Chapter 1: Multiphysics Modelling of Wind Turbines

1. **What is Multiphysics Modelling?**

According to The International Society of Multiphysics (“Definition — MULTIPHYSICS”), multiphysics (sometimes spelled as multi-physics) is defined as a coupled modelling approach of studies that demands simultaneous addressing of hitherto separate physical disciplines and combining them to generate relational mathematical models and validate them with controlled experiments to enhance the understanding of natural behaviour.

All problems arising from natural phenomena are of a multiphysics nature, whereas most of the engineered solutions available today are not. Therefore, while all research is interrelated, and is not conceivable anymore to neglect this fundamental issue within the scientific and industrial communities, most industrial solutions are simplified down to extremes to reduce the complexities in design. This is, of course, what engineering is all about, solution after simplification or ‘divide and conquer’. However, it also has consequences on the quality and cost of the products, which have now become central issues of simulations for researchers and engineers.

During the last couple of centuries, solutions have been devised to everyday problems via simplified mathematical models. Once the computers became more powerful, more complicated models were built while still ignoring the “real-time” interactions between the different disciplines. As models became complicated, i.e., more mathematical and less engineering-oriented, largely due to the application of numerical methods such as finite elements, the physical complexities were more and more ignored. It can be best summarised for convenience by “boundary conditions” of a differential equation at the expense of “freezing” their impact on the quality of the solutions. Do these boundary conditions really exist in nature? Where are the boundaries of a physical object, and what happens if those limiting conditions are extended a little bit further?

The problem is that even in this more realistic perception of boundary limits, the issue of physical complexity is still ignored, and often confused with complicated models. Recall that nearly all differential equations have “constant” terms or model parameters, and these represent the effects, or interactions, of another simultaneously present and important physical phenomena, which has been reduced to a simple, static effect.

There is obviously much ground here to be covered, and it is believed that multiphysics modelling is a particularly strong tool allowing for complex features of physical interaction to be considered. It is known that the key to the treatment of sources of dispersion is in the field interaction, which can only be taken into account via a true multiphysics treatment of the physical problems. This progress in coupled field problems' treatment depends heavily on the success of solution methodologies to provide robust and reliable solution algorithms.

Multiphysics analysis has hence been developed over the recent past to better represent the behaviour of complex processes by the use of simultaneous modelling of a number of systems. This development is driven by the industrial need to further the understanding of real physical phenomena in order to develop and design safer and more efficient products, which are environmentally friendly.

Such analyses and investigations were impossible to perform a number of years ago due to a lack of powerful computing systems. However, the advances in computer hardware have led to more sophisticated investigations brought about by increased computation speeds. Since this has been accompanied by new software packages that exploit the improved architecture of new generation microprocessors, there have been dramatic improvements in the coupling of many mathematical simulation techniques. Many research establishments are comparing the results of such studies with experimental tests to improve modelling accuracy and validate the processes for future certification.

There are now many large science and engineering communities whose research is being customised towards multiphysics analytical and simulation methods to save costs and reduce time to market with the use of rapid prototyping. This is certainly true in more advanced technologies for the more innovative design of products to market. The examples include a new generation of nuclear reactors, precision design of airbags; and crashworthiness of aerostructures. Although these communities have been using different modelling techniques, the real coupling of various phenomena is still a big challenge in academic applications let alone industrial real problems. The new methods are needed, and also indeed, the verifications and validations still remain the most challenging aspect of multiphysics analyses.

The multiphysics simulations trend in academia and industry are mainly focused on the availability of appropriate techniques for coupling aspects and, indeed, their credibility, which can be verified and validated. Many are still implementing Lagrangian or Eulerian methods to simplify simulations of applications with assumptions and boundary conditions but approaches such as Arbitrary Lagrangian-Eulerian (ALE), including penalty method, require robust validations. Therefore, it is essential to establish a clear direction for publications within the current need to provide appropriate reading materials accompanied by the latest techniques.

The enhancement of the use of multiphysics analyses mainly depends on two aspects. First, on a better understanding of physics and physical representations of interactions, and second on advancements in computing facilities to ensure complex and large mathematical equations can be solved.

The progress in both the fields above is of paramount importance. More research and developments are needed to ensure the accuracy of new tools for multiphysics simulations and the effectiveness of more significant and more stable and secure parallel computing facilities.

