Layout Optimisation for Offshore Wind Farms

Anthony Crockford*, Pim Rooijmans*, Jan Coelingh, Jean Grassin
Ecofys, Utrecht, The Netherlands

Summary
The first layout for an offshore wind farm is typically required for permit applications and a business case assessment. The design is based on perceived restriction at the site, preliminary site data and current knowledge of the wind market. This layout can remain frozen for many years, during the lengthy development phase.

Once permits are granted, there is an excellent opportunity for layout optimisation. The full permit conditions are defined, there may be on-site wind measurements and improved flow modelling, and there are advances in the available technologies on the market.

This paper outlines the layout design process for offshore wind farms with several examples of constructed projects. A method for layout optimisation is then presented. First, the optimum wind farm capacity is determined, in terms of the lowest Cost of Energy (e.g. €/MWh). Then, the layout is fine-tuned to minimise wake losses and ensure compliance with permits and wind turbine certification limits.

A real-world case study is presented to demonstrate the value of this approach. The Q10 offshore wind farm is being developed by Eneco, at 23 km from shore in the Netherlands. The layout optimisation began with an updated wind resource assessment and an evaluation of the permits to find the key constraints. Four categories of wind turbines were identified in the current offshore wind market, and an optimised layout was designed for each. The final layout of 43 x Vestas V112 – 3 MW wind turbines leads to a reduction in Cost of Energy of over 10%, compared to the initial layout.

Introduction
The first layout for an offshore wind farm is needed early in the feasibility phase, in order to estimate the expected wind farm energy yield and to determine the viability of the business case of the project. The layout is typically based on a simple grid spacing, staggered rows or similar rules of thumb. The design will use the best current technology, or possibly projections for wind turbines that will be available in the future.

![Figure 1 – Phases of an offshore wind farm](image)

This first layout will often form the basis for any permit requests and will be frozen throughout the development phase, which can last years as illustrated in the figure above. A study of offshore wind farms in Europe over the past decade shows that the feasibility and development phases can last 7 years or more, as shown in Figure 2 [1].

* Lead authors: A.Crockford@ecofys.com, +31 6 1114 9198
  P.Rooijmans@ecofys.com, +31 30 280 7802

EWEA 2012 Annual Event, Copenhagen, Denmark, 16-19 April 2012
During this time, there can be significant changes in technology, the market and knowledge of site conditions. The permitted wind turbines may no longer be available, or more suitable models may have been developed. Similarly, advances in foundation or electrical infrastructure could help improve the wind farm design. Typically, an on-site wind measurement campaign will have been carried out, leading to improved knowledge of the site conditions. And, new industry best practice regarding wake losses and turbulence intensity levels may dictate different spacing.

The first layout was based on current knowledge of site conditions and the market, and perceived restrictions. Once permits are granted, the restrictions are fully defined and there is an excellent opportunity to optimise the wind farm layout based on updated knowledge.

**Layout Design**

An offshore wind farm layout depends on several factors. First, there may be conditions within the permits for the offshore wind farm. Permits typically specify the site boundary and place limitations on the maximum capacity, tip height and/or rotor diameter for the wind farm. There may also be limits to the use of certain technologies, such as foundation types or installation methods. Permit conditions are generally based on an impact assessment during the permitting process. For example, they may relate to navigation safety, underwater noise or grid capacity. It is important to consider all conditions, and also to understand their basis, in order to ensure a fully compliant layout.

An example of a wind farm layout that is dictated by permit conditions is the 315 MW Sheringham Shoal project in the UK, as shown in Figure 3. This layout was designed to align with common flight paths for birds flying from the coast to feed offshore.
A second key factor in the design of wind farms is wake effects. Good wind farm design aims to reduce wake losses, with close attention to the dominant wind direction at the site. Wake losses can be reduced by increasing the spacing between wind turbines, although this may also lead to other changes such as a reduced wind farm capacity (fewer wind turbines within the boundary) or increased costs for array cables. Thus, the reduction of wake losses is a balance of technical and financial considerations.

