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BAHRAIN WORLD TRADE CENTER (BWTC): THE FIRST LARGE-SCALE INTEGRATION OF WIND TURBINES IN A BUILDING

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SUMMARY

This paper describes the design evolution of the large-scale wind turbines proposed for the Bahrain Trade Center. It will describe the details of the wind turbines and their control, showing how several innovative ideas have come together and have been technically validated to produce the design for this unique building. Copyright © 2007 John Wiley & Sons, Ltd.

1. INTRODUCTION

The Bahrain World Trade Center (Figure 1) forms the focal point of a master plan to rejuvenate an existing hotel and shopping mall on a prestigious site overlooking the Arabian Gulf in the downtown central business district of Manama, Bahrain. The concept design of the Bahrain World Trade Center towers was inspired by the traditional Arabian 'wind towers' in that the very shape of the buildings harnesses the unobstructed prevailing onshore breeze from the Gulf, providing a renewable source of energy for the project.

The two 50-story sail-shaped office towers taper to a height of 240 m and support three 29 m diameter horizontal-axis wind turbines. The towers are harmoniously integrated on top of a three-story sculpted podium and basement which accommodate a new shopping center, restaurants, business centers and car parking.

The elliptical plan forms and sail-like profiles act as aerofoils, funneling the onshore breeze between them as well as creating a negative pressure behind, thus accelerating the wind velocity between the two towers. Vertically, the sculpting of the towers is also a function of airflow dynamics. As they taper upwards, their aerofoil sections reduce. This effect, when combined with the increasing velocity of the onshore breeze at increasing heights, creates a near-equal regime of wind velocity on each of the three turbines. Understanding and utilizing this phenomenon has been one of the key factors that has allowed the practical integration of wind turbine generators in a commercial building design. Wind tunnel testing (see Section 3) has confirmed how the shapes and spatial relationship of the towers sculpt the airflow, creating an 'S' flow whereby the center of the wind stream remains nearly perpendicular to the turbine within a 45° wind azimuth, either side of the central axis. This increases the turbines' potential to generate power while also reducing fatigue on the blades to acceptable limits during wind skew across the blades.

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Figure 1. Design illustration of the Bahrain World Trade Center

The specific architectural forms of the Bahrain World Trade Center towers were borne from using the nautical expression of a sail to harness the consistent onshore breeze, potentially to generate energy using wind dynamics, as well as to create two elegant towers for Bahrain, which would transcend time and become one of a kind in the world.

2. BACKGROUND

While the impetus for this innovative design solution came entirely from the architect, the client readily embraced the concept to portray to the world that Bahrain is committed to options that reduce demand on fossil fuel energy reserves and will move urban and building design in desert climates in a more sustainable direction. The complexity of integrating large-scale wind turbines in a building structure is not to be underestimated and the client expects a key benefit from this project to be the knowledge and experience gleaned which can then be disseminated to design teams globally.

Like many architects around the world, the design team in the Middle East has considered design solutions that incorporate sustainability and have investigated the concept of utilizing integrated wind turbines on several previous concept designs. The wind climate in the Arabian Gulf, with its dominant sea breeze characteristic, is conducive to harnessing wind energy and allows designers to move away from the more conventional omnidirectional solutions and consider unidirectional wind turbine options that in many respects lend themselves to large-scale integration in buildings.

Research by the design team has shown that the large-scale integration of turbines into buildings mostly fails because of the excessive cost (up to 30% of the project value) associated with the adaptation of the building design, and also as a result of high research and development costs for special turbines. From the outset this project had as its primary basis of design the utilization of conventional technologies and the development of a built form that would be sympathetic to receiving wind turbines. The premium on this project for including the wind turbines was less than 3% of project value.

Therefore, with the benefit of a favorable wind climate and a design philosophy that minimized turbine R&D/building costs, the architects along with a team of world-leading technologists moved forward with the design and addressed the key issues of:

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- producing technically viable solutions;
- balancing energy yield/benefit with investment.

