The fast shift towards the « silent wind power revolution » in USA and the related huge energy and economic benefits

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Scope and methodology

- The “silent wind power revolution” (“SWR”) consists in the not sufficiently known but proven availability of new IEC 4, 3, 2 and 1 classes wind turbines optimized to deliver high and very high capacity factors on light to medium and strong wind speeds areas and sites.
- This “revolution” opens new opportunities for developers and investors and presents many advantages to deliver more TWh from installed GW, to increase the wind energy penetration rates, to ease wind power integration into the electric systems and to open vast new areas for development including in light wind speed regions that were not considered as valuable before, and last but not least, to decrease the required constant equivalent selling price of wind kWh.
- Historically, wind power development in USA was based on the use of conventional wind turbines with a low specific area ratio $Su$ (in m²/kW), optimized and used for sites with very good and good annual wind speed $Vm$ (in m/s) at hub height, corresponding to IEC classes 1 ($Vm$ from 8.5 to 10 m/s) and 2 ($Vm$ from 7.5 to 8.5 m/s).
- From those available very good and good sites, the average annual US onshore capacity factor at 32.7% in 2014 from 65.8 GW in operation at the end of the year was higher than in China, Germany and Spain and wind electricity production at 181.8 TWh is second only to the total of 235 TWh delivered from the 28 countries of the European Union.
- This document describes the electricity context and the historic development of wind power in USA with an emphasis on the changes in average specific area $Su$ of new installed wind turbines, of the average annual capacity factors and on the shift to less windy sites of class IEC 3 ($Vm$ from 6 to 7.5 m/s at hub height).
- Then, the potential of wind power development in US and in different States is summarized and reminds us that with the conventional wind turbines technology of the 2008-2010 period, large very good quality areas would be sufficient if completely developed to deliver 7.4 times more than the US electricity production in 2014.
- The recent availability of the new models of wind turbines of the SWR shows that commercial development of wind power is now possible in IEC class 3 areas. An example of such a site ($Vm = 7.2$ m/s at hub height) equipped with a wind turbine model of the SWR ($Su = 4.75$ m²/kW) is detailed and shows that even without ITC the required selling price of delivered kWh on 20 years compares well with conventional electricity.
- Recent updates of the US wind Atlas from NREL shows that some States and areas that were considered previously as not suitable for a commercial use of wind power (such as South East States) may present now large areas where those new models can deliver gross capacity factors of 40% or more if equipped by future SWR wind turbines models with a reference $Su$ value of more than 6 m²/kW and a hub height of up to 140 m. When cost and performance data for those kind of future SWR wind turbines will be available, the economic analysis performed for the present SWR model will show if commercial development will be possible.
Main General Results and Conclusions

- The growth of the US production of electricity from renewables since 2004 was based mainly on the development of wind power and with 181 TWh in 2014 (+ 8.3 %), wind power represented 4.5 % of the 4,093 TWh of US electricity production and 1/3rd of all renewables and hydro.

- There was a fast recent change in the IEC classes of new wind turbines installed in USA: IEC 3 class wind turbines (average wind speed from to 6 to 7.5 m/s at hub height) were near zero before 2008 but near 2/3rd in 2013 (see slide 13). This trend is based on the availability of new models of wind turbines of the SWR (specific area Su > 4 m2/kW for IEC3a class) from all wind turbines manufacturers active in USA.

- There was an increase of 3%/year since 2001 for the average annual capacity factor of wind turbines in operation (see slides 15 and 16). The 2014 value of 32.7 % is the best within the main world wind markets.

- There is since 2012 a fast increase of the specific area ratio Su (m2/kW) of new wind turbines installed (see slide 14). This shift towards the new models of the SWR has made possible an increase of the average US capacity factor even within the context of the rapid shift to less windy areas and site of the IEC class 3.

- There are large untapped wind energy resources in USA: on available and suitable US areas, the potential wind energy production with the 2008 wind turbines technology was 7.4 times the US electricity production in 2014 (slides 18 -20).

- With the previous models of wind turbines optimized for high wind speeds, many States and areas (mainly in the South-Eastern part of USA) were considered as not suitable for commercial wind power development. But the availability of the new models of wind turbines of the SWR and the models in development shows that there are and there will be many opportunities to develop wind projects in low wind speed States and areas.

- Using the new SWR wind turbines models in the 35 States with a potential of less than 60 GW with the 2008 models and a minimum gross capacity factor of 35 % would dramatically increase the aggregated areas suitable for wind power development (cf. slides 23-25): analysis from NREL shows that the aggregated areas suitable for a minimum gross capacity factor of 50 % is increased from zero to 2 million km2 by shifting from the 2008 wind turbines to the 2013 SWR wind turbine (Su > 4 m2/kW), and that with the near future SWR technology (Su > 6 m2/kW), there are 2 million km2 available to deliver more than 60 % gross capacity factors. At a minimum 35 % gross capacity factor, the increase of potential aggregated GW in those 35 States is from 178 GW to respectively 2,913 GW and to 6,160 GW.

