

A multi-stage methodology for wind park inter-array cabling: graph preparation, routing, and sizing

Response to Reviews

This document contains the response to the paper’s reviewers *A multi-stage methodology for wind park inter-array cabling: graph preparation, layout routing, and sizing*. The authors thank the reviewers and editor for their valuable suggestions. Each comment, suggestion, or recommendation was analysed in detail and answered in the context of the proposed paper. All changes in the paper were highlighted in blue and referenced in this response as a text box.

Editor:

Dear authors,

While the paper has been improved, some aspects remain insufficiently addressed. The main concern is that the manuscript’s methodological novelty appears limited, as most of the optimisation formulations, routing constraints, conductor sizing methods, and integrated-versus-sequential strategies are based on well-established approaches in the literature. The primary contribution is the integration of existing modelling components into a unified framework that accounts for realistic spatial constraints, representing a valuable engineering advancement rather than a fundamentally new optimisation methodology. The paper would benefit from a clearer positioning of its scientific contribution, more explicit differentiation from prior work, stronger benchmarking against state-of-the-art methods, and a more thorough discussion of limitations and scalability.

Please address the comments in a revised version of the paper. Thank you.

Best, Nicos

Authors’ comment

Following the reviewers’ concerns, the manuscript has been revised to position the work more clearly within the existing literature. The Introduction has been expanded, and both quantitative and qualitative benchmarking sections have been added to compare the proposed formulation with relevant state-of-the-art approaches. The contribution statement has also been reworded to clarify that the main contribution is an optimisation framework for radial inter-array grids, which evaluates how spatial feasibility constraints and conductor size restrictions jointly affect routing decisions from a pre-processed graph. In particular, the revised manuscript emphasises that the shortest routing solution is not necessarily the least-cost solution when CSS and conductor-type limits are considered. The supporting contributions are now presented as specific methodological components within this overall framework.

1 Reviewer 1

The manuscript improved significantly from the previous version. However, some recommendations from the previous review were not addressed. It also seems like the current version introduced inconsistencies in table D2. Please check the attached referee report for the specific issues.

Reviewer's Concern 1.1

Specify the sublinear relationship and add a reference to the newly added Appendix C - "As conductor capacity and cost do not scale linearly with diameter"

How does this conclusion follow from the premise? - "the shortest trench or cable layout does not necessarily correspond to the minimum total investment cost."

Authors' response 1.1

A clearer explanation has been added to the paper. In addition, plots showing the relationship between conductor cross-sectional area and power rating, as well as the relationship between power rating and cost, has been included to illustrate both the sublinear capacity relationship and its impact on investment cost. Appendix C is not referenced in this section directly, but is cited in Section 6, where the case-study conductor data are introduced.

5.2 Sequential algorithm

To address this limitation, a sequential approach is proposed. This formulation allows the routing stage to incorporate more detailed constraints that would otherwise overly restrict the integrated optimisation problem. However, it also highlights a limitation of single-pass routing approaches. When routing is performed independently of CSS, the routing stage primarily minimises geometric length, while conductor costs are determined **only** subsequently during cable size selection. As illustrated in Fig. 3a, the relationship between conductor cross-sectional area and power capacity is sublinear, such that progressively larger increases in conductor cross-sectional area are required to accommodate additional power. Furthermore, Fig. 3b shows that higher-capacity conductors incur disproportionately greater costs. Therefore, the shortest trench or cable routing typically concentrates power into fewer, larger conductors and does not necessarily correspond to the minimum total investment cost, as the routing stage optimises geometric cable length independently of conductor costs.

Reviewer's Concern 1.2

The "Type" column in the table must use some short handle that helps to identify the different methods. Using subsection numbers is too obscure. - "Table 1. Baltic Eagle [DE] and Moray East [GB-SCT] minimum path finding solutions"

Authors' response 1.2

In the section previously titled "Layout modelling", now renamed "Collector system routing modelling", the initial paragraph has been revised into a bullet-point description of the tested formulations. Each test is now assigned a descriptive name, which is also used in the corresponding table, providing readers with a clearer explanation of the cases being compared.

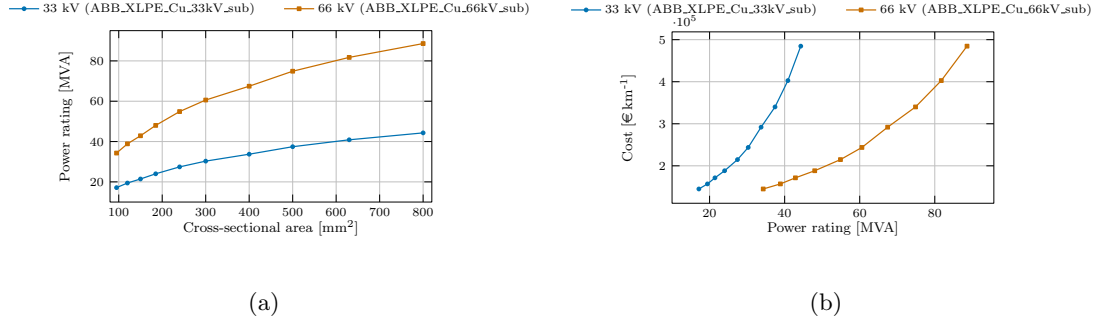


Figure 3: Relationship between conductor cross-sectional area, power capacity, and cost: (a) Cross-sectional area versus power rating; (b) Power rating versus cost.