Despite the importance of multiphysics modelling and analyses due to more accurate solutions for new products and problem-solving in industrial applications, compared to conventional one-way coupling, the cost of such analyses still plays an important role. Hence, it is essential to recognise the cost-effectiveness and identify the time and space to dedicate required modelling complexity in engineering and science applications.

Over the past years, many studies have focused on various issues to address the importance of multiphysics analysis; however, some modelling and simulations were presented as a multiphysics approach, but a multidisciplinary approach may simply describe it.

Particular focus is recently given to virtual engineering and how the modelling and simulations in multiphysics may be able to help the introduction of a digital twin to the world of production and maintenance. However, this may take a few more years to mature so that by then, Elsevier Multiphysics Series will be in a position to offer volumes in such an area.

In the coming years, virtual multiphysics simulations and real-time modelling will be more applicable to address real-world problems.

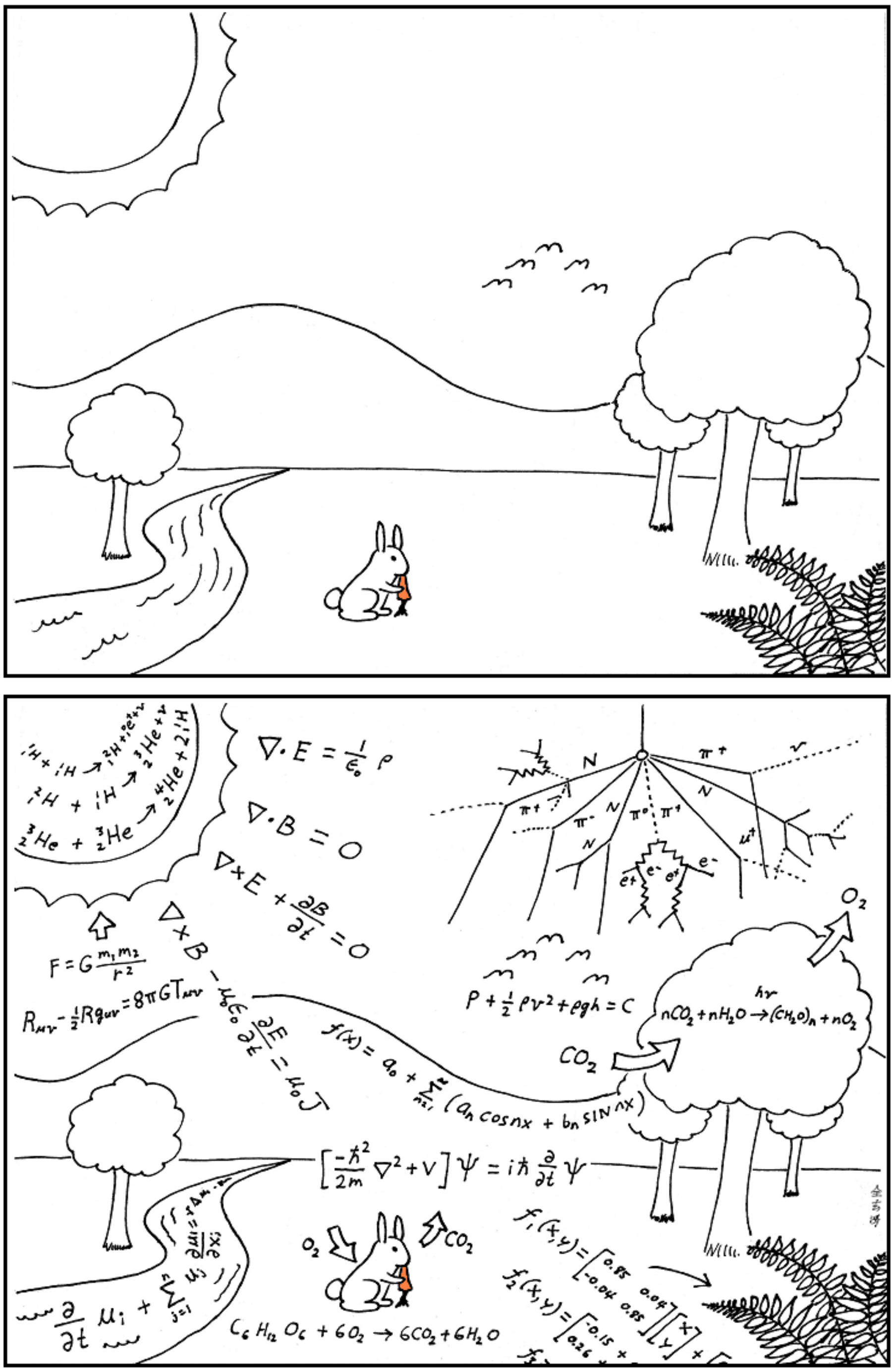
Multiphysics is interdisciplinary, drawing on expertise from multiple areas of engineering, physical sciences, computer science, and mathematics. It encompasses a wide range of research areas, such as:

Multiscale modelling: simulating systems that span multiple lengths and time scales, such as materials with microstructures that affect their macroscopic behaviour. For example, finite element analysis (FEA), computational fluid dynamics (CFD), discrete element model (DEM), smoothed-particle hydrodynamics (SPH), etc.

Multiphysics optimization: using multiphysics simulations to optimize the design of systems, such as finding the optimal shape of an aircraft wing for lift and drag, design of heat exchangers for effective heat transfer, etc.

Multiphysics data assimilation for validation and verification: combining data from multiple sources to improve the accuracy of multiphysics simulations, such as incorporating measurements from experiments or sensors into simulations as initial or boundary conditions.

Multiphysics is visually illustrated in the Fig 1. Please note the correlations are just illustrations and not necessarily complete or correct, however, do present an interesting and thought-provoking philosophical argument.



This is how scientists see the world.

Fig 1: Visual illustration of multiphysics [1]. Following physical models are shown: nuclear fusion reaction, Maxwell's equations, Newton's law of universal gravitation, Einstein's relativity theory, Feynman diagram, Bernoulli's equation, photosynthesis model, Fourier series, Schrödinger equation, finite element equation (Hooke's law), metabolic process model, and momentum conservation (Navier-Stokes equation). The interdependence between different physical models can result in a complex-coupled system, referred to as multiphysics, where the outputs of one or more models becomes the inputs for the others. (CC BY-NC 3.0 US)

Multiphysics research is used to better understand and predict the behaviour of complex systems, which can lead to the development of new technologies, improved products, and more efficient processes.

Multiphysics and computer-aided engineering (CAE) are closely interlinked. CAE tools and software are often integrated with multiphysics simulation software. CAE tools, for example, computer-aided design (CAD) provide the necessary geometrical information for simulating the multiphysics system. These tools can be used to analyse and optimize the performance of a wide range of industrial systems, including mechanical, electrical, fluid, thermal, etc. systems. CAE tools in particular relevance to multiphysics, such as computer-aided design (CAD), geometrical design optimization, and graphics rendering are discussed as follows:

Computer-aided design (CAD): software allows to create and manipulate 3D geometric models of a design, such as a product or piece of equipment. CAD information can be further fed to the discretization tools allowing for numerical discretization for the implementation of multiphysics multiscale modelling (e.g., FEA, CFD, etc.)

Geometrical design optimization: techniques used to find the optimal design of a system, such as finding the shape of an aircraft wing that provides the best performance by looping the information from CAD into multiscale multiphysics modelling and vice versa.

Graphics rendering: enables to visualize and analyse CAD models, results from multiphysics multiscale modelling (e.g., FEA, CFD, etc.), and other simulations. By rendering these simulations, one can gain insights into the behaviour and performance of engineered systems, identify potential design flaws, optimize designs, and communicate the findings effectively.

2. Future of Wind Turbines

Wind turbines are considered a key component of the future of sustainable energy for several reasons. They are a clean and renewable source of energy, producing no emissions or pollutants. Wind turbine technology is becoming increasingly efficient and cost-effective, making it a viable option for large-scale power generation. Wind power can help reduce dependence on fossil fuels and decrease greenhouse gas emissions, which are major contributors to climate change. The wind is abundant and widely available in many parts of the world, making it a widely accessible form of sustainable energy. It's scalable, which means it can be used in small or large-scale projects. As of 2021, wind energy is a significant source of renewable energy globally, providing around 7% of the world's electricity. According to the Global Wind Energy Council (GWEC), the global installed wind power capacity reached 791 GW by the end of 2020, and it's expected to continue to grow in the future. The GWEC also estimates that by 2030, wind energy could provide around 18% of the world's electricity. The exact amount of energy generated by wind turbines around the globe varies depending on factors such as wind conditions, turbine size and location, but it's a significant and growing source of renewable energy. According to International Energy Association, “The amount of electricity generated by wind increased by almost 273 TWh in 2021 (up 17%), 45% higher growth than that achieved in 2020 and the largest of all power generation technologies. Wind remains the leading non-hydro renewable technology, generating 1 870 TWh in 2021, almost as much as all the others combined" [2,3].