- Those new opportunities and potential offered by the SWR wind turbines are detailed in the case of Georgia (see slides 27 to 31): with the 2008 wind turbines, there are no areas able to deliver gross capacity factors higher than 20 %. With the present SWR technology (Su > 4 m2/kW), there are 30,000 km2 of area that can deliver gross capacity factors higher than 30 %. With the SWR technology in development (Su > 6 m2/kW), there are more than 60,000 km2 that could deliver gross capacity factors higher than 40 %.
Main Results and Conclusions from the Case Study (IEC3 site, Vm = 7.2 m/s)

- The detailed case study presented in this document is related to a 78 MW project in Minnesota with 39 IEC class 3a wind turbines well representative of the present SWR revolution ($S_u = 4.75 \text{ m}^2/\text{kW}$ from a diameter of 110 m and a rated power of 2 MW) installed on a site with an average annual wind speed at hub height (80 m) estimated here at 7.2 m/s.

- Best estimate from the SWR model for full load hours $N_h = A(V_m)*S_u + B(V_m)$, the reference $N_h$ value is 3,500 kWh/kW.year (hours/year) and the reference annual average capacity factor is 40 %, two values that were possible before the SWR only on the best windy sites.

- Available data and specific hypothesis about this project (detailed in slides 33 and 42) and the related analysis based on a targeted profitability index of 0.2 (the ratio between the net present value of the project and its initial investment cost, this target value being sufficient to attract private investors if the project risks are reduced to a minimum, mainly from a 20 years power purchase agreement or a FIT with 100 % of the selling price $T_e$ of kWh 100 % protected from inflation) shows that the reference required constant equivalent selling price $T_e$ is only 6.55 c$/\text{kWh}$ without ITC or other incentives. This result shows that wind kWh from the new SWR wind turbines installed in medium quality wind sites can be cost competitive with the full-price of the kWh from conventional and nuclear power plants.

- Sensitivity studies on all parameters (slides 38 to 57) show that this economic attractiveness of projects with the new IEC3a SWR wind turbines is robust, and even more attractive with the decreasing specific investment cost ratio $I_u$s (in $/\text{m}^2$ of rotor swept area) which is the best suited parameter to characterize the future progress of the SWR wind farms.

- In order to get a more accurate knowledge of the energy and economic benefits of the SWR, wind energy sector stakeholders should more communicate on the relevant parameters of their projects: model and IEC class of wind turbines, diameter, rated power, average annual wind speed at hub height, annual electricity production in GWh and investment cost.
References and disclaimer

- “Analysis of the “Silent Wind Power Revolution”, and some proposals to benefit from it within a large scale deployment scenario”, WWEA Quarterly Bulletin, Issue 2, June 2014.
- “Bright Strategic and Economic Perspectives for Onshore Wind in Medium to Low Wind Speed Areas”, WindTech International, Volume 9 N°6, September 2013.
- “Assessing the potential impact of the “Silent Wind Power Revolution” on onshore wind power development in France up to 2035“, Online May 2015 and downloadable as PDF at: www.renewablesinternational.net
- “How fast is Germany shifting to the Silent Wind Power Revolution?”, online May 8, 2015 and downloadable as PDF at : www.renewablesinternational.net/silent-wind-revolution-in-germany/150/435/87433/
- « Assessing the potential impact of the “Silent Wind Power Revolution” on onshore wind power development in Japan », on line January 14, 2015, and downloadable as PDF at: www.renewablesinternational.net/the-silent-wind-power-revolution-in-japan/150/435/84659/
- “First Comparisons of Selected Wind Power Scenarios Published in 2014”, on line October 24, 2014, and downloadable as PDF at: www.renewablesinternational.net/advancing-wind-power-as-fast-as-possible/150/435/82684/
- ”China at the Forefront of the “Silent Wind Power Revolution”, on line April 23, 2014 and downloadable as PDF at: www.renewablesinternational.net/chinas-silent-wind-revolution/150/435/78319/
- ”Is Offshore Wind Power Also Benefiting from the “Silent Wind Power Revolution”? A case study from the Dutch Gemini Offshore Project”, on line May 28, 2014 and downloadable as PDF at: www.renewablesinternational.net/a-cost-comparison-of-onshore-and-offshore/150/435/79097/

Disclaimer: The technical and economic analysis made in this document are based on reference and simplified values and models and neither the author nor the project’s developers and owners can be responsible of the consequences of decisions based on those analysis.
The US context
The growth of the US production of electricity from renewables since 2004 was based mainly on the development of wind power.