3. ENVIRONMENTALLY RESPONSIVE DESIGN

This building is not intended to be a low carbon emission solution by European and other worldwide standards. However, aside from the wind turbines, it does include a number of other design features that are of interest and reduce carbon emissions when compared to other buildings in the Middle East. These are summarized below:

- buffer spaces between the external environment and air conditioned spaces. Examples include a car park deck above and to the southern side of the mall, which will have the effect of reducing solar air temperature and reducing conductive solar gain;
- deep gravel roofs in some locations that provide dynamic insulation as a consequence of the gravel being heated by the sun and warm air percolating upwards against the direction of heat flow;
- significant proportion of projectile shading to external glass facades;
- balconies to the sloping elevations with overhangs to provide shading;
- where shading is not provided to glazing, a high-quality solar glass is used with low shading coefficient to minimize solar gains;
- low-leakage, openable windows to allow mixed-mode operation in winter months;
- enhanced thermal insulation for opaque fabric elements;
- dense concrete core and floor slabs presented to the internal environment in a manner that will level loads and reduce peak demand, with associated reductions in air and chilled water transport systems;
- variable-volume chilled water pumping that will operate with significantly less pump power at part loads than conventional constant volume pumping;
- low-pressure loss distribution for primary air and water transport systems that reduces fan and pump power requirements;
- total heat energy recovery heat wheels of fresh air intake and exhausts to recover 'coolth' from the vitiated air and recover it to the fresh make up air;
- energy-efficient, high-efficacy, high-frequency fluorescent lighting with zonal control;
- dual drainage systems that segregate foul and waste water and allow gray water recycling to be added at a later date;
- connection to the district cooling system that will allow an order of magnitude improvement on carbon emissions, since in Bahrain efficient water-cooled chillers are not allowed due to water shortage, whereas the district cooling solution will involve sea water cooling/heat rejection and much improved levels of energy conversion efficiency;
- dual-flush WC and electronic taps with excess water flow restrictors;
- reflection pools at building entrances to provide local evaporative cooling;
- extensive landscaping to reduce site albedo, generate CO_2 and provide shading to on grade car parks;
- solar-powered road and amenity lighting.

4. BUILDING-INTEGRATED WIND TURBINES

4.1 Wind analysis

Three wind turbines have been integrated into the building to generate electricity. Horizontal-axis wind turbines are normally pole mounted and turn to face the direction of the wind, thus maximizing energy yield. The practical application of such turbines to buildings in variable-direction wind climates is

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therefore very difficult. The majority of architectural studies deploying building-integrated, horizontal-axis turbines deploy the principle of a fixed turbine, as in the case of the Bahrain World Trade Center. Development for vertical-axis wind turbines is encouraging and of course they benefit from the advantage of being truly omnidirectional. However, at the time of design development for this project, large-scale proven vertical-axis turbines were not available for building applications.

The fixed horizontal turbine suffers the drawback of only being able to operate with wind from a limited azimuth range, if problems with blade deflections and stressing through excessive skew flow are to be avoided. From the outset of this project, the shape of the towers has been designed to capture the incoming wind and funnel it between the towers.

Extensive wind tunnel modeling that was latterly validated by CFD modeling, examples of which are illustrated in Figure 2, have shown that the incoming wind is in effect deflected by the towers in

