INTERIM REPORT
Wind Speed and Energy Yield Analysis of Small Wind Turbines on a 45m High-rise Building in the Built Environment

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1 INTRODUCTION

Nature is dynamic and has an abundance of energy, so it only makes sense to utilize what nature gave us—energy from the sun, wind, and waves coming through our tides from our co-existing alternator, the moon. Focusing our human energy efforts on accessible, natural wind energy is wise. Wind generators offer the most prosperity in technology at this juncture in time provided the wind resource is adequate, making wind an attractive strategy for self-generation, energy security from the grid, and for reducing one's carbon footprint. Provided the wind resource is adequate, before a wind turbine can be erected, they must be sited correctly—this is especially critical in the built and/or urban environment.

Recent results from the 12-month Warwick Wind Trials (WWT) in the UK returned discouraging wind energy yields for the 26 small, building-mounted wind turbines sited in a veritable plethora of urban canopies. Small wind turbine manufacturers capacity claims fell far short of the results returned in this trial. These results certainly warrant further investigation of wind turbine power, wind flow interacting with the respective building structures, (lack of proper) wind resource/availability, and more thorough evaluation of loads and inverter efficiencies, which might reveal why these discouraging results ensued in with WWT. Interestingly, however, some small wind turbines included in this trial, sited well above the urban canopy, did fair better. There was also another notable trial held in the Zeeuwse Schoondijke Testveld Kleine Wind Turbines Zeeland in The Netherlands.

As of today, there are over 356 small wind turbines (≤10 kW rated) from 146 manufacturers in the world marketplace that can be mounted on, or integrated near building structures.[1] Some of these wind turbines were used in the WWT and Zeeuwse Schoondijke Testveld Kleine Wind Turbines Zeeland. Surely this increase in attention to wind power generation has to do with the satisfaction of self-generation, that wind power generation is being promoted by utilities, and that our species is being more mindful about not wasting a valuable resource. Perhaps the results of this paper can stand as a precursor to becoming part of an exacting standard, where industry and policy-makers can utilize to discern if and when installation of a small wind turbine in the built environment is economically feasible.

1.1 Project Scope

Building-Augmented Wind Turbines (BAWTs) and Building-Integrated Wind Turbines (BIWTs) have drawn the assiduous attention of a number of researchers in recent years. This work draws on the attention of like-minded, mistral metro-denizens, garnering attention of industry experts and builds on the antecedent research of other Centre for Renewable Energy Systems Technology (CREST) MSc students and other industry experts—improving on the theoretical assessments in the anticipated energy yield for integrating small wind turbine mounted on urban, building structures. This report also looks at a number of real-world case studies.

1.2 Aims of the Project

More specifically, the aim is to perform a comparative computational fluid dynamics (CFD) data analysis of simple, average wind speeds of rooftop mounted wind turbine (WT) energy yields. Furthermore, the objective of this project is to perform a comparative investigation the performance parameters of small WT generators (<10kW rated power), looking at simple average wind speed relationship based on the lowest part of the boundary layer (BL). And, in doing so, create a benchmark to represent an exacting, helpful standard that industry and policy makers can use by attempting to discern at what height does a small WT generator become financially feasible in the urban or built-environment. Ultimately, to discern if there are indeed opportunities in the urban environment where a 4 m/s wind resource for an urban wind turbine could provide economic parity in cost-effectiveness with photovoltaics (PVs).

METHODOLOGY

This section describes the key, ensuing tasks for this research project.

1.3 Design the Experiment

The following information is built upon antecedent research work of predecessors. Annotating this antecedent work includes investigating infrastructure impacts associated with siting urban WTs near or on buildings, affects (growth) the internal boundary layer following a step change in surface roughness, with the ultimate goal to establish siting benchmarks for wind turbines on or near structures in the built environment. Key constituents of the experiment are addressed as follows:

1.3.1 Select the analytical methods

Check validity of existing data sets including NOABL reference data, develop a model, input and analyse the data using ANSYS CFX Computational Fluid Dynamics (CFD) modelling software with urban model location definitions similar to those used by The Carbon Trust's Wind Energy Yield Estimation Tool. Noting disadvantages with using NOABL data wind with the assumption the wind speed follows a Weibull cumulative distribution function [7]:

- Estimates annual mean wind speed at a1 km^2 resolution
- No information provided on the percentage of time wind speed will actually be within turbine operating range
- Terrain roughness effects not considered, so additional correction factors for sites in built-up areas required
- Wind direction not accounted; very important for roof-mounted turbines, typically an overestimate

1.3.2 Test, adjust and refine the methodology

The goal is to discern where urban wind turbines can be economically and realistically installed in a well defined, built environment setting. To do this requires defining a standard building type, analysis model, flow domain, building site locations to model power curves and energy yields of urban wind turbine scenarios. Constituents for building this model follow:

1 Draw building structure in CFD software. 3D building shape (D, depth; W, width; H, height) = (1:3:2) with a small (<10%) flow blockage for blunt and bluff (sharp-edged) bodies.

2 Select type of analysis model i.e. realizable κ-ε model using a very large flow domain.

3 Create key points i.e. define a flow domain to be at least 10 times the building height, where a single building is modelled in 3D with an averaged urban canopy roughness profile.

4 Create mesh lines and areas. Set up appropriate grid for finite differences schema.

5 Input boundary conditions (BCs) for flow field for a 3D building configuration and state assumptions:

- No-slip condition for external/internal flows
- Set x & y components of velocity (u & v) to zero at the stationary wall. Also consider inlets, top of the BC, outlets, far-field, and wall-gradients.
- Assumptions: Average domain wind speed, u_o=8 m/s; P_{atm}; uniform, steady, fully developed, incompressible flow; neutral atmospheric boundary layer, negligible temperature. This way the model will be valid up to 150-200m in neutral atmospheric winds.

6 Define locations on the building (corner, centre, edge) for velocity, pressure of symmetrical flow field above, below, in front, behind. There will also be a need to establish appropriate locations for near-building scenarios.

7 Analyze wind and pressure drops from 12 directions (skew angle, ø for 30° increments covering 360°), for building size verification using the relationship 20m z_o + d for high-rise buildings, with the Earths' surface roughness height, z_o = 0.03m, d is the displacement distance, and defining criteria for which the Log Law holds.

$$u(z) = \frac{u_*}{\kappa} \ln\left[\frac{z-d}{z_o}\right]$$

Additionally, use 3 m/s as the starting point, wind speed input for the wind turbine(s) cases to discern if there are any low-speed opportunities overlooked—that is to say, where 4 m/s could possibly establish a competitive opportunity versus photovoltaics.

8 Model scenarios for standard built environments on the roof (corner, edge, centre), where the hub heights selected are not too close to the rooftop.

9 Perform case studies. Base on investigating changes in the power coefficient, C_p not on individual manufacturers wind turbines, per se.

10 Post-processing. Plot calculations and investigate results for:

- Wind turbine performance
- Probability statistics for wind speeds using a 2-parameter (k – shape parameter, λ – scale parameter) Weibull distribution which works well for wind speeds between 4-16 m/s

- Energy yield & cost analysis (payback, net present value)

1.3.3 Data collection

Collecting data from historical Centre for Renewable Energy Systems Technology (CREST), and Warwick Wind Trials (WWT) data sets is required in this task. Data collection could also prospectively include data sets from acquired, real-world, case-study contributors i.e. Masdar City, UAE; 12W Building in Portland, OR, USA, and as time progresses, perhaps other EU and USA data sets.

1.4 Programming

This part of the project requires applying computational fluid dynamics (CFD) to verify results from antecedent data produced experimentally. This requires evaluation of governing flow equations in finite volumes defined by a grid. Turbulence model(s) and grid configurations will be chosen based on flow regime type.

1.4.1 Score and validate the data

Since data will be imported from different past studies, the data will require scoring and validation. A selective editing schema will need to be devised so numerical indicators can be arrived at to ensure the data imported meets the requirements, and that the is valid for use in the analyses.

1.4.2 Enter data into the CFD software

Enter data from historical Centre for Renewable Energy Systems Technology (CREST), and Warwick Wind Trials (WWT) data sets. This tentatively could include data sets from real world, case study contributors i.e. Masdar City, UAE; 12W Building in Portland, OR, USA, and perhaps other EU and USA data sets.

