2014-06-12

The Application of Boundary Layer Climatology and Urban Wind Power Potential in Smarter Electricity Networks

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‘The application of boundary layer climatology and urban wind power potential in smarter electricity networks’

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\textbf{American Meteorological Society Conference}

12\textsuperscript{th} June, 2014
Overview

- Aims and Objectives
- Research Context/ Motivation
- Methodology
- Findings
- Future Work
- Conclusions
Overview

- Aims and Objectives
  - Research Context/ Motivation
  - Methodology
  - Findings
  - Future Work
  - Conclusions
Aims & Objectives

- **Research Aim:**

*To develop novel modelling capability that is inclusive of the power engineering complexities associated with urban (electricity) network integration of small/micro wind generation, and informed by urban climate research.*

![](image)
Aims & Objectives

- Research Aim:

To develop novel modelling capability that is inclusive of the power engineering complexities associated with urban (electricity) network integration of small/micro wind generation, and informed by urban climate research

- Synergetic application of urban climatology (BLT) and electrical power engineering
- Empirical wind mapping/modelling cognisant of urban heterogeneity – in conjunction with urban wind observations
Aims & Objectives

- Research Aim:

To develop novel modelling capability that is inclusive of the power engineering complexities associated with urban (electricity) network integration of small/micro wind generation, and informed by urban climate research

Background

Urban Classification

Reference

Background

Urban Distribution Network

Cable Parameters/Configurations

Network Structure

Consumer configuration/loading

Earthing Configurations

Surface roughness parameterisation ($z_0$, $z_d$)

Wind turbine 'pure' (zero-turbulence) power characteristic

LCOE evaluation

AMC Power Flow Algorithm

T.I. $u_{\text{Urban}}$, $u_{\text{STD}}$, $T.u(turbulent)$, $P_u(turbulent)$, $P_u(\text{mean})$

Network node voltage/voltage unbalance profile based on the 'mean' urban wind resource

Network node voltage/voltage unbalance profile based on the 'mean' urban wind resource

Turbulence normalised network node voltage/voltage unbalance profile
Overview

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Research Context

Increasing need for localised supply within urban load centres.

Past: Centralised fossil fuel.

Future: Distributed renewable energy.

Bi-directional energy flow.

Energy flow diagram:
- Generation
- Transmission: 25kV, 110/220/400 kV, 38/20/10 kV, 400/230 V
- Distribution
- Consumption

K. Sunderland
Research Motivation

Micro/Small Wind *Electricity* Generation

**Rural Locations**
- Uninhibited Air Flows
- Statistically Predictable Airflows
- Maximum Energy Optimisation

**Urban Locations**
- Heterogeneity, Complex Building Morphology
- Chaotic, Turbulent Airflows
- Energy Capture Capability?
Research Motivation

Micro/Small Wind *Electricity* Generation
Research Motivation

Micro/Small Wind *Electricity* Generation

**WHY URBAN WIND?**

*Population Centres*

*Transmission/Distribution losses*

*Green solutions must include wind*

*Smarter energy diversification must be inclusive of wind within urban centres BUT solutions predicated on the resource and not specifically the technology are needed*
Smart Cities… **Smart Grids**

- An amalgamation of communication and electrical capabilities that allow utilities to understand, optimize, and regulate demand, supply, costs and reliability.

Facilitating electrical providers to interact with the power delivery system and determine whether electricity is being used and from where it can be drawn during the time of crisis and peak demand.

On the demand side – the smart grid empowers the consumer to become a ‘prosumer’…
Why is a Smart Grid needed?

- Future grid networks must be competitive and supportive of environmental objectives and sustainability.
- Reliability, flexibility, accessibility and cost-effectiveness are the primary objectives.
- Should accommodate both central and dispersed generation.
- Options for end-users to be more interactive with both market and grid; promoting the concept of a ‘prosumer’.
Research Motivation

- Why is a Smart Grid needed?
  - Future grid networks must be competitive and supportive of environmental objectives and sustainability
  - Reliability, flexibility, accessibility and cost-effectiveness are the primary objectives
  - Should accommodate both central and dispersed generation
  - Options for end-users to be more interactive with both market and grid; promoting the concept of a ‘prosumer’

Therefore the means of applying the primary energy resource (Wind) in this regard within urban centres must be achieved
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Urban Effects & Wind Modelling

Research Methodology

Two zones categorised in terms of local heterogeneity: (Urban and Suburban)

Urban Environment

Suburban

Urban

Two zones categorised in terms of local heterogeneity: (Urban and Suburban)
Urban Effects & Wind Modelling

Research Methodology

Two zones categorised in terms of local heterogeneity: (Urban and Suburban)

Urban Environment

Two zones categorised in terms of local heterogeneity: (Urban and Suburban)
Research Methodology

