Amida.

The innovative application of wind turbines vs the product engineering of wind turbines

The following article is written to promote the innovative concept of building mounted integrated wind turbines (BUWT) on stadium rooftops. The article addresses the concept as an innovative way to utilise otherwise dormant space (stadia roofs) to generate renewable energy. Central to this proposition is the wind yield possibilities, turbine type and overcoming technical challenges associated with mounting turbines. Ultimately this article proposes that innovative applications, can succeed the product engineering of urban wind turbines to produce better business cases.

Factors which are as equally or more so important than the actual engineering of a given turbine for an urban wind turbine project are; **Wind science, positioning of turbine, type of turbine used for specific positioning, type of building and its energy use, and a building's shape of roof.**

"A scaled-up building with an integrated HAWT would produce at least a 25% increase in annual energy yield in a typical urban setting over a freely yawing stand-alone machine. Further gains could be realised if the turbine(s) could be safely mounted higher from the ground thereby benefiting from higher atmospheric wind speeds." (Campbell. N, & Stankovic, S. 2002)

These **further wind yield gains can be achieved if urban wind turbines were successfully roof mounted, rather than integrated within ducts**, as illustrated within Campbell & Stankovic's Project Web EC Joule III's 2002 report.

Large roofs and sports stadium

Roofs are ideal locations as they are commonly of low pitch and experience large areas of attached flow, with low correlations between the pressure fluctuations acting on different parts. (Holmes, J, D. 1996)

Wind flow over large roofs

The wind flow over a low-pitched roof starts initially with the wind blowing normal to one wall. At the top of the windward wall, the flow 'separates' and 're-attaches' further along the roof, forming a separation 'bubble'. The turbulence in the wind flow plays an important role in determining the length of the separation bubble –high turbulence gives a shorter bubble length, low turbulence produces a longer bubble.

The separation bubble region is very important one for large roofs because the upwards pressure are the greatest in this region. In the re-attached flow region, the pressures are quite small. Thus, for very large flat or near-flat roofs, only the edge regions within 2-3 wall heights from the edge will experience large pressures, and large areas of the roof will experience quite low pressures. (Holmes, J, D. 2007)

As the roof pitch increases, the point of flow separation moves away from the leading edge of the roof and, in the case of a carved or arched roof, separation usually occurs downstream of the apex (Blessmann, 1991- Holmes 2007).

General effects of topography

As the wind approaches a shallow feature, its speed first reduces slightly as it encounters the start of the slope upwards. It then gradually increases in speed as it flows up the slope towards the crest. The maximum speed-up occurs at the crest, or slightly upwind of it.

The speed-up effects are greatest near the surface and reduce with height above the ground. (Holmes, 1996, 2007)

This can be referred to the stadium roof, in a sense that by achieving a speed-up effect the turbines can't be raised too high above the topography of its flat roof in order to be as close to the surface to avoid the un-separated flow from the along-wind direction across the roof. So the ideal would be to position the turbines in the centre of the roof as close to the top of the separation bubble slightly upwind of the crest at the end of the separation bubble.

Performance of a VAWT in skewed flow is shown by simplified Blade Element Momentum theory that, in contrast to HAWT, the VAWT should have a power increase in skewed flow. The reason is found in the increasing rotor area that experiences undisturbed flow. (Mertens,S. 2002)

A HAWT would have to be positioned above the internal boundary layer, away from turbulence in contrast to gain a linear undisturbed wind flow, which avoids the skewed flow.

As a function of the wind turbine's location on the roof, it should possibly operate in a wider range of wind speeds in order to harvest all the available wind energy at the roof. On the other hand it is questionable whether these locations have to be considered. (Mertens,S. 2002)

Undisturbed wind flow contacting the free standing yaw will create fatigue and stress on the rotors, due to the forecasted high wind shear experienced at a higher level from the ground. (Mertens,S. 2002)

Findings from Mertens' roof mounted turbines case studies

Mertens' found wind yield increases from roof mounted turbines in comparison to free standing turbines, which is relevant to exploring the most optimum type used and the positioning of roof mounted turbines for a roof. What he doesn't research is the possibility of increasing the co-efficiency of performance from roof mounted turbines even further through specific application to curved long span roofs, as oppose to flat roofs.

