Using CFD to Predict the Performance of Innovative Wind Power Generators

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Using CFD to Predict the Performance of Innovative Wind Power Generators

Topics

1. Motivation
2. Possible Solutions
3. Model
4. Results
5. Conclusions
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2. Possible Solutions
3. Model
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Motivation

Is it possible to offer

<table>
<thead>
<tr>
<th>Onshore &amp; Offshore</th>
<th>Rapid Deployable Power for Soldiers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Buildings</td>
<td>Schools</td>
</tr>
<tr>
<td>Urban Buildings</td>
<td>Naval Ships</td>
</tr>
<tr>
<td>Retail Stores</td>
<td>Rural Communities</td>
</tr>
<tr>
<td>Cruise Ships</td>
<td></td>
</tr>
<tr>
<td>Consumer Products</td>
<td></td>
</tr>
</tbody>
</table>

Affordable, Clean, Safe Energy for Everyone, Everywhere

Underdeveloped Countries

Economic Development

FEMA Homeland Security
Emergency Power Generation
Emergency Medical
Disaster Power Generation
Water Treatment
Powering Hospitals
Wind Power Generation Market

Primary Market

- Utility Scale Turbines
- Onshore
- SheerWind Primary Market Focus
- USA Market

Market Growth Targets
Annual Revenue [Billion] by 2030
(2010 GWEC Report)

- USA - 2010: $10
- USA - 2030: $50
- Global (2030): $380

Energy Consumption

Energy Consumption (Source: 2011 DOE-NREL Report)
U.S. vs World & U.S. Consumption Breakdown
Energy Consumption by Buildings

Building Sector vs Industry & Transportation

2010 Building Energy Consumption in USA [TWh] & Market Value [$B], Energy Price: $0.1/KWh

<table>
<thead>
<tr>
<th>Building Sector</th>
<th>Market Value [$B]</th>
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<tbody>
<tr>
<td>Total</td>
<td>8,792</td>
</tr>
<tr>
<td>20% Renewable</td>
<td>1,758</td>
</tr>
</tbody>
</table>

Energy Consumption by market sector (2011)

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### Possible Energy Solutions

#### Sources of Energy: Cost, Public Safety/Health, Environment

<table>
<thead>
<tr>
<th>Line No.</th>
<th>Type of Power Generation Plant</th>
<th>Average Price per MWh (1000 KWh), $</th>
<th>Public Safety</th>
<th>Public Health</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Wind - INVELOX</td>
<td>$69.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Hydro</td>
<td>$89.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Natural Gas Fired</td>
<td>$92.84</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Wind</td>
<td>$96.80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Geothermal</td>
<td>$99.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Advanced Nuclear</td>
<td>$112.70</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>6</td>
<td>Coal</td>
<td>$117.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Biomass</td>
<td>$120.20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Solar PV</td>
<td>$156.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Solar Thermal</td>
<td>$251.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Wind — Offshore</td>
<td>$330.60</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Possible Solutions: Wind Technologies

- **Traditional Wind Towers**
- **Makani Power**
- **Wind Lens (Ducted Turbines)**
- **OptiWind**
- **Joby Energy**
- **Megena Power**
- **Zero Blade**
- **V-Wind**
INVELOX Solves Traditional Wind Power Issues

Bird Strikes & Wildlife

Low Frequency Noise & Optical Flickering

High Cut-in Wind Speed

Turbine Reliability

Distance from Grid

Visual Impact

Low Cost

High Cut-in Wind Speed

Turbine Reliability

Distance from Grid

Visual Impact

No Bird Strike Or Wildlife issues

Reduced Distance from Grid

Improved Visual Impact

Improved Turbine Reliability (turbine & generator not exposed)

Low Cut-in Wind Speed

Minimizes Radar Interference

No Low Freq Noise & Flickering

Reduced Land by 90%

No Icing (turbine blades not exposed)

38% Less Cost

No Bird Strike Or Wildlife issues

Reduced Distance from Grid

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Improved Turbine Reliability (turbine & generator not exposed)
How it Works

INVELOX Operates Similar to **Hydropower**

1. Water intake
2. Water is channeled
3. Water accelerates
4. Hydro power conversion system
5. Excess water discharged

![Inside a Hydropower Plant](image1.png)

