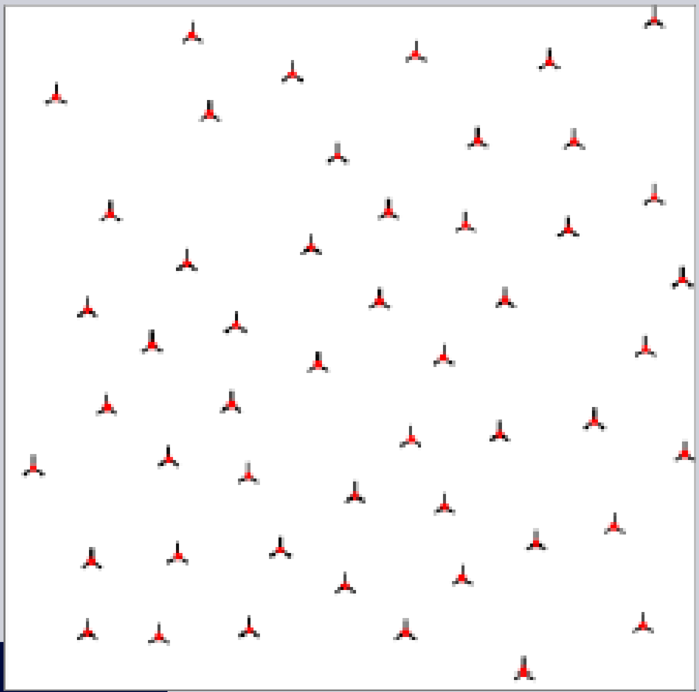
OPTIMIZATION FOR DATA SCIENCE

OPTIMIZING WIND FARM LAYOUT FOR MAXIMUM ENERGY PRODUCTION.

1. KRANTI PRAKASH -- M23IRM006
2. MUSKAN SUMAN -- M2IRM008
3. SWAPNIL SINGH -- M23IRM012

TABLE OF CONTENTS

INTRODUCTION



The optimal layout of wind turbines in a wind farm is crucial for maximizing **Annual Energy Production (AEP)**, as suboptimal layouts can result in up to a **5-15% loss in AEP**, potentially undermining the financial viability of wind energy projects. Properly optimized layouts not only improve energy output but also strengthen the case for renewable energy in the broader energy portfolio, supporting a shift toward sustainable and cleaner energy sources.

WHAT THIS PROJECT AIMS

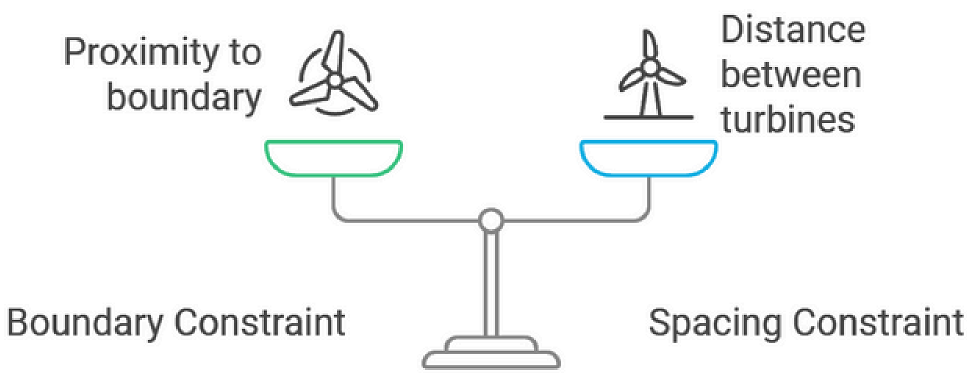
This project aims to **maximize energy production** in a wind farm by optimizing **turbine placement** to reduce power losses due to wake effects and ensure adequate spacing between turbines. Using a gradient descent-based optimization approach, we analyze and adjust turbine positions on a wind map, focusing on regions of high wind speed to enhance power output. This involves balancing the need for maximum energy capture while adhering to physical constraints and minimizing inter-turbine interference.

PROBLEM STATEMENT

This project addresses a simplified version of wind farm layout optimization to test numerical optimization techniques. Our goal is to maximize energy production by positioning turbines in high-wind zones on a wind map while managing wake effects and spacing constraints. Using gradient descent, we aim to find an optimal layout that enhances energy output and minimizes efficiency losses due to turbine interference.

