Historic development, current development and future potential

Precast concrete wind tower structures

The wind energy production is a growing industry and the energy produced is renewable and environmentally cleaner than most of the energy production systems. The supports of the wind energy generators may be built with precast concrete elements. The precast solutions for these structures are competitive in comparison to other structural systems. The evolution of the technology for wind energy production shows a clear need for larger wind turbines and longer blades and, consequently, taller towers. The experience also shows that precast concrete solutions increase their competitiveness as the tower height increases. Offshore wind farms have some advantages in relation to onshore ones, which explains recent investments in this area. Also in this case, the durability of concrete in the sea when compared to steel, gives advantages to precast concrete in relation to other structural solutions. This paper shows the evolution of the supports of the wind energy generators and the advantages of the use of precast concrete towers.

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The wind results from differences in the atmospheric pressure, generated by uneven heating of the Earth's surface. Since immemorial time, the power of the wind has been used as an energy source. Around 5000 BC there were already sailing boats on the Nile and in the fifteenth and sixteenth centuries the Portuguese sailed around the world, from Europe to Brasil (1500), went around Africa to India (1498) and Japan (1543), with the help of wind. Wind energy is a renewable source of energy and has been exploited over time to grind grain, pump water or putting machinery in operation.

There are records of simple wind mills in China in 200 BC to pump water and vertical axis windmills with sails for grinding grain in Persia and the Middle East. By the eleventh century, in the Middle East, windmills were widely used to produce food, and certainly merchants and crusaders brought the idea to Europe. The Dutch redesigned the windmills and adapted them for draining lakes and marshes in the Rhine River delta. Colonizers took this technology to the New World and in the late nineteenth century, began using windmills to pump water for farms and ranches and later to generate electricity for homes and industry. Industrialization, first in Europe and then in America, led to a gradual decline in the use of windmills. In Europe, steam engines replaced the windmills for pumping water. In the 1930s, the rural electrification programs have led to low cost electricity to most rural areas in the United States [2]. However, industrialization also caused the development of larger windmills to generate electricity. Wind turbine generators appeared in Denmark around 1890.

The popularity of wind energy has fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines waned. But when the price of oil rose in 1970, worldwide interest in wind turbine generators has increased significantly. Following the oil embargo in the 1970s the research and development in wind turbines allowed resuscitate old ideas and introduce new ways of converting wind energy into useful energy. Many of these approaches have been implemented in wind farms both onshore and offshore, all around the world.

The present market of wind energy

Nowadays, with the experience of over two decades of operation of wind farms, along with continued research and development, meant that the electricity generated by the wind is too close to the production cost of conventional energy. Wind energy is the energy source of the fastest growing in the

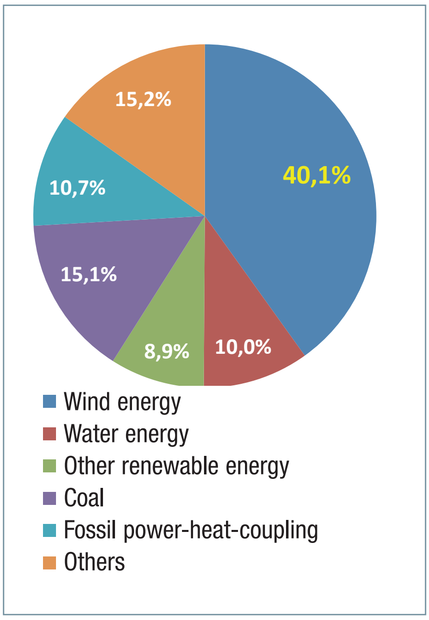

Fig. 1: Typical distribution of energy sources during 2012 in an office in Lisbon

Fig 2: Wind park in Torres Vedras, Portugal

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world, providing the industry, commerce and homes with clean, renewable energy (Fig. 1). In Portugal, wind is already the source of about 40% of the consumed energy of the year 2012, and renewable (including wind and hydraulic) energy is nearly 60% of the consumed energy in 2012 (Fig. 2). The evolution of the wind power capacity in the world is highly positive (Fig. 3). In 2012 the increase was about 19% in relation to 2011 [3]. The top 10 countries (Fig. 4) contributed in 85% for the world increase in the wind power capacity [3].

The most significant growth in 2012 was observed in Latin America, namely in Brazil where there was a 1.1GW [3] increase in new installed power capacity. This increase is an answer to the growth in electricity demands due to the present good economic situation of Brazil. Nevertheless, this increase was not enough to enter in the top ten countries club in 2013. In view of this tendency, it is clear that the wind energy is a promising area of business, namely for the construction of towers to support the wind generators.