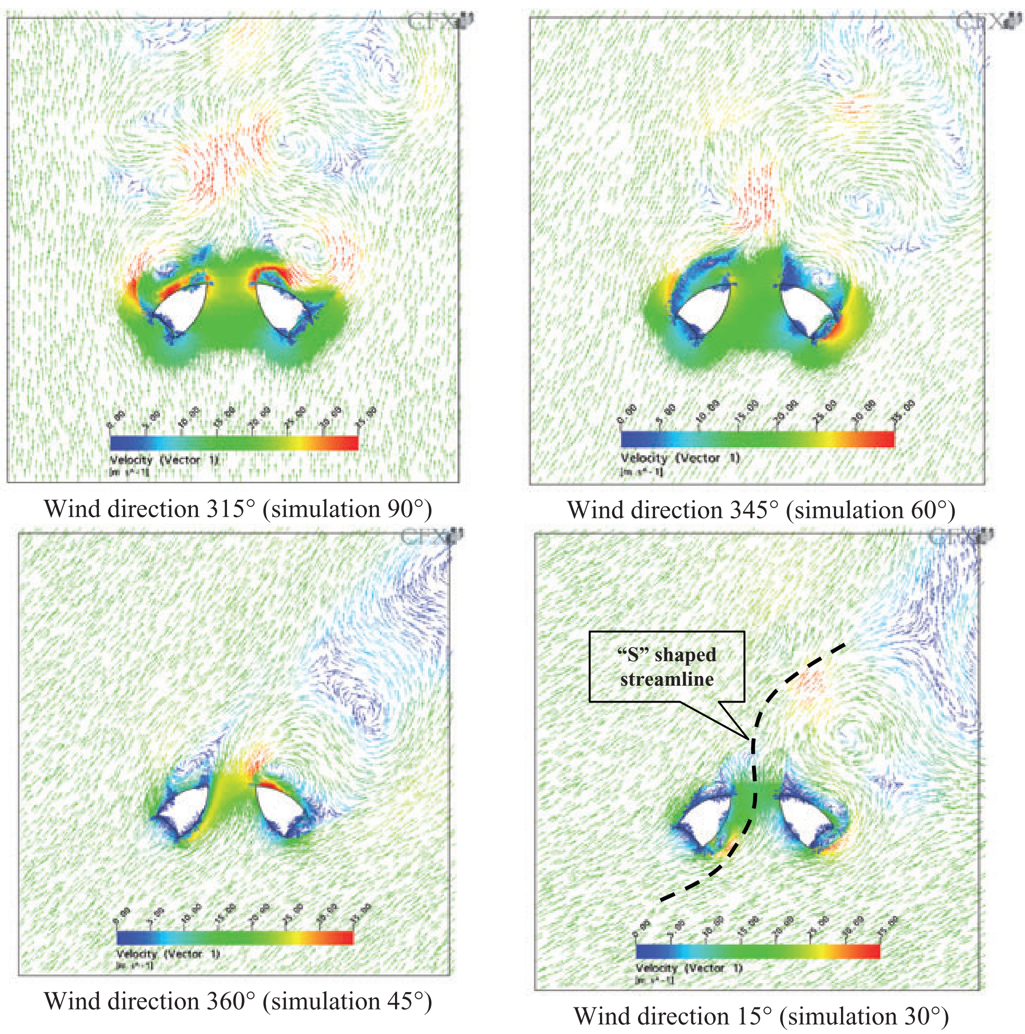

Figure 2. CFD Images by Ramboll, showing airflow patterns near towers, simulated at the level of the top turbine for different free, undisturbed wind incidence angles with respect to an 'x' axis (i.e., horizontal line connecting towers)

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the form of an S-shaped streamline which passes through the space between the towers at an angle within the wind skew tolerance of the wind turbine. Engineering predictions show that the turbine will be able to operate for wind directions between 270° and 360°; however, caution has been applied and turbine predictions and initial operating regimes are based a more limited range of between 285° and 345°. At all wind directions outside of this range the turbine will automatically adopt a 'standstill' mode. It is no coincidence that the buildings are oriented toward the extremely dominant prevailing wind.

The funneling of the towers has the effect of amplifying the wind speed at the turbine location of up to 30%. This amplification, in conjunction with the shape of the towers (larger effect at ground) and the velocity profile of the wind (lowest at ground), has the effect of balancing the energy yield to the extent that the upper and lower turbines will produce 109%and 93% when compared to 100% for the middle turbine.

4.2 *Wind turbine system components and control*

The fixed, horizontal-axis wind turbines on this project comprise the following key components:

- nacelle, including enclosure with gearbox, generator, cooling system and associated control systems;
- rotor;
- bridge;
- control, monitoring and safety systems;
- electrical building interface;
- nacelle and rotor.

The nacelle is the term used for the cowling containing the gearbox, brake, controls, etc. and, in addition, there is the rotor. Outline specification details for each wind turbine are detailed in Table 1.

Nacelles have been designed to sit on top of the bridge, rather than within it, to portray the functionality of the turbine. The turbine is a simple and robust 'stall-controlled' type. The stall control is a passive way of limiting power from the turbine. The rotor blades are bolted onto the hub at a fixed angle and the profile has been designed to ensure that the moment the wind speed becomes too high it creates turbulence on the leeward side of the rotor blade and prevents lift, stalling the blade so that the power output stabilizes at a maximum output.