Urban Effects & Wind Modelling

Urban Environment

Two zones categorised in terms of local heterogeneity: (Urban and Suburban)

Urban

Suburban

[SL]

CITY

[C]

[CH]

[SH]

<30m

5.5m

SUBURBAN

[S]

Hm

Z*

[SH]

12m

[SL]

5.5m

<30m

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Urban Effects & Wind Modelling

Research Methodology

(Electrical) Distribution Network considered in terms of both local climate zones

Two zones categorised in terms of local heterogeneity: (Urban and Suburban)

Urban Environment

Suburban

Urban

(K. Sunderland)
AIRPORT
– Rural reference
Boundary Layer Climatology in terms of surface roughness classification

AIRPORT – Rural reference
Boundary Layer Climatology in terms of surface roughness classification:

- Roughness Sub-Layer
- Canopy Sub-Layer
- Urban Boundary Sub-Layer
- Inertial Sub-Layer

Wieranga, Bottema approximation and a Logarithmic extrapolation based on fitted surface roughness parameterisation.

\[ u(z_{UBL}) \]

(Rural) Airport Background:

- (Statistically) Laminar Airflow based on a 'constant' frictional velocity

\[ (z^{*}) \]

Urban Boundary Sub-Layer:

\[ u(z^{*}) \]

Inertial Sub-Layer:

\[ (z^{*}) \]

Roughness Sub-Layer:

\[ (z_{H}) \]

Canopy Sub-Layer:

\[ (z_{02}) \]
Boundary Layer Climatology in terms of surface roughness classification

- Roughness Sub-Layer
- Canopy Sub-Layer
- Urban Boundary Sub-Layer
- Inertial Sub-Layer

Logarithmic Extrapolation based on a 'constant' frictional velocity $u(z^*)$

Wieranga, Bottema approximation and a Logarithmic extrapolation based on fitted surface roughness parameterisation
(Standardised) Distribution Network analysis

- Single-phase 4-Wire (and Ground)
- Complex/unbalanced (consumer) load configurations
DwG & DN Implications

(Standardised) Distribution Network analysis

- Single-phase 4-Wire (and Ground)
- Complex/unbalanced (consumer) load configurations

Energy flow - Mono-directional Power Flow
DwG & DN Implications

(Standardised) Distribution Network analysis

- Single-phase 4-Wire (and Ground)
DwG & DN Implications

(Standardised) Distribution Network analysis
- Single-phase 4-Wire (and Ground)

Research Methodology

Substation Transformer

Transformer Earthing Connection

Pillar Earthing Connection

(Mini) Pillar

Pillar (i) V1 V2 V3 V4

Pillar (i+1)

Consumer Connection/Load

Consumer Earthing Connection

SUBSTATION

A
B
C
D
(Standardised) Distribution Network analysis

- Single-phase 4-Wire (and Ground)

Enhanced modelling cognisant of the inherent complexities associated with connectivity and unbalanced load/generation integration at final consumer level
Embedded Generation Issues

- Bi-directional power flow
- Network Power Quality management
- Safety implications
Embedded Generation Issues

- Bi-directional power flow
- Network Power Quality management
- Safety implications
Embedded Generation Issues

- Bi-directional power flow
- Network Power Quality management
- Safety implications