Renewable Electricity Production in USA (GWh/year)
Total 2014: 540 TWh, 13.2% of total production. Source of data: EIA
With 181.8 TWh in 2014 (+ 8.3 %), wind power represented 4.5 % of the 4,093 TWh of US electricity production and 1/3rd of all renewables and hydro.

Compared to a 2014/2013 total production increase of only 0.7 %, yearly change was + 102 % for solar, + 8.3 % for wind and + 11.1 % for non-hydro RE. The nuclear production increase of + 8 TWh (+ 1 %) was lower than the increase of solar power (+ 9.3 TWh) and of wind power (+ 14 TWh).

### Electricity in USA. Data: EIA

<table>
<thead>
<tr>
<th>Source</th>
<th>2014</th>
<th>Change 2014/2013</th>
<th>2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>TWh</td>
<td>%</td>
<td>TWh</td>
<td>%</td>
</tr>
<tr>
<td><strong>Coal</strong></td>
<td>1 585,7</td>
<td>39,1%</td>
<td>1 581,1</td>
</tr>
<tr>
<td><strong>Gas</strong></td>
<td>1 133,5</td>
<td>27,9%</td>
<td>1 137,7</td>
</tr>
<tr>
<td><strong>Oil</strong></td>
<td>30,5</td>
<td>0,8%</td>
<td>27,2</td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>797,1</td>
<td>19,6%</td>
<td>789,0</td>
</tr>
<tr>
<td><strong>Hydropower</strong></td>
<td>258,7</td>
<td>6,4%</td>
<td>268,6</td>
</tr>
<tr>
<td><strong>Wind</strong></td>
<td>181,791</td>
<td>4,5%</td>
<td>167,840</td>
</tr>
<tr>
<td><strong>Biomass</strong></td>
<td>64,319</td>
<td>1,6%</td>
<td>60,860</td>
</tr>
<tr>
<td><strong>Solar</strong></td>
<td>18,321</td>
<td>0,45%</td>
<td>9,036</td>
</tr>
<tr>
<td><strong>Geothermal</strong></td>
<td>16,628</td>
<td>0,41%</td>
<td>15,8</td>
</tr>
<tr>
<td><strong>Other/ Storage</strong></td>
<td>6,367</td>
<td>0,2%</td>
<td>8,907</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4 093</td>
<td>101%</td>
<td>4 066</td>
</tr>
<tr>
<td><strong>Total RE with hydro</strong></td>
<td>539,8</td>
<td>13,3%</td>
<td>522,1</td>
</tr>
<tr>
<td><strong>Total Non-Hydro RE</strong></td>
<td>281,1</td>
<td>6,9%</td>
<td>253,1</td>
</tr>
</tbody>
</table>

### Net production GWh

<table>
<thead>
<tr>
<th>Source</th>
<th>Total USA</th>
<th>% Total 2014</th>
<th>Data from EIA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coal</strong></td>
<td>1 585 697</td>
<td>38,7%</td>
<td>67,2%</td>
</tr>
<tr>
<td><strong>Gas</strong></td>
<td>1 133 506</td>
<td>27,7%</td>
<td>19,5%</td>
</tr>
<tr>
<td><strong>Oil</strong></td>
<td>30 489</td>
<td>0,7%</td>
<td>13,2%</td>
</tr>
<tr>
<td><strong>Nuclear</strong></td>
<td>797 067</td>
<td>19,5%</td>
<td>0,2%</td>
</tr>
<tr>
<td><strong>Hydro</strong></td>
<td>258 723</td>
<td>6,3%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Non hyd. RE</strong></td>
<td>281 061</td>
<td>6,9%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Other &amp; stor.</strong></td>
<td>6 368</td>
<td>0,2%</td>
<td>100%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>4 092 911</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>
Half of 2014 U.S. wind power electricity production is from only 5 States

Wind Power Production in USA in 2014 (GWh)
Total: 181,791 GWh. Data from EIA

- Texas: 39,376; 21.7%
- California: 13,776; 7.6%
- Oklahoma: 11,862; 6.5%
- Iowa: 16,295; 9.0%
- Kansas: 10,844; 6.0%
- Illinois: 10,077; 5.5%
- Minnesota: 9,065; 5.0%
- Oregon: 7,580; 4.2%
- Colorado: 7,351; 4.0%
- Washington: 7,264; 4.0%
- Wyoming: 4,420; 2.4%
- New York: 3,971; 2.2%
- Michigan: 3,875; 2.1%
- Pennsylvania: 3,584; 2.0%
- Other states: 26,102; 14.4%
With 64,850 MW in operation at the end of 2014 (+ 4,855 MW, + 8 %), Wind power represented 6.2 % of the 1,047 GW in operation in the USA.
The growth of the U.S. installed wind power capacity was fast, but uncertainties on PTC has made annual markets too volatile.
Wind power capacity installations at the end of 2014. Total: 65,875 MW
Source: AWEA
Changes in the IEC classes of new wind turbines installed in USA: IEC 3 class wind turbines (average annual wind speed from 6 to 7.5 m/s at hub height) were near zero before 2008 but near 2/3\textsuperscript{rd} in 2013.