Structural solutions to support wind generators

Throughout the ages the windmills started to be constructed of wood or stone mason-

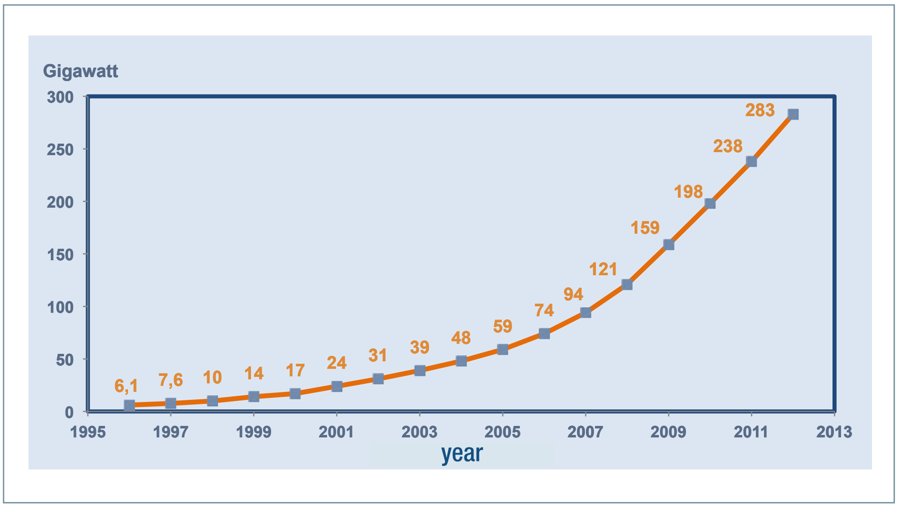

Fig. 3: Wind power global capacity, 1996–2012 (adapted from [3])

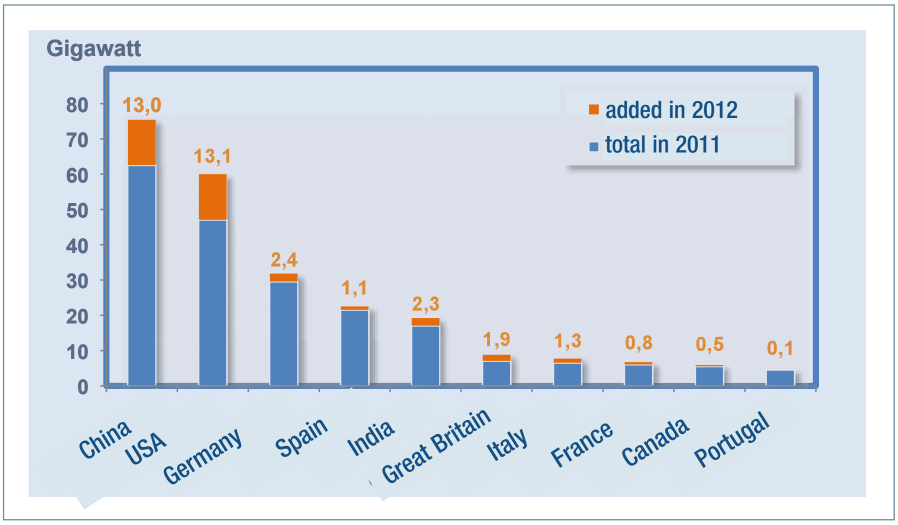

Fig. 4: Top 10 countries, wind power capacity in 2011 and additions in 2012 (adapted from [3])

Fig. 5: Precast staves

ry. With the industrial revolution, the first steel truss structures appeared. Concrete towers appear only in the XXI century as a credible alternative to steel towers. During the twentieth century various structural solutions and construction methods have been proposed for towers to withstand wind generators at a great height. The most current solutions are spied masts, steel shell structures, towers with steel sections and structures with cast on site or precast concrete walls, hybrid towers of concrete and steel shells, and towers with composite materials. The main actions to be considered in these structures are: i) the forces of the wind in the turbine blades and in the tower structure; ii) the weight of the turbine and the self weight of the tower structure; iii) the dynamic effects of wind and equipment; iv) the seismic actions, if relevant; and v) the effect of currents and waves in the case of offshore structures.

The tower foundations are usually very large, and its type depends mainly on the soil conditions of the wind farm location. Smaller foundations may be used in the case of tower truss structures because individual foundations for each column may be considered. Current solutions for offshore foundations are divided in floating, used in deep waters, and non floating in the case of shallow waters. The foundations for shallow waters operate by gravity and may be of the concrete coffin type or precast concrete cup. There are other solutions with piles or with tripod or truss shapes.

