AUT

Amirkabir University of Technology

Wind Farm Layout Optimization Using TopFarm Software

A Comprehensive Analysis of Turbine Arrangements and Multi-Farm Configurations

Project Type: TopFarm Software Analysis & Optimization

Turbine Models: V80, 3.35MW (IEA Task 37), DTU 10MW Reference Turbine

Site Locations: IEA37Site, Hornsrev1

Configurations: 9, 16, 36, and 64 turbine arrangements (24 total scenarios)

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1. Introduction

Wind farm layout optimization has become a critical aspect of renewable energy development, as proper turbine placement can significantly enhance energy production while minimizing wake effects and operational costs. TopFarm software provides advanced computational tools for analyzing and optimizing wind farm configurations through sophisticated algorithms that account for complex aerodynamic interactions between turbines. This study presents a comprehensive analysis of wind farm performance using TopFarm, systematically evaluating 24 different scenarios across multiple turbine densities (9, 16, 36, and 64 turbines), three turbine models (V80, 3.35MW IEA Task 37, and DTU 10MW reference turbine), and two distinct sites (IEA37Site and Hornsrev1). The research aims to quantify the impact of various configuration parameters on annual energy production and identify key factors contributing to performance variations, ultimately providing insights for optimal wind farm design strategies.

1.1 Project Scope

This project encompasses two primary phases of analysis using TopFarm software. The first phase involves a systematic comparison of 24 output scenarios generated from the combination of different turbine arrangements (9, 16, 36, and 64 turbines) across three turbine models and two site locations. Each configuration's annual energy production increase percentage is analyzed to identify factors influencing performance variations between different layouts. The second phase focuses on multi-farm configurations, where three different outputs are generated by modifying code input parameters, providing insights into the scalability and adaptability of optimization strategies across multiple wind farm installations. The scope includes comprehensive analysis of turbine-site interactions, wake effect mitigation, and energy production optimization under varying operational conditions.

1.2 Study Sites

Two distinct offshore wind farm sites are utilized in this analysis to provide comprehensive insights across different environmental conditions and validation approaches.

1.2.1 IEA37Site

The IEA37Site represents a standardized benchmark site developed by the International Energy Agency Task 37 specifically for wind farm layout optimization studies. This site features uniform wind conditions with consistent wind speed and direction distributions, making it ideal for controlled comparative analysis of different turbine arrangements. The site is characterized by its regular wind rose pattern with a simplified annual wind distribution and minimal terrain complexity, allowing for clear assessment of wake effects and optimization algorithms without external environmental variables. The standardized nature of IEA37Site enables direct comparison of optimization results across different research studies and provides a controlled testing environment for evaluating the performance of various turbine configurations under idealized conditions[1].

1.2.2 Hornsrev1

Hornsrev1, located in the Danish North Sea approximately 14-20 km west of the Danish coast, represents a real-world offshore wind farm environment with extensive operational history and validated performance data. This site presents more complex wind conditions with varying wind speeds, directional patterns, and seasonal variations that reflect actual offshore wind farm operational challenges. The wind resource at Hornsrev1 is characterized by predominantly westerly winds with moderate to high wind speeds typical of North Sea conditions. Hornsrev1's established wind resource characteristics, proven operational track record, and available measured data make it an excellent testbed for validating optimization strategies under realistic operational conditions, providing insights into how theoretical optimization translates to practical wind farm performance[2].

Figure1. Horns Rev 1 windfarm developed by Vattenfal

1.3 Turbine Model Overview

Three distinct turbine models are employed in this study to evaluate optimization performance across different scales and technological generations of wind turbine technology. Each turbine represents different design philosophies and operational characteristics that influence wake interactions and overall farm performance.

1.3.1 V80 Turbine

The V80 turbine represents a mature wind turbine technology with a rotor diameter of 80 meters and hub height typically ranging from 60 to 100 meters. This turbine model features a three-bladed horizontal axis design with variable speed operation and pitch control systems. The V80 has been widely deployed in commercial wind farms globally, providing extensive operational data and proven reliability. Its moderate size and well-characterized performance curves make it an excellent baseline for comparative analysis. The turbine's power curve and thrust coefficient characteristics are well-documented, enabling accurate wake modeling and energy production calculations in optimization studies[3].

Figure2. Vestas V80-2.0 Wind Turbine

1.3.2 3.35MW IEA Task 37 Turbine

The 3.35MW turbine from IEA Task 37 represents a standardized reference turbine specifically developed for wind farm optimization research and benchmarking studies. This turbine model features modern design characteristics with optimized aerodynamic performance and is designed to represent contemporary wind turbine technology. The standardized specifications include detailed power and thrust curves, making it ideal for comparative studies across different research groups and optimization algorithms. The turbine incorporates advanced control systems and aerodynamic design features that reflect current industry standards, providing insights into optimization performance with modern turbine technology[4].

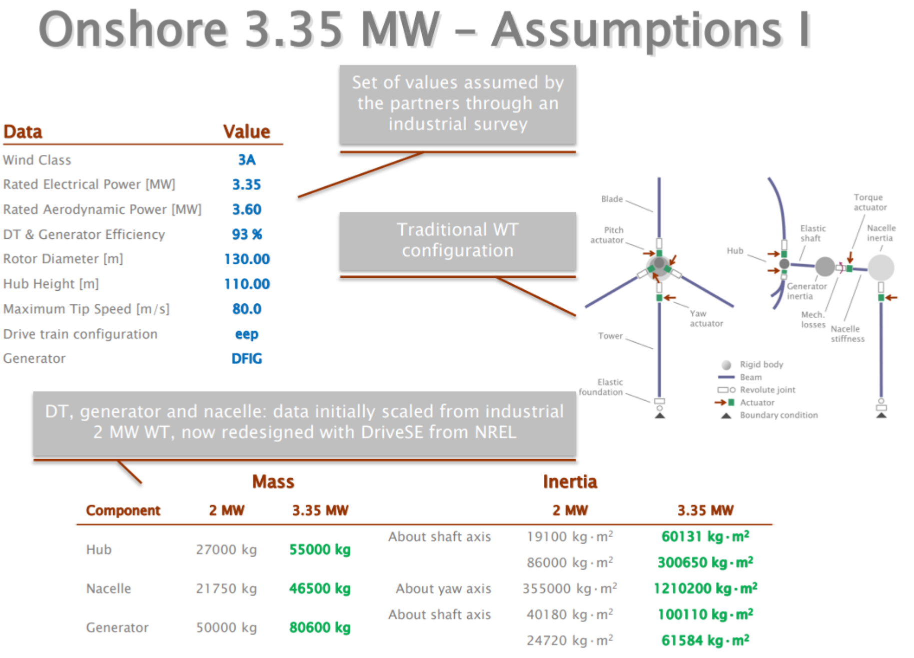


Figure3. Onshore Task 37 turbine model assumptions

1.3.3 DTU 10MW Reference Turbine

The DTU 10MW reference turbine represents large-scale offshore wind turbine technology with a rotor diameter of 178.3 meters and hub height of 119 meters. Developed by the Technical University of Denmark, this turbine model serves as a reference for large offshore wind turbine research and represents the scale of modern offshore wind developments. The turbine features advanced pitch and torque control systems optimized for offshore conditions, with detailed specifications available for research applications. Its large rotor diameter and high power rating create significant wake effects that are critical for understanding optimization challenges in modern offshore wind farms, making it essential for evaluating layout optimization strategies for next-generation wind farm projects[5].

The DTU 10 MW Reference Wind Turbine Design Summary

Description	Value
Rating	10MW
Rotor orientation, configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Medium speed, Multiple stage gearbox
Rotor, Hub diameter	178.3m, 5.6m
Hub height	119m
Cut-in, Rated, Cut-out wind speed	4m/s, 11.4m/s, 25m/s
Cut-in, Rated rotor speed	6RPM, 9.6RPM
Rated tip speed	90m/s
Overhang, Shaft tilt, Pre-cone	7.07m, 5° , 2.5°
Pre-bend	3m
Rotor mass	229tons (each blade ~41tons)
Nacelle mass	446tons
Tower mass	605tons

Figure4. DTU 10MW design summary

1.4 Constraint Definition for Turbine Models

The optimization process in TopFarm requires careful definition of spatial constraints to ensure realistic and practical wind farm layouts. These constraints govern turbine spacing and site boundaries, directly influencing the optimization algorithms' ability to find feasible solutions while maximizing energy production. Three distinct constraint functions have been developed for each turbine model, each tailored to the specific geometric and operational characteristics of the respective turbine technology while maintaining consistency in comparative analysis methodology.

1.4.1 Constraint Framework and Design Philosophy

All constraint functions implement two fundamental constraint types: spacing constraints and boundary constraints. The spacing constraints prevent turbines from being placed too close to each other, thereby avoiding excessive wake interference and ensuring operational safety. The boundary constraints define the allowable site area for turbine placement, establishing realistic limits for wind farm development. The constraint design follows a standardized approach across all turbine models to enable direct performance comparisons while accommodating the unique characteristics of each turbine technology.

1.4.2 V80 Turbine Constraints

The `get_v80_constraints` function implements constraints specifically designed for the V80 turbine model with its 80-meter rotor diameter. The function establishes a minimum spacing constraint of 160 meters (two rotor diameters) between any pair of turbines using the `SpacingConstraint` class. The boundary constraints utilize a `CircleBoundaryConstraint` centered at the origin with radii that scale according to turbine count: 900 meters for up to 9 turbines, 1300 meters for up to 16 turbines, 2000 meters for up to 36 turbines, and 3000 meters for larger configurations. This scaling approach ensures adequate site area for each configuration while maintaining realistic wind farm dimensions.

```python
def get_v80_constraints(n_wt=9):
    """Constraints for V80 wind farms

    Parameters
    ----------
    n_wt : int, optional
        Number of wind turbines in farm

    Returns
    -------
    constr : list of topfarm constraints
        Spacing constraint and boundary constraint for V80 model
    """
    from topfarm.constraint_components.spacing import SpacingConstraint
    from topfarm.constraint_components.boundary import CircleBoundaryConstraint
    import numpy as np

    # V80 rotor diameter is 80m
    diam = 80.0

    # Minimum spacing: 2 rotor diameters (160m)
    spac_constr = SpacingConstraint(2 * diam)

    # Boundary radius based on number of turbines
    # Simple scaling: more turbines need larger area
    if n_wt <= 9:
        bound_rad = 900
    elif n_wt <= 16:
        bound_rad = 1300
    elif n_wt <= 36:
        bound_rad = 2000
    else:
        bound_rad = 3000

    bound_constr = CircleBoundaryConstraint((0, 0), bound_rad)

    return [spac_constr, bound_constr]