From 2004 to 2011, there was a quasi-constant mean specific area $S_u$ (m$^2$/kW) of new wind turbines, but the increase was fast on 2012-2013, resulting from the increasing share of IEC Class 3 wind turbines.
From 2001 to 2014, annual wind power production increased by 29% per year and full-load hours and capacity factor increased by 3 %/year.
# 2014 wind power annual average capacity factors by States

(Note: data for Wisconsin corrected with 2014 capacity from AWEA and not from EIA)

<table>
<thead>
<tr>
<th>STATE</th>
<th>Nh (h/y)</th>
<th>CF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nebraska</td>
<td>4,897</td>
<td>55.9%</td>
</tr>
<tr>
<td>Kansas</td>
<td>4,082</td>
<td>46.6%</td>
</tr>
<tr>
<td>South Dakota</td>
<td>3,653</td>
<td>41.7%</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>3,644</td>
<td>41.6%</td>
</tr>
<tr>
<td>North Dakota</td>
<td>3,432</td>
<td>39.2%</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>3,415</td>
<td>39.0%</td>
</tr>
<tr>
<td>Montana</td>
<td>3,160</td>
<td>36.1%</td>
</tr>
<tr>
<td>Minnesota</td>
<td>3,158</td>
<td>36.1%</td>
</tr>
<tr>
<td>Wyoming</td>
<td>3,138</td>
<td>35.8%</td>
</tr>
<tr>
<td>Michigan</td>
<td>3,128</td>
<td>35.7%</td>
</tr>
<tr>
<td>Iowa</td>
<td>3,073</td>
<td>35.1%</td>
</tr>
<tr>
<td>Colorado</td>
<td>3,037</td>
<td>34.7%</td>
</tr>
<tr>
<td>Massachusetts</td>
<td>3,011</td>
<td>34.4%</td>
</tr>
<tr>
<td>Texas</td>
<td>2,992</td>
<td>34.2%</td>
</tr>
<tr>
<td>Idaho</td>
<td>2,886</td>
<td>32.9%</td>
</tr>
<tr>
<td>Illinois</td>
<td>2,859</td>
<td>32.6%</td>
</tr>
<tr>
<td>New Mexico</td>
<td>2,847</td>
<td>32.5%</td>
</tr>
<tr>
<td>Hawaii</td>
<td>2,845</td>
<td>32.5%</td>
</tr>
</tbody>
</table>

### Ranking by Full-load hours Nh and capacity factor. Average: \( N_{hm}=2,863 \text{ h/y}; \text{CF}_{m}=32.7\% \)

<table>
<thead>
<tr>
<th>Rank</th>
<th>STATE</th>
<th>Nh (h/y)</th>
<th>CF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>New Mexico</td>
<td>2,847</td>
<td>32.5%</td>
</tr>
<tr>
<td>18</td>
<td>Hawaii</td>
<td>2,845</td>
<td>32.5%</td>
</tr>
<tr>
<td>19</td>
<td>Ohio</td>
<td>2,716</td>
<td>31.0%</td>
</tr>
<tr>
<td>20</td>
<td>Pennsylvania</td>
<td>2,667</td>
<td>30.4%</td>
</tr>
<tr>
<td>21</td>
<td>Alaska</td>
<td>2,567</td>
<td>29.3%</td>
</tr>
<tr>
<td>22</td>
<td>Vermont</td>
<td>2,546</td>
<td>29.1%</td>
</tr>
<tr>
<td>23</td>
<td>Maine</td>
<td>2,543</td>
<td>29.0%</td>
</tr>
<tr>
<td>24</td>
<td>West Virginia</td>
<td>2,488</td>
<td>28.4%</td>
</tr>
<tr>
<td>25</td>
<td>Washington</td>
<td>2,471</td>
<td>28.2%</td>
</tr>
<tr>
<td>26</td>
<td>Missouri</td>
<td>2,467</td>
<td>28.2%</td>
</tr>
<tr>
<td>27</td>
<td>New Hampshire</td>
<td>2,439</td>
<td>27.8%</td>
</tr>
<tr>
<td>28</td>
<td>Oregon</td>
<td>2,398</td>
<td>27.4%</td>
</tr>
<tr>
<td>29</td>
<td>California</td>
<td>2,383</td>
<td>27.2%</td>
</tr>
<tr>
<td>30</td>
<td>Maryland</td>
<td>2,314</td>
<td>26.4%</td>
</tr>
<tr>
<td>31</td>
<td>New York</td>
<td>2,284</td>
<td>26.1%</td>
</tr>
<tr>
<td>32</td>
<td>Indiana</td>
<td>2,131</td>
<td>24.3%</td>
</tr>
<tr>
<td>33</td>
<td>Utah</td>
<td>2,050</td>
<td>23.4%</td>
</tr>
<tr>
<td>34</td>
<td>Nevada</td>
<td>2,000</td>
<td>22.8%</td>
</tr>
<tr>
<td>35</td>
<td>Arizona</td>
<td>1,989</td>
<td>22.7%</td>
</tr>
<tr>
<td>36</td>
<td>Tennessee</td>
<td>1,753</td>
<td>20.0%</td>
</tr>
<tr>
<td>37</td>
<td>New Jersey</td>
<td>1,600</td>
<td>18.3%</td>
</tr>
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</table>
Analysis of the present and future potential of onshore wind power in USA
There are large untapped wind energy resources in USA: example for the 48 contiguous States with the 2008 /2010 wind turbines technology