To meet the ambitious future goals anticipated in the wind energy sector, there are several areas in which wind turbine technology needs to be improved. 1) Increasing turbine efficiency: Developing more efficient turbine blades and designs that can capture more wind energy and increase power output. 2) Improving turbine materials: Advancements in materials science can lead to the development of stronger, lighter, and more durable materials for turbine blades and other components, which can increase the lifespan and reliability of wind turbines. 3) Reducing costs: Efforts are being made to reduce the costs of wind turbines, including through the use of more cost-effective materials and manufacturing techniques. 4) Increasing turbine size: Developing larger wind turbines can help increase power output and reduce costs per unit of energy generated. 5) Improving turbine control: Advances in control systems can help improve the efficiency and reliability of wind turbines by allowing them to respond more quickly to changing wind conditions. 6) Improving the integration of wind energy: Better integration of wind energy into the grid, such as through the use of advanced energy storage systems and improved forecasting methods. 7) Increasing durability: Wind turbines are exposed to harsh weather conditions, such as high winds, saltwater corrosion, and extreme temperatures. Therefore, research is being conducted to improve the durability of wind turbines and make them more robust.

Multiphysics Simulation of wind turbines can help in better design and development of future wind turbines in several ways. 1) Aerodynamic optimization: simulations can be used to optimize the design of wind turbine blades, which can increase the efficiency of the turbine and the amount of energy it generates. 2) Structural analysis: simulations can be used to analyse the structural behaviour of wind turbines, which can help identify potential problems and improve the durability and reliability of the turbine. 3) Cost reduction: simulations can be used to evaluate different design options and materials, which can help reduce the overall cost of wind turbines. 4) Power output prediction: simulations can be used to predict the power output of wind turbines, which can help inform the design and placement of turbines in wind farms. 5) Improved control: simulations can be used to optimize the control systems of wind turbines, which can help improve the efficiency and reliability of the turbine. 6) Environmental impact assessment: simulations can be used to predict the impact of wind turbines on the environment, such as the effect of turbine noise on wildlife or the effect of turbine shadow on the surrounding area. 7) Fatigue analysis: simulations can be used to predict the fatigue of the wind turbine components, which can help to optimize the design and improve the lifespan of the wind turbine.

3. History of Wind Turbines

The force exerted on structures by wind when blowing at significant velocities can be substantial. Historically, people have tried to harness this force to their benefit for multiple purposes. Over the past centuries there have been some success stories in turning this force usable through guiding it in ways friendly to mankind. Wind power has been, as such, utilised in windmills to grind grains or to pump water for irrigation or, as in Holland, to prevent the ocean from inundating lowlands into unusable marshes. As at the dawn of the twentieth century electricity came into use the traditional windmills gradually became wind turbines with the rotor being connected to an electric generator working based on the principles of electromagnetism.

While subsequent industrialisation started to decrease the proportion of wind energy in European energy portfolio, still over 10% of Dutch industry's required power was supplied by wind energy in 1904. At the same time, there were 18,000 windmill units installed and operational in Germany. With further technological advances made, the traditional windmills started to be obsolete in advanced industrial societies of Europe. Nonetheless, during the same period, windmills grew popular among migrant communities of America to the extent that in the 1920's and 1930's there were around 600,000 units of windmills in operation across the US [3].

As for electricity generation, LaCour was the first person who built an electric turbine in 1891 [4] in Denmark and later connected a windmill to an electric generator to be used on small farms. This revolutionary invention was nevertheless overshadowed by the advent of diesel and steam engines. During the Second World War when fossil fuels were in high demand by military industries a Danish company, F.L. Smidth built a model of wind turbines as the pioneering prototype of the modern versions to help liberate countries from being obligated to use fossil fuel for power generation. This was the first type that utilised the scientific knowledge of aerodynamics in its construction. Almost at the same time Palmer Putnam, a US engineer, built a large wind turbine with a diameter of over 50 m for an American enterprise i.e. Morgan Smith Co. While F.L. Smidth's model was based on an upwind rotor, the US-design was working with a downwind one (see Fig 2.) and possessed the advantageous variable pitch regulation mechanism [3].