\[ P_{Mech} = \frac{1}{2} c_p \rho_{air} A_{rotor} u^3 \]
Overview

- Aims and Objectives
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- Ongoing Work
- Conclusions
<table>
<thead>
<tr>
<th>Dir. [deg.]</th>
<th>Obs. Freq. [%]</th>
<th>$u_M$ [m/s]</th>
<th>$u_S$ [m/s]</th>
<th>Dir$_M$ [deg.]</th>
<th>Dir$_S$ [deg.]</th>
<th>$z_0$ [m]</th>
</tr>
</thead>
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<tr>
<td>0-30</td>
<td>1.8%</td>
<td>1.9</td>
<td>0.9</td>
<td>104</td>
<td>86</td>
<td></td>
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<tr>
<td>30-60</td>
<td>2.9%</td>
<td>2.4</td>
<td>1.0</td>
<td>91</td>
<td>47</td>
<td></td>
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<tr>
<td>60-90</td>
<td>3.5%</td>
<td>3.0</td>
<td>1.3</td>
<td>103</td>
<td>42</td>
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<tr>
<td>90-120</td>
<td>4.6%</td>
<td>2.8</td>
<td>1.6</td>
<td>127</td>
<td>51</td>
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<tr>
<td>120-150</td>
<td>12.1%</td>
<td>3.4</td>
<td>1.9</td>
<td>151</td>
<td>49</td>
<td>0.924</td>
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<tr>
<td>150-180</td>
<td>5.8%</td>
<td>3.7</td>
<td>1.8</td>
<td>179</td>
<td>37</td>
<td>0.395</td>
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<tr>
<td>180-210</td>
<td>10.1%</td>
<td>5.2</td>
<td>2.4</td>
<td>218</td>
<td>27</td>
<td>0.180</td>
</tr>
<tr>
<td>210-240</td>
<td>21.2%</td>
<td>5.0</td>
<td>2.2</td>
<td>244</td>
<td>23</td>
<td>0.342</td>
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<tr>
<td>240-270</td>
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<td>4.8</td>
<td>2.1</td>
<td>268</td>
<td>18</td>
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<tr>
<td>270-300</td>
<td>10.1%</td>
<td>3.4</td>
<td>1.6</td>
<td>281</td>
<td>30</td>
<td>0.602</td>
</tr>
<tr>
<td>300-330</td>
<td>3.7%</td>
<td>2.6</td>
<td>1.4</td>
<td>286</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>330-360</td>
<td>2.0%</td>
<td>2.1</td>
<td>1.1</td>
<td>219</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td><strong>$z_0$ (average)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.5171</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dir. [deg.]</th>
<th>Obs. Freq. [%]</th>
<th>$u_M$ [m/s]</th>
<th>$u_S$ [m/s]</th>
<th>Dir$_M$ [deg.]</th>
<th>Dir$_S$ [deg.]</th>
<th>$z_0$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>1.9%</td>
<td>2.3</td>
<td>1.0</td>
<td>82</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>30-60</td>
<td>3.0%</td>
<td>3.3</td>
<td>1.5</td>
<td>76</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>60-90</td>
<td>3.8%</td>
<td>4.1</td>
<td>1.8</td>
<td>91</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>90-120</td>
<td>3.9%</td>
<td>3.3</td>
<td>1.8</td>
<td>113</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>120-150</td>
<td>10.1%</td>
<td>3.6</td>
<td>1.8</td>
<td>139</td>
<td>42</td>
<td>1.145</td>
</tr>
<tr>
<td>150-180</td>
<td>4.4%</td>
<td>3.4</td>
<td>1.7</td>
<td>167</td>
<td>39</td>
<td>0.870</td>
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<tr>
<td>180-210</td>
<td>9.0%</td>
<td>4.9</td>
<td>2.2</td>
<td>211</td>
<td>26</td>
<td>0.640</td>
</tr>
<tr>
<td>210-240</td>
<td>22.0%</td>
<td>5.0</td>
<td>2.2</td>
<td>239</td>
<td>18</td>
<td>0.791</td>
</tr>
<tr>
<td>240-270</td>
<td>24.3%</td>
<td>5.1</td>
<td>2.1</td>
<td>263</td>
<td>14</td>
<td>1.0575</td>
</tr>
<tr>
<td>270-300</td>
<td>11.3%</td>
<td>3.9</td>
<td>1.8</td>
<td>282</td>
<td>17</td>
<td>0.724</td>
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<tr>
<td>300-330</td>
<td>4.0%</td>
<td>3.0</td>
<td>1.6</td>
<td>287</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>330-360</td>
<td>2.2%</td>
<td>2.2</td>
<td>0.9</td>
<td>231</td>
<td>117</td>
<td></td>
</tr>
<tr>
<td><strong>$z_0$ (average)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>0.8713</strong></td>
</tr>
</tbody>
</table>
For each $30^\circ$ sector, surface roughness was estimated by varying iteratively until the best fit was achieved so as to minimise the error between the predicted wind speed, based on the background climate, and the observed wind speed.
### Observation/Modelling: high-platform observations

<table>
<thead>
<tr>
<th></th>
<th>( \mathbf{C_H} )</th>
<th></th>
<th>( \mathbf{S_H} )</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Wieranga Model</td>
<td>Bottema Model</td>
<td>Log-Model</td>
</tr>
<tr>
<td>Roughness length ( z_0 )</td>
<td>--</td>
<td>1.15</td>
<td>1.15</td>
<td>0.8713</td>
</tr>
<tr>
<td>Friction velocity ratio</td>
<td>--</td>
<td>1.0</td>
<td>1.3312</td>
<td>1.7022</td>
</tr>
<tr>
<td>( u_M [m/s] )</td>
<td>4.5992</td>
<td>4.9728</td>
<td>3.2281</td>
<td>4.6165</td>
</tr>
<tr>
<td>( u_s [m/s] )</td>
<td>2.1288</td>
<td>2.2497</td>
<td>1.4604</td>
<td>2.0885</td>
</tr>
<tr>
<td>MAE [m/s]</td>
<td>--</td>
<td>0.7113</td>
<td>1.4248</td>
<td>0.6133</td>
</tr>
<tr>
<td>RMSE [m/s]</td>
<td>--</td>
<td>0.9790</td>
<td>1.6878</td>
<td>0.8651</td>
</tr>
</tbody>
</table>
Observation/Modelling: high-platform observations