United States (48 Contiguous States) - Wind Resource Potential
Cumulative Rated Capacity vs. Gross Capacity Factor (CF)

The estimates show the potential gigawatts of rated capacity that could be installed on land above a given gross capacity factor (without losses) at 80-m and 100-m heights above ground. Areas greater than 30% at 80 m are generally considered to have suitable wind resource for potential wind development with today’s advanced wind turbine technology. AWS Truewind, LLC developed the wind resource data for windNavigator® (http://navigator.awstruewind.com) with a spatial resolution of 200 m. NREL filtered the wind potential estimates to exclude areas unlikely to be developed, such as wilderness areas, parks, urban areas, and water features (see Wind Resource Exclusion Table for more detail).
On available and suitable US areas, the potential wind energy production with 2008/2010 technology is 7.4 times the US electricity production in 2014.

Total: 30,334 TWh

Source of data: NREL & AWS TruePower, 2010 wind turbines technology
10% of the 30,334 TWh of gross potential with the 2008 wind turbines technology could cover 75% of the 4,093 TWh produced in 2014 in US

<table>
<thead>
<tr>
<th>Rank</th>
<th>State</th>
<th>Gross TWh/y</th>
<th>Potential GW</th>
<th>Gross Nh (h/y)</th>
<th>Gross CF (%)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Texas</td>
<td>4,954</td>
<td>1,227</td>
<td>4,038</td>
<td>46,1%</td>
</tr>
<tr>
<td>2</td>
<td>Kansas</td>
<td>3,763</td>
<td>901</td>
<td>4,178</td>
<td>47,7%</td>
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<tr>
<td>3</td>
<td>Nebraska</td>
<td>3,712</td>
<td>880</td>
<td>4,218</td>
<td>48,2%</td>
</tr>
<tr>
<td>4</td>
<td>South Dakota</td>
<td>3,509</td>
<td>834</td>
<td>4,208</td>
<td>48,0%</td>
</tr>
<tr>
<td>5</td>
<td>North Dakota</td>
<td>3,181</td>
<td>756</td>
<td>4,205</td>
<td>48,0%</td>
</tr>
<tr>
<td>6</td>
<td>Montana</td>
<td>2,319</td>
<td>587</td>
<td>3,952</td>
<td>45,1%</td>
</tr>
<tr>
<td>7</td>
<td>Iowa</td>
<td>1,890</td>
<td>466</td>
<td>4,054</td>
<td>46,3%</td>
</tr>
<tr>
<td>8</td>
<td>Oklahoma</td>
<td>1,510</td>
<td>379</td>
<td>3,980</td>
<td>45,4%</td>
</tr>
<tr>
<td>9</td>
<td>Minnesota</td>
<td>1,458</td>
<td>370</td>
<td>3,941</td>
<td>45,0%</td>
</tr>
<tr>
<td>10</td>
<td>Wyoming</td>
<td>1,421</td>
<td>352</td>
<td>4,039</td>
<td>46,1%</td>
</tr>
<tr>
<td>11</td>
<td>New Mexico</td>
<td>1,025</td>
<td>260</td>
<td>3,947</td>
<td>45,1%</td>
</tr>
<tr>
<td>12</td>
<td>Colorado</td>
<td>810</td>
<td>209</td>
<td>3,880</td>
<td>44,3%</td>
</tr>
<tr>
<td>13</td>
<td>Illinois</td>
<td>287</td>
<td>79</td>
<td>3,645</td>
<td>41,6%</td>
</tr>
<tr>
<td>14</td>
<td>Missouri</td>
<td>216</td>
<td>59</td>
<td>3,672</td>
<td>41,9%</td>
</tr>
<tr>
<td>15</td>
<td>Indiana</td>
<td>110</td>
<td>30</td>
<td>3,681</td>
<td>42,0%</td>
</tr>
<tr>
<td>33 other States</td>
<td>170</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total contiguous US</td>
<td>30,334</td>
<td>7,433</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Assessment of the US wind energy potential with new SWR wind turbines models

Source of data: NREL-AWS Truepower

http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
With the 2013 wind turbines technology, wind energy potential at 110 m hub height and minimum gross capacity factor of 35% is huge in many States and appears in South-Eastern States that were not considered as suitable for development with the 2008 technology.