Wind velocity as a major factor to increase wind yield

The boundary layers and wind velocity in the vicinity of BUWT's.

Mertens' analysis of velocity profiles above a roof shows the non-dimensionalised velocity profile above the middle of a flat roof. Findings are similar to that above the separating streamline calculated with free streamline theory, there exists up to 30% higher total velocities, compared to the undisturbed velocity at building height. Higher above the roof this speed up effect becomes bigger.

Proposed type of roughness and type of separation bubble for stadium roof.

Larger roughness will indicate a more consistent speed of flow due to the velocity being parallel with the horizontal roof, thus creating a 0= skew angle. (Mertens, S. 2002)

Which is apt for a small HAWT, roof mounted turbine to perform well in these conditions, as the conditions are more likely to be more undisturbed due to a smaller separation bubble.

Wind energy density on long span roofs

The centre location has the largest energy density for both large and small roughness.

However of equal importance is the value of the skew angle of the wind velocity vector at the corner and edge, which is large compared with the skew angle at the centre location, because of the up-flow at the sides of the building. The corner position is also susceptible to high vortices which will inevitably create turbulence for the rotors of a HAWT in the windswept area. (Mertens, S. 2002)

Conclusions made from reviewing the functional performance and Sander Mertens' roof mounted wind turbine case studies

Mertens' case studies showed that the wind conditions at the majority of locations on the roof are very different from the undisturbed wind conditions.

Compared with a HAWT, a VAWT can give a larger energy yield on buildings set in small upwind roughness. This is caused by increased skewed flow wind speed across the roof, which the VAWT will yield due to its tri-dimensional design being able to yield wind from opni-directions. The wind vector at most roofs is not horizontal, but is skewed with an angle to the horizontal roof that varies across the roof. Because of the large power output and energy yield in skewed flow across a flat roof evidently proven from Sander Mertens' roof top studies, the VAWT seems to be more suitable on roofs at 1 -2 metre height near the outer edge of the roof as compared to the HAWT at the outer edge. The HAWT would be better placed above the 5 metre height of the small separation bubble in the centre of the roof.

However, the wind flow across a flat wide span roof like a stadium's gives a more undisturbed flow, whether the height of the turbine is positioned at a level within the separation bubble (i.e. lower than a height of 5 metres at the centre of a roof or lower than 1 metre at the corner and edges) or above the separation bubble, the wind speed will be relatively undisturbed due to laminar flow – i.e. a boundary layer of protective wind flow which doesn't separate when flowing across the flat roof. However, it is still advisable to raise the turbine as high as it can to gain a higher wind speed which is attained at increasing heights within the wind environment.

Whatsmore, it is believed that the average wind speed at the roof due to the laminar flow can create a speed up effect, thus create a higher wind speed than low or high pitched roofs, and has a higher wind speed compared to a relatively low undisturbed wind speed at the same height above the ground in the open surroundings at a specific site. This is substantiated by the wind flow becoming attached to the flat roof using the 'Coanda effect', as oppose to a freestanding yaw becoming susceptible to turbulence and wind shear due to a higher degree of disturbed wind flow coming from different directions and at different speeds, rather than being channelled more effectively across a flat roof.

Nevertheless wind velocities above the roof are still small compared with conventional wind turbines on towers in open surroundings, due to higher windswept area from larger rotors. Therefore, wind velocity is not the main determining key driver in choosing the turbine arrangement, but more the consistency of wind yield and efficiency of a turbine's performance which could result in increasing and sustaining the load capacity generated by the turbines in kWh per year. So for roof turbines, high buildings are necessary to compensate for the smaller wind speed in the built environment and for them to produce an acceptable energy yield.