```

1.4.3 DTU 10MW Turbine Constraints

The `get_dtu10mw_constraints` function addresses the spatial requirements of the large-scale DTU 10MW reference turbine with its 178.3-meter rotor diameter. The function implements a minimum spacing constraint of 356.6 meters (two rotor diameters), which is significantly larger than the V80 requirements due to the extended wake effects of larger rotors. Despite the different turbine scale, the function maintains identical boundary radius scaling as the V80 constraints, enabling direct comparison of optimization performance across different turbine technologies under equivalent site area limitations.

```python
def get_dtu10mw_constraints(n_wt=9):
    """Constraints for DTU10MW wind farms

    Parameters
    ----------
    n_wt : int, optional
        Number of wind turbines in farm

    Returns
    -------
    constr : list of topfarm constraints
        Spacing constraint and boundary constraint for DTU10MW model
    """
    from topfarm.constraint_components.spacing import SpacingConstraint
    from topfarm.constraint_components.boundary import CircleBoundaryConstraint
    import numpy as np

    # DTU10MW rotor diameter is 178.3m
    diam = 178.3

    # Minimum spacing: 2 rotor diameters (356.6m)
    spac_constr = SpacingConstraint(2 * diam)

    # Boundary radius based on number of turbines
    # Larger turbines need more space
    if n_wt <= 9:
        bound_rad = 900
    elif n_wt <= 16:
        bound_rad = 1300
    elif n_wt <= 36:
        bound_rad = 2000
    else:
        bound_rad = 3000

    bound_constr = CircleBoundaryConstraint((0, 0), bound_rad)

    return [spac_constr, bound_constr]

```

1.4.4 IEA Task 37 Turbine Constraints

The `*get_iea37_constraints*` function provides constraints for the standardized IEA Task 37 3.35MW turbine model. The function dynamically extracts the rotor diameter from the IEA37 turbine specification files using the `*read_iea37_windturbine*` function, ensuring consistency with the official benchmark parameters. The spacing constraint follows the standard two-diameter rule based on the extracted rotor specifications. The boundary constraints utilize an efficient numpy array mapping approach to assign appropriate radii based on turbine count, maintaining the same scaling progression as other turbine models while ensuring full compatibility with the IEA37 optimization framework[6].

1.4.5 Constraint Implementation Rationale

The decision to maintain identical boundary scaling across all turbine models, regardless of rotor size differences, serves a specific analytical purpose. This approach enables direct assessment of how turbine technology affects optimization performance under equivalent site constraints, isolating the impact of turbine characteristics from site area variables. While larger turbines theoretically require more spacing and site area, the standardized boundary approach provides valuable insights into the relative efficiency of different turbine technologies within fixed site limitations, which is representative of many real-world development scenarios where site boundaries are predetermined by environmental, regulatory, or economic factors.

1.4.6 Compatibility with IEA37 Framework and Hornsrev1 Site Limitations

A critical design consideration underlying all constraint functions involves ensuring compatibility with IEA37 initial layout conditions. The constraint implementations are specifically calibrated to work with standardized IEA37 initial positions, preventing the occurrence of negative improvement values that would compromise the validity of optimization results. This compatibility requirement ensures that optimization algorithms begin from feasible starting points and can demonstrate meaningful performance improvements, enabling robust comparative analysis across different turbine technologies and providing consistency with established wind farm layout optimization benchmarks used throughout the research community.

However, significant limitations arise when applying these constraint methodologies to the Hornsrev1 site. The Hornsrev1Site class does not include a predefined *site.initial* command, which creates fundamental challenges for optimization analysis across different turbine counts. Without standardized initial positions for varying turbine numbers (9, 16, 36, 64), the comparative analysis for Hornsrev1 lacks scientific validation and produces meaningless results. The absence of the *site.initial* functionality means that different turbine configurations cannot be properly initialized with appropriate spacing and boundary conditions relative to the actual site characteristics.

The constraint definition problem becomes particularly acute when attempting to optimize different numbers of turbines on Hornsrev1, as proper constraints should vary with both turbine count and site-specific characteristics. Without the ability to define appropriate initial conditions through *site.initial*, the optimization process often produces negative AEP improvements, indicating that the initial randomly-placed layouts are actually superior to the optimized results. This occurs because the constraint boundaries change during the optimization process without proper calibration to the site's actual operational parameters.

Due to time constraints in this project, modifying the Hornsrev1Site class to include proper *site.initial* functionality was not feasible. An alternative analytical approach would involve grouping similar turbine counts together (analyzing all 9-turbine systems collectively, all 36-turbine systems together, etc.), but even this approach yields unreliable results due to the fundamental constraint calibration issues. The core problem remains that when *site.initial* commands work effectively with IEA37Site but are unavailable for Hornsrev1, any constraint definitions based on turbine diameter alone cannot properly account for site-specific boundary conditions, leading to optimization results that lack practical validity and scientific rigor.

2. Optimization Results and Performance Evaluation

This section presents the comprehensive analysis of wind farm layout optimization results obtained through TopFarm software, structured into two distinct phases of investigation. The first phase examines individual wind farm performance through a systematic evaluation of 24 distinct scenarios, analyzing the impact of turbine model selection, site characteristics, and turbine density on optimization outcomes. The second phase extends the analysis to multi-farm configurations, exploring the complexities and optimization potential when multiple wind farms operate in proximity to each other. Throughout both phases, the primary metric tracked during the optimization process is Annual Energy Production (AEP), with all results presented as AEP improvement percentages calculated as the relative increase from initial to optimized layouts, enabling direct comparison across different turbine technologies and site conditions.

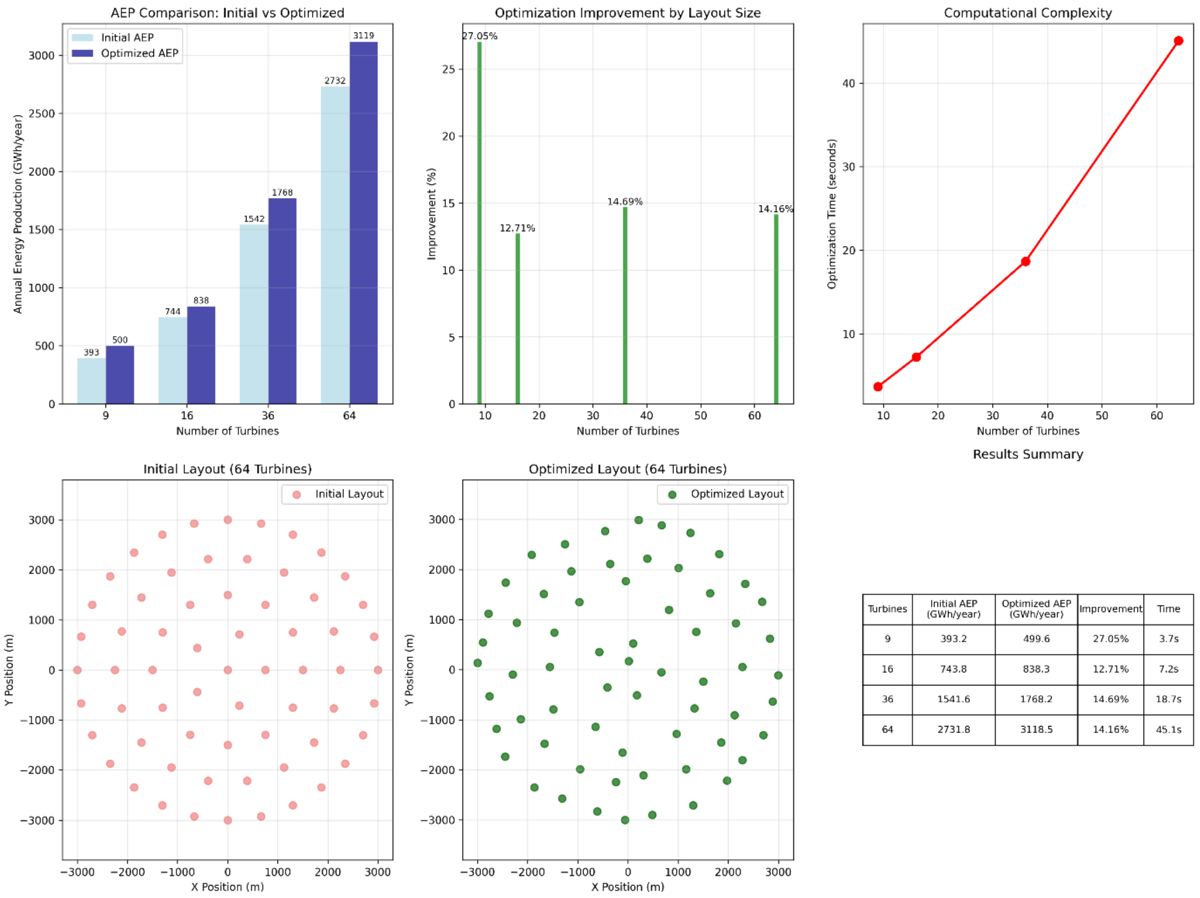
2.1 Optimizing under different scenarios (one farm)

IEA37Site - DTU 10MW Turbine Analysis

The DTU 10MW turbine optimization results on the IEA37Site demonstrate significant performance improvements across all turbine density configurations, with particularly pronounced benefits observed in low-density arrangements. The 9-turbine configuration achieved the highest relative improvement of 27.05%, increasing AEP from 393.2 GWh/year to 499.6 GWh/year. This substantial improvement indicates that large-scale turbines benefit considerably from spatial optimization when operating in sparse arrangements, where wake interactions can be effectively minimized through strategic positioning.

The optimization effectiveness shows a clear inverse relationship with turbine density. As turbine count increases from 9 to 64, the relative improvement decreases from

27.05% to 14.16%, despite absolute AEP values increasing substantially (from 499.6 GWh/year to 3118.5 GWh/year). This trend suggests that higher-density configurations face greater constraints in achieving optimal layouts due to increased wake interference and spatial limitations imposed by the minimum spacing requirements of 356.6 meters for the DTU 10MW turbines.



Turbines	Initial AEP (GWh/year)	Optimized AEP (GWh/year)	Improvement	Time
9	393.2	499.6	27.05%	3.7s
16	743.8	838.3	12.71%	7.2s
36	1541.6	1768.2	14.69%	18.7s
64	2731.8	3118.5	14.16%	45.1s

Figure5. DTU 10MW Optimization Performance Dashboard in IEA37Site

The layout optimization patterns reveal systematic reorganization of turbine positions to maximize wake recovery distances. In the 9-turbine configuration, turbines were repositioned to create more dispersed arrangements, while higher-density configurations show more subtle adjustments focused on fine-tuning inter-turbine spacing.