The challenge is to optimize the layout of 30 wind turbines within a 20 km x 20 km farm area wind farm area to maximize Annual Energy Production (AEP). Each turbine has an 80 m rotor diameter, and placement must respect the following constraints:

1. **Boundary Constraint:** All turbines must be within the farm perimeter, maintaining a minimum distance equal to one rotor diameter from the boundary.
2. **Spacing Constraint:** A minimum clearance of 400 m between any two turbines must be maintained to avoid wake interference and extend turbine lifespan.



Balancing spatial constraints for optimal turbine placement.

Problem Formalization

Let the position of each turbine i be represented by coordinates (xi, yi) within a 20x20 km farm area. The goal is to:

maximize (AEP)

where AEP is the Annual Energy Production after accounting for wake effects between turbines. This optimization is subject to the following constraints:

- **Boundary Constraint:** Each turbine i must be placed within the farm boundaries:

$$xmin \leq xi \leq xmax, ymin \leq yi \leq ymax$$

- **Spacing Constraint:** The minimum distance $D_{\min}$ between any two turbines i and j must be maintained to reduce wake interference:

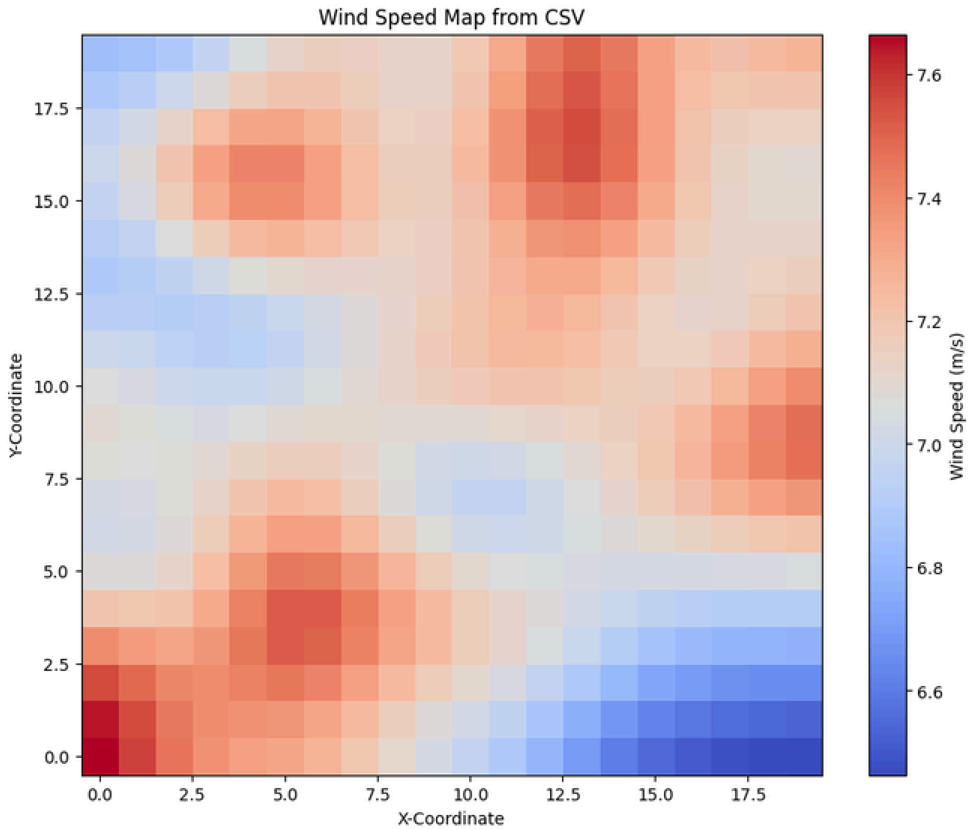
$$\sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq D_{\min}, \quad i \neq j$$

where x_{min} and y_{min} represent the minimum boundary offsets (one rotor diameter) and x_{max} and y_{max} are the maximum allowable farm boundaries. In this problem , $D_{\min}$ is set based on the rotor diameter to ensure operational safety and maximize energy yield.
The gradient descent algorithm iteratively adjusts the turbine coordinates (xi, yi) to achieve an optimized layout that maximizes AEP while satisfying the defined constraints.

Assumptions made

- **Identical Turbines:** All turbines share identical specifications (rotor diameter, height, power curve, etc.).
- **Uniform Wind Flow:** Wind speed is assumed uniform across the farm in turbine-free areas.
- **Effective Turbine Locations:** Turbine centers represent their locations, ignoring partial wake effects.
- **Jensen’s Wake Model:** Applied to represent wake interactions.
- **Boundary and Spacing Constraints:** Turbines are confined to a 20x20 km area with minimum spacing and perimeter limits.

