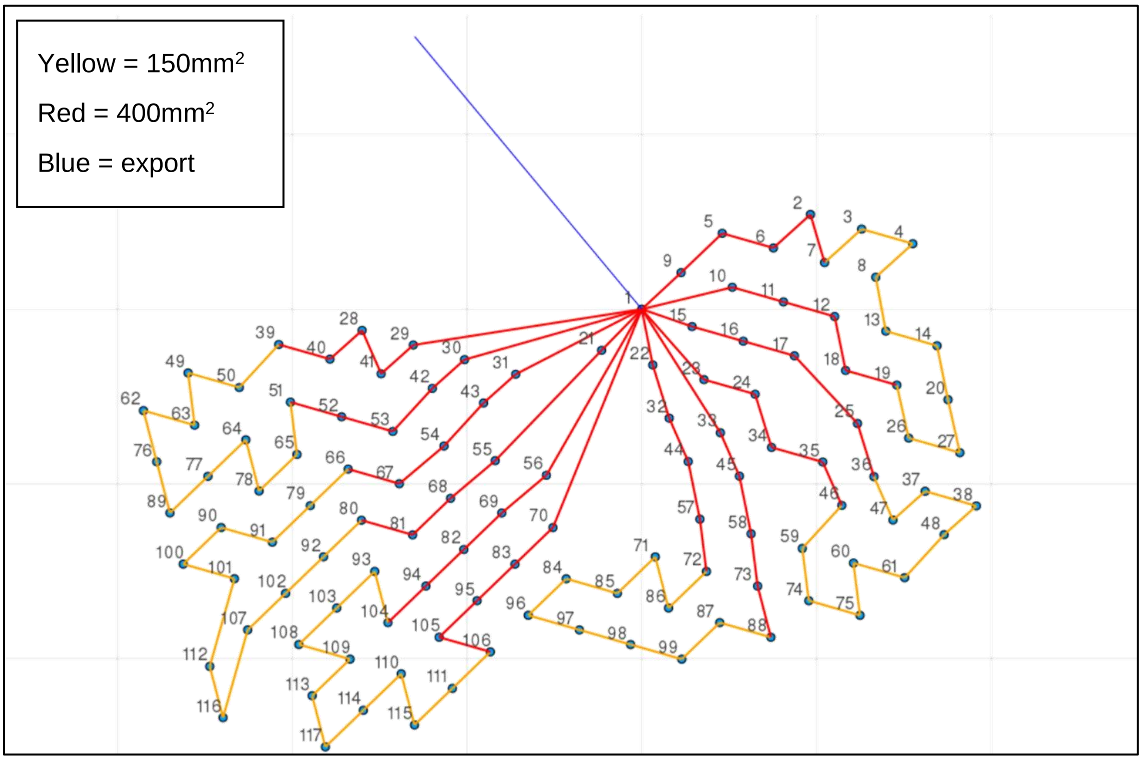

FIGURE 5 – RAMPION OPTIMISED ARRAY, OFFSHORE SUBSTATION IN AS-BUILT LOCATION.

Table 2 below shows a cost comparison between the as-built array cable layout and the optimised array cable layout:

Rampion	Cable Length (km)	Cable Capex (£m)	Curtailment Capitalised (£m)	Losses Capitalised (£m)	Crossings Capex (£m)	Total (£m)
As-built	116.0	77.6	5.2	14.2	0.0	97.1
Optimised Array	108.1	73.2	4.5	11.9	0.0	89.6

TABLE 2 – RAMPION: COST COMPARISON OF AS-BUILT AND OPTIMISED LAYOUTS

Table 2 shows the optimiser giving an array cable length improvement of 6.8% and an array cable cost improvement of 7.7%. These results validate our optimiser since it shows that it can provide very significant improvements in both length and cost, even when constrained to use the same cable types used in Rampion.

As noted previously, the assumptions we have used for factors such as energy cost may be different from those used by the Rampion project, but given the scale of the savings possible through use of the optimiser – and the fact that it saves money in every cost category – this is unlikely to affect our conclusions.

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When the optimiser is given a free hand to choose any two sizes of 33kV copper cable[3] (from 95mm^2 to 800mm^2) it chose to use 95mm^2 and 400mm^2. In other words, the optimiser is choosing to replace the 150mm^2 cable with the smaller and cheaper 95mm^2 size; the lower per-km cost of 95mm^2 relative to 150mm^2 turns out to more than offset the increased cost from needing to use 400mm^2 cables more widely. This design saved £0.7m relative to the design in Figure 5.

Designing a collector array to use a mix of *three* different cable sizes is less common but is sometimes done. When the optimiser is given a free hand to choose any three sizes of 33kV copper cable it chose to use 95mm^2, 240mm^2 and 400mm^2. This saved £1.7m relative to the design in Figure 5, and £1m relative to the best two-cable-size design. This £1m saving may be sufficient to justify the extra logistic costs associated with manufacturing and handling three different cable sizes.

In the work described above the offshore substation is kept at its as-built location. The next stage was to additionally allow the optimiser to find the best substation location. To do this a "fixed point" for the export cable route was set at the uppermost point on the blue line in Figure 6 below. Above the "fixed point" the export cable route was assumed to be the same regardless of the location selected for the offshore substation, so its cost is irrelevant to the optimisation. Below the "fixed point" the cost of the export cable route was estimated as the distance from "fixed point" to the offshore substation, multiplied by the cost of the export cables (2x200MW 150kV cables, estimated to cost £900k/km each).

This gave the result shown in Figure 6 below:

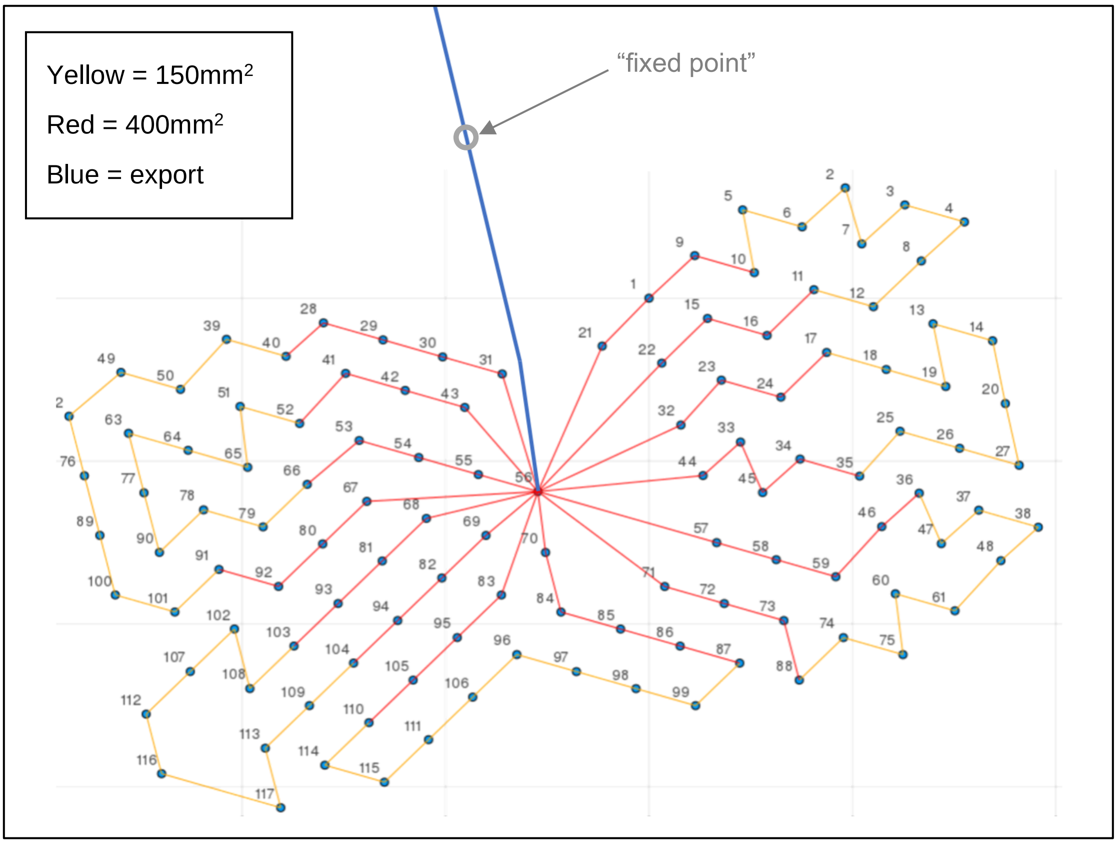

FIGURE 6 - RAMPION: OPTIMISED ARRAY AND SUBSTATION LOCATION

[3] For this test the optimiser can select any two conductor cross sectional areas from the following range of standard sizes: 95mm^2, 150mm^2, 240mm^2, 300mm^2, 400m^2, 500mm^2, 630mm^2 and 800mm^2.

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As can be seen in Figure 6, the optimiser's preference for the offshore substation is a point deep inside the array rather than a point on its edge as was the case in the as-built design. As shown in Table 3 below this allows further substantial savings:

i. Costs are 5% lower than the design shown in Figure 5, where the array layout had been optimised but the offshore substation remained in the as-built location. The new substation location reduces the array cost by £7.1m (with particular savings on curtailment costs and losses). This far exceeds the extra £2m export cable cost, which is associated with the export cable route being lengthened by 1.1km.

ii. Costs are nearly 12% lower than in the as-built design.

Rampion	Array Cable Length (km)	Cable Capex (£m)	Curtailm't Capitalised (£m)	Losses Capitalised (£m)	Crossings Capex (£m)	Export Cable (£m)	Total (£m)
As-built	116.0	77.6	5.2	14.2	0.0	9.1	106.1
Optimised array, as-built substation	108.1	73.2	4.5	11.9	0.0	9.1	98.6
Optimised array & substation	105.4	71.3	2.7	8.4	0.0	11.1	93.5

TABLE 3 – RAMPION: COST COMPARISONS OF AS-BUILT, OPTIMISED ARRAY AND OPTIMISED ARRAY AND SUBSTATION LOCATION. NOTE THAT THE EXPORT CABLE COST RELATES ONLY TO THE PART BELOW THE "FIXED POINT"

5.3 Veja Mate

The second windfarm chosen to test the optimiser was Veja Mate [12]. Veja Mate was chosen because:

i. Like Rampion, Veja Mate is a relatively new windfarm (commissioned in 2017).

ii. Although we cannot confirm whether an optimiser was used, its recent date suggests it was likely that some form of optimisation technique would have been applied. In addition, the turbine positions are somewhat irregular (i.e. not in a strict array with parallel, evenly spaced, rows). This also suggests a use of automated design tools.

iii. Data was available showing where differently sized cables were used (but not, in this case, the cross-sectional area of the cables).

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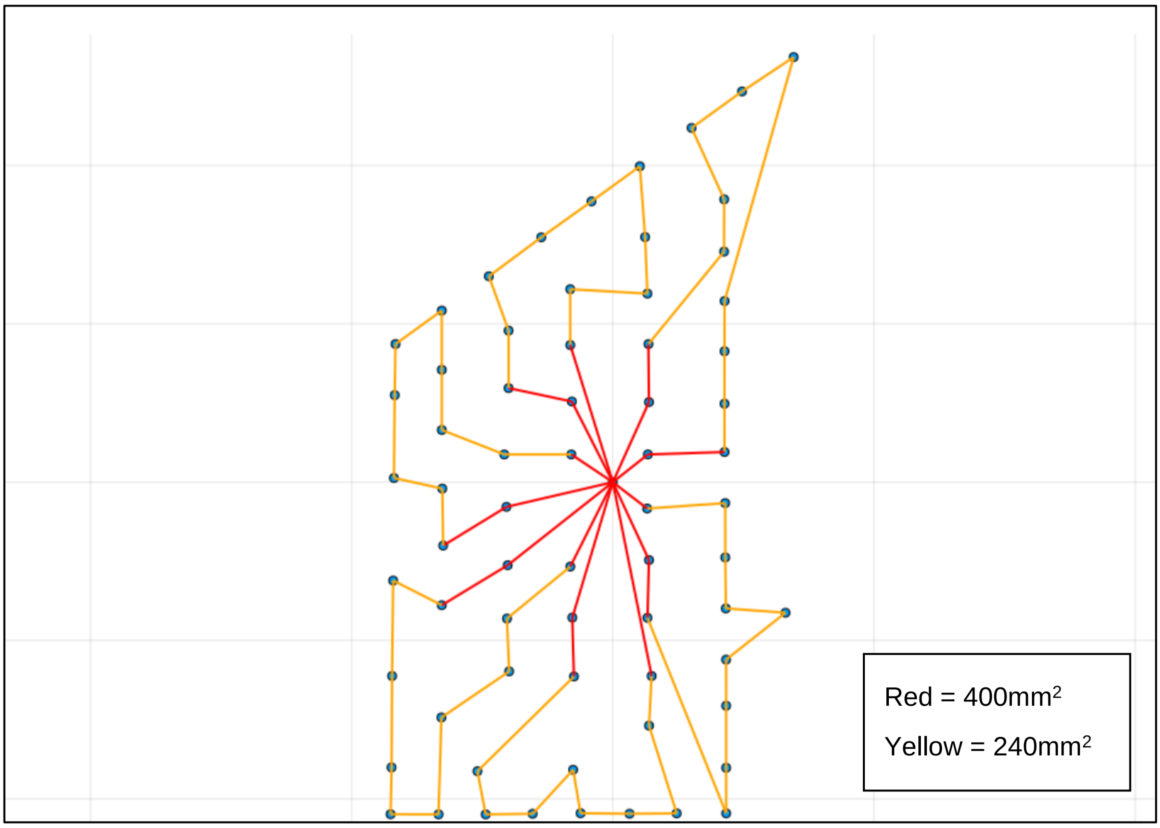