Table 1. Wind turbine details

Nominal electrical power generated	225 kW
Power regulation	Stall
Rotor diameter	29 m
Rotor speed at full load	38 rpm
Air brake	Centrifugally activated feathering tips
High-speed mechanical brake	Fail-safe type disk brake
Low-speed mechanical brake	Caliper type
Generator	Closed, four-pole asynchronous induction, 50 Hz
Yaw system	Fixed yaw
Cut in wind speed	4 m/s
Cut out wind speed	20 m/s (5-minute rolling average)—reduced from 25 m/s for this application
Maximum wind speed for blades	80 m/s (any direction) class IV hurricane ≥69 m/s

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The full power of about 225 kW will be achieved at 15–20 m/s (Figure 3), depending on air density. In the event of extremely high wind speeds under operating or standstill modes, the tip of the blade extends (Figure 4) by centrifugal force and rotates to act as a self-regulating governor brake, through the exertion of a drag force.

For this project, nacelles are a conventional design, with some enhancements to suit the desert application and to increase the structural safety. The guidelines in the Danish codes of practice (DSR09: Code of Practice for the Safety of Structures; DS412: Code of Practice for the Structural Use of Steel) have been used for increasing the structural safety to 'High Safety Class'. Conventionally, Eurocodes would be referenced, but they do not address high-safety classifications.

Each nacelle operates independently and is not affected by the failure of another nacelle.

The bridges

A key part of the design is the determination of loads on the rotor, through the nacelle and thence onto the bridges and buildings, so that structures can be analyzed for strength and fatigue.

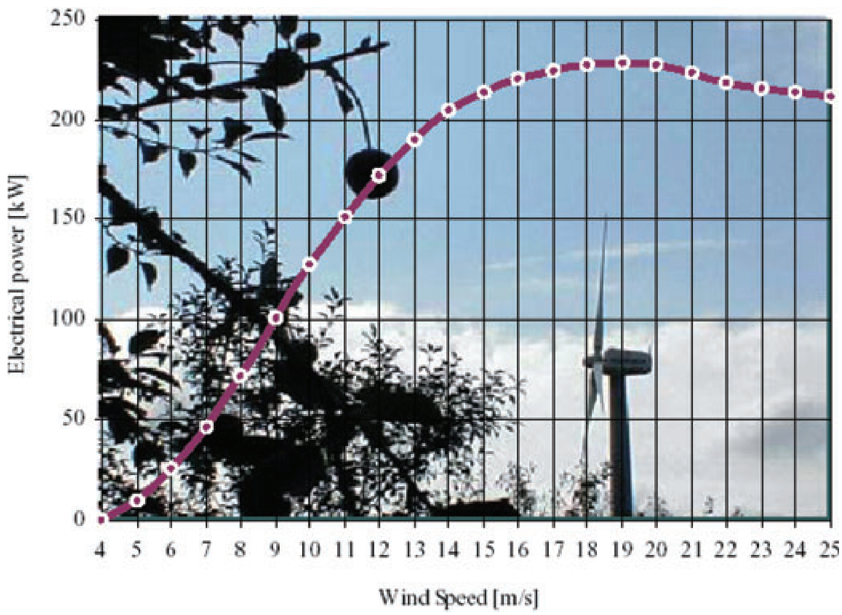

Figure 3. Electrical power versus wind speed

Figure 4. The tip of the extending blade

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The load calculation approach for this project has been made by the bridge design consultant in conjunction with the wind turbine manufacturer, using a specially adapted version of the industry-best wind turbine simulation tool, 'Flex4' (load analysis software used by Ramboll/Norwin and originally developed by the Technical University of Denmark). The tool has been adapted to take account of the influences of the buildings and the bridges. A total of a 199 different load cases have been modeled for each turbine and validating calculations or operational processes prepared to theoretically demonstrate that the turbine and bridge would survive without excessive fatigue. During the early stages of operation, this theoretical analysis will be validated and appropriate adjustments made to the operating regime that may increase or decrease energy yield.

The bridges are ovoid in section (Figure 5) for aerodynamic purposes and are relatively complex structures because they incorporate maintenance-free bearings where they connect to the buildings to allow the towers to move 0·5 m relative to each other. In addition, the bridges that span 31·7 m and support a nacelle with a mass of 11 tonnes have been designed to withstand and absorb wind-induced vibration and vibrations induced by both an operating and 'standstill' turbine. Analysis by the bridge designer has been undertaken to estimate the natural frequency of the bridge and to ensure it does not conflict with the frequency of exciting vibrations of itself or the building. Further precautions are included in the design to allow the bridge to be damped if, in practice, vibrations are found to be problematic during commissioning. These precautions include the facility in the design to add spoilers to the bridge and to adjust the tuned mass dampers.