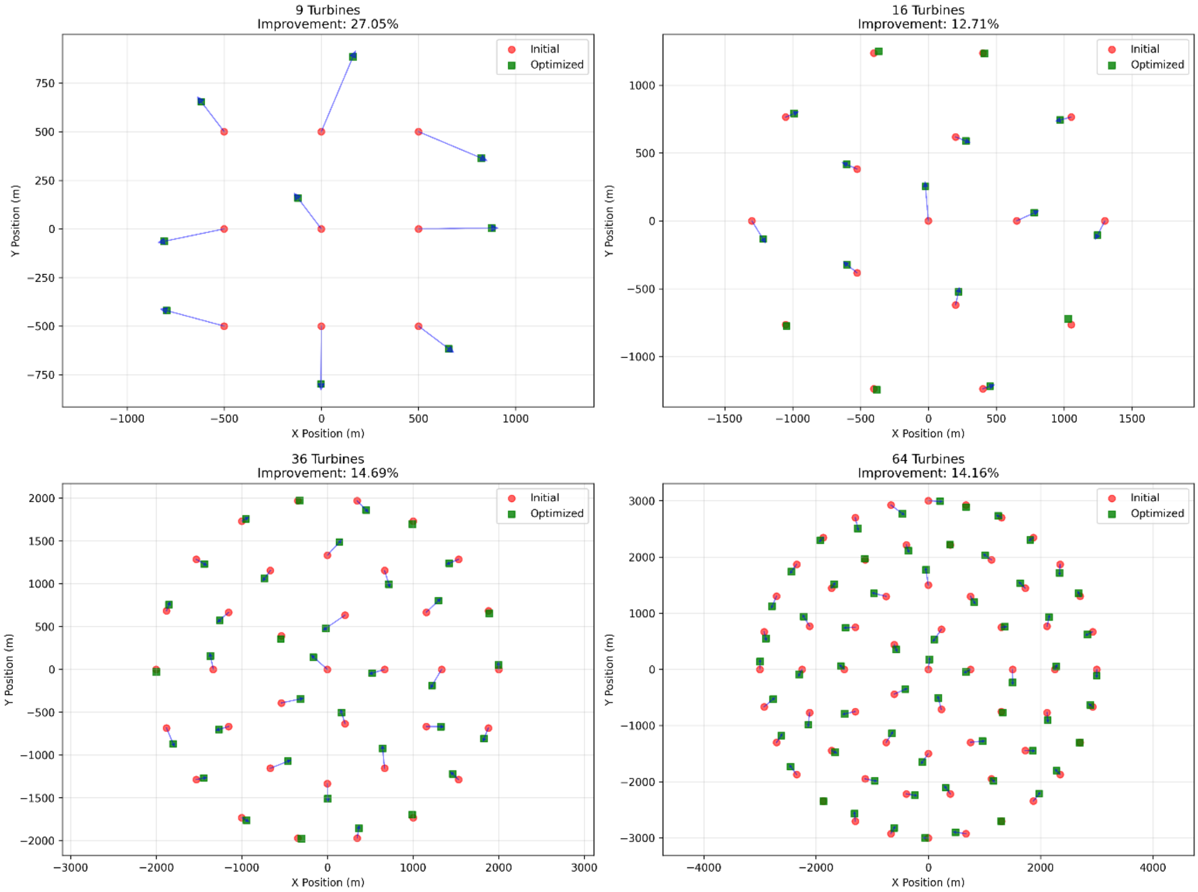
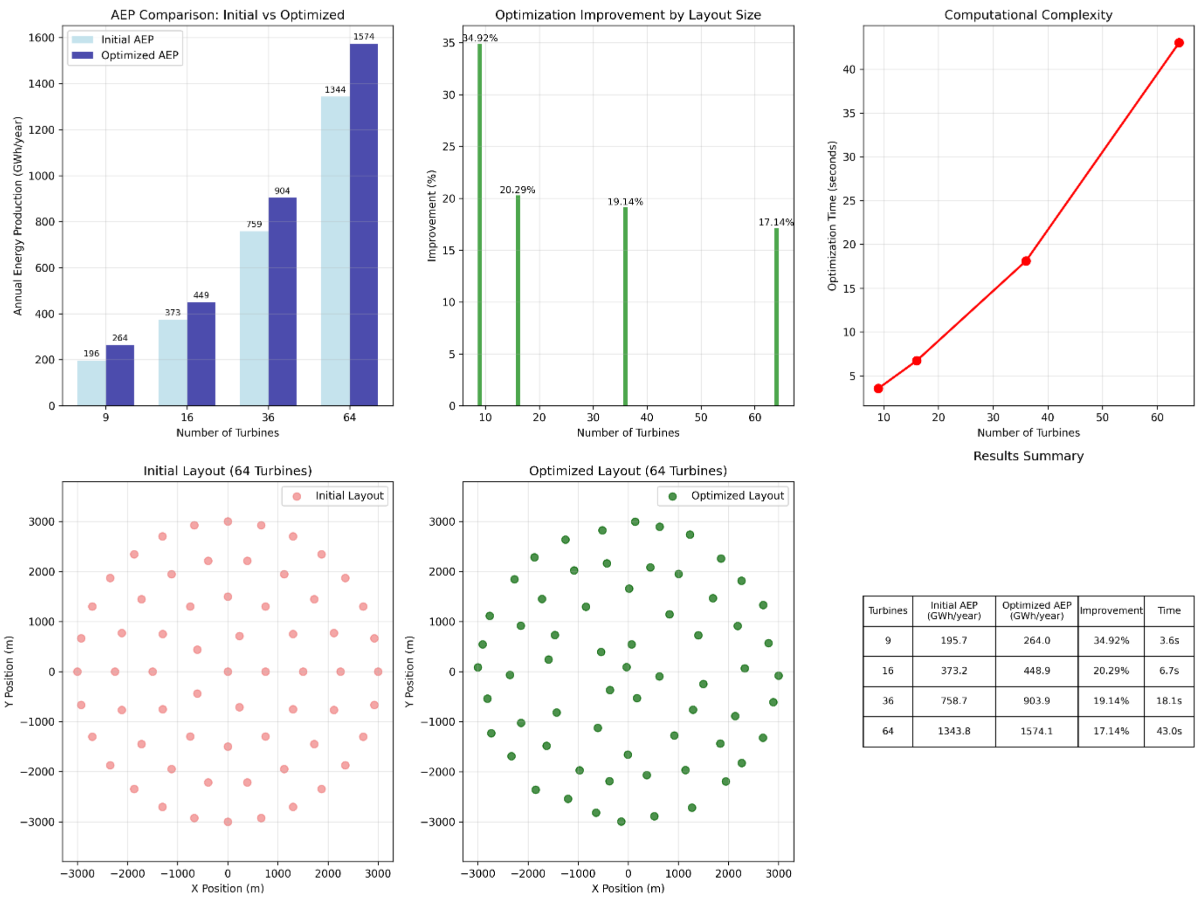


Figure6. Wind Farm Layout Optimization: Initial vs Optimized Turbine Positions

IEA37Site - IEA Task 37 3.35MW Turbine Analysis

The IEA Task 37 3.35MW turbine optimization results on the IEA37Site showcase exceptional performance improvements, particularly in low-density configurations where the system achieves the highest relative improvement of 34.92% for the 9-turbine arrangement. This outstanding result, increasing AEP from 195.7 GWh/year to 264.0 GWh/year, demonstrates the significant optimization potential when mid-scale turbines operate with adequate spatial freedom for wake management. The superior performance compared to the DTU 10MW results indicates that the IEA Task 37 turbine's design characteristics are particularly well-suited for layout optimization strategies.



Turbines	Initial AEP (GWh/year)	Optimized AEP (GWh/year)	Improvement	Time
9	195.7	264.0	34.92%	3.6s
16	373.2	448.9	20.29%	6.7s
36	758.7	903.9	19.14%	18.1s
64	1343.8	1574.1	17.14%	43.0s

Figure7. IEA37 turbine Optimization Performance Dashboard in IEA37Site

The optimization effectiveness maintains a consistent inverse relationship with turbine density, though the relative improvements remain substantially higher across all configurations compared to larger turbine models. The improvements decrease from 34.92% for 9 turbines to 17.14% for 64 turbines, while absolute AEP values scale proportionally from 264.0 GWh/year to 1574.1 GWh/year. This pattern suggests that the IEA Task 37 turbine's intermediate scale and optimized aerodynamic characteristics create more favorable conditions for spatial optimization across varying density scenarios.

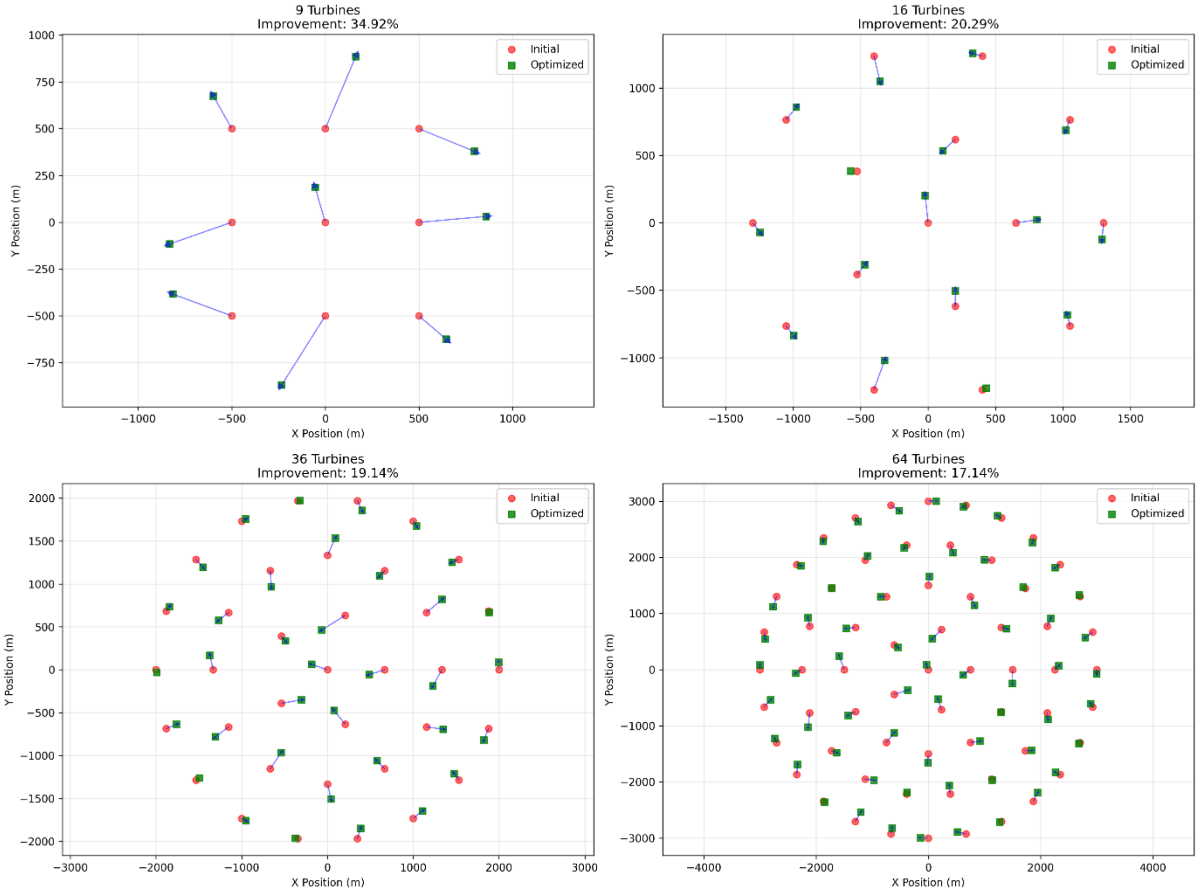


Figure8. Wind Farm Layout Optimization: Initial vs Optimized Turbine Positions

The layout optimization patterns reveal systematic redistribution of turbine positions to maximize wake recovery, with particularly pronounced spatial adjustments visible in lower-density configurations.

