Optimizing a wind farm layout considering access roads

B Roscher1, P Mortimer, R Schelenz, G Jacobs, A Baseer
Center for Wind Power Drives, Campus-Boulevard 61, 52074, Germany

1E-mail: Bjoern.roscher@cwd.rwth-aachen.de

Abstract
Considering building a wind farm, a quarter of the initial investment cost is accounted for planning, construction, and project preparation. Some of those expenses can be reduced within the project concept phase. The wind farm layout is one of the common aspects being optimized.

Commonly, wind turbines are placed such that wake losses are minimal. However, this might lead to long access roads. The cost of a gravel road is estimated to be 75 €/m. In this paper, an optimization problem considering access roads is developed.

Two methods are investigated to determine the influence of the access roads on a wind farm layout optimization. A case study with seven wind turbines is set up. The layout is optimized such that the LCOE is minimal. One method examines a wind farm with nearby existing roads. This method results in a reduction of road costs by 9 000€ while the AEP suffers a loss of 0.134 %. The second method neglects existing roads and develops a new access road network. Comparing an optimized wind farm layout without considering the access roads to an optimization that included the access leads to 22 000 € fewer road investment costs and a loss of AEP of 0.238 %. Those changes seem marginal but indicate a possible gain for large scale wind farms.

1. Introduction
Wind energy is one of the most relevant renewable energy systems. However, planning and constructing an onshore wind farm becomes more and more complicated. Regulation on distance, acoustic emission, shadow flicker, and bird strike prevention increases the degree of complexity. This results in less and less available locations onshore.

The optimization of wind farms deals with many different challenges and restrictions. One example is access to a wind turbine or wind farm. Access roads are determined to be 3 % of the initial investment costs [1, 2]. Those roads must be passable at all times. In some cases the access roads need to be constructed especially for the wind farm, resulting in an increased investment cost. Nassar and his colleagues showed the influence of the route planning on the construction time of a given wind farm. Depending on the selected route the construction time for 26 wind turbines in a complex terrain could vary by 50 days resulting in additional costs [3].

Commonly, wind turbines are placed such that wake losses are minimal leading to great distances between the wind turbines and consequently to further costs. The benefit was shown by Gu, who optimized the layout in complex terrain by integrating a road network. He was able to reduce the costs by 1.2 % for 26 wind turbines using a minimal spanning tree [4].
An optimal layout of the access roads for a wind farm consists of straight roads connecting the turbines directly with each other and an existing road network. Nonetheless, the curvature of the roads and construction sites of the wind turbine must be considered to fully use the access roads. This has been understood and researched.

This paper aims to investigate the influence of access roads onto a wind farm layout optimization with minimal Levelized Cost Of Energy (LCOE). Placing the wind turbine closer to existing roads or closer to each other leads to reduced road investment cost while the Annual Energy Product (AEP) reduced too. Consequently, the access roads are introduced as an additional aspect during the optimization. The access roads are designed such that it is possible to construct the wind turbines simultaneously while no construction site obstructs another one. Two cases are shown. (A) Connecting the wind farm to the existing road infrastructure. (B) Developing a new road network while optimizing the layout.

2. Methodology

At first, the determination of the road network needs to be elaborated. The existing road infrastructure is extracted automatically using the OpenStreetMap database. The incorporated XML-structure enables tracking of roads. Figure 1 displays the determined waypoints (blue) and housings (black dots). Roads that need to be constructed are estimated by 75 €/m [5]. The displayed map is limited to a resolution of 2000x2000 points. A higher resolution does not improve the output. Furthermore, the precise location is confidential, so the displayed maps are printed with low resolution and without coordinates. The important parts of the figure are highlighted.

