This technical release was issued in the context of the project INOLA (Innovations for a sustainable land and energy management on a regional scale) which is funded by the German Federal Ministry of Education and Research (BMBF) under the grant code 033L155AN in the period from 2014 to 2019. The author(s) is/are responsible for content and results of this study.

Author(s):
Veronika Locherer (née Hofer) (LMU Munich, Department of Geography, research and teaching unit “Physical Geography and Remote Sensing”)

© August 2018

Contact:
M.Sc. Veronika Locherer
Department of Geography
Ludwig-Maximilians-Universität München
Luisenstr. 37
80333 Munich
E-Mail: v.locherer@iggf.geo.uni-muenchen.de

All INOLA-Technical Releases are available on the project home page www.inola-region.de. Already published INOLA-Technical releases:

INOLA-Technical Release No. 4: INOLA Software Documentation. The Bioenergy Component
Content

List of Figures .................................................................................................................. IV

List of Tables .................................................................................................................... IV

1 The Wind Power Component ............................................................................................... 1

1.1 General Equations ......................................................................................................... 1

1.1.1 Wind Speed Module ................................................................................................... 1

1.1.2 Electric Power Production Module ........................................................................... 2

1.2 Pre-processing ............................................................................................................... 9

1.3 Input Data and Format .................................................................................................. 10

1.4 Output .......................................................................................................................... 11

2 Validation ....................................................................................................................... 12

2.1 Monthly Yield .............................................................................................................. 12

3 Implementation within the Energy Model ......................................................................... 13

References ........................................................................................................................ 15
List of Figures

Figure 1-1 Performance curve of the 1.5 kW wind turbine (based on LUVTEc GMBH n.d. .......... 4
Figure 1-2: Performance curve of the 8.5 kW wind turbine (based on BRAUN WINDTURBINEN GMBH
n.d.) ........................................................................................................................................ 5
Figure 1-3: Performance curve of the 12 kW wind turbine (based on BRAUN WINDTURBINEN GMBH
n.d.) ........................................................................................................................................ 6
Figure 1-4: Performance curve of the 600 kW wind turbine (based on BAUER UND MATYSIK n.d.) ....... 7
Figure 1-5: Performance curve of the 600 kW wind turbine (based on ENERCON 2016). ................. 8
Figure 1-6: Example of the input file for the Wind Power Model ...................................................... 11
Figure 2-1: ..................................................................................................................................... 12
Figure 2-2: ..................................................................................................................................... 13
Figure 2-3: ..................................................................................................................................... 13
Figure 3-1: Workflow of the Energy model with regarding components ............................................. 14

List of Tables

Table 2-1: Description of parameters used in the wind speed module with associated variable names
.......................................................................................................................................................... 1
Table 1-2: Description of the input-file for the Wind Power Model, Section General ....................... 10
Table 1-3: Description of the input-file for the Wind Power Model, Section WindPowerModel.......... 10
1 The Wind Power Component

The Wind Power Component aims to simulate power production via wind turbines. The component consists of five models representing five different types of wind turbines. Within all models, wind speed is calculated for the corresponding height of the turbine and inserted into a polynomial function that was derived individually for each turbine type. The component does include the possibility for dynamic decision-making about the new construction or refurbishment of windpower plants based on economic criteria (see INOLA-Technical Release No. 8: The Investment Cost Component).

1.1 General Equations

1.1.1 Wind Speed Module

The wind speed module calculates wind speed at hub height of each turbine and is based on the so-called power-law after Hellman as shown in Equation (1) (HAU 2013).

\[ v_{hub} = v_1 \times \left( \frac{h_{hub}}{h_1} \right)^\alpha \]  

with:

- \( v_1 \) = Wind speed near surface [m/s]
- \( h_1 \) = Height of near-surface wind measurements [m]
- \( h_{hub} \) = Hub height of turbine [m]
- \( \alpha \) = Hellmann exponent [-]

The Hellmann exponent is calculated via the following equation:

\[ \alpha = \frac{1}{\log \frac{h_{hub}}{z_0}} \]  

with:

- \( h_{hub} \) = Hub height of turbine [m]
- \( z_0 \) = Roughness length of ground [m]