6.1 Collector system routing modelling

To provide a visual example of the routing formulation and its refinements, the turbine distributions of *Baltic Eagle* [DE] and *Moray East* [GB-SCT] are used. Based on the turbine and substation locations, several tests are conducted. The evaluated formulations, summarised in Table I, are identified using the following short descriptive handles:

- **Core:** Core formulation for determining minimum paths (subsection 3.1).
- **Minimum turbines:** Inclusion of a constraint on the minimum number of turbines per string (subsubsection 3.2.1).
- **Substation connections:** Refinement of the formulation to determine substation connections (subsubsection 3.2.2).
- **Joint constraints:** Simultaneous inclusion of the minimum-turbine and substation-connection restrictions.
- **Bifurcation:** Relaxation of constraint (6) to allow bifurcations.
- **Additional substation:** For *Baltic Eagle* [DE], inclusion of a hypothetical additional substation limited to a maximum of ten turbines, illustrating substations with different power limits (subsubsection 3.2.3).

The corresponding cable routing solutions are shown in Fig. 5 for *Baltic Eagle* [DE] and Fig. 6 for *Moray East* [GB-SCT].

Reviewer's Concern 1.3

Changing from the previous manuscript's "hook-shaped strings" to "non-direct string" is not actually clarifying what is meant here.

By the description in the answer to the reviewers, it seems that you mean that the turbine sequence within a string does not have a monotonic distance-to-substation profile.

However, by pointing that out, you seem to assume either that a monotonic profile was expected or that such profile results from alternative solution methods. Neither of these assumptions seems

Table I: *Baltic Eagle [DE]* and *Moray East [GB-SCT]* minimum path-finding solutions

Test system	Type	Visual result	Trench length [km]	Solution time [s]	$\mathfrak{S}_s$	m
<i>Baltic Eagle [DE]</i>	Core	Fig.5(a)	59.69	95.72	50	
	Min. turbines	Fig.5(b)	61.18	81.78	50	6
	Substation conn.	Fig.5(a)	59.69	40.52	8	
	Joint constraints	Fig.5(b)	61.18	74.78	8	6
	Bifurcation	Fig.5(c)	56.31	203.59	8	6
	Additional substation	Fig.5(d)	49.11	7.43	50	
<i>Moray East [GB-SCT]</i>	Core	Fig.6(a)	149.52	30.92	100	
	Min. turbines				100	6
	Substation conn.	Fig.6(b)	151.44	102.40	5	
	Joint constraints	Fig.6(c)	152.04	141.65	6	5
	Bifurcation	Fig.6(d)	149.08	235.83	6	5

reasonable to me without supporting evidence. - ”Horn Rev 2 [DK] (Fig. 7(e),7(f)) illustrates how the routing mechanism can identify non-direct string layouts to optimise interconnections. ”

Authors’ response 1.3

We thank the reviewer for pointing this out. We agree that the previous wording was ambiguous and could imply an unsupported interpretation of the figure. The statement has therefore been revised. Rather than referring to “hook-shaped” or “non-direct” strings, the Horn Rev 2 case is now used only to illustrate the visible effect of the sequential balancing constraints, which favour a more even distribution of turbines across strings than in the integrated solution.

6.2 Test systems for joint optimisation

... *Horn Rev 2 [DK]* (Fig. 8(e),8(f)) illustrates the effect of the sequential balancing constraints, which favour a more even distribution of turbines across strings than in the integrated solution. ...

Reviewer’s Concern 1.4

Losses are non-linear, but the presentation of the input data suggests that the losses calculation assumed nominal current during the yearly full-load hours. Is this a reasonable assumption? - ”non-linear approach is applied. Assuming an LCoE of 91 e/MWh and 5,170 full load hours”

Authors’ response 1.4

Losses are considered through the non-linear ACOPF power-flow model. The input data correspond to a full-load operating point, in which the wind farm is analysed with turbines operating at rated power. If by nominal current the reviewer refers to full-load operation of the conductors, this is not the assumption used here, since many conductors operate below their rated capacity due to the conductor-type limitation as currents are calculated from the power flow. Additional text has been added to the Discussion to clarify this assumption, and the Limitations section has been expanded to discuss the implications of using an equivalent full-load-hours representation.