To support the wind generators steel towers have been used, with cylindrical or truncated cone shaped staves, mounted in place and bolted together, fixed to concrete foundations using anchor bolts. The expectations for the future of wind energy turbines are the development of increasingly powerful (over 6 MW), that need longer blades, with the consequent increase of the height of the towers. Another reason to have higher towers is to keep the turbine away from obstacles to wind flow and have better turbulence conditions and wind shear than near the surface. The development in recent years of the power turbines and the inherent increase in diameter of the blades, has led to a significant increase of the height of the towers. In 1990 the turbines produced 500 kW with a blade diameter of 40 m and a tower height of 54 m, in 2000 turbines achieved 2 MW with a blade diameter of 80 m, while in 2005 arrived to 5 MW turbines with a blades diameter of 124 m and towers height of 114 m.

The need to increase the height of the steel towers, with the consequent increase of diameter and wall thickness of the shell, has met increasing limitations on the use of steel towers. Added to this, the large fluctuations of steel price in the market, the production costs and shipping limitations, related to the size of the staves required for towers taller than eighty meters, are severe disadvantages to the use of steel towers.
Given these new limits, some features of the steel towers lose the advantages mentioned, namely: the maximum diameter of the base of the tower, for reasons of trans-

Fig. 6: Precast concrete truss tower developed by the authors for onshore (left) and offshore (right) [7]

Fig. 7: Precast staves with horizontal joints (source: Enercon)

port, must not exceed 4.30 m, which represents an awesome obstacle to increasing tower height; with increasing height of the tower and due to dimensional limitations mentioned steel towers become structurally more susceptible to phenomena of fatigue, instability, poor flexibility and dynamic behaviour for the actions of wind and earthquakes, due to reduced ductility behaviour; and require heavier foundations.

Although the precast concrete industry developed towers with heights slightly greater than steel towers, the precast concrete towers with staves are still limited by the maximum diameter of the base of the tower (Fig. 5) and require very high cranes for their assembly. The towers with concrete walls cast on site have the disadvantage that the construction process is time consuming, which affects the final cost of the tower. Given the expectations for the future development of wind energy onshore and offshore, it appears that the market requires higher wind towers and that the solutions in the market do not completely solve this need.

To answer this important market demand, based on the author's experience, a truss tower precast reinforced concrete (Fig. 6) was designed [6]. This precast concrete tower solution allows a fast assemblage and easy transportation. The truss tower is composed of precast elements and aims to be an alternative solution for towers over 80 m high and competitive in economic terms. The small dimensions of the precast elements of this structural solution do not require special transportation, provides

Fig. 8: Semicircular precast concrete stave at the base of the tower with vertical and horizontal joints (source: Enercon)

Fig. 9: Detail of a vertical joint (source: Enercon)

freedom of choice of the geometry of the tower (different number of columns and different spacing between, etc.) optimizing the load capacity and control of the natural frequency of vibration. The solution also presents savings in the foundation cost. The authors submitted a patent in Portugal and Brazil and, in 2009, this solution won a BES Innovation Award.

Precast concrete towers to support wind generators

The towers built with precast concrete may be composed of:
- Precast staves with horizontal joints and, usually, prestressed vertically (Fig. 7)
- Semi-circular staves in the base of the tower and closed staves on top, with vertical and horizontal joints, and usually prestressed vertically (Fig. 8)
- Flat (lateral faces) and round (corners) precast elements, being the vertical dimension of the elements, with prestress inside (Fig. 9)
- Truss structure of precast and prestressed concrete elements connected together (Fig. 6)

The precast concrete solutions have undoubted advantages compared to steel solutions:
- Ability to attain great heights and withstand large power generators, onshore and offshore
- Improvement of the dynamic behaviour, reducing fatigue, increasing equipment life and reducing maintenance
- Structural links reliable, tested, maintenance-free, providing a fast assemblage and all the advantages of monolithic construction
- Excellent response to seismic actions, thanks to the high ductility and structural damping
- Reduced need for maintenance in contrast to steel towers, especially in offshore environments

Fig. 10: ATS concept - precast concrete hybrid tower [8]

- Greater durability of such concrete structures in relation to steel towers, particularly in marine environments
- Lower noise generated by the damping effect of the concrete
- Reduction of CO_2 emissions in the manufacturing of the tower (between 55% and 65% of emissions involved in manufacturing a steel tower)
- The material of the towers is fully recyclable
- The durability of concrete towers is much higher than the turbines. This allows future replacement of wind turbines by other ones with higher power, multiplying the possibilities for amortization of the cost of the work and energy transport infrastructure, especially in costly offshore

Conclusions

The supports of the wind energy generators may be built with precast concrete elements with great advantages in relation to traditional solutions, either for onshore and offshore wind farms.

The main advantages of the precast towers, in relation to traditional steel structures, are the ability to attain greater height, with better dynamic behaviour and cheaper foundations, and the reduced need for maintenance, especially in offshore environments.

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