It is also assumed that if a new build stadium project is used, it could possibly induce higher power from the available wind at a given site due to a higher probability of increasing co-efficiency of wind yield. This can be achieved more so from a new build stadium, as the roof can be designed in such a way from the start of the stadium roof's design to harness the speed up effect of laminar wind flow by creating a more aerodynamic outer edge in the form of a; slight inclined curved area from the outer edge circumference towards the centre of a stadium roof. The predominant linear wind flow flowing across the stadium roof, would create a speed up effect which in turn will increase the amount of wind yield obtained by enhancing the angular windward flow by impacting the outer edge of roof and attaching its wind flow more consistently and speedily up the slight inclined curved area of the roof. The attached flow becomes more constant and consistent in capturing the wind yield by using the principle of the 'Coanda effect' in this way.

<u>Technical judgement from expert opinion interviews</u>

Capturing the most optimum availability of wind for roof mounted turbines

"A non-residential building which has a long span flat like roof surface, has a higher probability of reciprocating a longer consistency of wind yield as oppose to a roof structure which is pitched and not long span, as the wind would be channelled for that much longer and faster in a more constant linear flow over the roof structure when turbine generators are in operation," Professor Kevin P Garry (Professor of Experimental Aerodynamics- Department of Aerospace Sciences) School of Engineering, Cranfield University, 2002) Professor Gary describes the attachment of the wind flow to the roof of a stadium being much longer than a normal pitched roof. Suggesting that the configuration of the turbines, can be installed in rows of appropriate type turbines around the area of a stadium's roof, to take advantage of the wind passing through one row of turbines on the outer edge of the bowl of the stadium's roof to the second row of turbines being situated towards the centre of the roof.

Positioning of roof mounted turbines

Structural engineer, Mark Boyle commented, "I believe a much better place for turbines would be over the back of the bowl on the roof as in many designs this would require little or no strengthening to the roof, this would not cast moving shadows on the pitch and peripheral vision distraction to spectators and finally the wind flow in this area tends to be far more steady than near the leading edge which often have vortices shed from the adjacent edge. Currently, we work with the likes of new Anfield and city of Manchester Stadium to about 90% for critical elements and 95% for non critical elements such as purlins etc. Any new build stadium in the future will be regulated to have zero excess loading to comply with current standards." (Refer to appendix 11)

Concluding remarks:

This suggests that if retrofitted turbines applied to older or recently built stadiums become a success in practice, conversely applying a retrofitted turbine to a new build will not be possible due to no extra allowance for excess loading. Therefore, applying roof mounted turbines to stadiums in the long term future will need to be integrated into the new build design of the stadium. To allow foundations and structural support framing of the roof, to account for what would normally be excess loading for mounting the turbines, become a part of the total stressed capacity of loading for the structural support framing of the roof as a whole.

Structural loading of roof mounted turbines applied to stadium

Structural engineering contractor, Chris Wilkinson commented, "The bending movement and dynamic wind loading and wind shear will have an effect on the cantilever arm, so the pre-stressed structural framing will have to have sufficient excess loading to accommodate this, a 90% of the maximum structural loading capacity will be able to allow for excess static loading within a sensible parameter of say 1-3% excess.")

Structural engineer, Mike Otlet comments, "If the load is applied around the perimeter or circumference of a stadium roof, it would not be difficult to cope with a small additional vertical and horizontal load. A wind turbine load could be spread over two secondary trusses to share the load. A wind turbine at 1.5 tonnes would only represent a 1% additional load around the perimeter - if spread over a 21.9m length".