6.3 Comparison with non-linear CSS approach

To account for losses, a non-linear approach is applied. Assuming an LCoE of 91 €/MWh and

5,170 full-load hours annually over a 25-year project lifetime (Kost et al., 2024), a net present value analysis of losses relative to investment is conducted. Electrical losses are obtained from the ACOPF solution at the equivalent full-load operating point and are converted to a lifetime cost using the assumed full-load hours. To enable a direct comparison between losses and investment costs, the value of α in (18) is set to 1. For the non-linear simulation, the sequential algorithm is executed in a WSL environment, using OR-Tools (Perron and Furnon, 2025) for routing and Bonmin (Bonami et al., 2008) for the CSS.

8 Discussion

An important extension of the sequential algorithm is the ability to employ a non-linear CSS formulation that accounts for electrical losses in the overall cost. In this paper, losses are evaluated using an equivalent full-load-hours analysis, in which each turbine operates at its rated power and the resulting network currents are obtained from the corresponding ACOPF. The non-linear formulation allows conductor cross-sectional areas to be increased to reduce resistive losses. However, excessive conductor sizing also increases cable capacitance and the associated charging losses. This trade-off is explicitly considered within the non-linear CSS optimisation.

8.1 Limitations

The non-linear formulation is evaluated using an equivalent full-load-hours analysis, which represents the annual operation of the wind farm by a single operating point. Consequently, the optimisation does not capture the variation in active and reactive power flows under different operating conditions. In particular, it does not account for the increased relative contribution of cable charging losses at lower loading conditions, especially for oversized conductors with higher capacitance (Dakic et al., 2021). A more detailed representation could be obtained through a multi-scenario approach, as presented in Valerio et al. (2026), in which the wind speed Weibull distribution and turbine power curve are used to generate representative operating scenarios, each associated with a probability. Similarly, time-series data can be clustered into representative operating conditions to capture spatial and temporal variations in turbine production. The main limitation of these approaches is the substantially increased computational burden, as the optimisation must be solved simultaneously for multiple operating scenarios rather than a single equivalent operating point.

Reviewer’s Concern 1.5

The “Total cost” value in this table seems wrong (it is not the sum of conductor+installation costs). Table D2 makes more sense. The previous manuscript version also made sense. - ”Table D1. Integrated CSS wind test systems detailed results”

Authors’ response 1.5

We thank the reviewer for identifying this inconsistency. The detailed-results table has been checked and corrected so that the reported total cost is consistent with the sum of conductor and installation costs. The corrected values now follow the same cost aggregation used in the previous manuscript version and in the corresponding sequential-results table.

2 Reviewer 2

The manuscript addresses inter-array cable routing and conductor size selection for wind farm collection systems using a multi-stage MILP-based framework combined with graph construction, routing, and conductor sizing. The topic is relevant and well aligned with ongoing research in offshore wind farm electrical system optimisation.

Overall, the paper is technically solid, and the modelling framework is comprehensive, including realistic constraints and extensive case studies. The engineering integration of routing, graph construction, and conductor sizing is well executed.

However, relative to the existing literature in wind farm collection system optimisation developed over the past decade, the methodological novelty appears somewhat incremental. The contribution is best seen as a careful and useful integration of established modelling components rather than a fundamentally new optimisation paradigm.

Reviewer's Concern 2.1

1. Novelty and contribution: The manuscript builds on a substantial body of existing work on MILP-based wind farm collection system optimisation. Similar formulations for routing, including flow conservation constraints, substation allocation, and conductor sizing, have been widely studied in the literature (e.g., Pérez-Rúa et al., Fischetti et al., Souza de Alencar et al., and related works).

The main added value of the present work appears to lie in the integration of graph construction with spatial constraints (including 3D terrain and exclusion zones) and the combined treatment of routing and conductor sizing. While this is useful from an engineering perspective, the manuscript would benefit from a clearer distinction between methodological advancement and enhanced implementation of established approaches.

Authors' response 2.1

We acknowledge that the linear optimisation components used in this work, such as flow conservation, routing constraints, and linear conductor sizing, are not claimed as a new optimisation paradigm in themselves. The Introduction has therefore been expanded to position the manuscript more clearly relative to previous formulations that address individual parts of the problem, including graph construction, routing, conductor size selection, loss-aware sizing, and decomposition strategies.

In the revised manuscript, the contribution statement has also been restructured. Elements that were previously presented as separate contributions are now framed as supporting components of one main contribution. This main contribution concerns the formulation of a graph-prepared optimisation framework in which geographical constraints, such as trenching and spatial feasibility limitations, are combined with logistical constraints, such as string balancing and conductor-type standardisation. These requirements increase the complexity of translating the practical planning problem into a single mathematical workflow: candidate edges must first be generated through graph preprocessing, the routing MILP must remain adaptable to practical routing and balancing constraints, and conductor size restrictions must be allowed to affect the routing problem itself rather than being treated only after routing has been fixed.

To support this revised positioning, benchmarking sections have also been added at the end of the manuscript to compare the proposed methodology with relevant literature. These additions are discussed further in the responses to the benchmarking-related reviewer comments.

1 Introduction

...