The layout of the 120 MW Prinses Amaliawindpark is an example that aims to minimise wake losses. The rows in this wind farm are staggered, which increases the spacing in the dominant wind direction (the southwest).

Figure 3 - The layout of Sheringham Shoal offshore wind farm is largely determined by its permit. The rows are aligned with the flight paths of sea birds.

Figure 4 - The design of the Prinses Amaliawindpark is intended to minimise wake losses; the rows are staggered so that wind turbines are distantly spaced in the dominant wind direction.
A third constraint in offshore wind farm layout design is the site conditions, specifically turbulence intensity and extreme wind speeds. Wind turbines are certified according to IEC standards, which define design levels for maximum conditions, divided into different classes. For example, a site with a 50-year extreme wind speed of 45 m/s would require a Class I wind turbine [2].

The spacing of the wind farm will also be affected by site conditions. While ambient turbulence intensity levels are generally low offshore, it is necessary to also consider wake-added turbulence. As with wake losses, it is possible to reduce the wake-added turbulence by increasing spacing within the wind farm. This may be particularly important if the wind turbine is certified to Class B levels of turbulence intensity; Class IB or IIB certifications are increasingly favoured for offshore wind turbines.

A final factor that often determines the wind farm layout is cost. For example, deeper parts of the site may be more expensive due to larger or different types of foundations. Foundations can also be more expensive for larger wind turbines, although there may be overall savings if fewer foundations are needed. The wind farm design can also affect the costs of electrical infrastructure. Increasing the wind farm capacity may require a larger export cable, which could be difficult to source. Or, increasing the spacing between wind turbines could mean longer array cables.

The layout of the 330 MW Belwind offshore wind farm is driven by costs. The project has been divided into two phases, with the first 165 MW phase designed in the shallower waters along a sandbank, as shown in Figure 5. This was due to the limitations of monopile foundations; a different foundation will likely be required for the second phase.

Figure 5 - The layout of the first 165 MW phase of the Belwind offshore wind farm is designed in the shallower waters along a sandbank, due to limitations of the monopile foundations.

Offshore wind farm design is often a balance of these various factors, as can be seen in the layout of the 500 MW Greater Gabbard wind farm in the UK, in Figure 6. The site is divided into two sections by a major shipping lane, and the permit restricts construction on ecologically-sensitive sandbanks within each area. The final layout is irregular, but represents a balance between constraints, yield, site conditions and costs.
Electrical infrastructure generally have a more significant role, due to increasing water depth. Further from shore (up to 100 km from the coast), the costs for foundations to shore (about 20 km from the coast), the largest cost is for supply and installation of the wind turbine type, hub height, size of wind farm, steel price and fabrication costs. The installation cost of those foundations depends on distance to shore, wave heights, vessel type, vessel day rates, installation rate and weather delay. The costs of electrical infrastructure depend on the design of cabling, transformer stations, onshore grid connection and voltage.

For instance, the supply cost of foundations depend on water depth, soil conditions, wind turbine type, hub height, size of wind farm, steel price and fabricaiton. Other costs are also estimated, such as project management, contingencies and construction insurance.

A representative breakdown of CAPEX for two offshore wind farms is shown in Figure 7. Close to shore (about 20 km from the coast), the largest cost is for supply and installation of the wind turbines. Further from shore (up to 100 km from the coast), the costs for foundations and electrical infrastructure generally have a more significant role, due to increasing water depth.

**Layout Optimisation**

A key driver for the optimisation of an offshore wind farm layout is Cost of Energy, since it combines the many factors described above.

**Calculating Cost of Energy**

The Cost of Energy represents the costs of the wind farm, spread over the amount of production:

\[
\text{Cost of Energy} = \frac{(\text{CAPEX} \times \text{CRF}) + \text{OPEX}}{\text{Annual energy yield}}
\]

Where CAPEX (capital expenditures) is the total upfront investment, CRF (capital recovery factor) is a financial term that incorporates returns for debt (banks) and equity (investors), OPEX (operating expenditures) is the yearly cost of running the wind farm, and Annual energy yield is the long-term average production of the wind farm.