FIGURE 7 - VEJA MATE "AS-BUILT" DESIGN

Figure 7 above shows what we call the "as built" design for Veja Mate wind farm. It is based on the following source and analysis:

i. The actual cable layout for Veja Mate, as given by the 4COffshore website [1].

ii. According to a diagram in [13], Veja Mate's loops each comprise two strings connected by a normally open cable. Each string contains one or two larger cables, and then four cables of a smaller type (not including the normally open cable).

iii. The turbine size is 6MW, so it follows that the smaller cable type (shown green in Figure 4) must have a capacity of at least 4x6 = 24MW, while the larger cable type (shown red in Figure 4) must have a capacity of at least 6x6 = 36MW. Based on TX's database of cable ratings we believe that the green cable is most likely to be 240mm^{2}copper, while the red cable is most likely to be 400mm^2 copper.

Figure 8 below shows the optimized array layout that results when we apply our optimiser to Veja Mate and restrict it to using the same cable types as are used in the "as-built" project.

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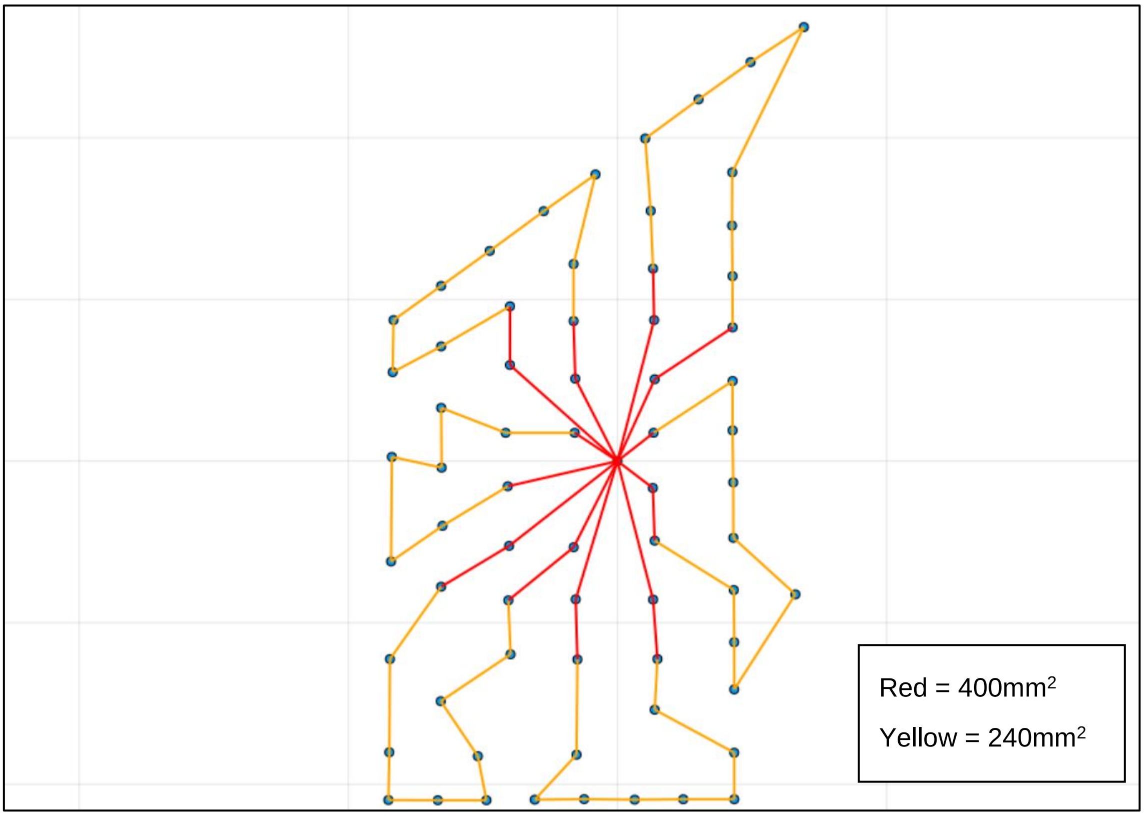

FIGURE 8 - VEJA MATE OPTIMISED DESIGN

Table 4 below shows a cost comparison between the Veja Mate as-built array cable layout and the optimised array cable layout:

Veja Mate	Cable Length (km)	Cable Capex (£m)	Curtailment Capitalised (£m)	Losses Capitalised (£m)	Crossings Capex (£m)	Total (£m)
As-built	104.3	70.9	2.8	11.5	0.0	85.2
Optimised	98.9	67.5	2.9	11.2	0.0	81.6

TABLE 4 – VEJA MATE: COST COMPARISON OF AS-BUILT AND OPTIMISED LAYOUTS

Table 4 shows that TX's optimiser gives an array cable length improvement of 5.2% and an array cable cost improvement of 4.2%. These results validate our optimiser since it shows that it can provide very significant improvements in both length and cost, even when constrained to use the same cable types used in Veja Mate.

When the optimiser is given a free hand to choose any two sizes of 33kV copper cable it chose to use 95mm^2 and 400mm^2 – the same sizes as on Rampion. This saved £0.5m relative to the design in Figure 7.

When the optimiser had a free hand to choose any three sizes of 33kV copper cable it chose to use 95mm^2, 240mm^2 and 400mm^2 – again, the same sizes as Rampion. This saved £1.4m relative to the design in Figure 7, and £0.9m relative to the best two-cable-size design. This £0.9m saving may be sufficient to justify the extra logistic costs associated with manufacturing and handling three different cable sizes

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5.4 Baltic 2

The third windfarm chosen to test the optimiser was Baltic 2 [14]. Baltic 2 was chosen to demonstrate the benefit of having the algorithm add a cost for cable crossings rather than forbidding crossings entirely, as is commonly done by array optimisers.

Baltic 2 was selected for this purpose because it has an unusually large number of export cables (4 cables) that connect to its single offshore AC substation[4].