Before optimising the connections between turbines, real-world site constraints must be translated into a mathematical graph model. Many studies construct a two-dimensional graph using Euclidean distances between candidate connection points. A notable exception is (Gong et al., 2018), which applies a geodesic algorithm on a three-dimensional seabed to calculate connection distances, although it does not include Geographic Information System (GIS) constraints. As offshore sites become more spatially constrained, several formulations have introduced Steiner nodes to model detours around exclusion zones (Fischetti and Pisinger, 2018a,b; Taylor et al., 2023). Penalty based treatments of spatial restrictions have also been used in complex offshore routing studies; for example, Taylor et al. (2023) penalise crossings of wind-farm boundaries and obstacle regions while using Steiner nodes to support obstacle navigation. More detailed spatial-preprocessing approaches include Delaunay triangulation based navigational mesh pathfinding (Pillai et al., 2015) and topology-embedding separation with post-optimisation detours for non-straight cable routes (Souza de Alencar et al., 2025). These approaches primarily address obstacle avoidance, penalised spatial violations, or feasible route construction, while the distinction between prohibited regions and feasible but undesirable routing areas is less commonly treated explicitly at the graph-construction stage, particularly when final cable routes are embedded only after topology optimisation.

Once the candidate graph has been defined, the routing formulation determines which connections are installed and which topological restrictions are enforced. In the collector system optimisation phase, multiple topologies have been implemented in practice, including radial, radial plus star, radial plus star with splices, single loop, and others (Pérez-Rúa and Cutululis, 2019). In the present work, radial arrays are interpreted as string-like routings in which turbine-node bifurcations are not permitted. To address collector system optimisation...

Existing routing formulations address these topological and spatial restrictions in different ways. Several MILP formulations represent candidate connections using directed arc-pairs, so that the selected direction follows the energy flow towards the substation rather than being fixed by geometry (Fischetti and Pisinger, 2018a,b; Pérez-Rúa et al., 2020a). Other approaches introduce iterative crossing constraints, practical topology variants, or topology-embedding separation to obtain feasible cable routes (Pillai et al., 2015; Fischetti and Pisinger, 2018b; Souza de Alencar et al., 2025). These studies demonstrate that routing constraints such as crossings, substation limits, conductor capacities, branching, and string structures have been widely considered. However, fewer studies explicitly consider how spatially feasible candidate connections should be constructed when strict string-like radial topologies, practical balancing constraints, and clearance requirements around fixed structures must be satisfied simultaneously.

Beyond the selection of cable routes, conductor sizes must be chosen to satisfy current limits while balancing investment and loss-related costs. This can be achieved either through static rated sizing, which assumes a continuous current over time, or through a dynamic load cycle profile, which accounts for the variability of power production (Pérez-Rúa and Cutululis, 2019). To address the CSS problem, studies have employed genetic algorithms (Smail et al., 2018; Rentschler et al., 2019), modified bat algorithms (Qi et al., 2019), and MILP formulations (Wedzik et al., 2016; Chen et al., 2016; Fischetti and Pisinger, 2018a; Pérez-Rúa et al., 2020a). Loss-aware cable selection has also been incorporated into rout-

ing and collection-system formulations through infrastructure and loss-related cost terms. For example, Cerveira et al. (2016) represent conductors using a short-line model and use precomputed loss terms within an integer linear programming formulation that minimises infrastructure and loss-related costs. Other formulations similarly use precomputed cable-cost coefficients or load-dependent loss approximations (Fischetti and Pisinger, 2018a; Pérez-Rúa et al., 2020b,a; Bae et al., 2023).

Several studies have also coupled conductor sizing with the routing or interconnection problem. For simultaneous interconnection configuration and conductor sizing, Sedighi et al. (2018) employs a harmony search algorithm for partial conductor sizing, whereby each branch along a route is assigned a conductor based on the ampacity of the final segment before it joins another route or connects to the substation. The study considers branches originating from bifurcation points; under that partial-sizing assumption the same conductor type is assigned to all sections of a string. Wedzik et al. (2016) combine network routing optimisation with CSS and include constraints on the number of cable cross-sections used for a single substation. In Pérez-Rúa et al. (2020a), an integrated routing algorithm is proposed that can adapt to multiple substations and limit static crossings; however, when considering CSS, the method does not limit the number of permitted conductors. Due to the cost associated with cable-laying vessel operations, the number of different conductor diameters used in offshore wind farms design is typically limited.

Because routing, conductor sizing, and loss representation are strongly coupled, other studies have used decomposition or hierarchical strategies to improve tractability. Benders-based formulations and decomposition-based heuristics have been proposed for collector-system planning and complex offshore routing. In Chen et al. (2016), the master problem handles cable-routing decisions while operational subproblems evaluate network feasibility. Similarly, Lumbreras and Ramos (2013) apply decomposition strategies to offshore wind farm electrical-system planning, separating investment decisions from operational scenarios and reliability-related constraints. In contrast, Taylor et al. (2023) use a decomposition-based ant colony optimisation heuristic in which selected strings are removed and re-optimised as subproblems while the remainder of the routing is fixed. However, less attention has been given to how CSS restrictions alter the routing problem itself under spatially constrained and balanced radial-array requirements. When conductor costs scale sublinearly with power capacity and only a limited number of conductor cross-sections can be used, the shortest feasible route is not necessarily the least-cost route.