Table 1-1: Description of parameters used in the wind speed module with associated variable names
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
<th>Variable name(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>Wind speed near surface</td>
<td>[m/s]</td>
<td>WindSpeed</td>
</tr>
<tr>
<td>$h_1$</td>
<td>Height of wind speed measurements</td>
<td>[m]</td>
<td>Height</td>
</tr>
<tr>
<td>$h_\text{hub}$</td>
<td>Hub height of turbine</td>
<td>[m]</td>
<td>HubHeight</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Hellmann exponent</td>
<td>[-]</td>
<td>HELLMAN</td>
</tr>
<tr>
<td>$z_0$</td>
<td>Roughness length of ground</td>
<td>[m]</td>
<td>Roughness</td>
</tr>
</tbody>
</table>

### 1.1.2 Electric Power Production Module

The electric power production module is based on performance curves of the individual turbine types as provided by the manufacturers and consists of five different models. For each of these types a mathematical model was developed to fit the performance curve. Thresholds used for the models were cut-in and cut-out wind speed (at which speed the turbines start or stop to perform) as well as rated output...
speed (where the turbine reaches its optimum). In the following the five different Wind Models are presented.

1.1.2.1 WindModel1

WindModel1 describes a turbine with a hub height of 10 m and a maximum output of 1.5 kW (LUVTEC GmbH n.d.). The power output is calculated via Equations (3) to (8) which are derived from the corresponding performance curve (Figure 1-1).

\[
E_{\text{Wind}} = 0 \quad v_{\text{hub}} \in [0; 3.5] \quad (3)
\]

\[
E_{\text{Wind}} = 0.0108 \times v_{\text{hub}}^2 - 0.0385 \times v_{\text{hub}} + 0.0321 \quad v_{\text{hub}} \in [3.5; 7] \quad (4)
\]

\[
E_{\text{Wind}} = 0.0225 \times v_{\text{hub}}^2 - 0.2115 \times v_{\text{hub}} + 0.6765 \quad v_{\text{hub}} \in [7; 10] \quad (5)
\]

\[
E_{\text{Wind}} = -0.02 \times v_{\text{hub}}^3 + 0.635 \times v_{\text{hub}}^2 - 6.395 \times v_{\text{hub}} + 21.26 \quad v_{\text{hub}} \in [10; 13]; E_{\text{Wind}} \in [0; 1.5] \quad (6)
\]

\[
E_{\text{Wind}} = 1.5 \quad v_{\text{hub}} \in [13; 17] \quad (7)
\]

\[
E_{\text{Wind}} = 0 \quad v_{\text{hub}} \in [17; \infty] \quad (8)
\]
1.1.2.2 WindModel2

WindModel2 describes a turbine with a hub height of 20 m and a maximum output of 8.5 kW (BRAUN WINDTURBINEN GMBH n.d.). The power output is calculated via Equations (9) to (13) which are derived from the corresponding performance curve (Figure 1-2).

\[ E_{Wind} = 0 \quad \text{if} \quad v_{hub} \in [0; 2.25] \quad (9) \]

\[ E_{Wind} = 0.0792 \times v_{hub}^2 - 0.2673 \times v_{hub} + 0.2071 \quad \text{if} \quad v_{hub} \in [2.25; 7.25] \quad (10) \]

\[ E_{Wind} = 0.0074 \times v_{hub}^4 - 0.3413 \times v_{hub}^3 + 5.5998 \times v_{hub}^2 - 37.701 \times v_{hub} + 91.091 \quad \text{if} \quad v_{hub} \in [7.25; 12]; E_{Wind} \in [0; 8.5] \quad (11) \]

\[ E_{Wind} = 8.5 \quad \text{if} \quad v_{hub} \in [12; 13] \quad (12) \]

\[ E_{Wind} = 0 \quad \text{if} \quad v_{hub} \in [13; \infty] \quad (13) \]
1.1.2.3 WindModel3

WindModel3 describes a turbine with a hub height of 25 m and a maximum output of 12 kW (BRAUN WINDTURBINEN GMBH n.d.). The power output is calculated via Equations (14) to (18)(9) which are derived from the corresponding performance curve (Figure 1-3).

\[
E_{\text{Wind}} = 0 \quad v_{\text{hub}} \in [0; 2.25] \quad (14)
\]

\[
E_{\text{Wind}} = 0.128 * v_{\text{hub}}^2 - 0.4792 * v_{\text{hub}} + 0.45 \quad v_{\text{hub}} \in [2.25; 7.25] \quad (15)
\]

\[
E_{\text{Wind}} = -0.0889 * v_{\text{hub}}^3 + 2.419 * v_{\text{hub}}^2 - 19.642 * v_{\text{hub}} + 52.917 \quad v_{\text{hub}} \in [7.25; 12] ; \quad E_{\text{Wind}} \in [0; 12] \quad (16)
\]

\[
E_{\text{Wind}} = 12 \quad v_{\text{hub}} \in [12; 13] \quad (17)
\]

\[
E_{\text{Wind}} = 0 \quad v_{\text{hub}} \in [13; \infty] \quad (18)
\]
1.1.2.4 WindModel4