IEA37Site - V80 Turbine Analysis

The V80 turbine optimization results on the IEA37Site demonstrate moderate but consistent performance improvements across all turbine density configurations, with the highest relative improvement of 14.39% achieved in the 9-turbine arrangement. This improvement, increasing AEP from 92.0 GWh/year to 105.3 GWh/year, represents the most conservative optimization gains among the three turbine models tested. The lower relative improvements compared to the IEA Task 37 and DTU 10MW turbines suggest that the V80's smaller rotor diameter (80m) and lower power rating create less pronounced wake effects, resulting in reduced optimization potential through spatial rearrangement.

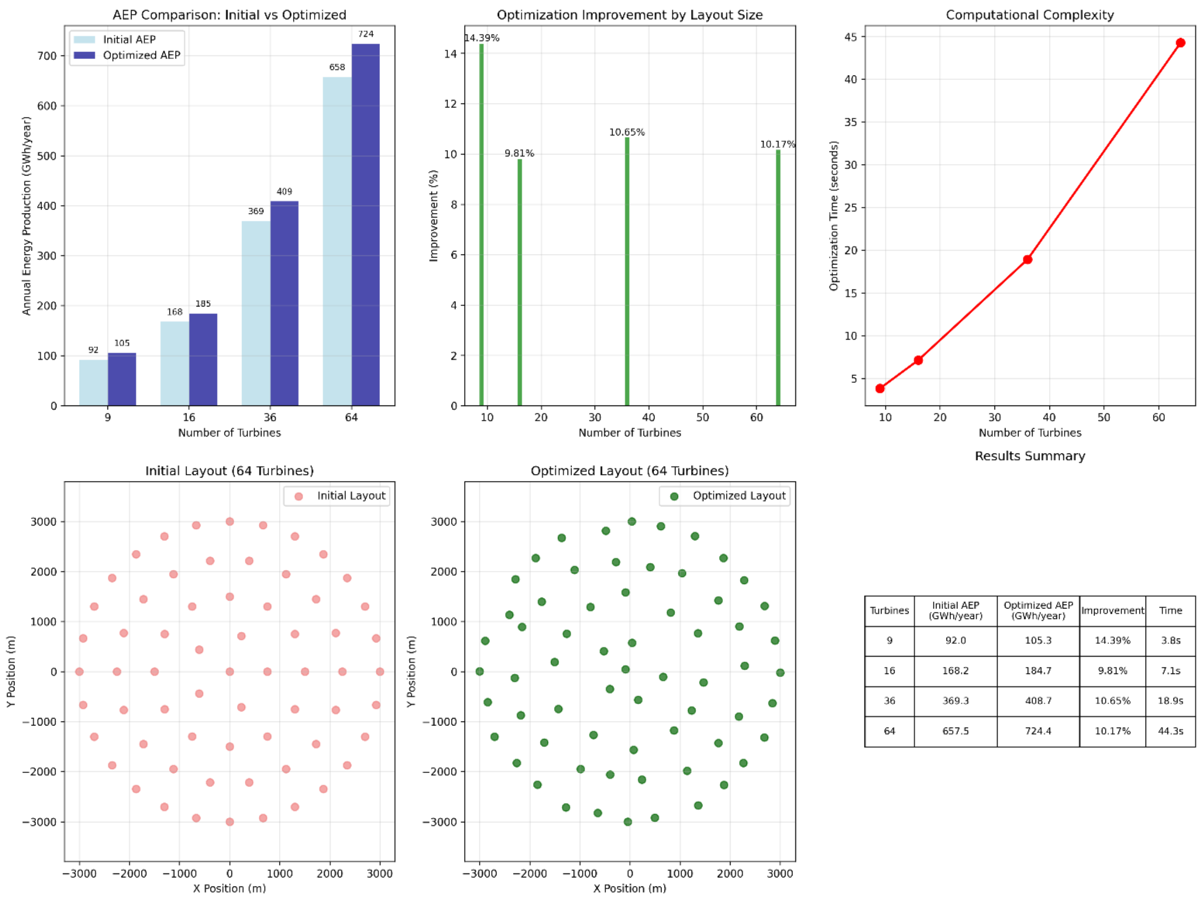


Figure9. V80 Turbine Optimization Performance Dashboard on IEA37Site

The optimization effectiveness shows a relatively flat performance curve across different turbine densities, with improvements ranging from 14.39% for 9 turbines to 10.17% for 64 turbines. This compressed range of improvement percentages indicates that the V80 turbine's wake characteristics are less sensitive to spatial optimization compared to larger turbine models. The absolute AEP values scale proportionally from 105.3 GWh/year to 724.4 GWh/year, demonstrating consistent but modest energy production gains across all configurations.

The layout optimization patterns reveal subtle spatial adjustments focused on fine-tuning inter-turbine spacing rather than dramatic repositioning, reflecting the V80's smaller wake footprint and reduced interference effects.. The consistently lower optimization improvements across all density configurations suggest that while the V80 turbine provides reliable baseline performance, it offers limited potential for significant energy gains through layout optimization, making it less suitable for applications where maximizing optimization benefits is a primary design objective.

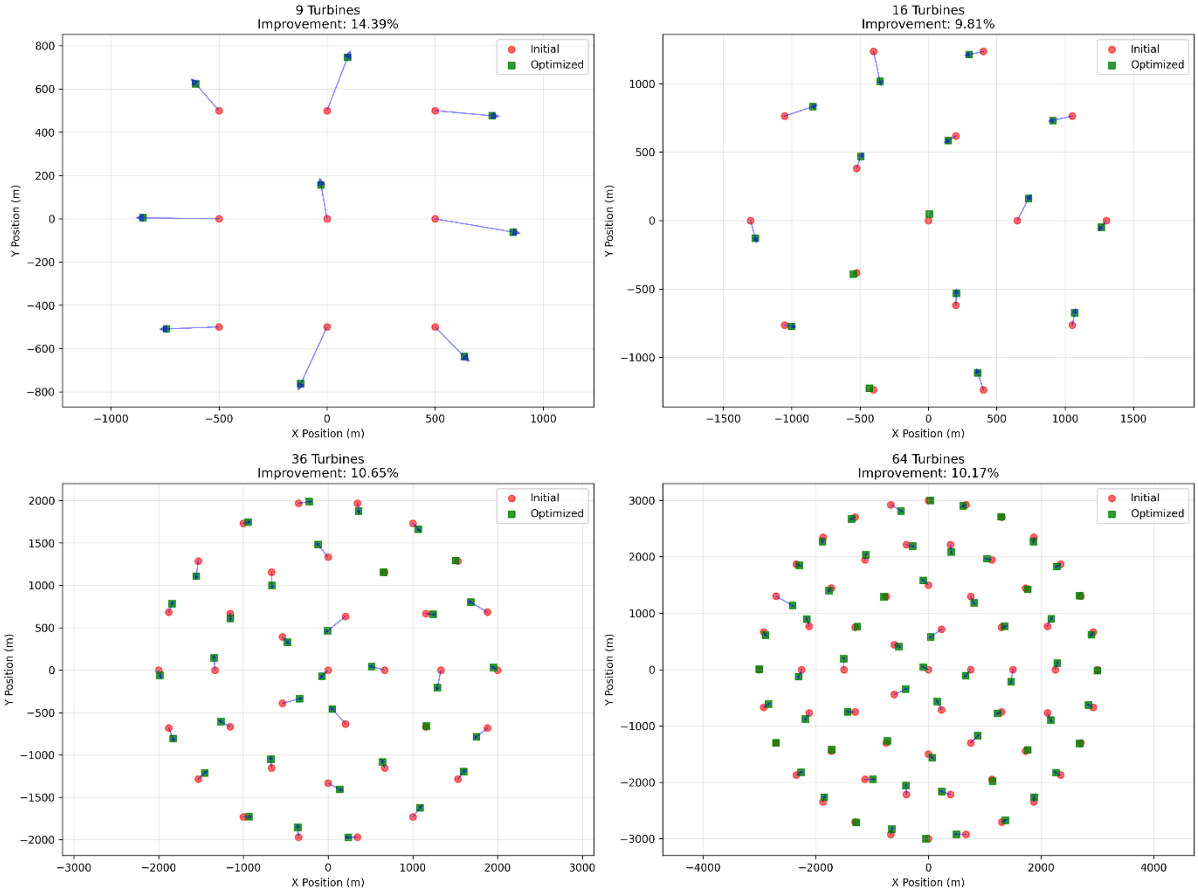
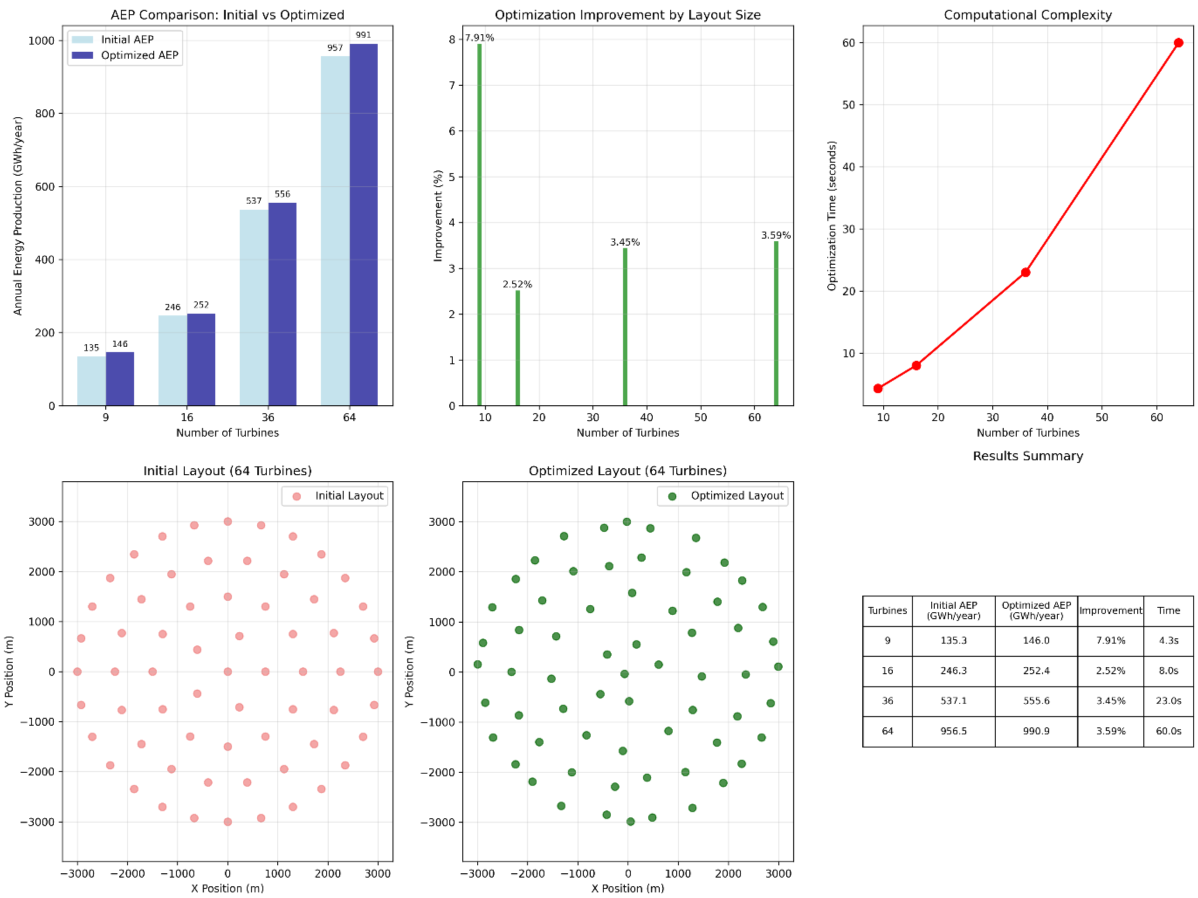