...

To address these criteria, the main contribution of this work is a graph-prepared optimisation framework for radial inter-array grids that evaluates how spatial feasibility constraints and conductor size restrictions jointly affect routing decisions, showing that the shortest routing solution is not necessarily the least-cost solution when CSS and conductor-type limits are considered. The supporting contributions are as follows:

- A graph construction methodology that incorporates three-dimensional terrain, inclination constraints, and both hard and soft exclusion zones into the candidate edge generation process.

- A reduced MILP formulation for inter-array routing using a single binary variable per arc, thereby decreasing the number of decision variables relative to standard formulations.
- A joint treatment of routing and conductor size selection, allowing CSS restrictions to influence routing decisions rather than being treated only as post-processing.
- The development and comparison of integrated and sequential approaches for joint routing and CSS, highlighting trade-offs between solution quality, modelling flexibility, and computational complexity.

Reviewer’s Concern 2.2

2. Mathematical formulation and originality: The MILP formulation for routing follows standard network design structures, including flow-based constraints, binary edge activation, and capacity restrictions. These formulations are well established in combinatorial optimisation and power system planning literature. No fundamentally new optimisation principle or decomposition approach is introduced, but the formulation is carefully adapted to the problem context.

Authors’ response 2.2

We agree that the routing MILP builds on established network design structures. The methodology was originally developed for a non-standard routing problem under the assumption that reducing the number of variables could improve computational efficiency. In much of the literature, the candidate graph is represented using two directed arcs for each node pair, with non-negative flow variables defined on each direction. This results in two binary activation variables and two flow variables for each candidate connection. In the proposed methodology, we depart from this common representation by assigning a single binary activation variable and a single flow variable to each node pair.

This formulation has been compared with OptiWindNet, presented by Souza de Alencar et al. (2025), using several pure routing cases to evaluate model size and computational performance. In addition, a qualitative benchmark of MILP-based routing formulations has been introduced.

7.1 Collector system routing benchmarking

Several state-of-the-art cable-routing formulations represent each candidate connection through two directed arcs, allowing the optimiser to select the direction associated with power flow towards the substation (Fischetti and Pisinger, 2018a,b; Pérez-Rúa et al., 2020a). This provides a useful structural reference for the routing component of the proposed formulation. For the quantitative benchmark, however, *OptiWindNet* (Souza de Alencar et al., 2025) is selected because it is available as an open-source framework and directly addresses the spatial embedding of selected connections. Its search space is built from a sparsified candidate graph based on constrained Delaunay triangulation, diagonals, and feeder links. In particular, it goes beyond purely static crossing constraints by separating topology selection from route embedding, enabling non-straight cable routes and reducing the number of crossing constraints considered during optimisation. *Gurobi* was selected as the common solver for both approaches with a six-hour time limit. For cases reaching the imposed time limit, the reported value corresponds to the best incumbent solution.

The comparison is restricted to the routing component and uses total cable length and solution time as common metrics. Three test types were used to enable comparison across the case studies. The first was a non-restrictive test, in which no substation-connection limit was enforced and the maximum string length was set equal to the number of turbines in the wind park, $\mathfrak{M} = |\mathcal{N}_t|$. In the second test, the maximum number of turbines per string was set according to the highest-capacity conductor available for the corresponding voltage level, as reported in Appendix B. In the third test, substation connections were limited to obtain a more balanced string configuration. The resulting $\mathfrak{S}_s$ and $\mathfrak{M}$ values are shown in Table 7. The first aspect evaluated is the problem size. Table 6 presents the number of variables and constraints considered by the solver. In the proposed formulation, the number of variables is reduced primarily because each candidate edge is represented by a single activation variable. However, the number of constraints increases substantially owing to the use of static crossing constraints.

The second evaluation concerns computational performance, shown in Table 7. The proposed methodology is slower in most cases. The explicit modelling of cable crossing restrictions increases the number of constraints and introduces a combinatorial structure that is more difficult for the branch-and-bound algorithm to resolve. Although feasible solutions of comparable quality are identified early in the search, the LP relaxation bound is weaker than that of the planar-embedding approach, making the optimality gap more challenging to close within a given time limit.

Both methodologies produce comparable routing lengths across the nine wind farms, with larger differences appearing mainly in the more constrained balanced cases. It is worth noting that *OptiWindNet*'s topology-optimisation objective can differ from the final embedded route length when post-processing detours are required. For example, in the third Horn Sea 2 test, the topology-optimisation length before re-routing is 325.87 km; however, post-processing re-routing to avoid physical cable crossings introduces additional cable length, increasing the final embedded route length to 334.56 km.

