Wind Turbine Spacing

and

Power Density

in

Onshore Windfarms

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Carbon emission reduction is one of our world's biggest challenges, and leading the fight in reducing those emissions is renewable wind. This requires the building of huge windfarms to provide the vast amounts of clean energy that is needed to accommodate an ever increasing, energy hungry global population.

However, wind farms are engineered not just for capturing wind, but for doing so efficiently. A critical design factor in any wind farm is how far apart the turbines are spaced. Turbine spacing impacts energy output, land use, environmental effects, and even project economics.

Spacing of Horizontal Axis Wind Turbines (HAWTs)

Proper spacing between wind turbines is crucial, primarily because of the wake effect. When a turbine generates power, it slows down the wind and creates turbulence in its wake – much like a boat leaves a wake in water. Any turbine positioned too closely downwind will sit in this disturbed air, receiving reduced wind speed and increased turbulence. The result is a drop in efficiency and power output for the downwind turbine. In fact, studies have shown that when turbines are spaced very tightly, the power deficit can be substantial, whereas spacing turbines further apart (e.g. ~10 rotor diameters apart downwind) makes wake losses “almost negligible”. Wake turbulence can also put extra stress on turbine components, potentially increasing wear and maintenance needs.

On the flip side, if turbines are spaced extremely far apart, you miss an opportunity to install additional turbines in a given area – potentially under-utilizing a windy site. Thus, there’s a trade-off between maximizing energy capture per turbine (which favours larger spacing) and maximizing the capacity per unit area (which favours tighter spacing). Wind farm designers seek an optimal balance where the overall energy yield of the farm is highest. In simple terms: too close and they steal each other’s wind; too far and you’re wasting space.

Additionally, terrain and predominant wind direction play a role. In a wind farm, turbines are often aligned in rows considering the main wind direction. The spacing along the prevailing wind (downwind spacing) usually needs to be larger to account for longer wakes, while the spacing perpendicular to the wind can be a bit tighter without as much performance loss. Overall, smart turbine spacing is about reducing wake interactions, optimizing airflow, and using the available land or sea area efficiently.

Industry practice has converged on general spacing guidelines expressed in multiples of the turbine’s rotor diameter (D). A common rule of thumb: keep around 5–9 rotor diameters of distance in the direction of prevailing winds, and about 3–5 diameters apart side-to-side (crosswind). This means, for example, two turbines with 100-meter rotors might be spaced roughly 500–900 meters apart in a row oriented with the wind, and perhaps 300–500 meters apart in neighbouring rows. These distances help ensure that a turbine isn’t sitting directly in the turbulent wake of another most of the time.

Choosing turbine distances isn't just an engineering decision – it has environmental, economic, and safety ramifications as well:

- **Environmental Impact:** The space between turbines can influence how a wind farm interacts with wildlife and the landscape. For example, if turbines are extremely tightly packed, a wind farm may present a large wall-like barrier for birds. Newer wind farms with larger spacing are *"less likely that birds perceive rows of turbines as impenetrable walls"*, potentially reducing bird collision risks as raptors and other birds can more easily fly between widely spaced turbines. However, a comprehensive review in Spain found no strict wildlife-driven rules for turbine spacing – the distances were mostly set for technical reasons, even though larger modern turbines naturally require bigger gaps. Spacing can also affect the visual footprint of a wind farm. Regulators now consider the visual impact on landscapes: in some cases, spreading turbines out (or aligning them neatly) might reduce visual clutter, but it also extends the area over which turbines are visible. There's a balance between concentrating turbines (for a smaller overall footprint) versus spreading them (to lower density in any one spot). Additionally, noise impacts are tied to distance – more spacing can mean any given point on the ground is farther from a turbine, potentially reducing noise and shadow flicker issues, which is beneficial for communities nearby. Overall, thoughtful spacing combined with careful siting can mitigate some environmental and social impacts of wind farms.

- **Economic Factors:** Turbine spacing has direct economic consequences for a project's viability. Land use and energy yield are two sides of the coin. Wider spacing means you need more land or sea area (or you'll install fewer turbines), which could increase site lease costs and require longer cables and roads. Tighter spacing allows more turbines in a wind farm (more installed capacity per area), but with each turbine producing less due to wakes. There is an economic sweet spot where the cost of adding one more turbine (and the wake losses it introduces) balances out with the value of the extra energy produced. If turbines are too densely packed, adding more will actually *"reduce the effectiveness of all the others"* beyond a point. According to the U.S. National Renewable Energy Lab, spacing is an important design factor for both overall performance and economic constraints of a wind farm. Developers must consider the cost of land/sea area, turbine equipment, and construction: a study noted that depending on land cost, the optimal economic spacing could vary – in scenarios with low land cost, much wider spacing (like 10–15D) might maximize profit, whereas with expensive land you'd accept closer spacing around ~7D.