*Figure10.*V80 Turbine Layout Optimization*:* Initial vs Optimized Positions

Hornsrev1 Site - IEA Task 37 3.35MW Turbine Analysis

The IEA Task 37 3.35MW turbine optimization results on the Hornsrev1 site reveal dramatically reduced optimization potential compared to the IEA37Site, with the highest relative improvement of only 7.91% achieved in the 9-turbine configuration. This substantial decrease from the 34.92% improvement observed on the IEA37Site demonstrates the significant impact of site-specific wind characteristics on optimization effectiveness. The Hornsrev1 site's complex wind patterns and directional variability create challenging conditions that limit the benefits achievable through spatial layout optimization, even when using the previously best-performing turbine model.



Turbines	Initial AEP (GWh/year)	Optimized AEP (GWh/year)	Improvement	Time
9	135.3	146.0	7.91%	4.3s
16	246.3	252.4	2.52%	8.0s
36	537.1	555.6	3.45%	23.0s
64	956.5	990.9	3.59%	60.0s

*Figure11.*IEA Task 37 Turbine Optimization Performance on Hornsrev1 Site

The optimization improvements show an extremely compressed range across different turbine densities, with performance gains decreasing from 7.91% for 9 turbines to just 3.59% for 64 turbines. This narrow improvement band, combined with the consistently low percentage gains, indicates that the Hornsrev1 site's wind regime creates inherent limitations for layout optimization strategies. The absolute AEP values range from 146.0 GWh/year to 990.9 GWh/year, reflecting proportional scaling but with minimal optimization benefits compared to the reference site conditions.

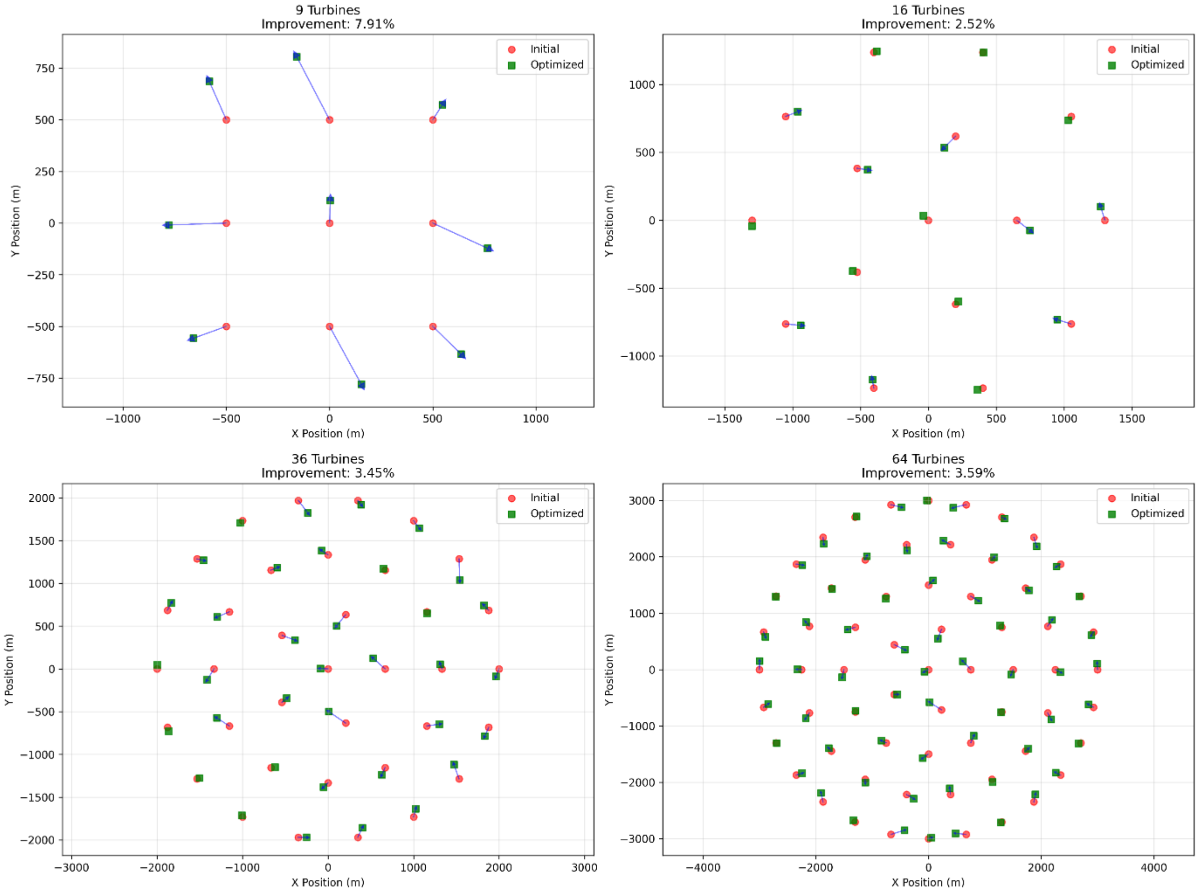
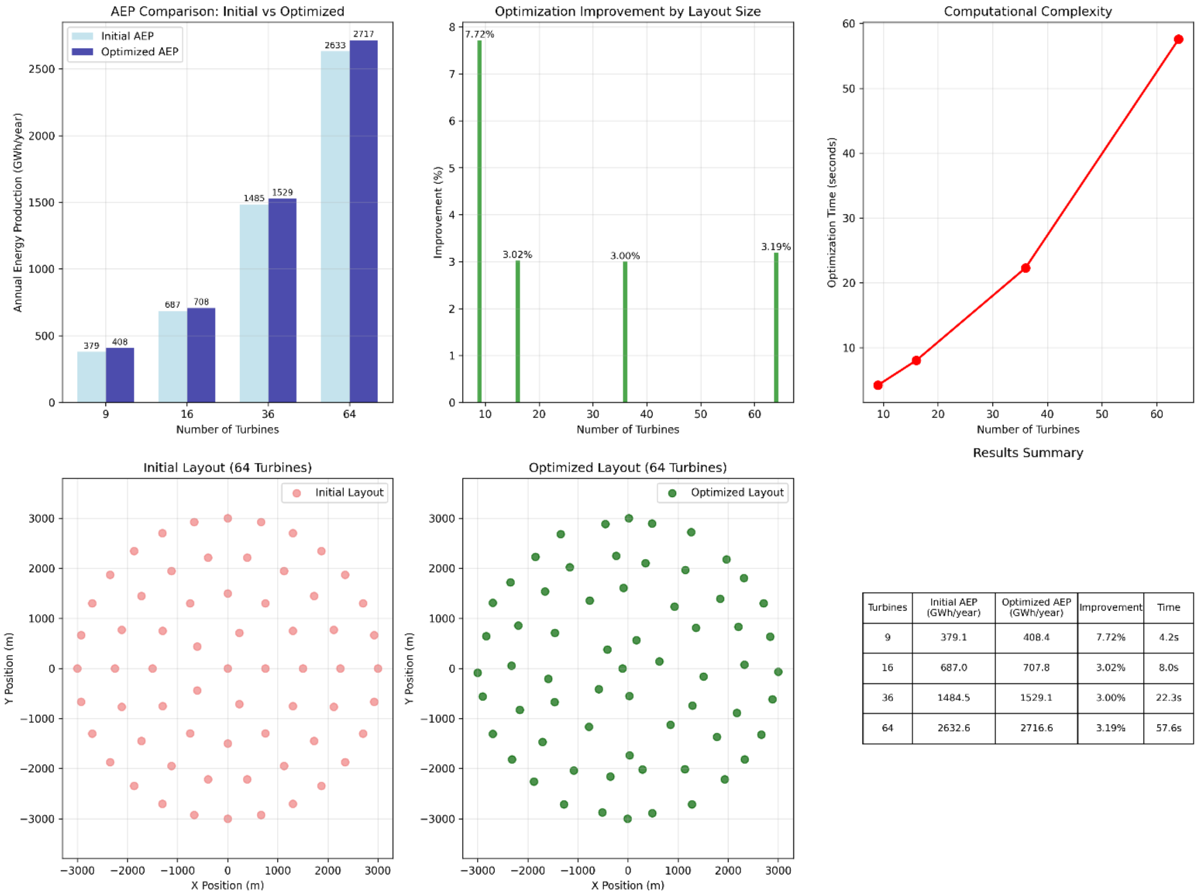


*Figure12.*Spatial Optimization: IEA Task 37 Turbines on Hornsrev1 Site

The layout optimization patterns show minimal spatial adjustments, with turbine positions exhibiting only subtle repositioning compared to the dramatic rearrangements observed on the IEA37Site. This conservative optimization behavior reflects the algorithm's recognition that significant layout changes provide limited benefits under the Hornsrev1 wind conditions. These results highlight the critical importance of site-specific wind characteristics in determining optimization potential, demonstrating that even optimal turbine selection cannot overcome challenging wind conditions that inherently limit the effectiveness of spatial layout optimization strategies.

Hornsrev1 Site - DTU 10MW Turbine Analysis

The DTU 10MW turbine optimization results on the Hornsrev1 site demonstrate similarly constrained performance improvements as observed with the IEA Task 37 turbine, with the highest relative improvement of 7.72% achieved in the 9-turbine configuration. This result, increasing AEP from 379.1 GWh/year to 408.4 GWh/year, represents a significant reduction from the 27.05% improvement achieved on the IEA37Site, confirming that the challenging wind conditions at Hornsrev1 severely limit optimization potential regardless of turbine technology. The large-scale DTU 10MW turbine's substantial wake effects, which provided significant optimization opportunities on favorable sites, become less advantageous under the complex wind patterns characteristic of the Hornsrev1 location.