![Figure 1. Example of extracted OSM-output [7]](image)

Both cases are based on available OSM-data exemplarily shown in Figure 1. It is possible to consider height differences and to account for a critical change of slope. If the slope changes to rapidly, it is not possible to use the street as the truck will hit the floor. However, local obstacles cannot be considered as they are not available at the required level of detail. This is also an issue when considering curvature, as local aspects cannot be accounted for. However, the road width is assumed to be wider in a curve based on Micelli [6]. Figure 2 shows a possible path of transportation. The road is displayed in grey, the paths of both the truck and the blade tip are indicated. It can be noted that the curvature area is bigger than the road. Therefore, curvatures are accounted for as penalties determined by an increased width of the road and subsequently an increased cost.
2.1. Connecting to existing infrastructure

The first proposed method is to include existing infrastructure (e.g. roads) while designing the layout of the wind farm. This means that the wind turbines will be connected via an optimal route, determined by the nearest neighbor algorithm [8]. The developed method determines the closest waypoint to a wind turbine. However, a single waypoint might not be the shortest connection. Between two-waypoints might be a distance of minimal 50 m leaving the chance that the connection between the waypoints is the shortest. Nonetheless, the shortest connection will have a right angle to the street, based on the least squared method. Subsequently, both angles spanned between the road and the connections of waypoint and wind turbines have to be less or equal to 90 degrees, as indicated in Figure 3.

![Figure 3: Angle condition for minimal distance [9]](image)

Such an approach is valid for most scenarios. However, there might be a situation that the wind turbine is located in a wedge formed by two roads. Then, there might be multiple points that fit the criteria. If this is the case, the connection with the lowest penalty of curvature is selected. If still, multiple points meet the criteria, the first found connection is selected.

2.2. Determine new road network

The second method determines a new road network if no roads exist. This approach means that entire access roads must be constructed. All wind turbines will be connected using the minimal spanning tree [10] and a route planning by Dijkstra [11]. The minimal spanning tree was already used by Gu [4] and had shown great potential.

In this paper, the algorithm suggested by Prim is used [10]. The algorithm starts with an arbitrary starting point. Subsequently, the starting will be connected to the next point with the lowest connection weight. The procedure will be repeated until all wind turbines are connected without constructing a
circle. This would be sufficient to connect all wind turbines. However, the determined solution means that the access roads go through the wind turbines. Such a solution is not physically feasible as seen on the left side of the example in Figure 4.

Therefore, the method will be extended by introducing a construction area around the wind turbine. This area is defined with a diameter equal to one rotor diameter and cannot contain a general road. The rest of the wind farm area will be discretized using a triangular mesh, indicated in light grey on the right side of Figure 4. Each node of the mesh can be used as a possible route. The navigation algorithm by Dijkstra is used to find the optimal route. As part of the algorithm, each possible connection is labeled with a weight equal to its distance. The sequence of how the wind turbines are approached is based on the results of the minimal spanning tree. By using this combined method, it is possible to determine an access road network, where no turbine is blocked, and simultaneous construction can be realized.

![Diagram](image)

**Figure 4.** Representative access road design according to minimal spanning tree (left side) in combination with navigation route planning (right side)

### 2.3. Combination with the layout optimization

Subsequently, the route planning can be integrated into the layout optimization. The layout optimization will be achieved by using WIFO (wind farm optimization), a developed methodology at the Center for Wind Power Drives. The underlying flow solver is the Jensen wake model [12]. The model allows having a low calculation time during the optimization iterations. Usually, a wind farm layout is bounded by a given construction area. This area is discretized using a triangular mesh. The mesh width is equal to one rotor diameter. At each node of the mesh, it is possible to place a wind turbine. WIFO can consider multiple regulations and constraints such as bird strike prevention, shadow flicker, and route planning. However, the majority of these aspects will be neglected. Such that the effect of road planning during the concept phase is quantifiable. WIFO minimizes the LCOE while trying to maximize AEP. This is not possible to achieve simultaneously. Therefore, the two aspects are weighted such that the focus is set onto the LCOE [13]. The optimization procedure is based on a genetic algorithm. During each iteration, the best layouts are combined using a uniform crossover. As a reference, the wind farm layout optimization is executed according to the state of the art. The access roads are determined after the layout is defined. Both access road cases are investigated and compared to optimized solutions. Throughout the optimization, the access roads are integrated by two different approaches.