1.4.3 Analyze and interpret the data

This task will include reviewing the CFD model and will additionally include analysis of incident wind speed profiles, error analysis, etc. Comparison of WT near-building energy yields vs. mounted WT energy yields from captured average wind speed data compared to power curves of respective wind turbines will be investigated. Distinctions for flow regime types will be required for near-wall regions, and judgments to discern whether to use where the wall function or near-wall model are applicable and appropriate.

A great deal of times shall expected to be invested on configuring the grid/mesh, and decisions will need to be made on whether a structured or unstructured grid is applicable. There will need to be some assumptions based on the flow in the built environment, which can be characterised as flow around buildings in a neutral atmospheric boundary layer. This way, the Log Law can be applied. It is anticipated that only bluff or blunt buildings, not aerodynamic buildings, will be investigated, since the former building types dominate urban landscapes.

Verification of CFD simulations for flow around a bluff body or flow in the atmospheric boundary layer will be compared against established initial verification guidelines to ensure results returned are qualitatively sound and reasonable.

1.4.4 Case study/studies

This task requires performing test cases involving an urban canopy model/profile vs. actual terrain model/profile that can be applied to both horizontal axis wind turbines (HAWTs) and vertical axis wind turbine (VAWTs) for any and all manufacturer's models, inclusive. Wind turbine model power curves and energy yield curves are to be considered in the analysis based on the following, baseline assumptions:

- 0.25 efficiency for any manufacturer's WT
- 3 m/s cut-in speed
- 12 m/s generating speed
- 22 m/s cut-out speed
- Power coefficient, C_p based on the wind cubed-expression

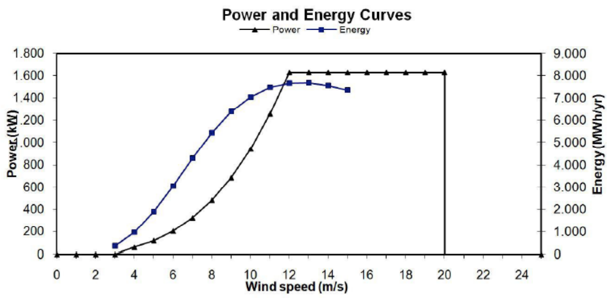

Figure 1. Example power and energy curve plot. [9]

1.5 Report writing and revision

Ample time will be allocated to report writing and revisions.

1.5.1 Write-up results

This will encompass revising the project plan into thesis format, write-up of conclusions, implications, and recommendations.

1.5.2 Address contingencies

Any contingencies that may arise can be addressed whilst the final manuscript is polished.

2 RISK MATRIX[0]

The risk matrix identifies the key risks for this project, and includes an estimate of the likelihood of completion of tasks based on the projected schedule, and impact on the project on a scale of 0-5. The results of the risk matrix are a function of risk impact and probability of occurrence. A description of the scoring is outlined in the following sections including the Borda voting method. This Borda voting method ranks risks from most-to-least critical on the basis of multiple evaluation criteria.

2.1 Project Risk Matrix[0]

2.1.1 Impact assessment (inputs)

Assessment of the impact a risk consequence may have on the overall project outcome. This schema was extricated from the MITRE Risk Management software application. The definitions follow:

- N, Negligible. If the risk event occurs, it will have no effect on the program. All requirements will be met.
- Mi, Minor. If the risk event occurs, the program will encounter small schedule increases. Minimum acceptable requirements will be met. Most secondary requirements will be met.
- Mo, Moderate. If the risk event occurs, the program will encounter moderate schedule increases. Minimum acceptable requirements will be met. Some secondary requirements may not be met.
- S, Serious. If the risk event occurs, the program will encounter major schedule increases. Minimum acceptable requirements will be met. Secondary requirements may not be met.
- C, Critical. If the risk event occurs, the program will fail. Minimum acceptable requirements will not be met.

2.1.2 Probability of occurrence (inputs)

The probability of occurrence is the assessment of the likelihood that the risk may occur. These probabilities are estimates and ascertained using a relative scale. The definitions follow:

0-10%: very likely the risk will occur
11-40%: unlikely the risk will occur
41-60%: even likelihood the risk will occur
61-90%: likely the risk will occur
91-100%: very likely the risk will occur

2.1.3 Borda Rank (outputs)

The Risk Matrix tool generates a Borda Rank where 0 represents the most critical risk and Borda Rank of 1 indicates that one other risk is more critical, etc.