The bridge is a shallow V-shape in plan (173°) to take account of blade deflection during extreme operating conditions and to afford adequate clearance and thus avoid blade strike. Under these conditions, blade clearance to the bridge of 1·12 m is achieved. The worst scenario is with blade tips extended giving a factor of 1·35 safety margin, and under this condition adequate clearance is still achieved. Additionally a laser blade position monitoring system is incorporated that will set the turbine to standstill if deflections become excessive.

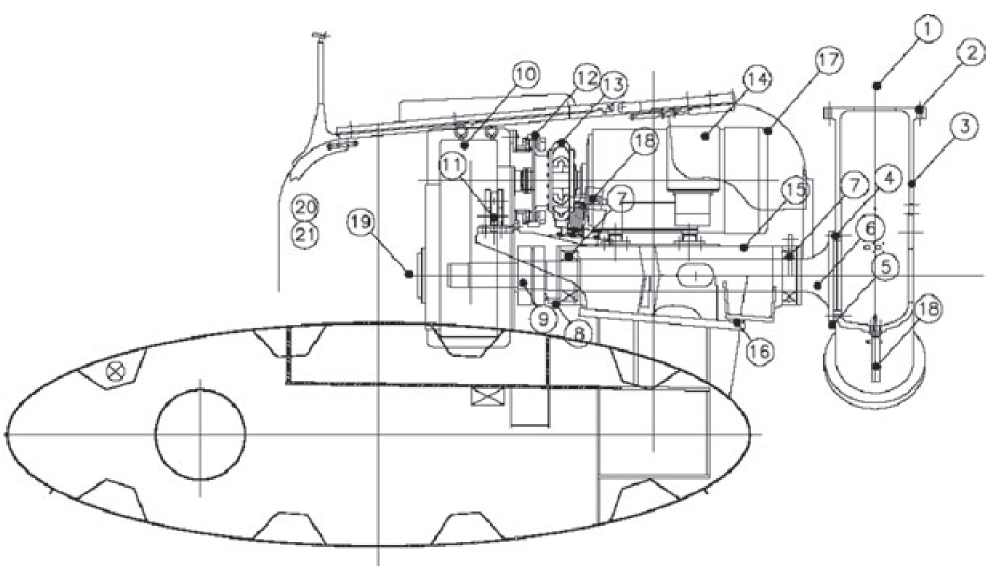

Figure 5. Section through bridge and nacelle

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Control, monitoring and safety

Turbine control, monitoring and safety are delivered through three systems:

- wind turbine control system (WTCS), which directly controls and monitors the turbines;
- extended wind turbine monitoring system (EWTMS), which is a separate monitoring system developed for this project;
- building monitoring system (BMS).

The WTCS is an industrial quality control system that has been specifically evolved to control and monitor wind turbines. It is robust and reliable and, as well its control and monitoring functions, it is able to shut down turbines safely in the event of adverse climatic conditions or other factors that will threaten life safety or turbine life. It is an online system that allows operators anywhere to gain access to the operating data and grant those with appropriate authorization control of the turbines. It has an in-built independent, emergency, safety surveillance system that will monitor possible faults in the turbine and the immediate turbine operating environment and bring it to a standstill, if required. This system overrides the electronic control system. The WTCS obtains data relating to the turbine operating environment via the BMS, which is summarized in Table 2. Finally, the WTCS retains significant data regarding turbine operation and provides tools for analysis.

For this specific application, where safety is crucial, the WTCS fully integrates the special control and monitoring functions given in Table 3.

The EWTMS is a project bespoke system that works in conjunction with WTCS to provide monitoring and calibration of the control system operational limits required for this specific application (Table 4). In total, the EWTMS has 43 additional sensors.

In the event of a control system failure, the turbine is brought to standstill by the tip brake working in conjunction with the hydraulic brake through a power fail–failsafe mechanism.

The BMS will be used as a means of providing connectivity from remote sensors to the WTCS and EWTMS.