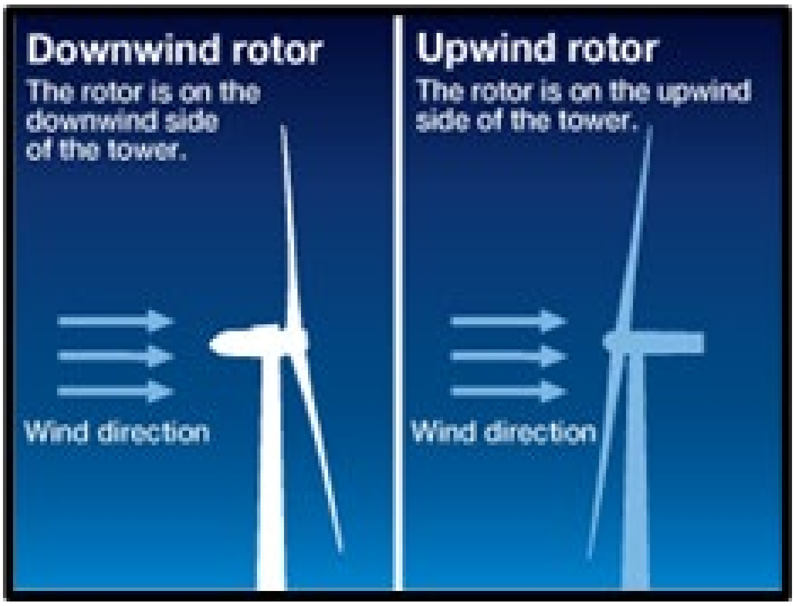


Fig 2. Downwind and upwind rotors [5]

Following the second World War the development of more efficient wind turbines continued primarily in Europe and North America (see Table 1). Shortly afterwards, in the 1950's, the Danish concept was introduced which led to the design of the Gedser turbine, possessing three blades and a stalled regulated rotor connected to an asynchronous AC generator [4].

Turbine model, Country	Diameter (m)	Swept area (m^2)	Power (kW)	Specific power (kW/m2)	Number of blades	Tower height (m)	Date in service
Poul LaCour, Denmark	23	408	18	0.04	4	-	1891
F.L. Smidth, Denmark	17	237	50	0.21	3	24	1941
Smith-Putnam, USA	53	2,231	1,250	0.56	2	34	1941
F.L. Smidth, Denmark	24	456	70	0.15	3	24	1942
Gedser, Denmark	24	452	200	0.44	3	25	1957
Hütter, Germany	34	908	100	0.11	2	22	1958

Table 1. Historical evolution of wind turbine models in different countries [6]

In the decades that followed more attention was paid to wind turbines and their potentials in the advanced industrial world as more countries wished to emancipate themselves from fossil fuel imports. Commercial large-scale wind turbines started to appear, and the industry grew during the 90's. In the US alone during this period the turnover from wind industry skyrocketed and turned beyond half a billion US dollars per annum. Since then this figure has consistently experienced an annual increase of 20%, and in terms of capacity the average grid-connected wind capacity worldwide has doubled every three years since the 90's (see Table 2).

Turbine, Country	Diameter (m)	Swept area (m^2)	Capacity (MW)	Operation hours	Generated (GWh)	Period
Mod-1, US	60	2,827	2	-	-	1979-1983
Growian, DK	100	7,854	3	420	-	1981-1987
Smith-Putnam, US	53	2,236	1.25	695	0.2	1941-1945
WTS-4, US	78	4,778	4	7,200	16	1982-1994
Nibe A, DK	40	1,257	0.63	8,414	2	1979-1993
WEG LS-1 GB	60	2,827	3	8,441	6	1987-1992
Mod-2, US	91	6,504	2.5	8,658	15	1982-1988
Näsudden I, SW	75	4,418	2	11,400	13	1983-1988
Mod-OA, US	38	1,141	0.2	13,045	1	1977-1982
Tjæcreborg, DK	61	2,922	2	14,175	10	1988-1993
École, CD	64	4,000	3.6	19,000	12	1987-1993
Mod-5B, US	98	7,466	3.2	20,561	27	1987-1992
Maglarp WTS-3, SW	78	4,778	3	26,159	34	1982-1992
Nibe B, DK	40	1,257	0.63	29,400	8	1980-1993