DATA USED



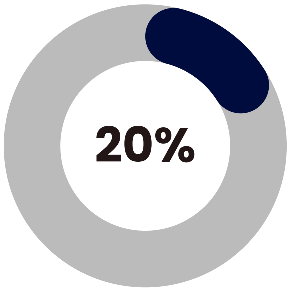
The data used in this project represents a wind speed map, stored in CSV format, which provides spatial wind speed distribution across a 20x20 km wind farm area. Each cell in the map corresponds to a specific coordinate on the grid, with values indicating wind speed (in m/s) at that location. High wind speed regions are marked in red on the visualized heatmap, suggesting areas with higher potential for energy production. This dataset serves as the basis for optimizing the placement of wind turbines to maximize energy output while considering wind variability across the farm.

WAKE EFFECT MODELLING

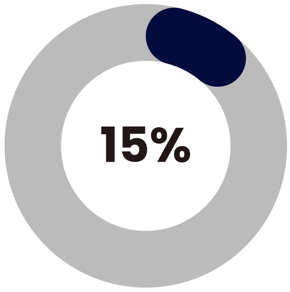
Modeling the wake effect is essential when planning wind farm layouts. Each turbine creates a "wake"—an area behind it with slower wind and more turbulence—which lowers the energy output of turbines located downwind and increases wear on them. By taking the wake effect into account, turbines can be arranged to reduce these energy losses, resulting in higher overall energy production.

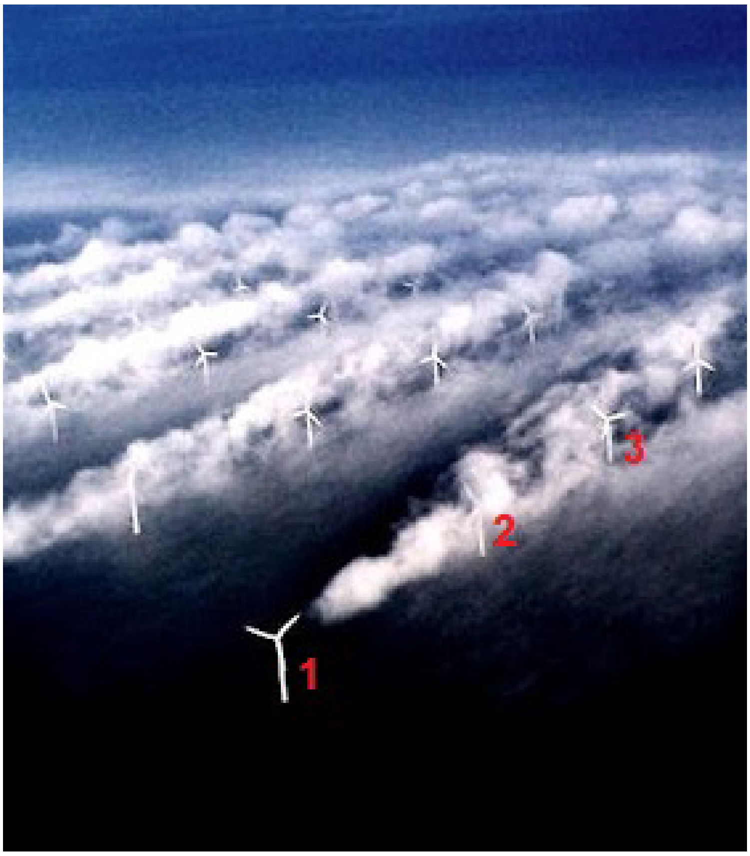
Wake Effect

Losses



AEP improvement





If the wake effect is ignored, energy losses for turbines downwind can reach 10-20%, depending on factors like turbine spacing and wind conditions. By carefully considering and minimizing these wakes, a wind farm's Annual Energy Production (AEP) can improve by around 5-15%, boosting its efficiency and profitability.

One common approach is using **Jensen's wake model**, which assumes a linearly expanding wake and calculates the resulting velocity deficit.

In Jensen's model, the wake velocity deficit **Δu** at a distance downstream from a turbine is given by:

$$\Delta u = U \cdot \left(1 - \sqrt{1 - \frac{C_t}{\left(1 + k \cdot \frac{x}{D}\right)^2}}\right)$$

where:

- U is the initial wind speed,
- C_t is the thrust coefficient of the turbine,
- x is the downstream distance from the turbine,
- D is the rotor diameter of the turbine,
- k is the wake decay constant (often depends on surface roughness and atmospheric conditions).