---

How it Works

INVELOX Operates Similar to **Hydropower**

1. Wind intake
2. Wind is channeled
3. Wind accelerates
4. Wind power conversion system
5. Excess wind discharged

![Omnidirectional INVELOX](image2.png)
Design Parameters for Wind Power Generation
Higher Towers & Longer Turbine Blades

Higher Tower ➔ Higher Wind Speed ➔ More Power

Longer Blades ➔ More Power

Power proportional to \((\text{Wind Speed})^3\)

Power proportional to \((\text{Turbine Radius})^2\)

---

Power versus Wind Speed and Blade Diameter

[Graph showing the relationship between blade diameter and power at various wind speeds.]

Increasing Speed
Example: **Increased in Velocity**

Assume Speed Ratio of 4 = Venturi Speed/ Free Stream Wind

**Free Stream Wind Speed:**
7 m/s [15 mph]

**Venturi Wind Speed:**
28 m/s [60 mph]

---

**Power Density versus Wind Speed**

**Wind Power Density [W/m²]**
Available Power in Sweep Area of a Blade

<table>
<thead>
<tr>
<th>Wind Speed [mph, m/s]</th>
<th>Wind Power Density [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>180</td>
</tr>
<tr>
<td>20</td>
<td>1,441</td>
</tr>
<tr>
<td>27</td>
<td>4,865</td>
</tr>
<tr>
<td>34</td>
<td>11,531</td>
</tr>
<tr>
<td>40</td>
<td>22,521</td>
</tr>
<tr>
<td>45</td>
<td>32,088</td>
</tr>
<tr>
<td>50</td>
<td>38,917</td>
</tr>
</tbody>
</table>

**Available Power Ratio:**
1 to 64

---

**Traditional Wind Towers**
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Computational Fluid Dynamics (CFD)

1) Solid Model of INVELOX
2) Virtual Wind Tunnel
3) Boundary Conditions
4) Input & Output
**Model**

*Figure 3* Detailed dimensions and geometry of omnidirectional INVELOX

**COMSOL Model**

*Figure 4* CFD model of INVELOX
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Computer Models & Simulations

Pressure Field in and around the INVELOX Tower

- Atmospheric Pressure
- Funnel Inlet Pressure is high
- Tower Outlet Pressure is Low
Velocity Field in and around the INVELOX Tower

Wind Speed
15 mph

Funnel Inlet Speed - Min:4, Max:10 mph

Speed at 1st Bend - Min:10, Max:33 mph

Tower Outlet Speed - Min:15, Max:24 mph
52% increase

at 2nd Bend - Min:9 mph Max:33 mph

Computer Models & Simulations

Energy Balance at 6.7 m/s (or 15 mph) Free Stream Wind
Energy Density : J/m³

<table>
<thead>
<tr>
<th>Stage</th>
<th>Static Pressure Energy (PE)</th>
<th>Dynamic Pressure Energy (KE)</th>
<th>Total Energy (PE+KE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Stream</td>
<td>100,000</td>
<td>27</td>
<td>100,027</td>
</tr>
<tr>
<td>At the Intake</td>
<td>100,021</td>
<td>6</td>
<td>100,027</td>
</tr>
<tr>
<td>At the End of Intake Funnel (1st Bend)</td>
<td>99,967</td>
<td>60</td>
<td>100,027</td>
</tr>
<tr>
<td>At the End of 2nd Bend</td>
<td>99,967</td>
<td>60</td>
<td>100,027</td>
</tr>
<tr>
<td>Right Before Exit (Turbine Location)</td>
<td>99,967</td>
<td>60</td>
<td>100,027</td>
</tr>
<tr>
<td>Far from Exit</td>
<td>100,000</td>
<td>27</td>
<td>100,027</td>
</tr>
</tbody>
</table>

Ratio of Dynamic Energies:
Turbine Location / Free Stream = 2.23 (or 123%)
Computer Models & Simulations