Turbines	Initial AEP (GWh/year)	Optimized AEP (GWh/year)	Improvement	Time
9	379.1	408.4	7.72%	4.2s
16	687.0	707.8	3.02%	8.0s
36	1484.5	1529.1	3.00%	22.3s
64	2632.6	2716.6	3.19%	57.6s

Figure13. DTU 10MW Turbine Optimization Performance on Hornsrev1 Site

The optimization effectiveness shows an extremely flat performance profile across different turbine densities, with improvements ranging from just 7.72% for 9 turbines to 3.19% for 64 turbines. This remarkably compressed improvement range, even narrower than observed with the IEA Task 37 turbine, indicates that the DTU 10MW's large rotor diameter and associated wake characteristics are particularly disadvantaged by the Hornsrev1 site conditions. The absolute AEP values scale from 408.4 GWh/year to 2716.6 GWh/year, reflecting the turbine's high power output while highlighting the minimal benefits achievable through layout optimization.

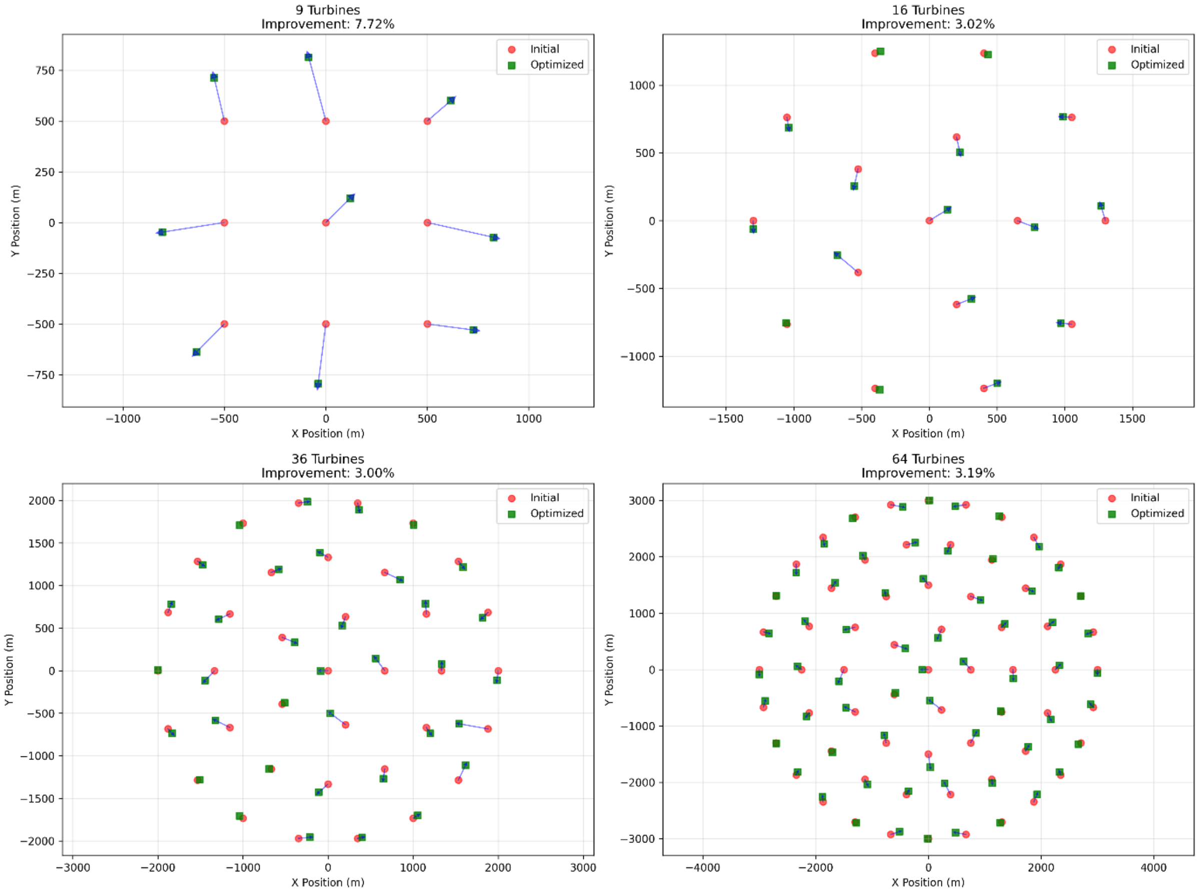


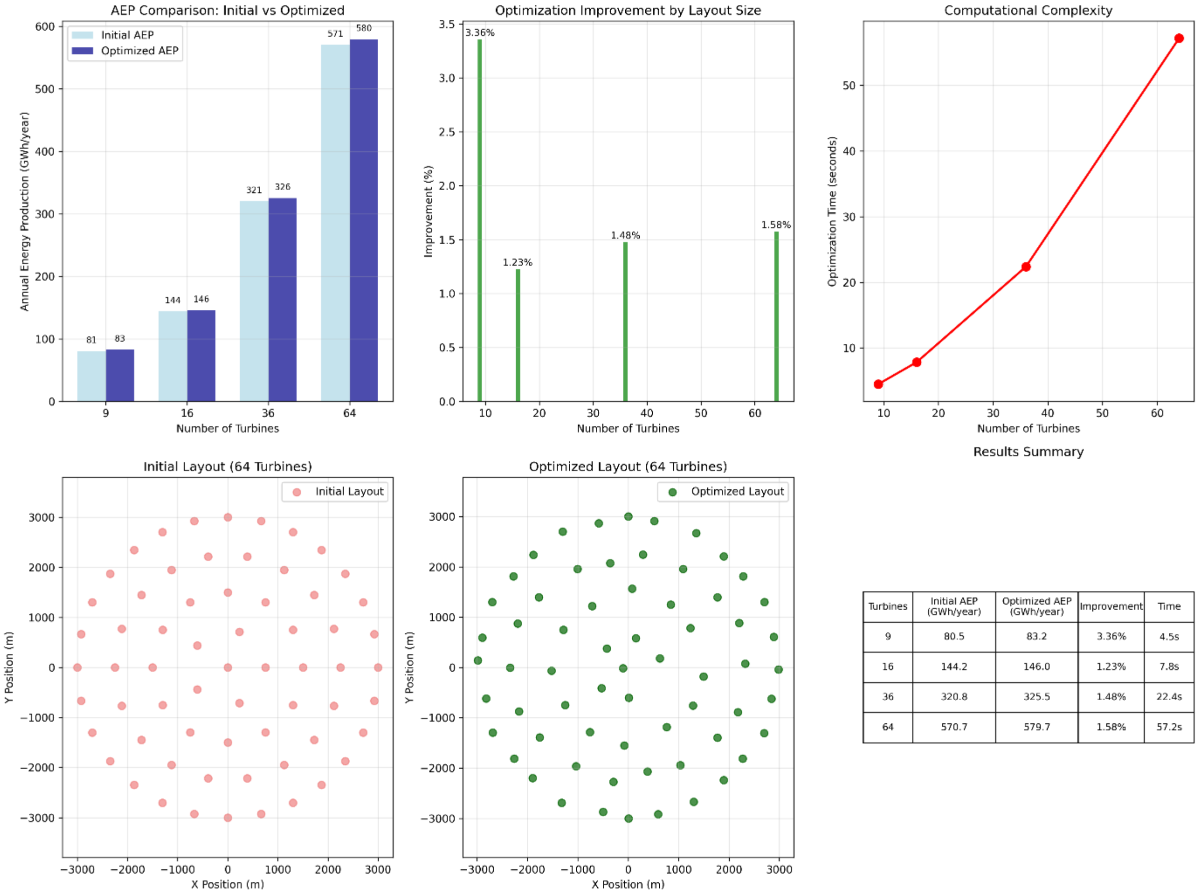
*Figure14.*DTU 10MW Turbine Layout Optimization on Hornsrev1 Site

The layout optimization patterns reveal minimal spatial adjustments across all turbine density configurations, with the algorithm making only conservative repositioning decisions due to the limited benefits available under the prevailing wind conditions. These results reinforce the critical finding that site-specific wind characteristics can completely override turbine selection advantages, demonstrating that even the most advanced large-scale turbines cannot overcome inherently challenging wind conditions that fundamentally limit the effectiveness of spatial layout optimization strategies.

Hornsrev1 Site - V80 Turbine Analysis

The V80 turbine optimization results on the Hornsrev1 site reveal the most severely constrained performance improvements across all tested scenarios, with the highest relative improvement of only 3.36% achieved in the 9-turbine configuration. This minimal improvement, increasing AEP from 80.5 GWh/year to 83.2 GWh/year, represents the lowest optimization potential observed throughout the entire study and demonstrates how the combination of challenging site conditions and smaller turbine characteristics creates extremely limited opportunities for layout enhancement. The

V80's smaller wake footprint, which already provided modest optimization benefits on favorable sites, becomes virtually negligible under the complex wind patterns of the Hornsrev1 location.



Turbines	Initial AEP (GWh/year)	Optimized AEP (GWh/year)	Improvement	Time
9	80.5	83.2	3.36%	4.5s
16	144.2	146.0	1.23%	7.8s
36	320.8	325.5	1.48%	22.4s
64	570.7	579.7	1.58%	57.2s

*Figure15.*V80 Turbine Optimization Performance on Hornsrev1 Site

The optimization effectiveness exhibits an exceptionally compressed performance range across all turbine densities, with improvements varying minimally from 3.36% for 9 turbines to 1.58% for 64 turbines. This remarkably narrow band of improvement percentages, representing the smallest range observed in the study, indicates that the V80 turbine's inherently limited wake effects are further diminished by the Hornsrev1 site's challenging wind characteristics. The absolute AEP values scale proportionally from 83.2 GWh/year to 579.7 GWh/year, reflecting the V80's lower power output while highlighting the minimal benefits achievable through spatial optimization under these conditions.