In contrast, the proposed methodology enforces crossing avoidance directly within the MILP solution. While *OptiWindNet* resolves many crossing issues through topology-embedding separation and post-optimisation detours, the proposed methodology considers crossing candidate edges explicitly within the optimisation through static crossing constraints.

The case study information used for benchmarking is available in the Zenodo repository (Castro Valerio, 2026).

7.2 Qualitative benchmark

The comparison in Table 7 evaluates the routing formulation quantitatively, while several modelling aspects require qualitative positioning. Existing routing formulations already include many of the individual components used here: Delaunay-based pathfinding and GIS obstacle avoidance (Pillai et al., 2015), Steiner-node obstacle detours and practical routing variants (Fischetti and Pisinger, 2018a,b), penalty-based obstacle and boundary treatments (Taylor et al., 2023), and topology-embedding separation with post-optimisation detours (Souza de Alencar et al., 2025). These approaches differ mainly in where spatial feasibility is imposed: during path generation, through additional graph nodes, as penalty terms, or after topology optimisation. The proposed formulation instead applies routing constraints to candidate routes generated by the graph preparation stage, so hard exclusions, soft-exclusion weights, clearance constraints, and static crossing constraints are reflected before or within

the MILP solve.

The core routing MILP follows standard network-design principles, including edge activation, flow conservation, capacity limits, and crossing constraints. Similar routing structures have been used in wind farm collection-system formulations based on directed arc-pairs representations (Fischetti and Pisinger, 2018a,b; Pérez-Rúa et al., 2020a; Souza de Alencar et al., 2025). As shown in the quantitative benchmark, the distinction of the present core routing formulation is the use of a single activation and flow variable per candidate edge, together with the enforcement of a strict radial topology. The formulation is further extended through constraints on the minimum number of turbines per string, the determination of substation connections under unfavourable GIS constraints, and the possibility of unbalanced substation capacities, thereby expanding the range of user-defined design requirements that can be represented.

Reviewer’s Concern 2.3

3. Conductor sizing and loss modelling: The conductor sizing component, including linear and nonlinear loss representations, is consistent with established methods in the literature. Techniques such as piecewise linearisation and big-M formulations are standard in similar MILP-based energy system optimisation problems. The manuscript would benefit from a more explicit positioning relative to prior integrated routing and sizing studies.

Authors’ response 2.3

The general linear conductor-sizing component is consistent with existing literature. In particular, Wedzik et al. (2016) is one of the few references that also limits the number of conductor types selected from a larger available set, which is one of the main objectives considered in this paper. However, integrating this constraint within a joint routing-CSS model involves trade-offs with other routing requirements, such as minimum turbines per string and balanced string distribution. In addition, the non-linear representation is included to evaluate how losses are treated within the optimisation model, rather than only through matching to precomputed loading instances.

This comparison has been added to the qualitative benchmark to clarify the positioning of the proposed CSS and loss-modelling components relative to prior work.

7.2 Qualitative benchmark

...

For CSS and loss-aware design, Cerveira et al. (2016) and Fischetti and Pisinger (2018a) provide the closest comparison with precomputed loss treatments. Both approaches estimate loss-related costs from the cable type and the number of turbines carried by a segment, while Fischetti and Pisinger (2018a) further include wind-scenario probabilities in the expected loss contribution. This keeps the optimisation tractable, but the loss assigned to each segment is based on local loading assumptions rather than on the full electrical state of the selected network. Consequently, upstream voltage conditions, reactive power flows, cable capacitance effects, and cumulative losses along preceding segments are not explicitly represented. In this paper, the ACOPF-based CSS formulation captures losses within the optimisation by representing voltage magnitudes and angles, as well as the full π -model of the cable sections. However, this formulation is computationally demanding. For this reason, the linear CSS formulation is used to enable joint routing-CSS optimisation in both the integrated and

sequential approaches, although losses are not included in the linear CSS objective.

Reviewer’s Concern 2.4

4. Integrated vs sequential optimisation: The comparison between integrated and sequential optimisation strategies is relevant and well executed. However, similar hierarchical and iterative approaches have been previously explored in related contexts. The results are useful in illustrating known trade-offs between trenching cost, conductor selection, and network topology, though the novelty of the insight should be framed cautiously.

Authors’ response 2.4

To better position the novelty of our approach, we have expanded the qualitative benchmark to compare it with the closest integrated routing-CSS formulation in Wedzik et al. (2016) and clarify that the contribution lies in the proposed routing-CSS coupling and its integration within the overall workflow, rather than in the sequential strategy itself.

7.2 Qualitative benchmark

...