2.1.4 Rank (outputs)

R represents a rating of high, medium or low risk as mapped to the I (impact) and Po (probability of occurrence) pair variables. The rank definitions follow:

- H: High risk
- M: Medium risk
- L: Low risk

Table 1. Risk Rating Scale

Po	Impact Category				
	Negligible	*Minor*	*Moderate*	*Serious*	*Critical*
0-10%	Low	Low	Low	Medium	Medium
11-40%	Low	Low	Medium	Medium	High
41-60%	Low	Medium	Medium	Medium	High
61-90%	Medium	Medium	Medium	Medium	High
91-100%	Medium	High	High	High	High

2.1.5 Project Risk Matrix

Project Risk Matrix is located in the Appendix.

3 GANTT CHART

The updated Gantt Chart is included in the Appendix.

4 LITERATURE REVIEW

The literature review of published articles, peer-reviewed journals, reports and conference proceedings will progress in-perpetuity whilst this project is in-progress.
Below is a sample compendium of published articles, peer-reviewed journals, reports and conference proceedings reviewed thus far for this project. A synopsis of each follows.

4.1 Urban wind turbines

All small wind turbines web site [1]

Always a work in-progress, this web site is comprised of a compendium of all small/micro-wind turbines in the world. At last check there were 356 Small Wind Turbines from 146 manufacturers indexed:

* 291 Horizontal Axis Wind Turbines (HAWT)
* 65 Vertical Axis Wind Turbines (VAWT)

Small wind turbines for the built environment [2]

This document explores the technical potential of small wind turbines on buildings and investigates manners in which the new wind turbine designs can meet the requirements for installation into the built environment. This document provides enlightenment on existing examples of urban wind turbines, potential markets for small wind turbines, requirements for wind turbines in the built environment, locating of wind turbines on buildings, novel wind turbine designs developed for building installation, and opportunities for architects to develop integrating wind turbines in building designs.

Wind energy in urban areas, concentrator effects for wind turbines close to buildings [3]

This read, which appeared in the *Refocus* Magazine, explores a concept that is often overlooked—that energy from the wind could be produced close to where it can be used, as such, in the built environment. Technology and design issues in the use of wind energy in the built environment are discussed including suitable wind turbine designs and suitable positioning of the wind turbines.

4.2 Energy yield

Estimating the Potential Energy Yield of Small Domestic Roof-Mounted Wind Turbines [4]

Employing corrected Wind Atlas data to match the built environment, this text investigates how different housing geometries and arrangements of these structures can have an effect on the local wind speed.

Estimating the Potential Yield of Small Building-mounted Wind Turbines [5]

Utilizing computational fluid dynamics (CFD) model ANSYS CFX, this paper models wind flow around a house in isolation in within an array of similarly configured houses to show the level of speed-up effect around the top and sides of a house.

The energy yield of roof-mounted wind turbines [6]

A pioneering effort, the main thrust of this paper concerns developing flow features criteria to enable siting roof top wind turbines. The main building blocks covered in this paper include how one would go about ascertaining desirable height above the roof for installing a wind turbine, investigating the change of the undisturbed wind to the wind speed above the roof and the probability distribution of the wind speed above the roof. Example calculations are provided to assist the reader.

4.3 Urban buildings and infrastructure considerations

Siting Micro-turbines on House Roofs [7]

This report describes a program of wind tunnel testing that measure wind speeds above house roofs, and provides data that concerns siting of micro-wind turbines on house roofs. It also addresses the calculation of these micro-wind turbines' power output.

Wind Energy in the Built Environment [8]

Sander Mertens, pre-eminent wind energy researcher in Europe, provides information of vital interest for engineers, scientists and architects in this text. Ideas for how to maximize harvesting wind energy by utilizing building augmented wind turbines (BAWTs). Chapters 5, 6 and 7 address a number of mathematical models for basic concentrator configurations seen the built environment including wind turbines close to buildings, wind turbines between airfoil-shaped buildings and wind turbines in ducts through buildings. Of particular note, performance close to a building, at the roof, and at the sides of a building are offered a great deal of scrutiny.