Source: http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
With the near future wind turbines technology ($Su > 6 \text{ m}^2/\text{kW}$), wind energy potential at 140 m hub height and minimum gross capacity factor of 35% is huge in all States.

With the 2008 wind turbines technology, there are no areas allowing a gross capacity factor of 50%, compared to near 2 M km² for the 213 technology at 110 m. The near future technology at 140 m will allow gross capacity factor of 60% on near 2 M km².

Source: http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
In the States with less than 60 GW of wind energy potential with the 2008 wind turbines technology and gross CF > 35 %, the shift to the 2013 models at 110 m leads to an increase to 2,913 GW, and up to 6,160 GW with the near future technology.

Source of data: http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
Example of assessment of States wind energy potential with new SWR wind turbines models: Georgia

Source of data: NREL-AWS Truepower

http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
With average annual wind speeds at 80 m of 4 to 6 m/s, Georgia was considered up to now as not suitable for the commercial development of wind power.

With the available SWR technology (Su values from 4.4 to 5.2 m²/kW, hub height 110 m), some areas in Georgia can deliver gross capacity factors higher than 35%.

Source: http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
With the future SWR wind turbines technology (Su > 6 m2/kW, hub height up to 140 m), many areas in Georgia can deliver gross capacity factors higher than 35%.

Source: http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
With the 2008-2010 technology, there are no areas able to deliver gross capacity factors higher than 20%. With the present SWR technology (red curve), there are 30,000 km² of area that can deliver gross capacity factors higher than 30%. With SWR technology in development (blue curve), there are more than 60,000 km² of area in Georgia that can deliver gross capacity factors of more than 40%.

Source: http://apps2.eere.energy.gov/wind/windexchange/wind_maps.asp
Case study: a 78 MW wind farm in Minnesota on a IEC3a site with a present model of IEC3a wind turbine of the SWR
(Su = 4.75 m²/kW)
Information, data and main hypothesis for the case study

- Project’s simulation: joint wind farms “Black Oak” and “Getty”, Stearns County, Minnesota, USA, to be put in operation in mid-2016
- Main source of information on the project http://www.geronimoenergy.com
- Total rated power: 78 MW from 39 Vestas V110/2MW wind turbines, IEC class 3a, specific area Su = 4.75 m²/kW, well representative of the new models of the SWR
- Reference mean wind speed at hub height (80 m): Vm = 7.2 m/s. Sensitivity study from 6.9 to 7.5 m/s. Assumption for the Weibull distribution: form factor K = 2
- Estimated annual electricity sold to the grid from the SWR model: Nh = A(Vm)*Su + B(Vm) with total wind farm losses 13 %, mean availability on 20 years 97 %, hub altitude 470 m
- Reference initial investment cost ratio Ius = 370 $/m² ➞ ratio Iup = Ius*Su = 1,758 $/kW. Sensitivity study to + or – 20 % on Ius
- Estimated constant equivalent O&M expenses: O&M ratio Domu = 60 $/kW.year
- Constant equivalent selling price Te of electricity : 100 % indexed on inflation within a 20 years power purchase agreement (constant in constant $ of year 2015)
- Reference discount rate: t = 5 % real
- Targeted profitability index PI = Project’s Net Present Value / Initial investment = NPV / I = 0.2. Sensitivity study : 0 < PI < 0.6

Disclaimer: those data and hypothesis may differ from the actual data of the real final project, the intent of this case study being only to make a best theoretical estimate and simulation of this type of SWR project, and neither the author nor the project’s developer and owner or the wind turbine manufacturer or other project’s stakeholders may be responsible of the consequences of any decisions taken from this case study. The results of this case study should not be extrapolated to other actual wind power projects as each wind power project requires a specific study taking into account its real detailed conditions.
Location of the joint Black Oak and Getty wind farms in Minnesota
Total: 78 MW from 39 Vestas 110 m/2 MW wind turbines (Su = 4.75 m²/kW)
Vm at hub height in the site in the Stearns County is between 7 and 7.5 m/s at 80 m. Best available estimate is 7.2 m/s at 80 m.
There are large untapped wind energy resources in Minnesota

At 40% gross capacity factors from wind turbines with 80 hub height (3500 gross full-load hours/year), there are available sites in Minnesota for more than 160 GW of wind power, that could deliver 560 gross TWh/y. compared to a 2013 consumption of 69 TWh in Minnesota, or 15% of the 2013 US electricity consumption of 3,725 TWh.
Detailed Data and Results of the case study
With a reference $Su$ value of 4.75 m²/kW and the linear SWR model $Nh = A(Vm) \times Su + B(Vm)$, nominal equivalent full-load hours $Nh$ is 3,500 h/y.