WindModel4 describes a turbine with a hub height of 70 m and a maximum output of 600 kW (BAUER AND MATYSIK n.d.). The power output is calculated via Equations (19) to (22) which are derived from the corresponding performance curve (Figure 1-4).

\[
E_{\text{Wind}} = 0 \quad \text{for} \quad v_{\text{hub}} \in [0; 2.5] \quad (19)
\]

\[
E_{\text{Wind}} = -0.0116 \cdot v_{\text{hub}}^5 + 0.197 \cdot v_{\text{hub}}^4 - 0.3087 \cdot v_{\text{hub}}^3 - 0.46 \cdot v_{\text{hub}}^2 + 1.879 \cdot v_{\text{hub}} - 0.9234 \quad \text{for} \quad v_{\text{hub}} \in [2.5; 11.5]; \quad E_{\text{Wind}} \in [0; 600] \quad (20)
\]

\[
E_{\text{Wind}} = 600 \quad \text{for} \quad v_{\text{hub}} \in [11.5; 19] \quad (21)
\]

\[
E_{\text{Wind}} = 0 \quad \text{for} \quad v_{\text{hub}} \in [19; \infty] \quad (22)
\]
1.1.2.5 WindModel5

WindModel5 describes a turbine with a hub height of 149 m and a maximum output of 3000 kW (ENERCON 2016). The power output is calculated via Equations (23) to (30) which are derived from the corresponding performance curve (Figure 1-4).
\[ E_{\text{Wind}} = 0 \quad v_{\text{hub}} \in [0; 1] \]  
(23)

\[ E_{\text{Wind}} = 3 \times v_{\text{hub}} - 3 \quad v_{\text{hub}} \in [1; 2] \]  
(24)

\[ E_{\text{Wind}} = 0.1771 \times v_{\text{hub}}^4 + 0.8495 \times v_{\text{hub}}^3 + 12.247 \times v_{\text{hub}}^2 
- 42.64 \times v_{\text{hub}} + 29.417 \quad v_{\text{hub}} \in [2; 5] \]  
(25)

\[ E_{\text{Wind}} = -13.056 \times v_{\text{hub}}^3 + 320.17 \times v_{\text{hub}}^2 - 2073.8 \times v_{\text{hub}} 
+ 4344.3 \quad v_{\text{hub}} \in [5; 12]; \quad E_{\text{Wind}} \in [0; 3000] \]  
(26)

\[ E_{\text{Wind}} = 3000 \quad v_{\text{hub}} \in [12; 27] \]  
(27)

\[ E_{\text{Wind}} = -28.708 \times v_{\text{hub}}^3 + 2349.1 \times v_{\text{hub}}^2 - 64194 \times v_{\text{hub}} 
+ 588810 \quad v_{\text{hub}} \in [27; 31]\]  
(28)

\[ E_{\text{Wind}} = -18.25 \times v_{\text{hub}}^3 + 1912.3 \times v_{\text{hub}}^2 - 66774 \times v_{\text{hub}} 
+ 776974 \quad v_{\text{hub}} \in [31; 34]; \quad E_{\text{Wind}} \in [0; 3000] \]  
(29)

\[ E_{\text{Wind}} = 0 \quad v_{\text{hub}} \in [34; \infty] \]  
(30)

---

Figure 1-5: Performance curve of the 600 kW wind turbine (based on ENERCON 2016).
1.2 Pre-processing

The pre-processing includes the identification of all existent wind turbines within the region under assessment with their exact positions and technical design. Positions as well as rated output of devices within the EWO region were taken from BAYStMWi (2015) and ENERGYMAP (2015). Appropriate performance curves were then taken from LUVTEC GMBH (n.d.) and BRAUN WINDTURBINEN GMBH (n.d.). For
future turbines, a common turbine type for weak wind regions is chosen that can already be found in wind parks around the EWO region (ENERCON 2016).