- **Safety and Regulations:** There are also safety considerations linked to spacing. While turbines themselves don't pose much hazard to each other if spaced properly, setback distances are often mandated for safety of people and infrastructure. Many jurisdictions require a minimum distance from a turbine to any occupied building, road, or power line. For example, some regulations stipulate turbines must be at least 3 times their total height away from residences as a safety buffer (this helps address risks like ice throw, and also reduces noise for homeowners). In parts of Europe, rules include things like maintaining 200+ meters between large turbines and high-voltage transmission lines for safety. These rules indirectly affect how a wind farm can be laid out on a given site. Within the farm itself, adequate spacing ensures that in the unlikely event of a structural failure (like a blade failure or a turbine collapse), debris will not strike neighbouring turbines.

Moreover, sufficient spacing provides room for maintenance operations – large cranes need to maneuver around turbines for repairs or repowering, and that's easier when turbines aren't too tightly clustered. Finally, from a grid and electrical safety perspective, spacing out turbines can prevent all units from being impacted by a localized extreme wind gust or turbulence event at once, adding resilience.

- **Bottom line:** safety codes and prudent design demand that turbines aren't placed too close to anything – be it other turbines, homes, or infrastructure.

In summary, turbine spacing affects the power density (MW per square km) of a wind farm and its capacity factor. Wind farms with generous spacing tend to have higher capacity factors (each turbine can run closer to its maximum) but lower installed capacity for the area, whereas tightly spaced farms have more capacity but each turbine yields less. Finding the right layout is key to maximizing the return on investment. (Source: RESDM)

Capacity density of HAWT wind farms

The National Renewable Energy Laboratory have published a technical report: NREL/TP-6A2-45834 August 2009, in which they obtained and analysed one or more categories of land-use data for 172 major windfarm projects, with 161 projects having total land-use area data, in the United States, representing 26,462 MW of proposed or installed capacity.

Many estimates of total area often express wind plant land use in terms of capacity density (capacity per unit area, typically MW/km2). Of the 161 projects with total land-use area data, 125 (representing 80% of the evaluated capacity) have reported area of between 10 and 50 hectares/MW, or a capacity density range of 2-10 MW/km2, thus giving a general overall average capacity density of **6.0 MW/km2**. (Source: NREL)

Spacing of Vertical Axis Wind Turbines (VAWTs)

Vertical axis wind turbines (VAWTs) can be spaced much closer than horizontal axis wind turbines (HAWTs), typically 4 to 6 diameters (D) apart, due to their ability to operate in turbulent winds and improved wake recovery. Close spacing (e.g., 1.25D–3D) can enhance efficiency in clusters by accelerating airflow between rotors, particularly with counter-rotating configurations. (Source: ScienceDirect)

Key Spacing and Performance Data:

- **Optimal Spacing:** VAWTs perform well with 4D spacing, causing significantly less wake loss than the 15D-20D required for HAWTs.
- **Cluster Advantage:** Unlike HAWTs, which lose 20%–50% power in close proximity, closely spaced VAWTs (around 1.65D–4D) can increase overall farm efficiency by 5–10%.
- **Array Layout:** Compact configurations, such as 1.25D to 3D, are efficient because they form high-velocity flow regions between adjacent rotors.
- **Wake Recovery:** The wake behind a VAWT typically recovers within 6D. (Source: ScienceDirect)

Benefits of Close Spacing:

- **Higher Power Density:** Closer spacing allows for more turbines per unit area, boosting total power density compared to HAWT farms.
- **Better Performance in Turbulence:** VAWTs handle turbulent wind, making them ideal for dense, small-scale, or urban installations. (Source: AIP Publishing)

Considerations:

- **Rotational Direction:** Arranging adjacent VAWTs to be counter-rotating (e.g., two turbines turning opposite directions) can maximize the efficiency of closely spaced systems.
- **Configuration:** Parneix et al, found that compact designs where turbines operate at optimal tip-speed ratios and specific angles (closer than 3D) maximize power coefficients. (Source: ScienceDirect)

Accepting the above **array layout** assessment and using the upper 3D configuration for our onshore unit spacing, but instead of using 3 x rotor diameter; which in the Windstorm unit has a turbine diameter of 14m, we use the 3 x external enhancer diameter of the Windstorm system, which is 24m diameter, giving a spacing of 72m, see figure1.