(A) Connecting the wind farm to the existing road infrastructure
(B) Developing a new road network while optimizing the layout

At each possible layout, the best access road connection is determined. This introduces a high amount of calculations. However, the final optimization represents a layout where the LCOE is lowest under consideration of access routes as an additional cost driver. Each optimization is executed with a
population of 100 members until the solution is converged over a period of 20 iterations. To ensure an estimation of a global optimum, the optimization is executed multiple times. Each optimization is run ten times. Convergence history is shown in Figure 5. The black lines show the convergence history of the 10 runs of Case (A) and in red Case (B). It can be noted that the optimization of Case (A) converge earlier as the problem is less complex. In Case (B) the optimization shows a stair-like behavior. The algorithm stagnates for a while. This is mainly due to some local minima resulting from the integration of the access roads. The steps in Case (B) are the results of the mutations during the genetic algorithm [7]. For each run, the convergence is achieved after at least 150 iterations. The runs differ slightly, so the best results are presented in this paper.

Figure 5: Convergence history

2.4. Initial conditions
The layout optimization is based on a location in the middle of Germany. The wind speed can be estimated using a Rayleigh distribution with an average wind speed of 6.1 m/s. The wind direction distribution is displayed in Figure 6. The reference site has a preferred wind direction out of the southwest. The construction site has a complex shape. It is stated that the wind farm should contain 7 wind turbines with specifications stated in Table 1.

Table 1. Considered wind farm parameter

| Wind turbine parameter | Unit | Value |
|------------------------|------|-------|
| Amount                 | [-]  | 7     |
| Rated Power           | [MW] | 3.5   |
| Diameter              | [m]  | 120   |
| Wind speed range      | [m/s]| 3.5-25|

Figure 6. Distribution of the wind direction [7]

3. Results
Firstly, the optimal layout is determined to focus on minimizing the LCOE. In Figure 7 the result of the layout optimization can be seen. The red dots mark the placement of a wind turbine. It is estimated that the seven wind turbines will produce 41.187 GWh. It should be stated that the turbine at the lower right corner is placed close to the street. WIFO is implemented such that existing streets are not considered as possible locations. The shown layout is the initial layout for the reference case where the access roads are considered after the layout is determined.
Figure 7. Optimized wind farm layout neglecting any access roads.

Figure 8 displays the access roads for both situations. The connection to existing streets is shown on the left-hand side. As the wind turbines have been placed close to existing routes, a low number of roads were added. In total, the length of 320 m must be constructed to connect the wind turbines. This means an additional cost of 24 000 € when using a gravel road. These additional expenses result in a total LCOE equal to 5.668€ct/kWh. The turbine on the right in the left picture is connected directly into the corner of a close-by street indicating the shortest connection.

The right-hand side of Figure 8 displays the access road network being developed from scratch based on the combined method of minimal spanning tree and Dijkstra. As expected, this results in a far longer connection. In total, a connection of 3.3 km with 250 200 € as additional costs. Such a value increases the LCOE by 0.033 €ct/kWh. The developed road network allows a simultaneous construction of the wind turbine. The benefit of this aspect is not included in the LCOE calculation and should be kept in mind. The feasibility of such a road network is questionable because some T-Connections lead to angles below 90° that aggravate transportation. Those connections origin from the triangular mesh.

It is advised to inspect the generated solution and to round down any critical curvatures. Other aspects of the generated solution are the dents in some of the straight lines, mainly originating from the used mesh. One dent on the west side of the park is due to outer construction dimensions, as it is wanted to have the access roads inside the owned site.

Figure 8. Reference case with access road design (red lines) using existing infrastructure (left) constructing a new road network (right)

Figure 9 contains the results of the layout optimization while considering the access roads. The left-hand side considers the existing infrastructure while optimizing (Case (A)). It can be noted that the solution is similar to the left side of Figure 8. The main difference is that the wind turbine east at the
corner and the one in the south are placed closer towards the streets. This reduces the overall access road length to 201 m, so a reduction by 120 m. The AEP of the new layout is reduced by 0.055 GWh. This is due to an increased amount of wake loss between the two most eastern wind turbines. Usually, such a loss results in an increased LCOE. However, the LCOE remains almost constant as the cost of access roads is reduced as well.

The right-hand side of Figure 9 represents the wind farm layout when considering a new road network during the layout optimization (Case (B)). The optimization tries to reduce the road costs by placing the turbines closer to each other and in a circular shape. The circular connection leads to the fact that the roads can be connected without using the middle of the field. This approach means a reduction of 295 m. Consequently, the closer spacing means also a greater wake loss resulting in 0.098 GWh less power production.