1.3 Input Data and Format

The setup file contains the following sections:

- [General]:

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Description</th>
<th>Unit</th>
<th>Data format</th>
</tr>
</thead>
<tbody>
<tr>
<td>ObjectType</td>
<td>Type of renewable energy = windp</td>
<td>[-]</td>
<td>character</td>
</tr>
<tr>
<td>ObjectName</td>
<td>Explicit Name of device</td>
<td>[-]</td>
<td>character</td>
</tr>
<tr>
<td>ObjectID</td>
<td>Explicit ID of device</td>
<td>[-]</td>
<td>integer</td>
</tr>
<tr>
<td>Position-Proxel</td>
<td>Row and column of position within the model rectangle; divided by multiple spaces</td>
<td>[-]</td>
<td>Integer</td>
</tr>
</tbody>
</table>

- [WindPowerModel]:

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Description</th>
<th>Unit</th>
<th>Data format</th>
</tr>
</thead>
<tbody>
<tr>
<td>WindPowerActive</td>
<td>Status of the Power Plant</td>
<td>[-]</td>
<td>integer</td>
</tr>
<tr>
<td>WindPowerYear, WindPowerMonth, WindPowerDay</td>
<td>Start time of the Power Plant</td>
<td>[-]</td>
<td>integer</td>
</tr>
<tr>
<td>WindPowerModel</td>
<td>Type of turbine; Models 1 to 5 (see Sections 1.1.2.1 to 1.1.2.5)</td>
<td>[-]</td>
<td>integer</td>
</tr>
<tr>
<td>Hub Height</td>
<td>Hub Height of the turbine</td>
<td>[m]</td>
<td>real</td>
</tr>
<tr>
<td>Roughness</td>
<td>Roughness length of ground</td>
<td>[m]</td>
<td>real</td>
</tr>
</tbody>
</table>

Example setup for a wind power plant:

```plaintext
[General]
ObjectType   windp
ObjectName   E3117701000000005007505353-0000
ObjectID     1
Position-Proxel  240    183
[end]
```
1.4 Output

The output of the wind power model includes the produced electrical energy in kWh on hourly resolution.
2 Validation

For Validation, time series of measured wind speed and energy output data were provided for one wind turbine situated within the model region (SCHRAMM 2016a, b). The turbine is of the type described in Section 1.1.2.4 with 600 kW rated output and a hub height of 70 m. Wind Speed at hub height

\[ R^2 = 0.7118 \]

![Scatter plot of simulated vs. measured wind speed at hub height](image)

*Figure 2-1:*

2.1 Monthly Yield
3 Implementation within the Energy Model
The wind power component is completely integrated within the energy model. The workflow within the PROMET model and its components for the calculation of the energy paths is shown in Figure 3-1.

- **Calc Wind Power**
- **Calc Solar Power**
- **Calc Solar Heat**
- **Calc Surface Geothermal Energy**
- **Calc Deep Geothermal Energy**
- **Calc Hydro Power**
- **Energy Consumption**
  - Electrical Energy
  - Heat Energy
  - Gas
- **Calc Availability of Substrate**
- **Calc Biogas Production**
- **Calc Gas Feed-In of Biomethane**
- **Calc Energy Generation from CHP**
- **Calc Availability of Wood Fuel**
- **Calc Gasifiers**
- **Calc Combustion Plants**
- **Calc Central heating systems**

**Model Components**
- Wind Power component
- Solar Energy component
- Geothermal Energy component
- Hydro Power component
- Bioenergy component
- Energy Consumption component
- Energy Management Component
- Energy Storage Component

**Storage Management**
- **Domestic scale**
  - Calculation of the domestic energy deltas
    - Storage operation of Buffer Tanks
    - Storage operation of domestic battery devices
- **Regional scale**
  - Storage Management of LHNs
    - Operation of buffer tanks and STES-plants
    - Operation of community batteries
  - Calculation of the regional energy deltas
    - Storage operation of batteries, PSPs and GSPs
    - Storage operation of hydrogen and methane plants
    - Storage operation of PTH-systems in LHNs
  - Calculation of the input/output flows of electrical energy and gas

*Figure 3-1: Workflow of the Energy model with regarding components*
References


LUVTEC GMBH N.D.: (Eds.) Kleinwindkraftanlage 1,5 kW.

BRAUN WINDTURBINEN GMBH N.D.: (Eds.) ANTARIS Kleinwindanlagen.


ENERCON 2016: (Eds.) E-115 / 3.0 MW.


ENERGYMAP 2015: Anlagen zur Produktion Erneuerbarer Energien (Datensatz). Available at: http://www.energymap.info/energieregionen/DE/105/111/166.html (07.05.2015: 07.05.2015).