<table>
<thead>
<tr>
<th></th>
<th>$C_H$</th>
<th>$S_H$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Wieranga Model</td>
</tr>
<tr>
<td>Roughness length ($z_0$)</td>
<td>--</td>
<td>1.15</td>
</tr>
<tr>
<td>Friction velocity ratio</td>
<td>--</td>
<td>1.0</td>
</tr>
<tr>
<td>$u_s [m/s]$</td>
<td>2.1288</td>
<td>2.2497</td>
</tr>
<tr>
<td>MAE [m/s]</td>
<td>--</td>
<td>0.7113</td>
</tr>
<tr>
<td>RMSE [m/s]</td>
<td>--</td>
<td>0.9790</td>
</tr>
</tbody>
</table>
Observation vs. Modelling

Scattergram comparison of high-platform observed and modelled wind speeds (Nov. 2010 –to– Jan 2011)

Energy implications with respect to height variation for a wind generator at both sites (Nov. 2010 –to– Jan 2011)

Urban Comparison

Suburban Comparison
Typical Mean Year of Wind Speed (Markov Chain)

<table>
<thead>
<tr>
<th>Statistical Comparison</th>
<th>Urban Modelled Wind Speed ($C_H$)</th>
<th>Suburban Modelled Wind Speed ($S_H$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Modelled Wind Data (4789 Hrs)</td>
<td>Markov chain Extended Data set (8760hrs)</td>
</tr>
<tr>
<td>$u_{\text{Mean}}$</td>
<td>4.62</td>
<td>4.58</td>
</tr>
<tr>
<td>$u_{\text{STD}}$</td>
<td>2.09</td>
<td>2.18</td>
</tr>
</tbody>
</table>
Results & Findings

Distribution Network Reaction

Line-1

Line-2

Line-3

Neutral

Pillar/Customer Voltage [pu]

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To be applicable from the ISL into the RSL, neighbourhoods of homogeneity need to be identified – distinctly different surfaces can be considered separately.


Future Work

- Rastered Digital Elevation Model (DEM) building footprints (Dublin)
- Divide the city into distinct neighbourhood regions – Adaptive Grid

**Geometric Parameterisation:** Employing an adaptive grid to calculate the geometric parameters
Future Work

- Rastered Digital Elevation Model (DEM) - building footprints (Dublin)
- Divide the city into distinct neighbourhood regions – Adaptive Grid
- Geometric Parameterisation

Morphemetric Model

\[
d = \int_{0}^{h_{\text{max}}} f_d (\lambda_p (z)) \, dz, \quad \frac{d}{h_{m}} = f_d (\lambda_p) = \begin{cases} 
\frac{19.2 \lambda_p - 1 + \exp(-19.2 \lambda_p)}{19.2 \lambda_p [1 - \exp(-19.2 \lambda_p)]}, & \text{for } \lambda_p \geq 0.19 \\
\frac{117 \lambda_p + (18.7 \lambda_p^3 - 6.1) [1 - \exp(-19.2 \lambda_p)]}{(1 + 114 \lambda_p + 187 \lambda_p^3) [1 - \exp(-19.2 \lambda_p)]}, & \text{for } \lambda_p < 0.19
\end{cases}
\]

- Divide city into Neighbourhood regions
- Calculate geometric parameters for each neighbourhood
- Use a simplified array to represent the neighbourhood geometry
- Apply a morphometric model

Diagram:
- Current method and adaptive grid
- Blocks with variable height and aspect ratio
- Output: aerodynamic parameters $z_0$ and $d$
Overview

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Conclusions

- In the context of smart cities and smarter (electricity) grids, this type of research is essential if renewable energy is to facilitate a cultural shift towards an era of prosumers.

- In terms of the limits available to wind energy extraction in an urban context, the analyses illustrated limited opportunities below a height $2 \rightarrow 4 \times z_{Hm}$

- By linking urban wind observations to a background reference, an empirical logarithmically matched profile was possible. (Analytical linkages to observations within the canopy suggested that knowledge of the background resource in this regard is of limited value)

- Analyses of a fully described 4-wire unbalanced section of Dublin city network, in respect of increasing levels of prosumer (with a grid-tied commercially available DwG), illustrated that for exemplar consumer load and a typical mean year of wind speed, voltage tolerance breaches are unlikely and of marginal concern (<2% of occasions)

- Future work will focus on validating the empirical logarithmic extrapolation models through morphhemtric means of deriving the Dublin city urban aerodynamic parameters
Thank you

e: keith.sunderland@dit.ie