# Summary of Wake Models

## Introduction

Wake models are mathematical representations of how wind flow is affected by wind turbines. As wind passes through a turbine, it loses energy and becomes more turbulent, creating a **wake** behind the turbine. Proper wake modeling is essential for optimizing wind turbine placement, maximizing energy production, reducing turbine fatigue loads, and minimizing maintenance costs.

Wake effects can reduce downstream turbine power output by **10–40%**, making wake analysis a critical component of wind farm design for both onshore and offshore projects.

## Key Wake Modeling Approaches

### 1. Analytical Wake Models

These simplified engineering models provide fast calculations and are widely used during preliminary wind farm layout optimization.

**Jensen (Park) Wake Model**

**Overview:**

- One of the earliest and most widely used wake models
- Assumes a linearly expanding wake cone downstream of the turbine.

**Advantages:**

- Computationally efficient
- Easy to implement
- Suitable for large-scale optimization studies.

**Limitations:**

- Simplified physics
- Less accurate in complex terrain and highly turbulent environments.

**Best Applications:**

- Initial onshore and offshore wind farm layout studies

- Large optimization runs requiring thousands of simulations.

**Frandsen Wake Model**

**Overview:**

- Extension of the Jensen model
- Developed to better estimate wake interactions in large wind farms.

**Advantages:**

- Better handling of multiple wake interactions
- Useful for fatigue load estimation.

**Limitations:**

- Moderate accuracy
- Less effective in complex atmospheric conditions.

**Best Applications:**

- Large offshore wind farms
- Structural load assessments.

**Larsen Wake Model**

**Overview:**

- Based on boundary-layer theory and conservation equations.

**Advantages:**

- More physically realistic wake expansion
- Improved accuracy over Jensen in some conditions.

**Limitations:**

- Increased computational complexity.

**Best Applications:**

- Offshore farms with stable atmospheric conditions

- Detailed energy yield calculations.

## 2. Gaussian Wake Models

Modern industry-standard engineering wake models.

**Bastankhah Gaussian Wake Model**

**Overview:**

- Represents wake velocity deficit using a Gaussian distribution
- Developed using theoretical and experimental validation.

**Advantages:**

- High accuracy
- Computationally efficient
- Captures wake recovery more realistically.

**Limitations:**

- Requires calibration for site-specific conditions.

**Best Applications:**

- Onshore and offshore wind farm optimization
- Energy production forecasting.

**FLORIS Wake Model**

**Overview:**

- Developed by the National Renewable Energy Laboratory
- Uses Gaussian-based wake formulations with advanced wake steering capabilities.

**Advantages:**

- Supports yaw optimization
- Industry-recognized open-source framework
- Fast execution.

**Limitations:**

- Less detailed than high-fidelity CFD methods.

**Best Applications:**

- Wind farm control optimization
- Wake steering studies
- Real-time operational decision-making.

## 3. Computational Fluid Dynamics (CFD) Models

High-fidelity simulations solving fluid flow equations directly.

**RANS (Reynolds-Averaged Navier-Stokes)**

**Overview:**

- Solves averaged fluid flow equations.

**Advantages:**

- Detailed flow representation
- Captures terrain and atmospheric effects.

**Limitations:**

- Computationally expensive.

**Best Applications:**

- Complex onshore terrain
- Detailed micrositing studies.

**LES (Large Eddy Simulation)**

**Overview:**

- Resolves large-scale turbulence structures explicitly.

**Advantages:**

- Very high accuracy
- Captures atmospheric turbulence and wake interactions.

**Limitations:**

- Extremely computationally intensive.

**Best Applications:**

- Research studies
- Validation of engineering wake models
- Offshore floating wind farms.

## 4. Hybrid and Data-Driven Models

**Dynamic Wake Meandering (DWM)**

**Overview:**

- Models wake movement caused by atmospheric turbulence.

**Advantages:**

- Improved fatigue load prediction
- Better wake interaction representation.

**Limitations:**

- More complex than engineering models.

**Best Applications:**

- Structural design
- Offshore wind farms.

## 5. Machine Learning and AI-Based Models

**Overview:**

- Use historical SCADA, lidar, met mast, and weather data to predict wake effects.

**Advantages:**

- Fast predictions after training
- Adaptive to site-specific conditions.

**Limitations:**

- Requires large datasets
- Generalization challenges.

**Best Applications:**

- Operational optimization
- Predictive maintenance
- Real-time control systems.

# Wake Model Selection: Onshore vs Offshore

| **Model** | **Onshore** | **Offshore** | **Accuracy** | **Computational Cost** |
|---|---|---|---|---|
| Jensen (Park) | Good | Good | Medium | Low |
| Frandsen | Moderate | Good | Medium | Low |
| Larsen | Moderate | Good | Medium-High | Medium |
| Bastankhah Gaussian | Excellent | Excellent | High | Low-Medium |
| FLORIS | Excellent | Excellent | High | Low-Medium |
| DWM | Good | Excellent | High | Medium |
| RANS CFD | Excellent | Good | Very High | High |
| LES CFD | Excellent | Excellent | Very High | Very High |
| AI/ML Models | Emerging | Emerging | High (site-dependent) | Medium |

# Considerations for Onshore Wind Farms

Onshore wind farms face:

- Complex terrain effects
- Forests and vegetation
- Surface roughness variations
- Thermal stratification
- Local turbulence

Commonly used models:

- Bastankhah Gaussian
- FLORIS
- RANS CFD
- DWM for fatigue analysis

# Considerations for Offshore Wind Farms

Offshore wind farms experience:

- Lower ambient turbulence
- Longer wake persistence
- Strong wake interactions
- Stable atmospheric boundary layers
- Larger turbine spacing requirements

Commonly used models:

- Bastankhah Gaussian
- FLORIS
- DWM
- LES for advanced studies

- Frandsen for large-array analysis

# Industry Trends

Current wind farm developers increasingly use a **multi-fidelity approach**:

1. **Layout Optimization:** Jensen, Gaussian, or FLORIS models
2. **Detailed Design:** RANS CFD simulations
3. **Validation and Research:** LES simulations
4. **Operations & Control:** FLORIS and AI-driven wake prediction models.

For modern utility-scale projects, **Gaussian-based wake models (especially Bastankhah and FLORIS)** have become the industry standard because they provide a strong balance between computational efficiency and predictive accuracy for both onshore and offshore wind farm development.