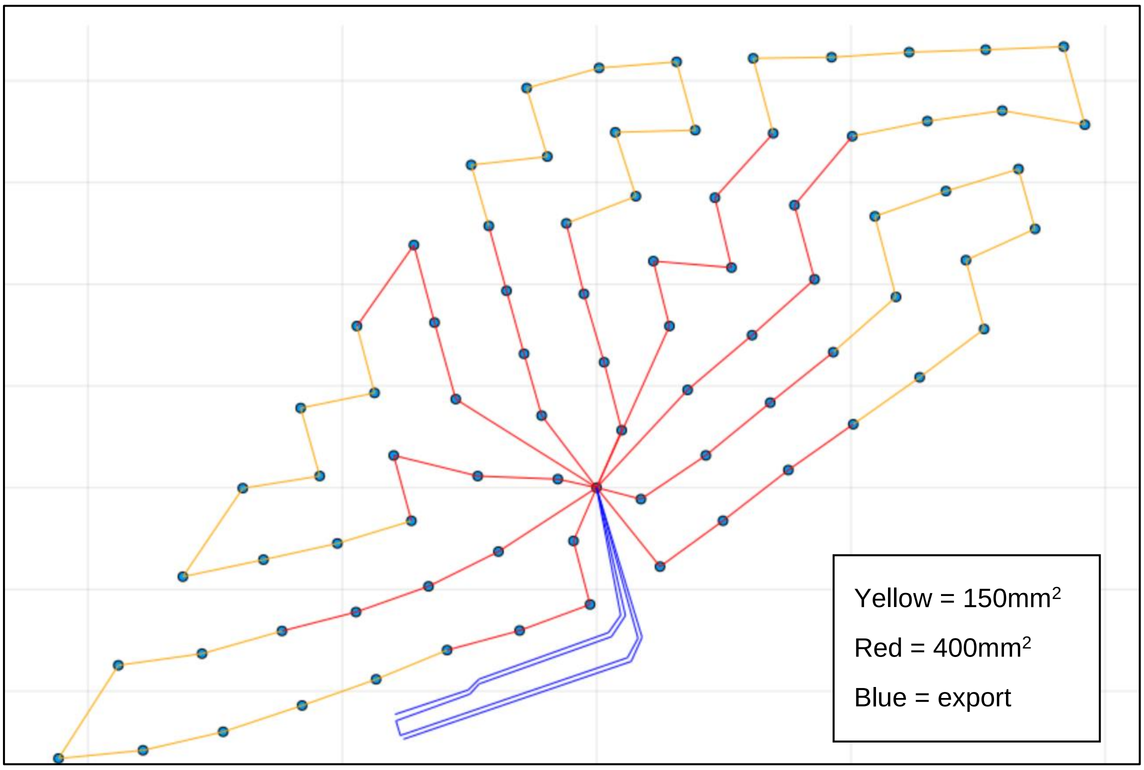

FIGURE 9 - BALTIC 2: AS-BUILT EXPORT CABLE ROUTE

Figure 9 above shows:

i. The actual turbine sizes, turbine positions, offshore substation position, and export cable route for Baltic 2. These are taken from the 4COffshore website [1].

ii. Array cable routes are as output by our array cable layout optimiser, which is allowed to choose from 33kV 150mm^2 copper and 400mm^2 copper cables.

In Figure 10 below, the as-built export cable route is replaced with a shortened route that goes to the substation in a straight line. This reduces the length of the export cable route by 0.8km; with four parallel 150kV export cables costing (say) £1m/km this would equate to a saving of £3.6m.

[4] This is because it forms part of a wider integrated offshore transmission system.

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As can be seen in Figure 10 our array cable layout optimiser has chosen not to move any of the array cables, instead accepting that one of the array cables will be crossed by all four export cables. Our base case (see Section 7 – Assumptions, which ignores economies of scale[5]) is that each crossing will cost £0.3m, so this extra cost is massively outweighed by the saving from a more direct export cable route.

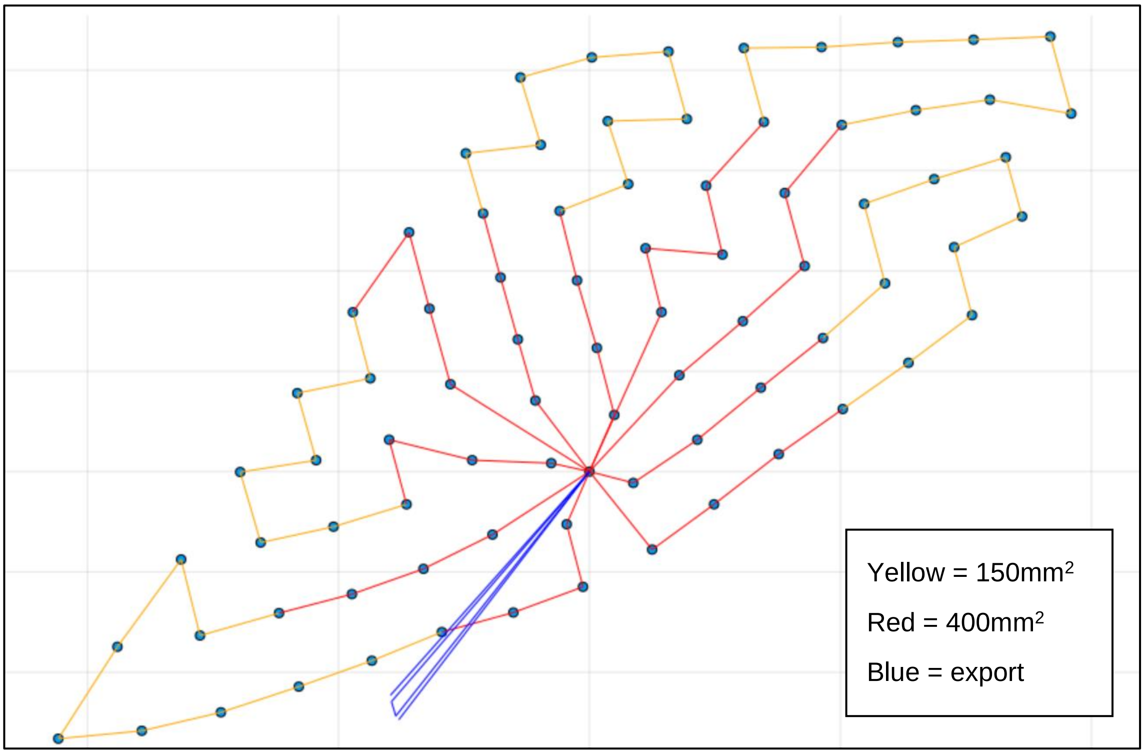

FIGURE 10 – BALTIC 2: SHORTENED EXPORT CABLE ROUTE

If the optimiser was of the type that did not allow cable crossings then it might still have been possible to save money by having a straight-line export cable route and re-routing the array cables to avoid it. This can be simulated in our optimiser by increasing the cost of each crossing so that the optimiser prefers to avoid them. Doing this, the result is as shown in Figure 11 below.

[5] Arguably having a single array cable cross four close-together export cables should cost much less than four separate cable crossings (at least assuming that the export cables are installed first).