Concluding remarks:

Mike also concluded that applications of roof mounted turbines will differ when applied to different types of stadium structural framing systems;

"When retrofitting turbines to existing stadiums – a truss / cantilever structural framing to support the roof would be more appropriate, due to wind excitation and vibration affecting a cable and mast structural framing system. A cable and mast structural framing system would be susceptible to more dynamic wind loading from its existing roof load and the additional load of turbines. This reduces the amount of margin available for any additional load from the turbines being mounted with this type of structural system. Alternatively, the application of turbines to 'New build stadiums' – a cable and mast structural framing system could be considered if dynamic loading is accounted for in the total loading system (i.e. allowing for additional excess loading for turbines to be mounted within the total structural limits of the roof design), from the start of the design scope.

Aerodynamic assessment

Concluding remarks from the interview discussion with Volker highlighted that HAWTs turbines would be better primarily to use on the roof of a stadium, due to the wind blowing generally from the West to East and vice versa, so in his view an opni-directional axis like a VAWT is not needed as the HAWT doesn't become dependent upon the wind flow from all angles due to the windward flow being predominant from West to East direction. HAWTs are more type tested at a larger scale level which also makes them more favourable as they have proven technology. However, a VAWT type turbine could be positioned to the outer leading edge in the more disturbed wind flow with more of a skew angle of attack, which is more prevalent on the North and South side of the roof of the stadiums, due to no prevailing linear wind flow.

Volker Buttgereit also mentioned that the type of roof used to apply the turbines is not significant to increasing efficiency, only if BAWTs were used in a duct design.

Therefore, the two main drivers for increasing the wind yield will be;

1. Increasing the roof area size to increase the amount of turbines to be used within the control limits of additional stress loading if turbines were applied.

2. Low energy use for the particular building to use when operating and when the facility is not in use.

A common miss-conception is that football clubs use a lot of energy, when all its majority of use is used only partially through the week on match days. (Les Catchpole, Electrical consultant for MFC, 2008).

This gives the building the opportunity to meter most of its energy generated from the roof top to neighbouring houses or buildings. Suggesting that the innovation comes from the type of building and its use rather than specifically the type of roof (i.e. aero-elastic) the turbines will be applied to.

The response from Volker answers one of the initial objectives set out at the beginning of the research. To gain expert opinion on whether the specific roof type such as an aero-elastic long span canopy can enhance wind yield? Volker's response was as follows:

"I am not sure that 'the coanda effect' is really what you are concerned about – the flow does not stay attached to the surface of the roof but forms a separation bubble whatever you do."

Concluding remarks from Wind specialist Volker Buttergeit:

Indicating the type of roof does not increase wind yield significantly, it's the operational use of the facility and the size of the roof giving a potential opportunity as a large base for more roof mounted turbines to increase energy generation, thus increase revenue income from metering more to the grid.

Conflicting views from other experts

Contrary to some experts' views on an aero-elastic long span roof restraining the aerodynamic wind flow and the Coanda effect not being able to increase the wind yield, some experts such as CREST's Aeronautical engineer – Duncan Walker, who agreed in principle with the abstract concept and proven tests results carried out by leading roof mounted turbine specialist Dr. Sander Mertens studies and Dr. Campbell and Stankovic's project web EC Joule III study that a 30% increase in yield could be achieved from a turbine if it was mounted on a flat roof as oppose to free standing. However, the improved co-efficiency doesn't mean that it will be constant, which is where an aero-elastic roof could harness the constant high co-efficiency by sustaining the re-attached windward flow. Duncan agreed on the view that an aero-elastic roof could improve the consistency of yield due to attaching the windward flow more so than a normal flat roof because of the low pressure at the outer edge using the coanda effect more so when wind excitation occurs, the flexibility of the aero-elastic roof responds to the windward flow experiencing a disturbance from the downward flow at the outer edge at a particular turbulent time, and streamlines its flow more constantly and rapidly. The type of roof will hold on to the attached linear flow more so during this time as it will respond to the direction of the windward flow by moving in the same direction more so than a more rigid flat roof, thus creating a more constant linear flow.

As follows Duncan's response to the question answering the key objective of the study: "Can you comment on, laminar flow inducing the speed up effect of wind flow across a flat aero-elastic building to increase wind yield more so, than if the same undisturbed wind-flow was in open air at the same height?"