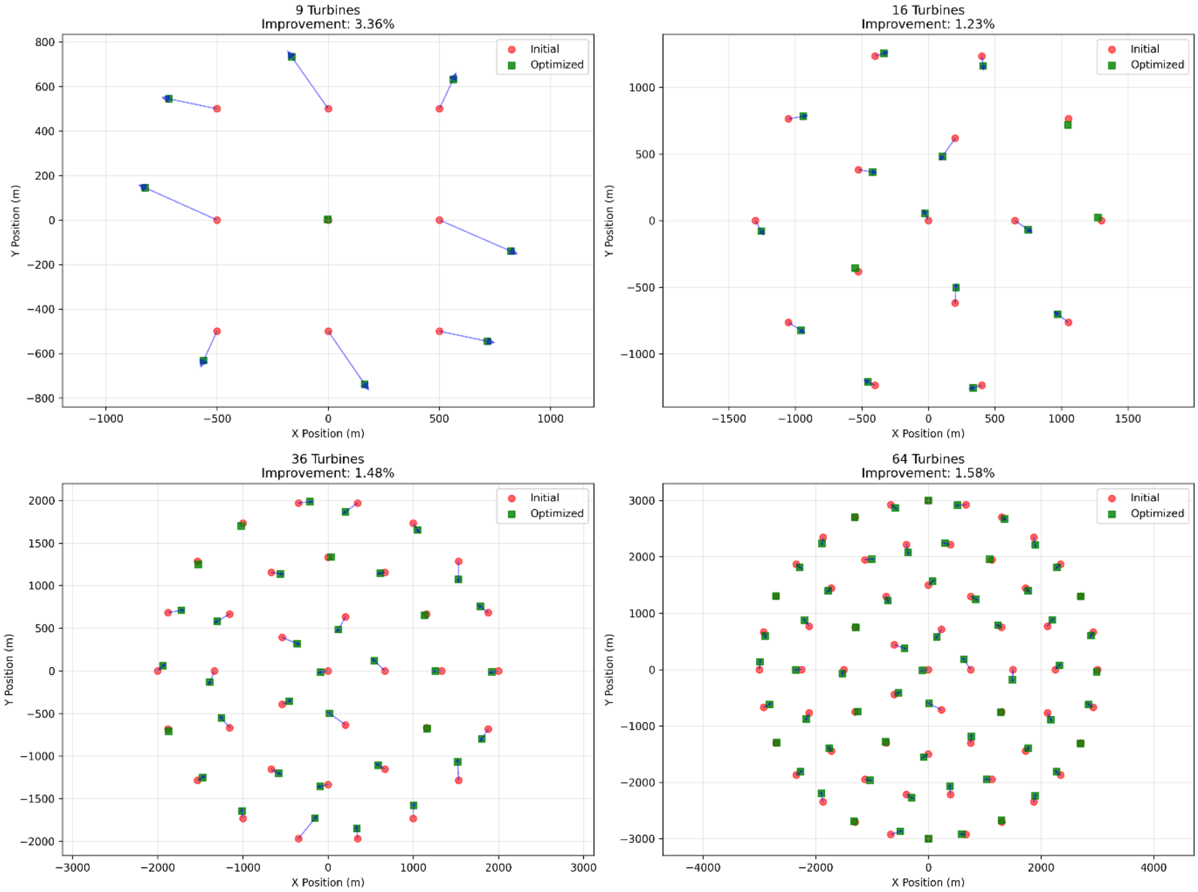


*Figure16.*V80 Turbine Layout Optimization on Hornsrev1 Site

The layout optimization patterns show virtually no meaningful spatial adjustments across all configurations, with turbine positions remaining nearly identical to their initial arrangements. This minimal optimization behavior reflects the algorithm's recognition that the combination of small wake effects and challenging wind conditions provides insufficient justification for significant layout modifications. The computational complexity maintains the expected scaling pattern, with optimization times ranging from 4.5 seconds for 9 turbines to 57.2 seconds for 64 turbines. These results conclusively demonstrate that the combination of unfavorable site characteristics and turbine technologies with limited wake effects can render layout optimization strategies essentially ineffective, establishing a clear threshold below which optimization interventions provide negligible practical benefits.

I. Comprehensive Wind Farm Layout Optimization Results Comparison

Site	Turbine Model	9 Turbines	16 Turbines	36 Turbines	64 Turbines	Average	Site Ranking
IEA37Site	IEA Task 37 3.35MW	**34.92%**	20.29%	19.14%	17.14%	**22.87%**	**1st**

IEA37Site	DTU 10MW	27.05%	12.71%	14.69%	14.16%	**17.15%**	**2nd**
IEA37Site	V80	14.39%	9.81%	10.65%	10.17%	**11.26%**	**3rd**
Hornsrev1	IEA Task 37 3.35MW	7.91%	2.52%	3.45%	3.59%	**4.37%**	**4th**
Hornsrev1	DTU 10MW	7.72%	3.02%	3.00%	3.19%	**4.23%**	**5th**
Hornsrev1	V80	3.36%	1.23%	1.48%	1.58%	**1.91%**	**6th**

II. Key Performance Metrics Summary

Configuration	Initial AEP (GWh/year)	Optimized AEP (GWh/year)	Max Improvement	Optimization Time (64T)
IEA37 + IEA Task 37	195.7 → 1343.8	264.0 → 1574.1	**34.92%**	43.0s
IEA37 + DTU 10MW	393.2 → 2731.8	499.6 → 3118.5	**27.05%**	45.1s
IEA37 + V80	92.0 → 657.5	105.3 → 724.4	**14.39%**	44.3s
Hornsrev1 + IEA Task 37	135.3 → 956.5	146.0 → 990.9	**7.91%**	60.0s
Hornsrev1 + DTU 10MW	379.1 → 2632.6	408.4 → 2716.6	**7.72%**	57.6s
Hornsrev1 + V80	80.5 → 570.7	83.2 → 579.7	**3.36%**	57.2s

III. Turbine Performance Rankings

By Maximum Optimization Potential (9 Turbines)

1) **IEA Task 37 3.35MW**: 34.92% (IEA37) / 7.91% (Hornsrev1)
2) **DTU 10MW**: 27.05% (IEA37) / 7.72% (Hornsrev1)
3) **V80**: 14.39% (IEA37) / 3.36% (Hornsrev1)

IV. By Average Performance Across All Densities

1) **IEA Task 37**: 22.87% (IEA37) / 4.37% (Hornsrev1)
2) **DTU 10MW**: 17.15% (IEA37) / 4.23% (Hornsrev1)
3) **V80**: 11.26% (IEA37) / 1.91% (Hornsrev1)

V. Site Impact Analysis

Site Comparison	IEA Task 37	DTU 10MW	V80	Average Site Effect
IEA37Site Performance	22.87%	17.15%	11.26%	**17.09%**
Hornsrev1 Performance	4.37%	4.23%	1.91%	**3.50%**
Site Impact Factor	**5.2x**	**4.1x**	**5.9x**	**4.9x**

🏆 **Best Overall Configuration**: IEA37Site + IEA Task 37 3.35MW (34.92% improvement)

VI. Optimization Results by Turbine Density Configuration

A. 9 Turbines Configuration

Rank	Site	Turbine Model	AEP Improvement	Initial AEP (GWh)	Optimized AEP (GWh)	Optimization Time
1st	IEA37Site	IEA Task 37 3.35MW	**34.92%**	195.7	264.0	3.6s
2nd	IEA37Site	DTU 10MW	**27.05%**	393.2	499.6	3.7s
3rd	IEA37Site	V80	**14.39%**	92.0	105.3	3.8s
4th	Hornsrev1	IEA Task 37 3.35MW	**7.91%**	135.3	146.0	4.3s
5th	Hornsrev1	DTU 10MW	**7.72%**	379.1	408.4	4.2s
6th	Hornsrev1	V80	**3.36%**	80.5	83.2	4.5s

B. 16 Turbines Configuration

Rank	Site	Turbine Model	AEP Improvement	Initial AEP (GWh)	Optimized AEP (GWh)	Optimization Time
1st	IEA37Site	IEA Task 37 3.35MW	**20.29%**	373.2	448.9	6.7s
2nd	IEA37Site	DTU 10MW	**12.71%**	743.8	838.3	7.2s
3rd	IEA37Site	V80	**9.81%**	168.2	184.7	7.1s
4th	Hornsrev1	DTU 10MW	**3.02%**	687.0	707.8	8.0s

5th	Hornsrev1	IEA Task 37 3.35MW	**2.52%**	246.3	252.4	8.0s
6th	Hornsrev1	V80	**1.23%**	144.2	146.0	7.8s

C. 36 Turbines Configuration

Rank	Site	Turbine Model	AEP Improvement	Initial AEP (GWh)	Optimized AEP (GWh)	Optimization Time
1st	IEA37Site	IEA Task 37 3.35MW	**19.14%**	758.7	903.9	18.1s
2nd	IEA37Site	DTU 10MW	**14.69%**	1541.6	1768.2	18.7s
3rd	IEA37Site	V80	**10.65%**	369.3	408.7	18.9s
4th	Hornsrev1	IEA Task 37 3.35MW	**3.45%**	537.1	555.6	23.0s
5th	Hornsrev1	DTU 10MW	**3.00%**	1484.5	1529.1	22.3s
6th	Hornsrev1	V80	**1.48%**	320.8	325.5	22.4s

D. 64 Turbines Configuration

Rank	Site	Turbine Model	AEP Improvement	Initial AEP (GWh)	Optimized AEP (GWh)	Optimization Time
1st	IEA37Site	IEA Task 37 3.35MW	**17.14%**	1343.8	1574.1	43.0s
2nd	IEA37Site	DTU 10MW	**14.16%**	2731.8	3118.5	45.1s
3rd	IEA37Site	V80	**10.17%**	657.5	724.4	44.3s
4th	Hornsrev1	IEA Task 37 3.35MW	**3.59%**	956.5	990.9	60.0s
5th	Hornsrev1	DTU 10MW	**3.19%**	2632.6	2716.6	57.6s
6th	Hornsrev1	V80	**1.58%**	570.7	579.7	57.2s

2.2 Boundary-Constrained Multi-Farm System Optimization

The boundary-constrained multi-farm optimization analysis examines the performance characteristics and layout optimization potential when multiple wind farms operate within defined property boundaries, representing real-world development constraints. Three distinct boundary-constrained configurations were evaluated to understand how farm boundaries and turbine technology diversity impact optimization effectiveness under realistic land ownership and regulatory limitations. This analysis provides critical insights into the trade-offs between unconstrained optimization and practical development constraints.

2.2.1 Two-Farm Boundary-Constrained Configuration (Mixed Technology)

The two-farm boundary-constrained system comprises 13 turbines distributed across V80 Farm (9 turbines, 69.2%) and DTU10MW Farm (4 turbines, 30.8%), achieving a substantial improvement of 15.12% with total AEP increasing from 813.24 GWh/year to 936.21 GWh/year. Despite the significant boundary constraints that restrict turbine placement to designated farm areas, the optimization successfully balances inter-farm wake effects while respecting property limitations. The boundary compliance analysis demonstrates full adherence to farm boundaries, with maximum distances from centers of 760m for V80 Farm and 1140m for DTU10MW Farm, both well within their respective 800m and 1200m limits.