Energy Balance at 15 m/s (or 34 mph) Free Stream Wind
Energy Density : J/m$^3$

<table>
<thead>
<tr>
<th>Stage</th>
<th>Static Pressure Energy (PE)</th>
<th>Dynamic Pressure Energy (KE)</th>
<th>Total Energy (PE+KE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free Stream</td>
<td>100,000</td>
<td>135</td>
<td>100,135</td>
</tr>
<tr>
<td>At the Intake</td>
<td>100,106</td>
<td>29</td>
<td>100,135</td>
</tr>
<tr>
<td>At the End of Intake Funnel (1st Bend)</td>
<td>99,834</td>
<td>301</td>
<td>100,135</td>
</tr>
<tr>
<td>At the End of 2nd Bend</td>
<td>99,834</td>
<td>301</td>
<td>100,135</td>
</tr>
<tr>
<td>Right Before Exit (Turbine Location)</td>
<td>99,834</td>
<td>301</td>
<td>100,135</td>
</tr>
<tr>
<td>Far from Exit</td>
<td>100,000</td>
<td>135</td>
<td>100,135</td>
</tr>
</tbody>
</table>

Ratio of Dynamic Energies:
Turbine Location / Free Stream = 2.23 (or 123%)

CFD Models & Simulations

Velocity Field in and around the INVELOX Tower

Wind Speed
15 mph

Funnel Inlet Speed-
Min: 4, Max: 10 mph

Tower Outlet Speed-
Min: 15, Max: 24 mph

52% increase

at 2nd Bend –
Min: 9 mph
Max: 33 mph
Capable of Creating Donut-Shaped Velocity Profile at Turbine Location

Wind Speed over the hub does not generate power

CFD (Computational Fluid Dynamic) Model Comparison between Two Independent Models

1. ANSYS CFD was utilized by CCNY (CCNY = City College of New York)

2. COMSOL CFD was employed by QRDC (QRDC is an R&D Company in Chaska, MN)

3. A virtual wind tunnel was constructed to examine the performance of an INVELOX system

4. The results are in agreement
CFD (Computational Fluid Dynamic)  
Model Comparison between Two Independent Models

The Model

Figure 1 – Solid model with dimensions

Summary Results
Free Stream Wind Speed: 6.7 m/s (or 15 mph)

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>CCNY</td>
<td>Normal</td>
<td>10.0</td>
<td>6.0</td>
<td>10.6</td>
<td>12.1</td>
<td>28.2</td>
<td>34.5</td>
</tr>
<tr>
<td>QRDC</td>
<td>Normal</td>
<td>10.0</td>
<td>6.0</td>
<td>10.6</td>
<td>12.1</td>
<td>29.6</td>
<td>36.3</td>
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<tr>
<td>QRDC</td>
<td>Fine</td>
<td>10.0</td>
<td>6.0</td>
<td>11.7</td>
<td>13.1</td>
<td>30.5</td>
<td>37.4</td>
</tr>
</tbody>
</table>

Speed Ratio Based on Average Speed: 1.6  
Speed Ratio Based on Maximum Speed: 1.8
CFD (Computational Fluid Dynamic) Model Comparison between Two Independent Models

Summary Results

Velocity Contours

Velocity Contours

Summary Results - Close-up

Velocity Contours

Velocity Contours
CFD (Computational Fluid Dynamic) - Additional Results Using COMSOL Model

(a) Velocity Field in the x-z plane
(b) Pressure Field in the x-z plane

Figure 5 Velocity and pressure field in x-z plane at the center of INVELOX

(a) Velocity vectors in the x-z plane
(b) Velocity Profile inside the Fanbox in y-z plane

Figure 6 Velocity vector and profile

Supporting Columns

Figure 7 Velocity field in the x-z plane
CFD (Computational Fluid Dynamic) - Additional Results Using COMSOL Model

Dom-Shaped Top

(a) Velocity field in the x-z plane

Velocity vectors in the x-z plane

Figure 8 Inflence of a dome top on the velocity fields of INVELOX

(b) Pressure field inside the Venturi in the y-z plane

Figure 10 Velocity and pressure field in y-z plane inside the Venturi
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1) It was shown that INVELOX can be designed to capture and accelerate wind to speed ratios of 2 and 3 for omnidirectional INVELOX without and with fins, respectively.

2) Increasing wind speed by a factor of 2 or 3, results in increased power output by a factor of 4 to 8.

3) It was further shown that COMSOL is an effective computational tool to model and analyze the INVELOX systems.