Setting the units in an equilateral triangular pattern of 72m spacing, will also allow for the vast majority of wake recovery; which as stated in the **wake recovery** section, typically recovers within 6D (rotor diameters) downwind of a VAWT, which would be 6 x 14 = 84m. As the Windstorm units would be sited in a triangular matrix, the majority of the time the closest unit in the downstream wind flow would be a minimum of about 124m.

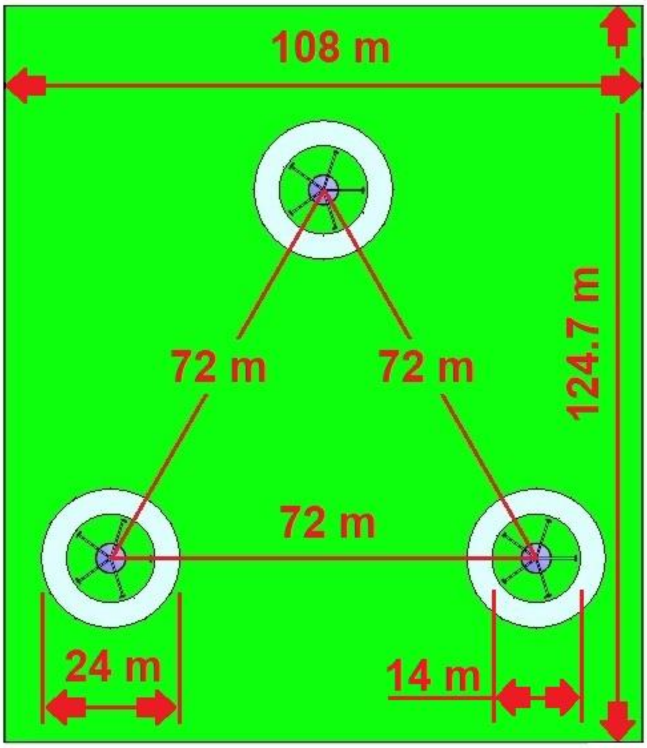

Figure 1

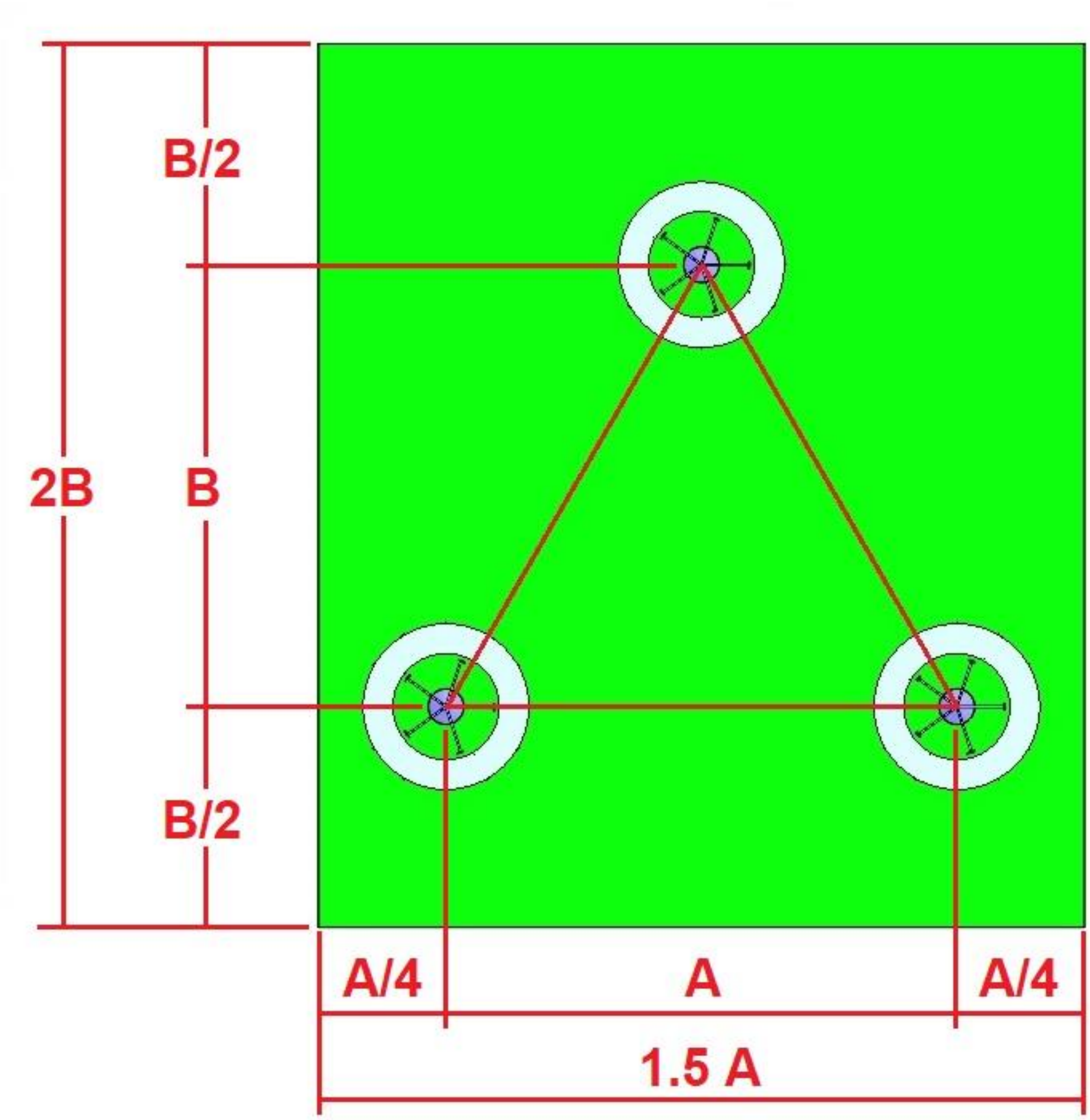

Figure 2

Figure 2 details the dimensions of the area of land required to accomodate the 3 equispaced Windstorm units. This allows the 3-unit clusters to be easily integrated into much larger configurations, whilst keeping the same unit separation distance, in this case of 72m.

From the above figure we have the following:

Distance “A” = 72m

Distance “B” = A sin 60° = 0.866 A = 62.35m

From the above, the perimeter lengths are as follows and shown in figure 1:

1.5A = 108m

2B = 124.7m

Thus, the area of a 3 turbine - 9MW cluster is 108 x 124.7 = 13,468 m²

Figure 3, shows four groups of the 3-turbine cluster in figure 1, arranged optimally in a larger configuration, thus allowing for the same spacing of 72m between each of the turbine units.