Tvind, DK	54	2290	2	50,000	14	1978-1993

Table 2. Performance of the first large-scale demonstration wind turbines in United States (US), Denmark (DK), Great Britain (GB), Sweden (SW), Congo (CD) [7]

Currently wind energy is popular in developed countries as a share of both green energy and total energy portfolios. The rise in production may be observed during the period of 2000 to 2015 (Fig 3). There are several reasons behind wind energy's attractiveness. Wind generated electricity is green and produces zero CO_2 emissions (apart from during the manufacturing and decommissioning processes). In desolate areas or areas of weak grid connection, wind energy may be used for charging batteries which could then be used to release the stored energy at desired rates. Moreover, many related sectors could benefit from the opportunities granted to create jobs in research and development and in engineering.

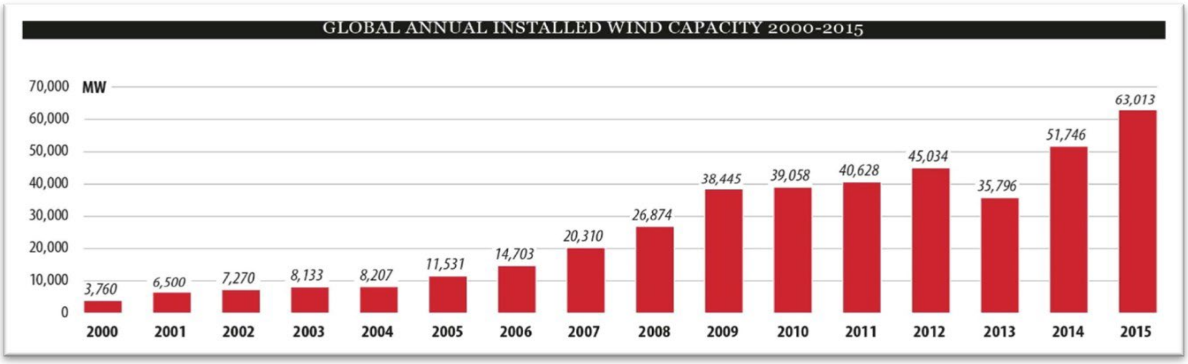


Fig 3. Global annual installed wind energy capacity [8]

4. Types of Wind Turbines

There are two fundamental categories wind turbines fall into:

Horizontal-axis wind turbines

Vertical-axis wind turbines

The two types differ in the plane of rotation of their blades (hence the terminology), the design of blades, the mechanisms of lift and drag and their efficiency. While horizontal axis wind turbines are versatile, the vertical axis wind turbines are used exceptionally. There are other types of turbines which can generate electricity through wind induced energy but due to their very limited use and extremely low capacities they may not be considered as industrial generators and are thus not discussed in this monograph.

Horizontal-axis turbines

Horizontal-axis wind turbines, as the name suggests, possess blades which rotate in a plane perpendicular to the horizontal axis of the nacelle. They are similar to propeller airplane engines and possess blades like propellers with the obvious difference that instead of consuming energy to produce lift they use the wind velocity to capture energy. There can be two or multiple blades but normally there are three blades at equal angles of 120^o apart. They could be small with power production capacities up to KWs or large and reach MW production power capacity. The largest horizontal-axis turbines reach the height of 40-story buildings and have blades more than 100m long. Obviously, taller turbines with longer blades generate more electricity but also cause higher stress amplitude at blade roots. Almost all wind turbines currently operational are horizontal-axis turbines.

Vertical-axis turbines

Vertical-axis turbines have different blade designs and rotate about the vertical axis perpendicular to the plane of horizon. They look like eggbeaters with blades attached to the of a vertical rotor at the top and the bottom. Some versions of the vertical-axis turbine are over 30 m tall and 14 m wide. Due to the superior performance of horizontal-axis wind turbines very few vertical-axis wind turbines are currently being used.

5. Sustainability of Wind Turbines

Sustainability of wind turbines is a two-fold problem. On the one hand the question is ‘are wind turbines sustainable in the long run?’ and on the other hand ‘what is the impact of wind turbines and wind farms on the sustainable production of electricity?’. Experts believe any response to the former question is inconclusive as these structures have not been around for long enough so that an objectively verifiable thesis may be put forward. As for the latter question there is little controversy as to why wind turbines are useful to the environment. This aspect of sustainability has attracted some attention in the past few years.