Assumptions: wind farm losses 13%, availability 97%, hub height 80 m at 470 m a.s.l.
With a reference Su value of 4.75 m²/kW and the linear SWR model $N_h = A(V_m) * Su + B(V_m)$, nominal average annual capacity factor is 40 %

Assumptions: wind farm losses 13%, availability 97 %, hub height 80 m at 470 m a.s.l.
With a reference Su value of 4.75 m²/kW, nominal annual electricity production is $E_Y = 273$ GWh/year

Assumptions: wind farm losses 13%, availability 97 %, hub height 80 m at 470 m a.s.l.
With a reference $S_u$ value of 4.75 $m^2/kW$ nominal specific energy yield $E_{ys} = E_y/S$ is 737 kWh/m$^2$.year

Assumptions: wind farm losses 13%, availability 97 %, hub height 80 m at 470 m a.s.l.
# Data and results for the economic analysis of the reference wind farm

## Profitability analysis of a wind farm

<table>
<thead>
<tr>
<th>Source of data: Geronimo Energy, Vestas</th>
<th>IEC Class (1, 2 or 3): 3</th>
</tr>
</thead>
</table>

### Project Details
- **Project:** Black Oak Getty Wind Farm
- **Site:** Minnesota, Stearns County
- **V_{m} at hub height:** 7.20 m/s
- **Hub height:** 80 m
- **Wind turbine:** Model 110/2 MW IEC 3a
- **D:** 110.0 m
- **S = \pi \times D^2/4:** 9503 m²
- **Pu:** 2000 kW
- **Ps = P/S:** 0.210 kW/m²
- **Su = S/P = 1/Ps:** 4.75 m²/kW
- **N wind turbines:** 39
- **P wind farm:** 78,00 MW
- **Ey:** 273 175 MWh/year
- **Nh wind farm = Ey/P:** 3 502 h/year
- **CF = Nh/8760:** 39.98 %
- **Eys = Ey/S:** 737 kWh/m².y
- **l:** 137 133 k$%

### Calculation of a tiered FIT with 2 levels T1 and T2

<table>
<thead>
<tr>
<th>J (years at T1)</th>
<th>7 years</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRF(t,n)</td>
<td>0.08024</td>
</tr>
<tr>
<td>Iup = I/P</td>
<td>1 758 $/kW</td>
</tr>
<tr>
<td>Ius = I/S</td>
<td>370 $/m²</td>
</tr>
<tr>
<td>Domu = Dom/P</td>
<td>60,0 $/kW.year</td>
</tr>
<tr>
<td>Kom = Dom/I</td>
<td>3.41 %</td>
</tr>
<tr>
<td>PI</td>
<td>0.200</td>
</tr>
</tbody>
</table>

### Tariff on J years: T1
- **8,00 c$(0)/kWh**

### Tariff on (n-J) years: T2
- **5,29 c$(0)/kWh**

### Project IRR
- **7,26% % real**

### Present IRR on equity
- **12,00 % nominal**

### Interest on debt
- **5,00 % nominal**

### Inflation rate i
- **2,00 %**

### (% nominal)
- **7,10 % nominal**

### Real WACC = t
- **5,00 % real**

## Targeted Profitability Index (PI) Values According to Risks and Growth Strategies

<table>
<thead>
<tr>
<th>Non Profitable Projects</th>
<th>Defensive Growth</th>
<th>Offensive Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Towards failure</td>
<td>Low Risks</td>
<td>Low Risks</td>
</tr>
<tr>
<td>Surviving</td>
<td>No Risks at all</td>
<td>High to very high risks</td>
</tr>
<tr>
<td>No Growth</td>
<td>FTIS</td>
<td>FTIS</td>
</tr>
</tbody>
</table>

**Targeted zone For « Fair and Efficient tariffs »**
Mapping of the required constant selling price of electricity $T_e = f(lus, Vm)$. Targeted Profitability Index $PI = \frac{NPV}{I} = 0.2$, $n = 20$ years

**Equivalent Constant Tariff $T_e$ ($c$/kWh) = $f(lus, Vm)$**

- **$lus$ ($$/m^2$)**
  - 280
  - 300
  - 320
  - 340
  - 360
  - 380
  - 400
  - 420
  - 440
  - 460