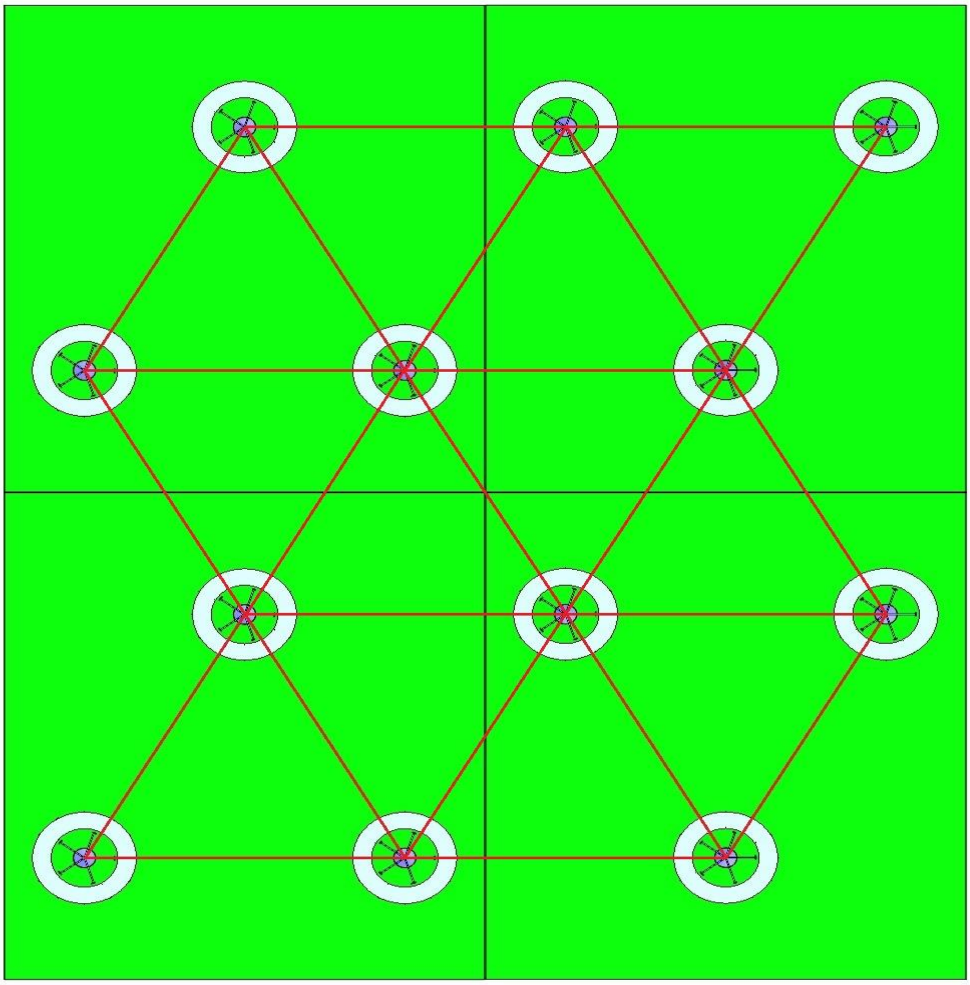

Figure 3

There are two ways to obtain the power density of a 1km² windfarm. One is to simply divide the windfarm area by the cluster area, but this ignores the physically fixed external boundary of each cluster, resulting in a slightly higher ratio than the actual of 1,000,000 m² / 13,468 m² = 74.25.

This equates to 74 complete clusters, giving a power density of 74 x 9MW = 666 MW / km².

The second and more accurate method, is to calculate the number of clusters that can actually physically fit into an area of 1,000m x 1,000 m, which is 9 along the horizontal axis (972m) and 8 along the vertical axis (998.8m).

This equates to 9 x 8 = 72 clusters, giving a power density of 72 x 9 = **648 MW/ km².**

Figure 4