By the virtue of its very existence a wind turbine is supposed to produce carbon-free electricity. This implies sustainability as an intrinsic property of wind turbines. Wind turbines do not release emissions that pollute the air and they do not require water for cooling. They can abate our need to produce energy from fossil fuels which results in lower air pollution and reduction in carbon dioxide emissions. It must, however, be mentioned that the process of decommissioning of the turbine and recycling or disposing the blades is not carbon-free and the footprint may depend upon the technologies used to achieve these goals and the methods adopted. While in operation, the turbines are designed to have a reasonable fatigue life (20-30 years) and are expected to achieve the target production capacities when the conditions of design and operation are as good as or exceed the assumptions made in design.

Wind energy as a clean source of electricity production has proved itself to be effective and accessible in most geographic locations. A single wind turbine may be installed anywhere in a village, a town or a city to produce homegrown electricity and is not obligated to be connected to the grid. Wind farms on the other hand are supposed to produce large amounts of energy and get connected to a gird. It is this requirement that makes the different phases of wind turbine design complex. The wake of wind turbines and their relative positions to each other must be studied for a given terrain and optimisation algorithms must be implemented to ensure sustainable and disruption-free production.

Continuous growth in wind energy production in the coming decades is crucially contingent upon answering the questions put forward above.

6. Concluding Remarks

Multiphysics modelling of wind turbines involves simulating the interactions between different physical phenomena that occur within a wind turbine. These phenomena include fluid dynamics, structural mechanics, aerodynamics, and electrical systems. The goal of multiphysics modelling is to predict the behaviour of the wind turbine under different operating conditions and to optimize its performance.

Multiphysics computational fluid dynamics (CFD) simulations are used to predict the flow of air around the wind turbine blades, taking into account factors such as wind speed and direction, blade shape, and turbine operating conditions. These simulations can be used to predict the power output of the turbine, as well as the loads on the blades and other structural components.

Multiphysics finite element analysis (FEA) simulations are used to predict the behaviour of the wind turbine blades, tower, and other structural components under different loads, such as wind and gravity. These simulations can be used to predict the structural integrity of the turbine, as well as to optimize the design of the blades and other components for maximum performance and minimum weight.

In a wind turbine, the blades are subjected to aerodynamic loads as the wind flows around them. These loads cause the blades to bend and twist, which in turn affects the fluid flow around the blades. This creates a feedback loop between the fluid flow and the structural behaviour of the blades. Multiphysics FSI simulations take into account this feedback loop and can accurately predict the behaviour of the blades and the power output of the turbine under different wind conditions.

Multiphysics fluid-structure interactions (FSI) simulations are typically performed using a combination of CFD and FEA methods. The fluid flow is modelled using CFD, while the structural behaviour of the blades is modelled using FEA. The two simulations are coupled together, allowing for the exchange of information between the fluid and structural models. This allows for a more accurate simulation of the turbine's behaviour and can be used to optimize the design of the blades and other components for maximum performance.

FSI simulations are also important for simulating the behaviour of the turbine under extreme wind conditions, such as high wind speeds or gusts. These simulations can be used to predict the loads on the blades and other components, and to ensure that the turbine can withstand these loads without failure.

Multiphysics modelling can also be used to simulate the behaviour of the turbine's control systems under different conditions. These simulations can be used to predict the performance of the turbine's control systems under different wind speeds and directions. This information can be used to optimize the design of the control systems to ensure that the turbine operates safely and efficiently under extreme conditions.

Electrical systems are also considered in the multiphysics modelling of wind turbines. These simulations consider the behaviour of the electrical generators, power electronics, and control systems that make up a wind turbine. The goal of these simulations is to predict the power output of the turbine, as well as the efficiency of the electrical systems. The simulations can be used to optimize the design of these systems to minimize losses and maximize performance.

In summary, multiphysics modelling can help in understanding extreme loading conditions in wind turbines by simulating the interactions between different physical phenomena that occur under these conditions. These simulations can be used to predict the behaviour of the turbine under different wind speeds and directions, as well as other environmental conditions such as temperature and atmospheric pressure. This can help to optimize the design of the turbine components and control systems to ensure that they can withstand these conditions without failure and perform optimally.

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