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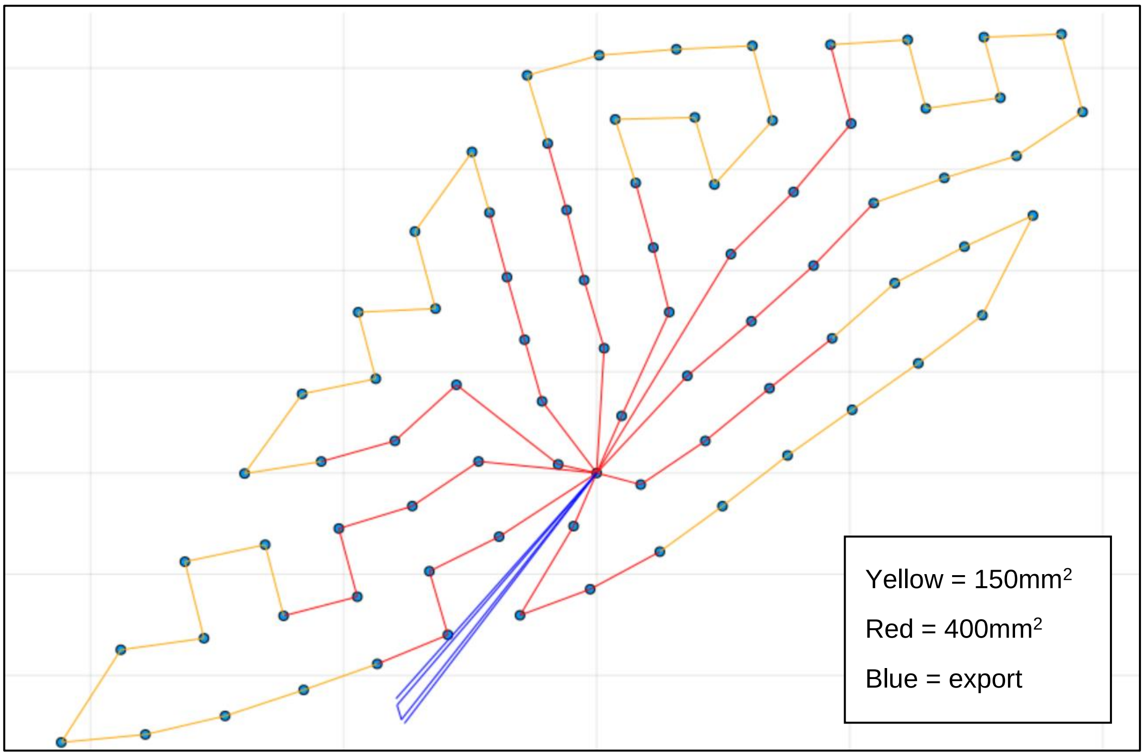

FIGURE 11 - BALTIC 2: SHORTENED EXPORT CABLES, NO CROSSINGS

The cost of the designs shown in Figures 9, 10 and 11 are set out in Table 5 below:

Baltic 2	Array Cable Total Cost (£m)	Change in Export Cable Cost (£m)	Total (£m)
As-built export cable route, optimised array	51.8	0.0	51.8
Shortened export cable route, optimised array	53.0	- 3.6	49.4
Shortened export cable array, no crossings	53.4	- 3.6	49.8

TABLE 5 - BALTIC 2 DESIGN COMPARISON

As can be seen, the approach taken by TX's optimiser (i.e. to allow crossings, but to penalise them with a higher cost) provides a material cost saving (in this case £0.4m) relative to the approach commonly taken by optimisers.

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5.5 Sofia

The last windfarm chosen to test the optimiser was Sofia [15]. Sofia was chosen because:

i. Sofia is Britain's newest offshore wind farm (due to be commissioned in 2025).

ii. Data was available regarding the array cable layout, the cross-sectional area and the conductor material used [16]. Using our optimiser we examined all possible cable-size combinations for aluminium core cables[6] and confirmed that the cable sizes chosen for the Sofia windfarm – 400mm^2 and 1000mm^2 – were the lowest-cost solution if aluminium conductors are being used and the number of cable cross sections is limited to two.

Figure 12 below shows the "as built" layout of Sofia (taken from [16]), and our calculated mix of 400mm^2 and 1000mm^2 cables. We used the optimiser to find the optimum mix of 1000mm^2 and 400mm^2 cables but found that this was identical to the design that connected the 14MW turbines at minimum capex.

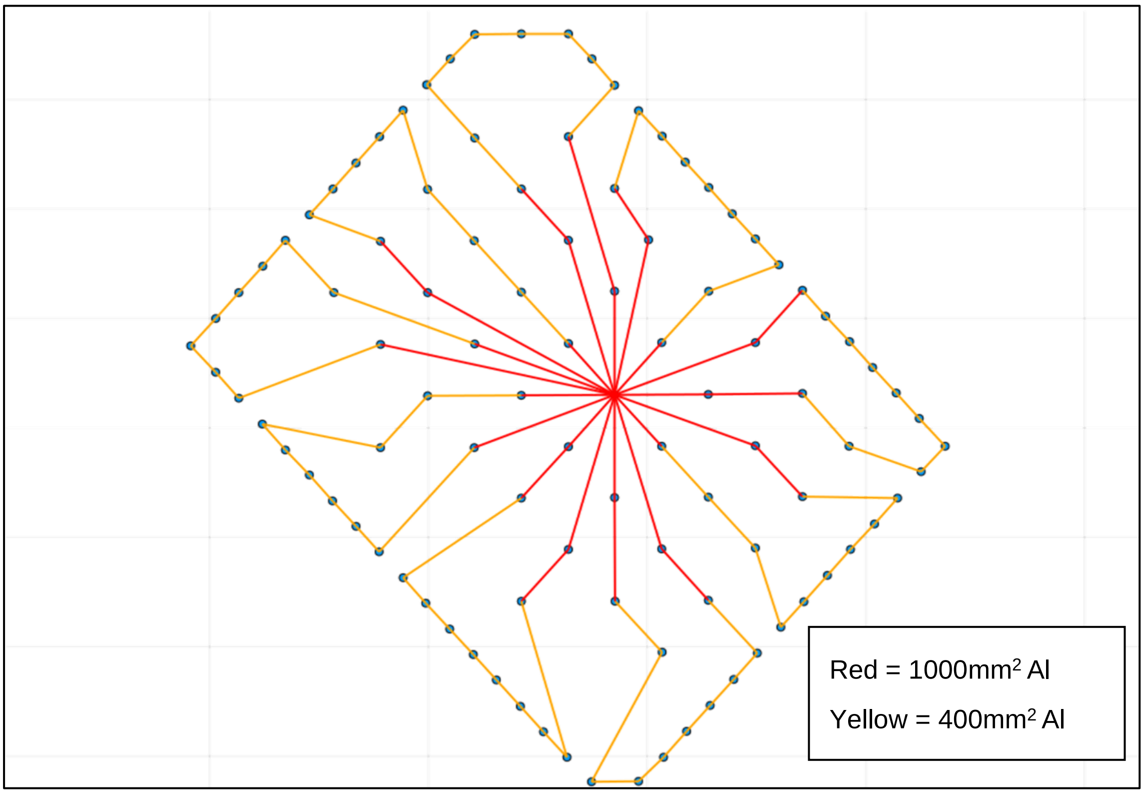

FIGURE 12 - SOFIA "AS-BUILT" DESIGN

Note that, in addition to the 100 expected turbine positions, the published data in [16] also shows the array cables routed via a "spare" turbine position. To ensure a fair comparison between as-built and optimised designs, we have required our optimiser to treat this spare position as an additional turbine.