Explanation of Parameters

- **Thrust Coefficient** (C_t) : Represents the fraction of the wind's kinetic energy that is absorbed by the turbine.
- **Rotor Diameter** (D): The diameter of the turbine's rotor; larger rotors have larger wakes.
- **Wake Decay Constant** (k): Determines how quickly the wake expands with distance; often influenced by environmental conditions like terrain roughness.

OPTIMIZATION ALGORITHM

The optimization algorithm used in your code is Gradient Descent for maximizing the **Annual Energy Production (AEP)** in a wind farm layout. The algorithm iteratively adjusts the positions of turbines to maximize AEP, considering constraints on turbine proximity and farm boundaries.

Steps of the Gradient Descent Algorithm

- **Initialize Turbine Positions :** Start with an initial layout of turbine positions (xi,yi) within the farm boundaries.
- **Compute AEP :** Calculate the AEP based on the current layout, considering the wake effect on each turbine.
- **Compute Gradient :** Evaluate the gradient (partial derivatives) of AEP with respect to the turbine positions to determine how changes in position affect energy production.
  - The gradient $\frac{\partial \text{AEP}}{\partial x_i}$ and $\frac{\partial \text{AEP}}{\partial y_i}$ for each turbine iii is computed to guide the direction for improving turbine positions.
- **Update Positions :** Adjust the positions based on the gradient and a learning rate **α**

$$x_i^{\text{new}} = x_i^{\text{old}} + \alpha \cdot \frac{\partial \text{AEP}}{\partial x_i} \qquad y_i^{\text{new}} = y_i^{\text{old}} + \alpha \cdot \frac{\partial \text{AEP}}{\partial y_i}$$

- **Apply Constraints :** At each step find **Boundary Constraint** & **Proximity Constraint**
- **Repeat :** Continue iterating until convergence, i.e., when the positions stabilize or the improvement in AEP is minimal.

Formulation

- **AEP Calculation:** AEP is derived by considering wind speed reductions from wakes:

$$\text{AEP} = \sum_{\text{turbines}} \text{Power Output} \times \text{Operating Hours}$$

- **Wake Velocity Deficit:** The wake effect on downstream turbines is modeled as:

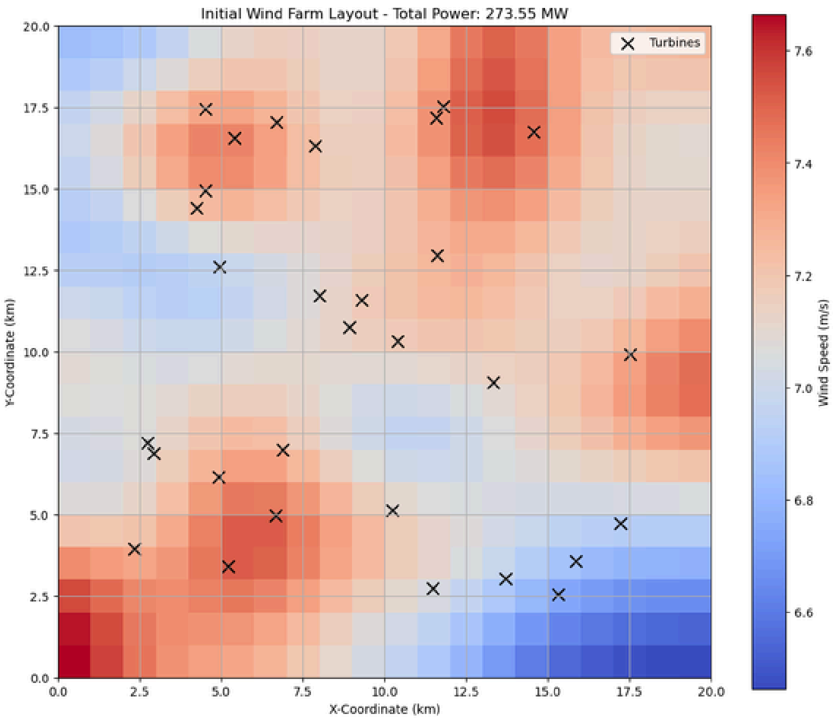
$$\Delta u = U \cdot \left(1 - \sqrt{1 - \frac{C_t}{\left(1 + k \cdot \frac{x}{D}\right)^2}}\right)$$

By iteratively optimizing turbine positions while accounting for these constraints and effects, the algorithm aims to maximize the wind farm's total energy production.