The strongest joint routing-CSS benchmark is Wedzik et al. (2016), which integrates network routing optimisation with CSS and includes restrictions on the number of cable cross-sections used. However, coupling CSS with balanced radial-routing constraints introduces an additional difficulty: the routing balance depends on the maximum number of turbines that can be carried by the largest conductor selected, but this conductor is itself an optimisation outcome. If this maximum capacity is fixed in advance, the routing problem can enforce balanced strings more easily, but the conductor-selection problem is partially predetermined. Conversely, if the conductor set is left fully open, the routing formulation cannot directly know which turbine-per-string limits should be imposed to obtain a balanced configuration. The sequential strategy is therefore used to explore this dependency step by step, restricting the available conductor set across iterations and re-solving the routing problem with the corresponding balance and substation-connection constraints. This allows the effect of conductor availability on routing, trenching cost, and CSS cost to be evaluated more explicitly than in a single integrated solve.

Reviewer’s Concern 2.5

5. Benchmarking and validation: The numerical results are extensive and provide useful insights into the performance of the proposed framework. However, most comparisons are internal (between model variants), and there is limited benchmarking against external state-of-the-art methods. Including such comparisons would strengthen the claims regarding performance and robustness of the proposed approach.

Authors’ response 2.5

Following the previous concerns, and in particular the request for stronger benchmarking, we have added a quantitative benchmark for the routing component. The benchmark uses Souza de Alencar et al. (2025), as the methodology is available through the open-source tool *OptiWindNet*. For the remaining components of the proposed framework, a qualitative benchmark has been added to clarify

the differences with respect to related methods. For conciseness, the box below only shows the titles of the new benchmarking subsections. The corresponding benchmark text has already been included in the responses to the previous concerns and is therefore not repeated here in full.

7.1 Collector system routing benchmarking

7.2 Qualitative benchmarking

Reviewer's Concern 2.6

6. Scientific vs engineering contribution: The manuscript appears to primarily integrate several well-established modelling components into a unified framework, including graph construction, routing optimisation, and conductor sizing. This integration is valuable and relevant for practical applications, but the scientific contribution should be more clearly articulated to avoid overstating methodological novelty.

Authors' response 2.6

The contribution statement has been revised to present the work as one unified contribution, rather than as a set of separate methodological claims. The graph construction, routing formulation, joint routing-CSS treatment, and integrated/sequential comparison are now framed as supporting components of the main contribution: a graph-prepared optimisation framework for radial inter-array grids in which spatial feasibility constraints and conductor size restrictions jointly affect routing decisions.

To address these criteria, the main contribution of this work is a graph-prepared optimisation framework for radial inter-array grids that evaluates how spatial feasibility constraints and conductor size restrictions jointly affect routing decisions, showing that the shortest routing solution is not necessarily the least-cost solution when CSS and conductor-type limits are considered. The supporting contributions are as follows:

- A graph construction methodology that incorporates three-dimensional terrain, inclination constraints, and both hard and soft exclusion zones into the candidate edge generation process.
- A reduced MILP formulation for inter-array routing using a single binary variable per arc, thereby decreasing the number of decision variables relative to standard formulations.
- A joint treatment of routing and conductor size selection, allowing CSS restrictions to influence routing decisions rather than being treated only as post-processing.
- The development and comparison of integrated and sequential approaches for joint routing and CSS, highlighting trade-offs between solution quality, modelling flexibility, and computational complexity.

Reviewer's Concern 2.7

Minor concern 1. The manuscript is generally well structured, though some sections are dense and could be simplified for readability.

Authors' response 2.7

While the Introduction has been expanded to address the requested positioning relative to prior work, it has also been restructured to improve readability. The revised Introduction now separates the discussion of graph construction, routing formulations, conductor size selection, integrated/decomposition strategies, and the final contribution statement. In addition, the graph-preparation description and figure caption have been revised with explicit step labels, and short signposting sentences have been added in the routing and CSS sections to guide readers to the notation summary. The benchmarking and limitations discussions have also been separated into dedicated subsections.

Reviewer's Concern 2.8

Minor concern 2. Notation could be introduced earlier and clarified more systematically.

Authors' response 2.8

The notation is summarised in Appendix A to aid the reader. References have now been added at the start of the relevant methodology sections to direct readers to the corresponding notation summary when needed.

3 Collector system routing.

... Each turbine lies on a simple path to a substation and may connect to at most two neighbouring nodes. The routing formulation uses the network sets, edge-flow variables, binary edge-activation variables, and routing parameters summarised in Appendix A, A1-A3.

4 Conductor size selection

....

Here, $\xi_{a,\iota}$ is a binary variable indicating whether conductor type ι is assigned to edge a , and L_a denotes the pre-computed length of edge a obtained during the graph preparation step (e). The CSS formulations use the active-edge set, conductor-type set, conductor-selection variables, electrical quantities, and economic parameters summarised in Appendix A, A1, A2, A4, A5.

Reviewer's Concern 2.9

Minor concern 3. Figures illustrating algorithmic structure and graph construction could benefit from improved clarity and labelling.

Authors' response 2.9

The captions of Fig. 1 and Fig. 4 have been expanded to describe the graph preparation steps and the sequential routing-CSS algorithm more clearly.