[6] For this test the optimiser can select any two conductor cross sectional areas from the following range of standard sizes: 95mm^2, 150mm^2, 240mm^2, 300mm^2, 400m^2, 500mm^2, 630mm^2, 800mm^2 and 1000mm^2. Because of the lower rating of aluminium cables, this range extends up to 1000mm^2, while copper cables were limited to 800mm^2.

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Figure 13 below shows the optimized array layout that results when we apply our optimiser to Sofia and restrict it to using the same cable types as are used in the "as-built" project.

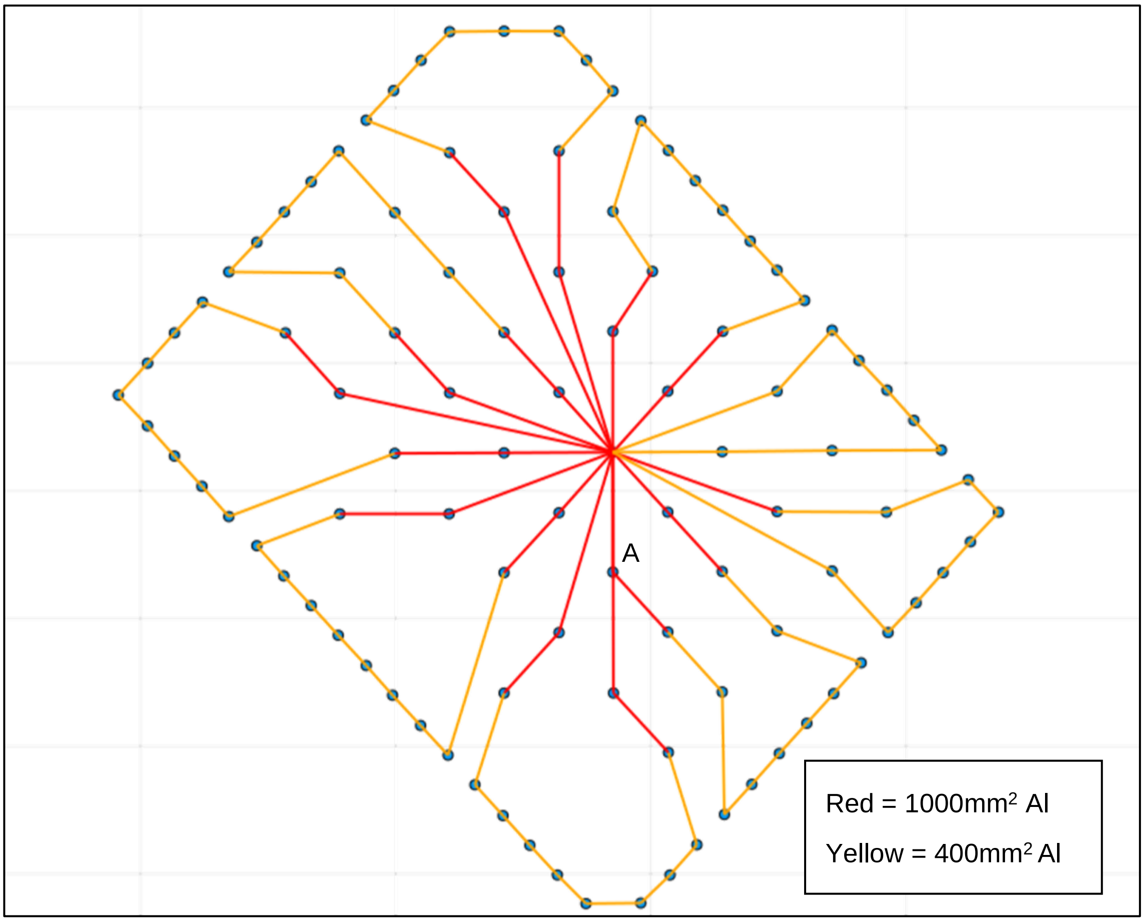

FIGURE 13 - SOFIA OPTIMIZED DESIGN

From Figure 13 it can be observed that:

i. The optimised solution consists of two smaller loops (around the 3-c'clock position) with 8-9 turbines, while the rest of the loops are of the largest possible size (12 turbines). In contrast, all of the loops in the "as-built" design are similar in size, with 10 - 12 turbines each.

ii. Between the wind turbine at location "A" and the substation, there are actually two cables belonging to different loops. However, due to the resolution of the image, these cables (which are parallel and close together) appear to be a single cable.

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Table 6 below shows a cost comparison between the Sofia as-built array cable layout and the optimised array cable layout:

Sofia	Cable Length (km)	Cable Capex (£m)	Curtailment Capitalised (£m)	Losses Capitalised (£m)	Crossings Capex (£m)	Total (£m)
As-built	355.9	278.2	11.5	65.3	0.0	354.9
Optimised	346.2	269.4	11.6	65.5	0.0	346.5

TABLE 6 – SOFIA DESIGN COMPARISONS

It can be seen that TX's optimiser gives an array cable length improvement of 9.7km and an array cable cost improvement of £8.4m. These results show that the optimiser is delivering quite significant cost savings.

We also used the TX optimiser to consider the optimum cable sizes if the design rules were changed to allow three (rather than two) different sizes of aluminium-conductor cables to be used. It was found that by using cable sizes of 300mm^2, 630mm^2 and 1000mm^2 a further saving of £8.7m (over and above the £8.4m saving described above) was possible.

5.6 London Array

The last windfarm chosen by the windfarm to be tested by the optimiser is London Array. London Array was chosen for the following reasons:

i. London Array is a large windfarm consisting of 175 turbines. This makes it comparable to the very large future wind farms that any software developed today may be called on to design.

ii. While there are many offshore wind farms that use loops and have multiple offshore substations, most of these are ruled out as good test cases due to other factors. For instance, some projects have two offshore substations deliberately built next to each other, in some projects the areas served by each offshore substation are widely separated (so our algorithm for dividing the wind farm into areas served by different substations would hardly be challenged), and in others there are a mix of arrangements rather than just loops. London Array is one of very few projects that do not suffer from any of these issues.