![Figure 9](image)

**Figure 9.** Combined layout optimization with access road design (red lines) using existing infrastructure (left, Case (A)) constructing a new road network (right, Case (B))

The overview of all outputs can be found in Table 2. The combined optimization does not necessarily lead to improved power output. If the wind site is within an existing road network, the LCOE cannot be reduced significantly. The benefit is approximately 0.001 €/ct/kWh equal to 175 € over 20 years. This is not attractive particularly with the aspect that the calculation time is increased by approximately 50%.

However, the approach should be considered if the site has no existing infrastructure. Such a site would mean that an entire road network needs to be constructed causing an increase in the investment costs. This aspect scales directly with the number of wind turbines in the wind farm. It needs to be kept in mind that the shown procedure is an estimation. Meaning that there is still some uncertainty due to local obstacles or regulations. Nonetheless, this analysis shows an indication that could be further investigated.

**Table 2. Summary of the optimization results**

| Parameters                  | Ref. Case | Case (A) | Case (B) |
|-----------------------------|-----------|----------|----------|
| AEP [GWh]                   | 41.187    | 41.132   | 41.089   |
| LCOE [€/ct/kWh]             | 5.668     | 5.667    | 5.685    |
| Length of access roads [m]  | 320       | 201      | 3 041    |
| Invest of access roads [€]  | 24 000    | 15 075   | 228 075  |
4. Conclusion
In this paper, it was shown that considering the access road network while optimizing the wind farm layout can lead to a reduction of road investment costs and therefore to a slightly smaller LCOE. The application of the methods to the shown case, a seven-turbine wind farm, did not change the LCOE by a detectable amount but indicated that it is possible to gain a certain decrease in the investment costs by optimizing the access road network. Depending on the site of interest, a different method to plan access roads should be used. A site with existing infrastructure should pursue the approach to firstly design the park and subsequently the access roads. This is not necessarily the case if no road network is available. In this case, the access roads should be considered during the layout.

5. References
[1] Wallasch AK, Lüers S., Rebennack S., Ekkert M. 2013 Kostensituation der Windenergie an Land in Deutschland Deutsche WindGuard
[2] Krohn S., Morthorst PE., Awerbuch S. 2009 Economics of Wind Energy European Wind Energy Association
[3] Nassar K, El Masry M and Osman H 2010 - 2010 Simulating the effect of access road route selection on wind farm construction Proceedings of the 2010 Winter Simulation Conference 2010 Winter Simulation Conference - (WSC 2010) (Baltimore, MD, USA, 05.12.2010 - 08.12.2010) (IEEE) pp 3272–82
[4] Gu H, Wang J, Lin Q and Gong Q 2015 Automatic Contour-Based Road Network Design for Optimized Wind Farm Micrositing IEEE Trans. Sustain. Energy 6 281–9
[5] Daniels L 2007 Community Wind Toolbox - Chapter 8: Costs www.windustry.org/community_wind_toolbox_8_costs (accessed 6 Feb 2020)
[6] Micelli F 2012 Wind farm internal roads bends additional widening http://www.windfarmbop.com/category/roads/ (accessed 6 Feb 2020)
[7] Roscher B 2020 Multi-Dimensional Wind Farm Optimization in the Concept Phase Dissertation Center for Wind Power Drives, RWTH Aachen
[8] Gutin G, Yeo A and Zverovich A 2002 Traveling salesman should not be greedy: domination analysis of greedy-type heuristics for the TSP Discrete Applied Mathematics 117 81–6
[9] Mortimer P. 2019 Optimierte Routenplanung zur Installation eines Windparks Masterarbeit Chair for Wind Power Drives, RWTH Aachen
[10] Prim R. C. 1957 Shortest Connection Networks And Some Generalizations Bell System Technical Journal 36 1389–401
[11] Bang-Jensen J and Gutin G Z 2010 Digraphs: Theory, algorithms and applications (Springer monographs in mathematics) 2nd edn (London, New York: Springer)
[12] Jensen NO., Katic I., Højstrup J. 1986 A simple model for cluster efficiency (Rome)
[13] Roscher B., Harzendorf F., Schelenz R., Jacobs G. 2018 Reduced Levelized Cost of Energy through Optimization of Tower height, Rotor Diameter and Wind Farm Layout American Journal of Engineering Research (AJER) 130–8