Duncan: "You are investigating, placing the BUWT above the flow separation which ultimately occurs from the corner of any building. The separation bubble will generally have a low static pressure generating what we call a 'Coanda effect'. This will cause the flow external to the separation to accelerate around the bubble – and I believe this is what you talk about when you mention enhanced yield. i.e. you place the BUWT above the separation in this accelerated flow."

The second question: "If an aero-elastic roof is used can the wind yield be even more enhanced hypothetically, due to these types of roofs being more aerodynamic with wind speed?"

Duncan: "Almost definitely, a roof could be specifically designed to enhance / stabilize the separation bubble. For example an apex roof will generate a strong 'Coanda effect' and shaping of the apex such as that which occurs naturally over snow covered mountain tops further enhances this. So there is no doubt that wind yield can be (hypothetically) enhanced further. Again a computational simulation is the best way to ascertain this and optimize any roof aerodynamics. (However, one caveat, encouraging a strong separation can encourage strong turbulent fluctuations in the wind which can then cause structural problems with the roof)."

Concluding remarks from other experts' views regarding aerodynamics:

Wind specialist Dr. Holmes. D, also supported the argument. Stating that, large stadium roofs are commonly of low pitch and experience large areas of attached flow. Wind flow at the top of the windward wall (outer edge crest of a curved stadium roof), the flow 'separates' and 're-attaches' further along the roof, forming a separation 'bubble'. The effect of the topography of a curved outer edge would precipitate a gradual increase and consistency of wind speed as the windward flow flows up the slight inclined curved roof towards the crest. The maximum speed-up occurs at the crest, which is where the proposed HAWTs would be positioned above the 5 metre high separation bubble to avoid turbulence.

This clearly suggests a recommendation for further research to evidently prove the aero-elastic roof can demonstrate a more consistent wind yield by utilising the Coanda effect more successfully than a rigid flat roof.

The idea for further research was supported by the opinion of Duncan Walker's response suggesting that CREST would be most interested in researching the science behind the idea, by using; computational fluid dynamics, simulation models, wind flow techniques, and wind tunnel testing, as quoted in the appendices. World leading wind technology expert - Sander Mertens' response to the project's research proposal was, "I am most interested in the idea of identifying the maximum amount of wind energy output that can be feasibly generated from an area the size of a football stadium's roof regarding retrofitted turbines."

Further Study

Recommending that further studies to be carried out on larger stadiums, experimenting with different configurations of roof mounted applications. Duncan Walker's expert opinion mentions:

"The aero-elasticity and the inclined topography form the outer edge of a stadium's long span roof, can attach the prevailing windward flow; more constantly, and at a higher speed-up effect, by using the co-anda effect more so than a building with a flat roof. Which can lead to a more constant and higher co-efficiency of performance for small roof mounted turbines to generate district power."

It is also assumed that if a new build stadium project is used, it could possibly induce higher power from the available wind at a given site due to a higher probability of increasing co-efficiency of wind yield. This can be achieved more so from a new build stadium, as the roof can be designed in such a way from the start of the stadium roof's design to harness the speed up effect of laminar wind flow by creating a more aerodynamic outer edge in the form of a slight inclined curved area from the outer edge. This would create a speed up effect which in turn will increase the amount of wind yield obtained by enhancing the angular windward flow which impacting the sloped outer edge of roof as the predominant linear flow, flows across the stadium roof. The attached flow becomes more constant and consistent in capturing the wind yield by using the principle of the 'Coanda effect' in this way.

Design workshop

Communication followed, between a design team interested in developing the design at a recent engineering work shop, to propose a revised design solution. Including a revised concept drawing for the feasibility design to be taken forward as a pilot study, so that the concept can be tested on football clubs before commercialisation of a full roof mounted turbine array.