CODE IMPLEMENTATION

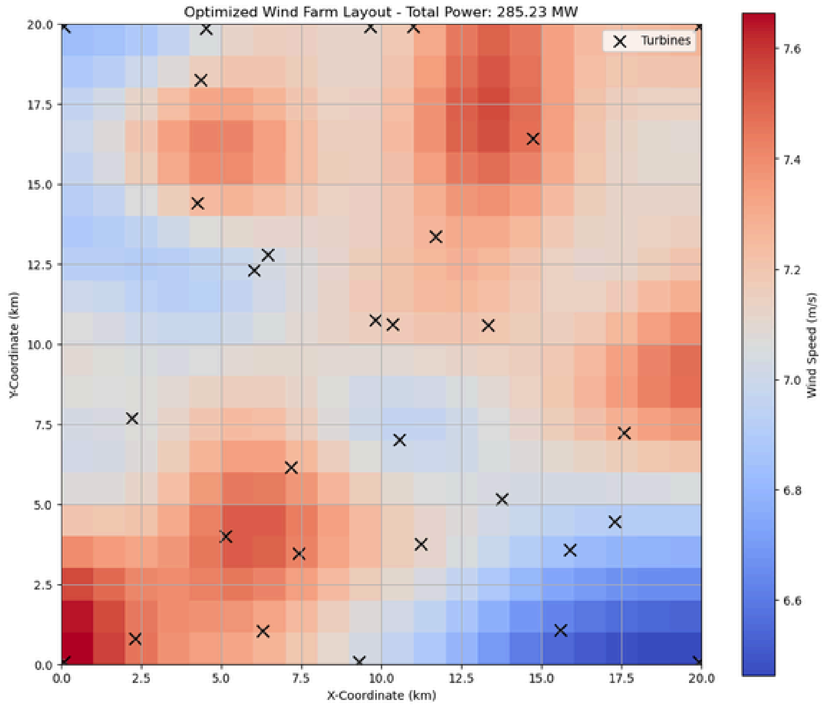
1. **Data Loading:** It reads wind speed data from a CSV file to identify high-wind areas within the farm.
2. **Power & Wake Calculations:** It calculates each turbine's power based on wind speed and uses a wake model to factor in how turbines downwind lose power due to reduced wind speed from nearby turbines.
3. **Objective & Spacing Penalties:** It defines an objective function to maximize energy output while applying penalties if turbines are too close, ensuring sufficient spacing to reduce turbulence effects.
4. **Optimization (Gradient Descent):** Using a gradient descent approach, it adjusts each turbine's position to maximize overall output while staying within farm boundaries.
5. **Visualization:** The optimized layout is visualized, showing how turbine positions change to boost energy production.

RESULTS



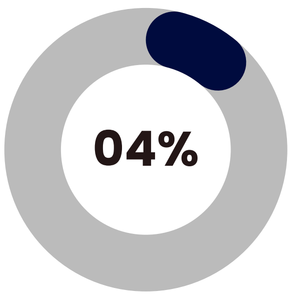
This plot shows the initial layout of wind turbines in a wind farm, marked by black "X" symbols on a colored wind speed map. The turbines are positioned to capture energy from higher wind speed regions, aiming to maximize total power production, which is displayed at the top as **273.55 MW**.

This plot shows the optimised layout of wind turbines in a wind farm, placed optimally used contrained optimzation method which captures the maximum energy from higher wind speed regions as shown in the figure of about **285.23 MW** which is approximately **4.26%** boost.



OBSERVATION

We observe that the optimized turbine layout improves the total power output from 273.55 MW to 285.23 MW. This increase indicates that strategically repositioning the turbines within the wind farm allows for better capture of wind energy, reducing wake losses and enhancing overall efficiency.
In general, this demonstrates that careful layout optimization can significantly boost the Annual Energy Production (AEP) of a wind farm by minimizing interference (wake effects) between turbines, which is crucial for maximizing renewable energy output and economic viability



Therefore,
4% Improvement
in AEP is achieved

CONCLUSION

Using constrained optimization with the gradient descent method, we successfully found the best turbine locations to maximize power generation in the wind farm. By adjusting turbine positions step-by-step while following boundary and spacing rules, we minimized the negative wake effects and improved overall energy output. The optimized layout produced noticeably more power than the initial setup, showing that gradient-based optimization is a valuable tool for real-world projects. This method highlights how effective placement of resources can greatly boost efficiency and support sustainable energy goals.