Ecofys has developed an Offshore Wind Cost Model to calculate these costs, based on a database of prices from constructed offshore wind farms, complemented with quotations from major suppliers for new projects. These market prices are modified for new sites, based on calculated relationships to site parameters. CAPEX includes the supply and installation costs for wind turbine, foundation and electrical infrastructure. Other costs are also estimated, such as project management, contingencies and construction insurance.

A representative breakdown of CAPEX for two offshore wind farms is shown in Figure 7. Close to shore (about 20 km from the coast), the largest cost is for supply and installation of the wind turbines. Further from shore (up to 100 km from the coast), the costs for foundations and electrical infrastructure generally have a more significant role, due to increasing water depth.
and export cable length. The results are highly site-dependent and rely on accurate data regarding site conditions.

![Illustrative range of CAPEX breakdown for two example offshore wind farms, as calculated by the Ecofys Offshore Wind Cost Model. Close to shore, the wind turbine supply and installation accounts for over half of the total CAPEX. Further from shore and in deeper waters, the other components have larger shares of the total CAPEX. This breakdown is highly site-dependent. Note that the total CAPEX is not the same for the two examples; further from shore the total CAPEX is higher.](image)

The model also calculates the annual operating expenses based on the wind farm layout and selected technologies. Finally, the annual energy yield can be calculated for each layout using industry standard software.

Thus, possible layouts can be compared in terms of Cost of Energy. This forms the basis for the layout optimisation explained below.

**Trends in Cost of Energy**

The first step in the optimisation process is to determine the total wind farm capacity with the lowest Cost of Energy. The principle of optimum wind farm capacity is based on the general trends in costs and yields with increasing capacity, as shown in Figure 8.

![General trends in costs and yields with increasing wind farm capacity](image)

The costs of an offshore wind farm (both CAPEX and OPEX) generally rise with increasing wind farm capacity. There is also a relatively fixed component of these costs, which is independent of the wind farm size. For instance, the cost for export cable installation will be roughly the same for one wind turbine as for a larger wind farm. Thus, increasing the wind farm capacity leads to a gradual decrease in costs per MW, as the fixed costs are spread over more MW.
The total annual energy yield also increases with larger wind farm capacity. However, with each additional wind turbine, the wake losses increase. Therefore, increasing the wind farm capacity leads to progressively smaller improvements in annual energy yield.

The result of these trends is that the Cost of Energy decreases with larger wind farm capacities, as fixed costs are spread over higher yields. Beyond a certain size though, the Cost of Energy begins to increase again as wake losses become a significant driver. These trends are reflected in Figure 9; the optimum wind farm capacity can be identified from the lowest point in the curve.

![General trend in Cost of Energy with increasing wind farm capacity.](image)

**Figure 9** - General trend in Cost of Energy with increasing wind farm capacity. The optimum wind farm capacity is at the lowest point in this curve.

**Iterative approach**

In order to determine the optimum capacity in practice, an iterative approach can be employed. The Cost of Energy is calculated for many different layouts, covering a large range of wind farm capacities. The following example demonstrates this process for a fictional wind farm site.

Many iterations of the wind farm layout are generated, using variations in orientation and wind turbine spacing in order to cover a wide range of wind farm capacities. Three iterations are shown in the maps below. For each iteration, it is important to also consider the limitations due to wake-added turbulence intensity, to ensure that the layout is feasible.

![Three iterations of the layout for the example wind farm.](image)

**Figure 10** - Three iterations of the layout for the example wind farm. Many iterations are required with different spacings and orientations, to cover a large range of wind farm capacities.