The design workshop participants and companies who are interested in developing the design as a pilot test study before committing to a commercial application, are as follows: Ramboll Whitby Bird – Stephen Appleton (Sustainability Director), and Mark Boyle (Structural Engineering Director), Quiet revolution – Stephen Crosher (Product Design Director), Proven - Lindsay Garman (Business development manager for UK and Ireland), Atkins Special Structures group - Mike Otlett (Structural Engineering Director).

Recommendation

In order to develop the design as a pilot test study a suitable client such as a; football club, energy company, or both as a stakeholder consortium, must be interested and willing to invest in developing the pilot test study. As either; research for the energy industry, or with the view to benefiting from committing to a full commercial application of small turbine array, depending upon the success of the pilot study.

At the engineering work shop, the specific design engineering question was asked in relation to the proposed stadium roof mounted project:

Please could you offer your views on how you would change the configuration to best suit the most optimum layout for both VAWT and HAWT types of turbine array, to achieve the most optimum wind yield? Based on the professional and practitioners' views from the design workshop participants, I have created an indicative design resolution below.

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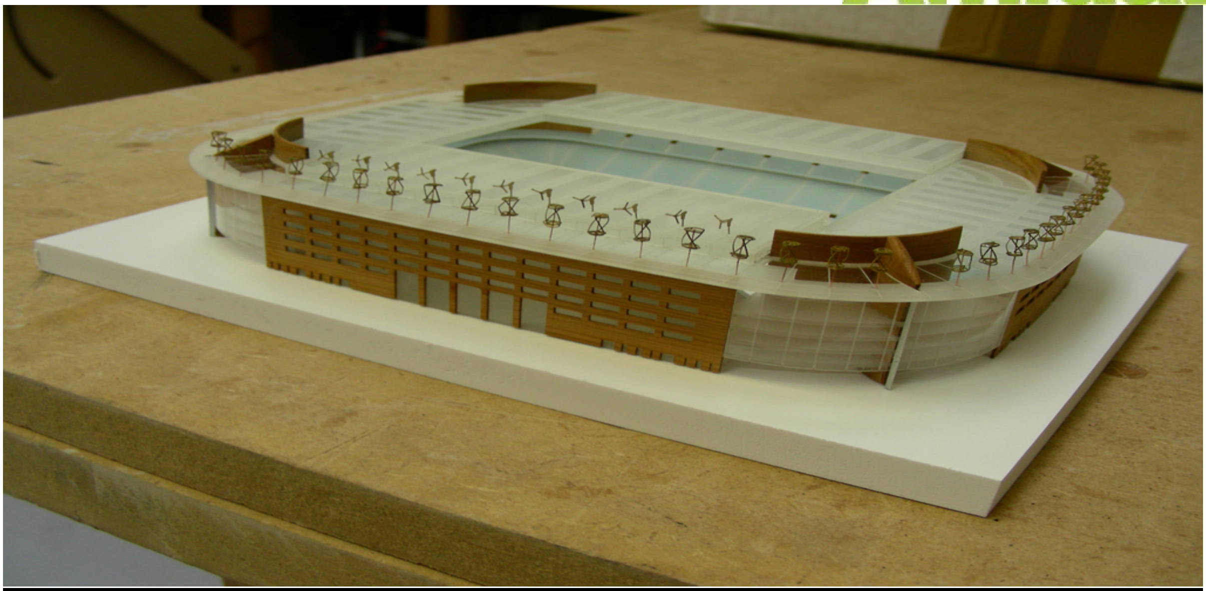
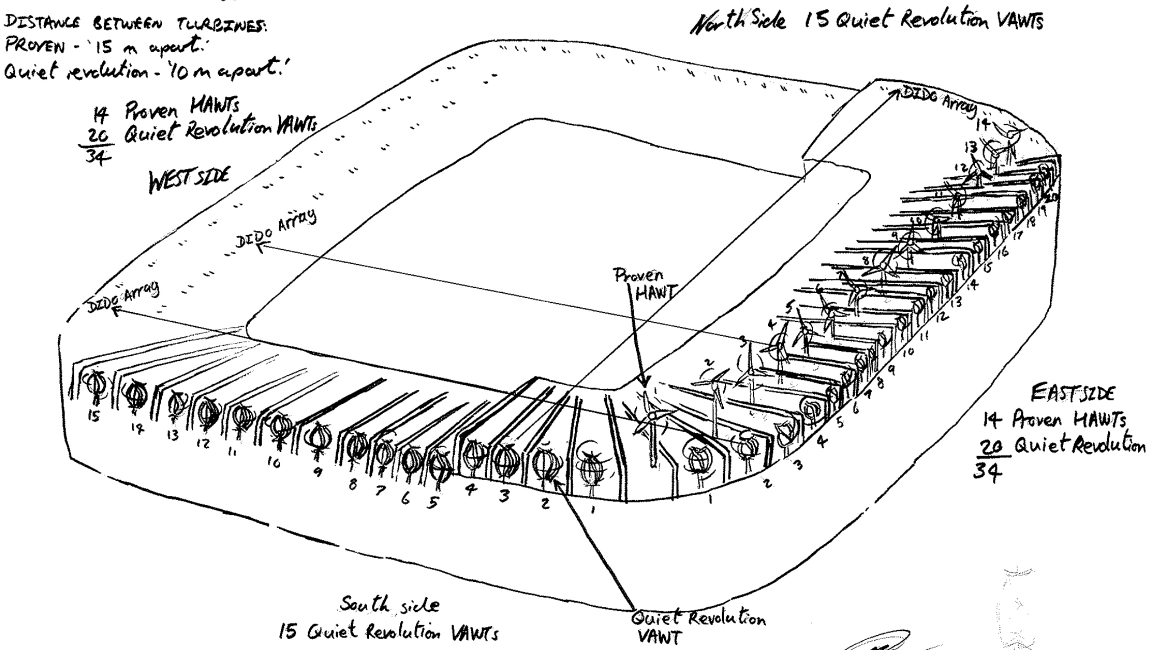