Figure 4, illustrates the two types of turbine systems, a standard 3MW Horizontal Axis Wind Turbine and the 3MW Windstorm system.

Figure 5

Figure 5, illustrates how commercial Horizontal Axis Wind Turbines in an area of 1km², with an average power density of 6MW/km² would appear to scale.

This would house 2 x 3MW turbines.

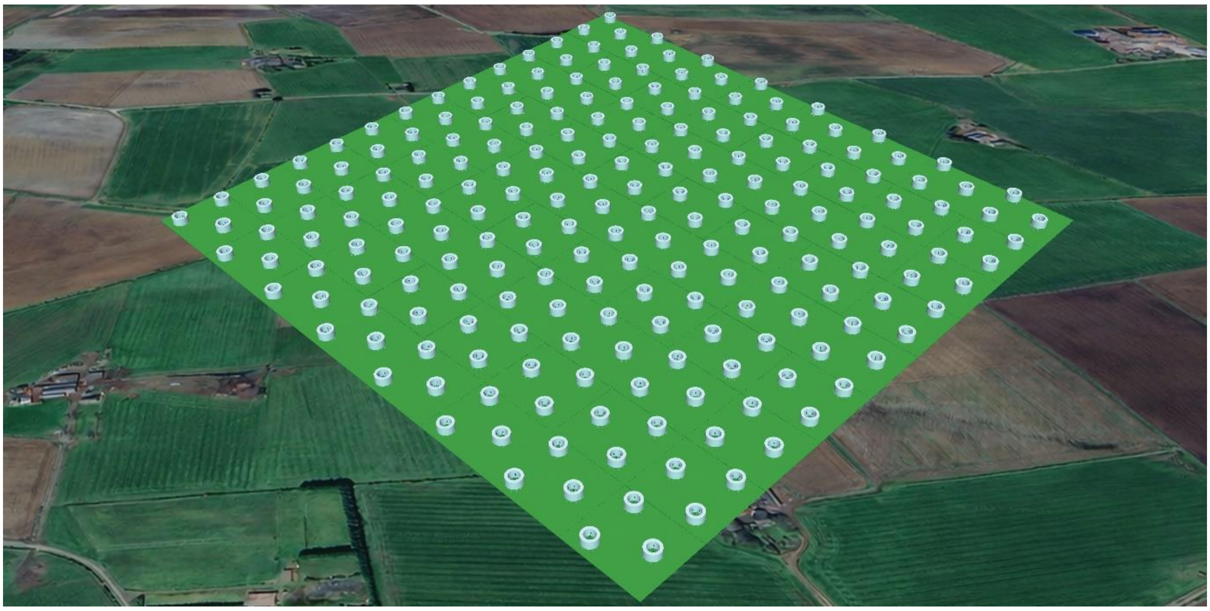

Figure 6

Figure 6, illustrates how a Windstorm windfarm in an area of 1km^2, with a power density of 648MW/km^2 would appear to scale.

This would house 216 x 3MW turbines.

Summary

The average power density of a commercial HAWT windfarm is **6MW/km^2.**
The power density of a Windstorm windfarm is **648MW/km^2.**

The Windstorm system reduces the land requirement for wind farms by over **99%**.