For each iteration, the Cost of Energy is calculated, and the results are plotted against wind farm capacity, as shown in Figure 11. A trend line is plotted through these data points. As expected from the analysis of trends above, the Cost of Energy falls sharply as the total capacity increases, but then begins to rise again. For this example, the optimum wind farm capacity is in the range of 320-360 MW.
The modelled Cost of Energy for many iterations of the example wind farm (each a green dot). The blue line indicates the general trend. The Cost of Energy decreases as the wind farm capacity increases to about 300 MW. Above 350 MW, the Cost of Energy increases again, due to high levels of wake losses. These calculations are done for a single wind turbine type.

**Fine-tuning the layout**

The first step identifies the optimum wind farm capacity (or a small range), but further optimisation is possible. The iterative approach can again be applied in order to determine the optimum spacing and orientation. The wind farm capacity is fixed for this round of iterative layouts, so the focus is on minimising wake losses. This will lead to increased yield for the same cost level, and thus a lower Cost of Energy.

![Figure 11](image1.png)

Figure 11 - The modelled Cost of Energy for many iterations of the example wind farm (each a green dot). The blue line indicates the general trend. The Cost of Energy decreases as the wind farm capacity increases to about 300 MW. Above 350 MW, the Cost of Energy increases again, due to high levels of wake losses. These calculations are done for a single wind turbine type.

![Figure 12](image2.png)

Figure 12 - Two iterations of the layout for the example wind farm, with a fixed wind farm capacity. Iterations with different spacings and orientations will lead to the layout with the lowest wake losses, and hence lowest Cost of Energy.

Once the optimum orientation and spacing is determined, some positions may still be fine-tuned. Spreading the positions over the entire area will often mean the lowest wake losses, and ensures clear wind farm boundaries which may be important for navigation safety. Detailed
design of the electrical infrastructure can also be carried out at this stage. It is good practice to make a final check of the permit conditions, turbulence intensity levels and Cost of Energy.

The final optimised layout for the example wind farm is presented below.

![Figure 13 - The optimised layout for the example wind farm. The electrical infrastructure is shown in grey.](image)

**Case Study: Q10 Offshore Wind Farm**

The Q10 offshore wind farm site is located 23 km from the coast of the Netherlands. The site is being developed by Eneco, a Dutch utility. Eneco applied for a permit in 2007 with a proposed layout of 67 x 3 MW (V90) wind turbines. The final permits led to concerns of shipping safety. About 25% of the site was removed, leaving 51 of the original positions, as shown in Figure 14.

![Figure 14 - The first layout for the Q10 offshore wind farm used 67 x 3 MW wind turbines, but the permit reduced the wind farm area, leaving 51 positions of the original layout.](image)

The layout optimisation process began in 2010 once the permits were finalised for the site. The permit allowed for only a single wind turbine type, which was seen as a big risk during
contracting. In addition to optimising the layout for the V90 – 3 MW wind turbine, other wind turbine types were also considered.

An evaluation of the wind farm permits shows that the key constraint is the total swept area of the wind turbines (used in calculations in the environmental impact assessment). Thus, new layouts should not exceed this parameter.

The wind resource assessment was updated, using the latest data, software and industry best practice. Optimised layouts were designed for four different categories of wind turbines, with rotor diameters ranging from 90-120 m.

The optimised layout of 43 x V112 – 3 MW wind turbines is shown in Figure 15. The calculated reduction in Cost of Energy (€/MWh) is over 10% for this layout, compared to the initial layout (Figure 14). This decrease is largely due to the selection of a more suitable wind turbine, and to minimised wake losses.

![Figure 15 – Optimised layout for the Q10 offshore wind farm, with 43 x V112 – 3 MW wind turbines. The Cost of Energy (€/MWh) is over 10% lower for this layout than for the first layout, shown in the figure above.](image)

**Conclusions**

The first layout for an offshore wind farm is often based on current knowledge of the site and market, and perceived restrictions. After permits are granted, there is an excellent opportunity to optimise the wind farm layout based on known restrictions and updated knowledge.

It is critical to leave room in permits to allow for future optimisation of the wind farm design. This requires some insight into the future, in terms of expected technologies and models. It works best in a permitting system with scope for future changes (e.g. the ‘design envelope’ in the UK), but can also apply to more restrictive permits.

**References**