Figure 1. Graph edge preparation procedure: (a) **Input layout**, turbine group and substation; (b) **Grid densification**, spatial grid for intermediate points; (c) **Terrain overlay**,

elevation or bathymetry data; (d) **Feasible graph**, densified graph after spatial constraints; (e) **Shortest paths**, feasible inter-turbine paths; (f) **Candidate graph**, final graph used in the MILP optimisation.

Figure 4. Sequential routing-CSS algorithm: **Routing**, determine the active edge set for the current conductor set; **CSS**, size the selected connections using the linear or non-linear formulation; **Evaluation**, compute the total routing and conductor investment cost; **Update**, restrict the conductor set and repeat until no further cost reduction is obtained.

Reviewer’s Concern 2.10

Minor concern 4. A more explicit discussion of limitations (e.g., scalability of MILP formulations, sensitivity to graph discretisation, and parameter selection such as big-M values) would strengthen the manuscript.

Authors’ response 2.10

Limitations related to the graph-construction stage were previously discussed within the general Discussion section. In the revised manuscript, these paragraphs have been moved into a dedicated Limitations subsection for clearer identification. The subsection now also discusses the restrictive effect of static crossing constraints, the impact of explicit crossing constraints on MILP scalability and optimality-gap closure, and the operational limitation introduced by evaluating the non-linear CSS formulation using an equivalent full-load-hours operating point.

7.3 Limitations

In all cases, the routing algorithm is constrained by the graph preparation process. Connections that may appear feasible upon visual inspection can be excluded due to cable crossing constraints, an inherent limitation of using static constraints. As illustrated in Fig. 12(a), a visually preferable layout might involve connecting the leftmost turbine (highlighted in blue) of the orange string, directly to the substation, thereby reducing total cable length. However, this configuration is excluded by the algorithm because it intersects with other inter-turbine edges.

In another example, shown in Fig. 12(c), the connection set in orange originates from the original project documentation but would be excluded under the current method, as it crosses other active connections. Another restriction concerns the connectivity of possible turbine-to-turbine links. In the methodology proposed in Section 2, such connections are defined using Delaunay and diagonal edges. In Fig. 12(b), the orange link, also derived from the project documentation, would not be considered under a Delaunay-diagonal configuration. This could be extended, optionally, by incorporating k -nearest neighbours into the search; however, doing so increases the graph preparation time and complicates the routing problem. Moreover, under the graph preparation procedure, connections originating from the substation and overlapping with other substation links are not classified as crossings by the algorithm. Consequently, multiple such connections are permitted. This is also visible in Fig. 12(a), where area constraints result in parallel segments running from the substation to different turbines. These examples underscore the importance not only of careful graph

preparation but also of incorporating human oversight to mitigate limitations inherent in automated routing strategies.

Some of the limitations discussed above could be alleviated by refining the candidate-edge construction. Additional Steiner points, as used in related routing studies, could be introduced to increase the number of feasible detours and reduce the restrictive effect of static crossing constraints. In the limiting case, the routing optimisation could be performed directly on the densified graph produced during graph preparation step (d), rather than on the reduced candidate graph. This would provide greater routing flexibility, but would substantially increase the number of candidate edges and crossing constraints. A practical compromise is therefore to adjust the density of the graph preparation stage according to the size and complexity of the test case. Higher densification improves the spatial resolution of the three-dimensional path assessment, but also increases the computational cost of pathfinding and subsequent routing optimisation.

The MILP scalability is mainly limited by the explicit crossing constraints. These constraints increase with the number of intersecting candidate-edge pairs and can make it difficult for the solver to close the optimality gap, particularly in larger or more constrained cases. The optimality gap is the difference between the best feasible solution and the solver's lower bound, which is obtained from LP relaxations and provides a provable bound on the optimal objective (Gurobi Optimization, LLC, 2026).

In the linear CSS formulations, losses are not included in the objective in order to keep the routing-CSS problem linear and computationally tractable. Loss-related terms could be incorporated through precomputed coefficients, as in previous loss-aware routing formulations, but such an extension would require assumptions on segment loading and would not represent the full AC state of the selected network. For this reason, losses are instead evaluated through the separate non-linear CSS formulation.

The non-linear formulation is evaluated using an equivalent full-load-hours analysis, which represents the annual operation of the wind farm by a single operating point. Consequently, the optimisation does not capture the variation in active and reactive power flows under different operating conditions. In particular, it does not account for the increased relative contribution of cable charging losses at lower loading conditions, especially for oversized conductors with higher capacitance (Dakic et al., 2021). A more detailed representation could be obtained through a multi-scenario approach, as presented in Valerio et al. (2026), in which the wind speed Weibull distribution and turbine power curve are used to generate representative operating scenarios, each associated with a probability. Similarly, time-series data can be clustered into representative operating conditions to capture spatial and temporal variations in turbine production. The main limitation of these approaches is the substantially increased computational burden, as the optimisation must be solved simultaneously for multiple operating scenarios rather than a single equivalent operating point.

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