- **$T_e$ ($c$/kWh)**
  - 4.0
  - 4.5
  - 5.0
  - 5.5
  - 6.0
  - 6.5
  - 7.0
  - 7.5
  - 8.0
  - 8.5

- **$Vm$ (m/s)**
  - 6.90 (dotted line)
  - 7.00 (red line)
  - 7.10 (green line)
  - 7.20 (blue line)
  - 7.30 (cyan line)
  - 7.40 (orange line)
  - 7.50 (black dashed line)
Mapping of the required constant selling price of electricity $Te$ on 20 years:

$Te = f(I_{up}, V_m)$ with $I_{up} (\$/kW) = I_{us} (\$/m^2) \times S_u (m^2/kW)$

**Constant Equivalent Tariff**

$Te (c\$/kWh) = f(I_{up}, V_m)$
Mapping of the required constant selling price of electricity $T_e$ on 20 years: 

$T_e = f(\text{Discount rate}, V_m)$. Targeted Profitability Index $\text{PI} = \frac{\text{NPV}}{I} = 0.2$

**Constant Equivalent Tariff $T_e$ (c$/kWh) = f(t \%, V_m)$**

![Graph showing the relationship between $T_e$, $t$, and $V_m$.](image-url)
Reference project Profitability Index \( PI = \frac{NPV}{I} \) versus the constant equivalent selling price of electricity \( Te \) ($/MWh) on 20 years.
Sensitivity of the selling price $T_e$ and the overall discounted manufacturing cost of the kWh ODC versus the targeted profitability index $\text{PI} = \text{NPV}/I$

$T_e = \text{ODC} + C_i \times \text{PI}$, with $C_i = \text{part of ODC created by the initial investment cost}$

**Te and ODC (cent/kWh) = f(PI = NPV/I)**

$t = 5\%$, $n = 20$ years
Sensitivity of the project’s real internal rate of return (IRR) to the targeted profitability index $\text{PI} = \text{NPV}/I$ and $\text{Te}$ values corresponding to IRR values.
Sensitivity of the project’s margin between IRR and discount rate to the targeted profitability index $\text{PI} = \frac{\text{NPV}}{I}$ and $T_e$ values corresponding to margin values.
Sensitivity of the project’s discounted pay-back time (DPBT) and simple pay-back time (SPBT) to the targeted profitability index $\text{PI} = \frac{\text{NPV}}{I}$.
Sensitivity of the project’s kWh manufacturing cost ODC and of the required selling price Te (c$/kWh) to the O&M annual expenses ratio Domu ($/kW.year) for a targeted profitability index PI = NPV/I = 0.2 (discount rate 5 % real, n = 20 years)
Sensitivity of the project’s kWh manufacturing cost ODC and of the required selling price \( Te \) (c$/kWh) to the hub altitude above sea level for a targeted profitability index \( PI = NPV/I = 0.2 \) (discount rate 5 % real, \( n = 20 \) years)

**Te and ODC (cent/kWh) = f(Hub altitude)**

Targeted \( PI = 0.2 \), \( t = 5 \% \), \( n = 20 \) years
Potential impact of a 30 % ITC
Potential impact of a 30% ITC on the required constant equivalent selling price of electricity $Te = f(Ius, Vm)$ on $n = 20$ years

Equivalent Constant Tariff $Te \text{ (c$/kWh$)} = f(Ius, Vm)$

- $Te$ (c$/kWh$) vs $Ius$ ($\$/m^2$)
- $Vm$ (m/s) as a parameter
- Lines represent different wind speeds: 6.90, 7.00, 7.10, 7.20, 7.30, 7.40, 7.50

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Potential impact of a 30% ITC on the required constant equivalent selling price of electricity $T_e = f(I_{up}, V_m)$ on $n = 20$ years.
Potential impact of a 30% ITC on the required constant equivalent selling price of electricity $Te = f(\text{Discount rate, Vm})$ on $n = 20$ years.
Potential impact of a 30% ITC on the sensitivity of the profitability of the reference project versus the constant selling price of electricity $Te$
ANNEX

Results of the model used for the full-load hours of reference wind farms:

\[ Nh = A(Vm) * Su + B(Vm) \]
Examples (in dotted red lines) of reference Nh values for the new models of wind turbines of the SWR

- Vm is the average annual wind speed at hub height
- Post 2020 wind turbines models for the SWR scenario will offer higher Su and Nh values

\[ \text{Nh} = f(\text{Su}, Vm) \] for IEC class 1, 2, 3 and 4 Wind Turbines

\[ k = 2, \ M_{\text{vair}} = 1,225 \ \text{kg/m}^3, \ \text{wind farm losses 10\%, 100\% availability} \]

Source: Bernard Chabot, “Analysis of the “Silent Wind Power Revolution”, and some proposals to benefit from it within a large scale deployment scenario”, WWEA Quarterly bulletin N°2, June 2014