Table 2. Data obtained by WTCS

Wind direction (masts in front and on top of buildings)	Building electrical consumption demand
Building maintenance system operational	Manual start, stop and emergency stop
Bridge access opening	

Table 3. Special data obtained by WTCS

Wind speed at bridge	Accelerometers at front wind turbine bearing and in bridges—threshold function
Free wind direction near ground level and at top of the building—redundant function	Blade distance from bridge—threshold function

Table 4. EWTMS monitoring and calibration functions

Wind speed at bridges and ground level	High-speed gear shaft
Free wind direction near ground level and at top of the building	Accelerometers at front wind turbine bearing
Ambient temperature and atmospheric pressure	Accelerometers in bridges
Blade strain	Distance between blades and bridge
Transmission torque strains	Rotor rotational position

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Electrical building interface

Each nacelle has a 225 kW nominally rated, 400 V, closed, four-pole induction, 50 Hz asynchronous generator that is connected to a generator control panel inside each tower. From each generator control panel, separate low-voltage feeders connect to the interfaces on the main low-voltage switchboard at three substations. These substations supply electricity to the landlord areas of the Bahrain World Trade Center development.

Generators are designed to start and run in an asynchronous mode and in parallel with the electricity authority's grid, but at this stage it is not possible to export electricity to the electricity supply authority in the event of a surplus being available.

In the event of an outage or reduction in voltage/frequency from the board's power supply, the turbines will be shut down.

The length of the LV feeders from the generator control panels to the building electrical system interface points required careful study in order to avoid excessive voltage drop and to ensure there were no problems with harmonics and voltage disturbances. Extensive dynamic simulation studies were carried out by the turbine manufacturers' electrical specialist partner company to ensure compliance with relevant IEC standards.

5. DESIGN VALIDATION THROUGH SAFETY, AVAILABILITY, RELIABILITY AND MAINTAINABILITY (SARM)

The design has been validated using a SARM analysis by Ramboll with designers Science & Technology team in a review role. Table 5 shows the issues that were addressed.

6. ENERGY YIELD

The projected energy yield from the turbines, taking into account wind and availability data, is summarized in Table 6. This amounts to between 1100 and 1300 MWh per year and will amount to approximately 11–15% of the office towers' electrical energy consumption. In carbon emission terms this equates to an average of 2900 kg C (oil-burning power station) or 2000 kg C (gas-burning power station). These figures are conservative. Since this is a world first and because wind turbines have not been placed 160 m above ground level and between buildings, the yield may even be higher.

Table 5. Issues addressed by validation team

Remote sensor viability	Tip break-off	Unusual flow and fatigue life
Power outage impact	Blade penetration	Dirt build-up on blades
Electricity board acceptance	Blade/bridge strike	Galloping vibration at standstill
Cooling system availability	Blade fall	Maximum twisting moment for a blade
Maintenance viability	Climate—sand ingress	Noise emitted from blades/generator
Rain water thrown off blades	Bird strike	Shadow flicker
Exciting vibrations	Turbine operation outside of azimuth range	Reflection of blades through windows
Bridge resonant frequency	Availability	Electromagnetic interference
Construction tolerance—bridge resonant frequency	Reliability and maintainability	Electrical flicker
Bridge vortex shedding	Operability and durability	Electrical harmonics
Source/sink coincidence	Previous performance of proposed turbine	
BMS reliability	Project-specific operating and control strategy	
Lightening strike		
Blade loss		

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7. FINAL LESSON

It should be appreciated that this was a fast-track design and construction program and that the integration of large-scale wind turbines into a building has involved extensive research and development by probably some of the most capable specialists available. It is recognized that the initial phases of operation of this project will be the final part of the learning curve. During this stage significant monitoring and fine tuning are required in order that the full potential of this innovative application may be properly realized and understood.

Table 6. Energy yield

Turbine #1	340–400 MW h/year
Turbine #2	360–430 MW h/year
Turbine #3	400–470 MW h/year

Figure 6. Latest construction images

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Figure 7. Turbine image

ACKNOWLEDGEMENTS

The decision to include this technology has not been taken lightly and has been the subject of rigorous design and validation. The building's design team (all technical disciplines) was Atkins—Middle East. The wind turbine and bridge design and manufacturing specialists involved are Ramboll Danmark A/S (consultants), Norwin A/S (turbine manufactures), Elsam Engineering A/S (power generation). Wind tunnel testing was done by BMT and Atkins; DE2 and Atkins, Science & Technology have executed high-level technical reviews.

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