REVISED CONCEPT DESIGN!

Assumptions:

STADIUM DIMENSIONS:
'EAST & WEST SIDE 200 m in length
NORTH & SOUTH SIDE 150 m in Width.'

DISTANCE BETWEEN TURBINES:
PROVEN - '15 m apart.'
Quiet revolution - '10 m apart.'



15/06/09

Total = North = 15
EAST = 34
SOUTH = 15
WEST = 34
98 turbines (i.e. 28 Proven HAWTs & 70 Quiet Revolution)

If anyone within the industry was inspired by these views, and would like to help endorse an innovative programme involving pilot testing the proposed concept design with UK football clubs, then please don't hesitate to contact me.

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2. DESIGN ENGINEERING WORKSHOPS

Stephen Appleton – Director of Sustainability, Ramboll UK. Mark Boyle – Director of Structural Engineering, Ramboll UK. Lynda Garmen – Business development manager for UK and Ireland, Proven UK. Stephen Crosher – Product Design Director, Quiet revolution.

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7. EXPERT OPINION INTERVIEWED

Volker Buttgereit, BMT Fluid Mechanics

Chris Wilkinson, and Peter Whatling- Directors of Structural engineering contractor,-'Doorman Long technology Ltd.'

Mike Otlet- Director of structural engineering, Atkins special structures group, Oxford

Mark Boyle, Associate Director f Structural Engineering – Ramboll UK

Keith Chapman, UK's premier innovative developer with roof mounted turbines

Dr A D Walker, Aerodynamics Research Dept. Aeronautical and Automotive Engineering, Loughborough University

Professor Kevin P Garry (Professor of Experimental Aerodynamics- Department of Aerospace Sciences) School of Engineering, Cranfield University, 2002

Sander Mertens- World's leading urban wind scientist and wind engineering specialist, DELFT University, Holland