Fundamentals of Fluid Mechanics 5th Edition [9]

Laminar, transitional and turbulent fluid flow applications to the actuator concept required review of basic fluid mechanics concepts. This text thoroughly covers fundamental concepts of the governing Navier-Stokes equations, differential analysis of fluid flow, including irrotational flow, viscous flow, similitude based on governing differential equations. Dimensional analysis, modelling and scaling are covered, as well as are some simple solutions for viscous incompressible fluids, all which are paramount for investigating fluid flow in the built environment.

4.4 Analysis tools and measurement techniques

Carbon Trust Wind Yield Estimation Tool [10]

The Carbon Trust, in collaboration with the UK Met Office, recently launched an innovative web tool for prospective installers of small-scale wind power generation at specific locations in the UK, called the Carbon Trust Wind Yield Estimation Tool. This tool allows users in the UK to enter a postcode, select a relevant building type, and environment. After inputting the regional, site terrain location information, wind turbine datum and running the tool, users are returned an estimate the local annual mean wind speed, mean energy generation and carbon dioxide savings provided by a small wind turbine.

Encraft WindPower Calculator [11]

The Encraft WindPower Calculator provides theoretical output of a selected wind turbine in varying wind speeds. Similar to the Carbon Trust tool, this calculator requires the user only input a postcode, terrain (including MCS3003 standards for urban and rough terrain) and wind turbine type. This tool covers most makes of wind turbines (up to 250 kW) and utilizes data from the UK national wind speed database (NOABL). The report returns energy, carbon and financial savings by location and terrain type.

Wind Energy in the Built Environment [8]

Sander Mertens, pre-eminent wind energy researcher in Europe, provides information of vital interest for engineers, scientists and architects in this text. Ideas for how to maximize harvesting wind energy by utilizing building augmented wind turbines (BAWTs) whilst also considering an architectural aesthetic are addressed. This text covers basic theory of wind energy, wind characterizations and analysis tools as applied wind in the built environment, incorporating physical and mathematical descriptions throughout. It also provides savvy, scientific analysis of three scenarios including wind turbines close to buildings, wind turbines between airfoil-shaped buildings and wind turbines in ducts through buildings.

Internal boundary layer growth following a step change in surface roughness [12]

Using dimensional analysis, D. H. Wood performs tests for the simple correlation for the height of the internal boundary layer, and how it is controlled by the larger of the upstream and downstream roughness length scales.

Procedures for Substituting Values for Missing NWS Meteorological Data for Use in Regulatory Air Quality Models [13]

This read discourages using data for modelling if more than 10% of the on-site surface data is missing. Applicable to this research, surface data includes wind direction and wind speed. This read provides two procedures for providing substitute values for missing data--an objective procedure and a subjective procedure. The former involves applies to single isolated hours with missing surface data and single isolated days of missing mixing height data. The latter applies to longer sequences of missing data, requiring rendering of judgement calls by seasoned experimenters and modellers.

4.5 Policy insights and practical guidance

The, Carbon Trust Report: Small-scale wind energy, Policy insights and practical guidance [14]

The Carbon Trust commissioned research from the UK Met Office and Entec to determine the potential UK carbon savings from small-scale wind energy, and to evaluate the potential of small wind turbines at specific locations. The main audiences of this report are policy makers, organizations and parties interested in installing small wind turbines. Engineers and scientists will find the review of existing scientific literature and engineering methods revealing for calculating energy yields combined with cost data by utilizing the Carbon Trust Wind Yield Estimation Tool. Using this tool will enable the user to obtain an initial evaluation by application following simple rules of thumb, so more certainty about the potential of a site can be arrived at in a more timely ‘to be or not to be—that is the question’ verdict.

Urban Wind Turbines: Guidelines for Small Wind Turbines in the Built Environment [15]

WINEUR is a project of the European Programme “Intelligent Energy Europe”, and is a consortium five organizations from France, the UK and The Netherlands. This document covers aspects important to the deployment of small wind turbines in built environments, including practical guidelines and recommendations for future projects and market development. It also identifies current significant constraints, and presents possible solutions for stakeholders involved in the installation of small wind turbines in urban locales. This document should help reduce the gap between what the scientific community understands, and what is known and understood by the people who need to know, the public and policymakers.

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