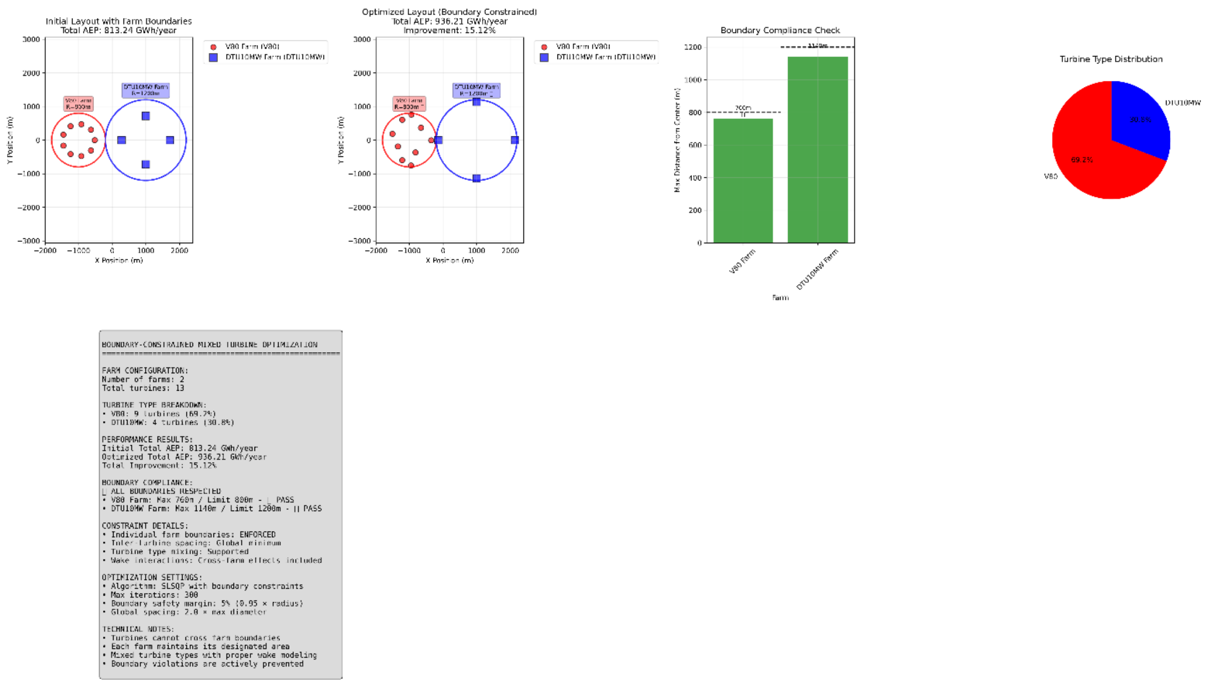


*Figure17.*Property-Limited Wind Farm Layout: V80 and DTU 10MW Configuration

The optimization results reveal that boundary constraints significantly impact performance compared to unconstrained scenarios, yet still provide meaningful improvements through strategic positioning within allowable areas. The mixed turbine technology approach requires careful consideration of different rotor diameters and wake characteristics while maintaining compliance with individual farm boundaries, demonstrating the algorithm's capability to handle complex multi-constraint optimization scenarios.

2.2.2 Three-Farm Boundary-Constrained Configuration (Mixed Technology)

The expanded three-farm boundary-constrained system incorporates 18 turbines across Legacy Farm (6 V80 turbines, 33.3%), Offshore Farm (4 DTU 10MW turbines, 22.2%), and Reference Farm (8 IEA Task 37 turbines, 44.4%). This configuration achieved an impressive improvement of 24.55%, increasing total AEP from 440.19 GWh/year to 548.25 GWh/year. The higher improvement percentage compared to the two-farm system suggests that additional farms provide greater optimization flexibility, even under boundary constraints, by offering more spatial arrangement possibilities.

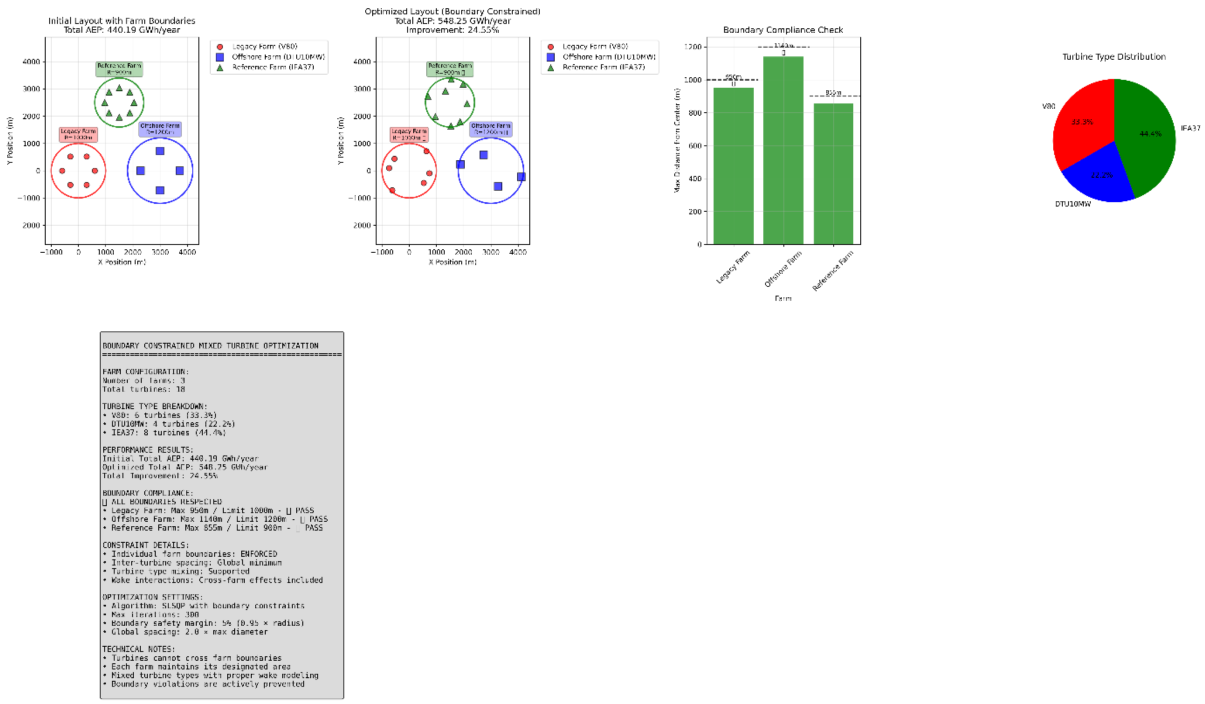


*Figure18.*Multi-Property Wind Development: Legacy, Offshore, and Reference Farms

The boundary compliance verification shows successful adherence to all farm limits: Legacy Farm (max 659m / limit 1000m), Offshore Farm (max 1200m / limit 1200m), and Reference Farm (max 855m / limit 900m). The Offshore Farm operates at its boundary limit, indicating maximum utilization of available space for the large DTU

10MW turbines. This configuration demonstrates how boundary-constrained optimization can achieve substantial improvements while respecting property boundaries, though the performance remains below unconstrained optimization potential.

***Here the project is done but here is other plots used to create the overall comparison that is being used in the document, I only write this section because creating these plots took a lot of time: (even though I made a mistake in border plotting)**

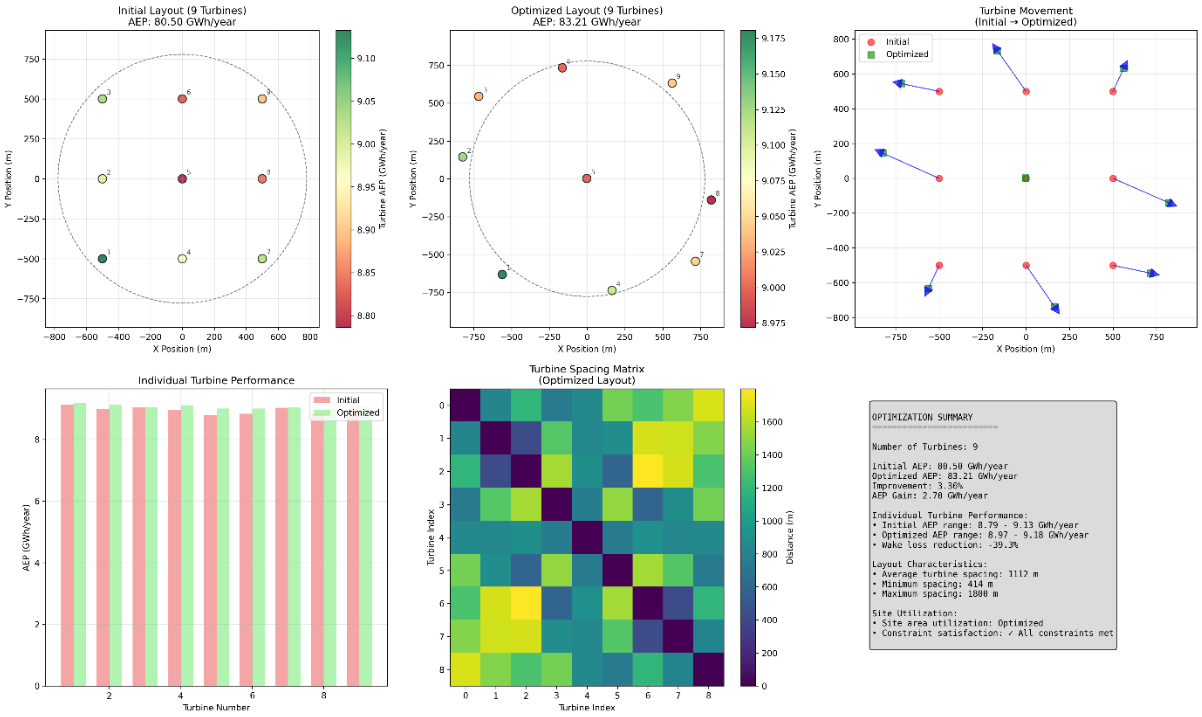


Figure19.Example of separated outputs

References:

[1] “Site Object — PyWake 2.6.12.dev12+g9271b313 documentation.” Accessed: Jun. 01, 2025. [Online]. Available: https://topfarm.pages.windenergy.dtu.dk/PyWake/notebooks/Site.html

[2] “Power plants: Horns Rev 1 - Vattenfall.” Accessed: Jun. 01, 2025. [Online]. Available: https://powerplants.vattenfall.com/horns-rev/

[3] “Vestas V80-2.0 - 2,00 MW - Wind turbine.” Accessed: Jun. 01, 2025. [Online]. Available: https://en.wind-turbine-models.com/turbines/19-vestas-v80-2.0

[4] P. Bortolotti, C. L. Bottasso, K. Dykes, K. Merz, and F. Zahle, “IEA Wind Task 37 on Systems Engineering in Wind Energy WP2-Reference Wind Turbines”, Accessed: Jun. 01, 2025. [Online]. Available: http://www.ieawind.org/

[5] C. ; Bak *et al.*, “General rights The DTU 10-MW Reference Wind TurbineMW Reference Wind Turbine. Sound/Visual production (digital),” *Citation*, 2025.

[6] N. G. Nygaard, S. T. Steen, L. Poulsen, and J. G. Pedersen, “Modelling cluster wakes and wind farm blockage,” *J Phys Conf Ser*, vol. 1618, no. 6, Sep. 2020, doi: 10.1088/1742-6596/1618/6/062072.