TX has assumed cable conductor sizes of 150mm^2 and 400mm^2 for the London Array design.

The as-built layout is shown in Figure 14 below, while the output of our optimiser is shown in Figure 15. For the optimised design:

i. The optimiser automatically splits the array into two parts, each with its own offshore substation.

ii. The optimiser automatically selects where the offshore substations are to go.

iii. The optimiser also designs the array cable system around each offshore substation.

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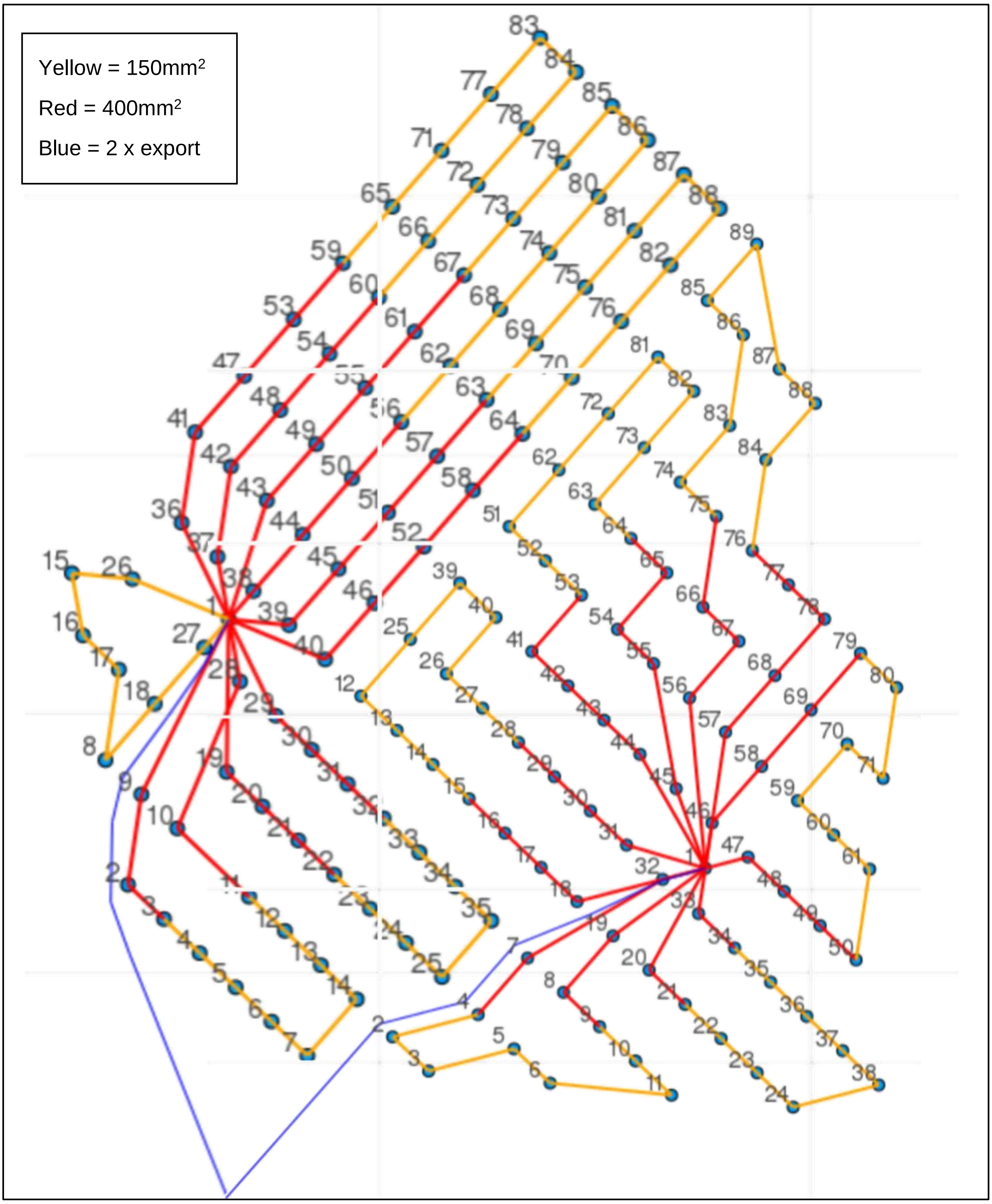

FIGURE 14 - LONDON ARRAY AS-BUILT LAYOUT

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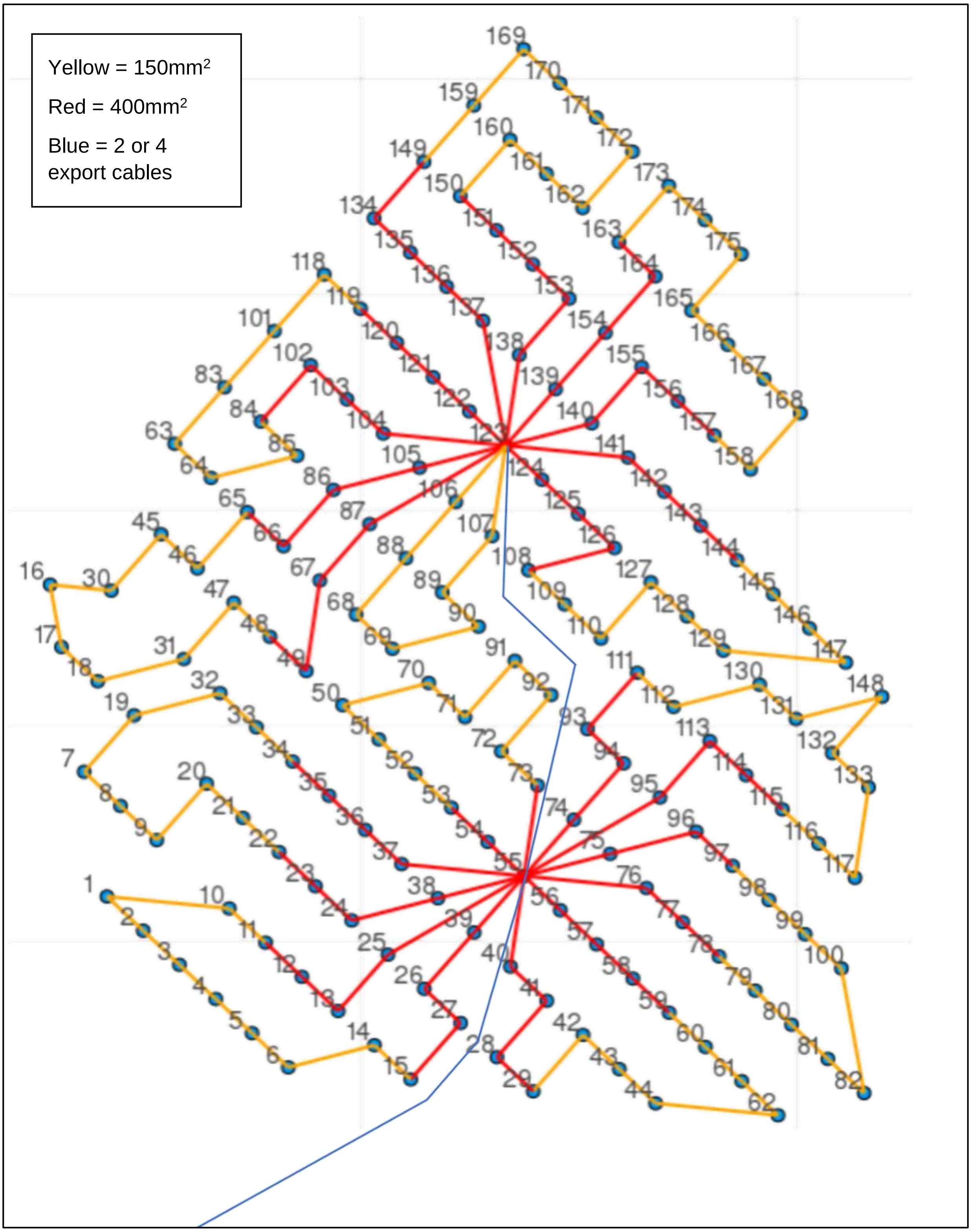

FIGURE 15 - LONDON ARRAY: OPTIMISED ARRAY AND SUBSTATION LOCATION (NOTE: ARRAY POINT NUMBERING DIFFERS FROM FIGURE 14)

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As shown in Table 7 below, the optimiser gives a net cost saving of £6.6m (or 4.6%) relative to the as-built design. This comprises a saving of £11.5m on the array cables, partially offset by an extra cost of £4.9m for longer export cables.

London Array	Cable Length (km)	Cable Capex (£m)	Curtailment Capitalised (£m)	Losses Capitalised (£m)	Crossings Capex (£m)	Export Cable (£m)	Total (£m)
As-built	153.0	100.5	5.2	13.4	0.0	25.7	144.8
Optimised Array and Substation Location	140.4	94.1	3.6	9.9	0.0	30.6	138.2

TABLE 7 – LONDON ARRAY: COST COMPARISON FOR AS-BUILT AND OPTIMISED ARRAY AND SUBSTATION LOCATION

As noted in section 2, the optimiser does not route the export cables: this must be done manually after the algorithm has finished, and the final cost saving will depend on the length of these manually routed export cables.

In this case it was found that the shortest (manually found) route for the export cables that avoids crossings of array cables is to route the two 150kV export cables from the northern substation to the southern substation, rather than directly out of the wind farm and towards land. From the southern substation a corridor of four export cables (two originating in each of the offshore substations) is routed out of the wind farm and towards land.

Having the two cables from the northern substation go via the southern substation will incur some modest extra costs (e.g. extra J-tubes) and also create some opportunities for improved reliability. These costs and opportunities have not been explored.

In the as-built design the wind turbines from a regular array, but the offshore substations sit outside this array. The optimiser, however, includes the constraint that both turbines and offshore substations must be sited on the same set of array points. In the optimised design, therefore, the offshore substations sit at array points that are also occupied by turbines. If this is unacceptable then the substations can be moved a few hundred metres away from their designated array points without significantly changing the results.

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6 Application within FLOTANT

TX has developed a tool that can optimise the layout of loop-based power collection arrays. Loop-based designs offer greater resilience since electricity can still be exported following a cable outage (albeit not necessarily at full load) and auxiliary power supplies to the turbines can always be maintained. String-based array cable layouts cannot offer the same resilience, and are particularly vulnerable if an array cable near the substation should fail.

As discussed in Section 1, the extra resilience offered by loop-based layouts array is likely to have particular benefits for floating wind since floating wind projects will have cables subject to higher stresses, and since planned maintenance may require the temporary removal of turbines, disrupting the operation of the cables connected to these turbines.

TX's array cable layout optimiser has the potential to be used in several further aspects of the FLOTANT project. The following are currently envisaged:

i. Given a suitable set of input assumptions, the optimiser will generate values for the total cost of the collector array (capital cost, losses cost, and income foregone due to faults). This can be applied to hypothetical windfarms using FLOTANT technology to help determine whether the project's Levelized Cost of Electricity (LCoE) targets can be achieved.

ii. Subject to the availability of suitable input data, the optimiser can be used to assess the benefits of HydroBond's proposed connector technology, which allows turbines which are removed for planned maintenance to be bypassed.

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7 Appendix

The assumptions used by the optimiser are input by the user. This section sets out the particular set of assumptions used in Section 5 (Verification)

Assumption	Values	Notes
Cost of energy	50 (£/MWh)	Typical of current fixed-bottom projects. Has tended to fall over time. Floating wind projects will be substantially higher.
Capitalisation factor	15	Typical of current fixed-bottom projects. For floating wind projects the capitalisation factor will be lower due to shorter assumed lives and higher technical risk.
Mean Time between Failure	200 (years)	Based primary on anecdotal evidence: a project to gather anonymised data for fixed cable reliability has only just started. Even less data for dynamic cables.
Mean Time to Repair	0.2 (years)	To date array cable repairs have generally taken longer than this to repair, often with long delays before a repair vessel is mobilised. It is assumed that in the future this will shorten to the value indicated.
Crossing capex	£300,000	Based on the crossing cable being surface laid with c. 1m of rock placed on top. This is a low-end price which assumes low risk of anchor-strike (few vessels expected in wind farm), low wave energy (site not too shallow), and a fall-pipe vessel mobilised anyway.
Cable types	95mm^2, 150mm^2, 240mm^2, 300mm^2, 400mm^2, 500mm^2, 630mm^2, 800mm^2 Cu conductor Same sizes plus 1000mm^2 aluminium conductor	When given a free hand to choose cable sizes the optimiser will examine all possible 2-cable-type and 3-cable-type combinations from either the copper or aluminium sets. Mixed copper and aluminium designs can be optimised, but this had not been used in any of the tests to date.
Cable parameters	See notes	Data provided for cable ratings (from Nexans data sheet) [17], losses at full load (from Nexans data sheet) [17], and cost (from TX in-house database).
Mean Wind Speed	10.5m/s	Typical for recent fixed-bottom offshore wind farms. Floating wind farms may be deployed far from shore, where wind speeds are higher.
Turbine power curve	Cut-in at 3m/s Full load at 13 m/s Cut out at 25m/s	Simplified description of typical modern turbines

TABLE 8 - ASSUMPTIONS USED IN VERIFICATION STUDIES

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