Combined Electric Power Generating Systems

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January 2008

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ABSTRACT

This presented work is the first part of a project, that deals with the problem to analyse complex systems that are built up with different combinations of Combined Electric Power Generating Systems” that are working with the combination of “Wind Power” and “Sun Power”. The systems includes “Energy Storages”. The power producing systems are connected to two types of grids; “Local grids” and “External grids”.

The local grid represents an electric load, for example the electric load from an industry area, the electric load from a residential area, the electric load from a combination of these areas and so on. The external grid has the possibility to act as a load, for exporting of generated surplus energy but also as an energy buffer, for importing of deficit energy.

For theoretic analyse of the complex power systems a simulation program has been developed.

To get suitable input parameters to some of the simulation modules, measurements have been performed. These measurements, including adequate analysis, have been focused on three important areas, namely Wind power, Sun power and Electric load.
1 INTRODUCTION

This presented work is the first part of a project, that deals with the problem to analyse complex systems that are built up with different combinations of Combined Electric Power Generating Systems that are working with the combination of “Wind Power” and “Sun Power”. The systems includes “Energy Storages”. The power producing systems are connected to two types of grids; “Local grids” and “External grids”. See Figure 2.1-1 in chapter 2 (System Principle).

The local grid represents an electric load, for example the electric load from an industry area, the electric load from a residential area, the electric load from a combination of these areas and so on. The external grid has the possibility to act as a load, for exporting of generated surplus energy but also as an energy buffer, for importing of deficit energy.

For theoretic analyse of the complex power systems a simulation program has been developed. This program is described in chapter 3 (System Simulation). The simulation program consists of a number of blocks. The majority of this blocks are modelling different physical processes, for example the wind rate, the wind power generator, the solar radiation, the electric load and so on.

To get suitable input parameters to some of the simulation modules, measurements have been performed. These measurements, including adequate analysis, have been focused on three important areas, namely Wind power, Sun power and Electric load. The results of these activities are presented in chapter 4 (Wind Power), chapter 5 (Sun Power), and chapter 6 (Electric Load).

The energy storages, that could be realized based on different principles, are discussed in paragraph 2.5 (Energy storage).

The principle of the power electronics that is to be used in the total power systems is treated in paragraph 2.6 (Power Electronics).

Simulations based on some system configurations and environments have been performed. This is treated in chapter 7 (Simulations).

Chapter Error! Reference source not found. (Future Work) gives proposals on further work that is suitable to complete the project in question.

A conclusion of the study is presented in chapter Error! Reference source not found. (Conclusion).

Chapter 8 (References) gives the used references of the study in question.
2 SYSTEM PRINCIPLE

The power system that is studied in this project is fundamentally illustrated in Figure 2.1-1.

![Diagram of power system]

Figure 2.1-1 The principle of the power systems. The arrows show the energy flow

The different blocks in Figure 2.1-1 represent the following functions:

*Wind Power:* A number of wind power systems (turbines/generators) including power electronics. See point 2.1.
**Sun Power:** A number of sun power systems (solar panels) including power electronics. See point 2.2.

**Local grid:** Consumer grid. See point 2.3.

**External grid:** The ordinary distribution grid or consumer grid. The connection to this grid has two purposes: 1) To give the possibility to export generated surplus energy. 2) to give the possibility to import deficit energy. See point 2.4.

**Energy storage:** The storage device has two purposes: 1) To store surplus energy. The storing is possible up to a specific limit. If this limit is exceeded (the storage in the storage device is too high), the surplus energy is exported to the external grid. 2) To supply deficit energy to the local grid. This supply is possible up to a specific limit. If this limit is exceeded (the storage in the storage device is too low), the deficit energy is imported from the external grid. See point 2.5.

**Power electronics:** Power electronic devices to control the energy flows. See point 2.6.

### 2.1 Wind Power

The block *Wind Power* in Figure 2.1-1 represents a number of connected wind power systems for conversion of kinetic wind energy into electric energy. A system like this consists of turbine, generator, control systems and power electronic devices. Figure 2.1-1 illustrates the principle of a total *Wind Power* block.
2.1 Wind Power

Figure 2.1-1 Wind power systems (1, 2, 3, …., n) connected to a total Wind Power block. The block Power Electronics (PE) represents the corresponding Power Electronics block in Figure 2.1-1.

2.2 Sun Power

The block Sun Power in Figure 2.1-1 represents a number of connected sun power systems for conversion of radiated solar energy into electric energy. A system like this consists of solar panels, control systems and power electronic devices. Figure 2.2-1 illustrates the principle of a total Sun Power block.
9(259)

Figure 2.2-1  Sun power systems (1, 2, 3, …, m) connected to a total Sun Power block. The block Power Electronics (PE) represents the corresponding Power Electronics block in Figure 2.1-1.

2.3 Local grid

The Local grid (Figure 2.1-1) acts as a load to the Combined Power System. The grids could act as Consumer grids or as Distribution grids. Two types of local grids are defined: Isolated Systems and Not Isolated Systems.
2.3.1 Isolated systems

The principle of the isolated system is illustrated in Figure 2.3-1 (consumer grid) and Figure 2.3-2 (distribution grid). The system consists of an isolated grid. The term “isolated” refers in this matter to the fact, that the grid has no connection to any other power supplier, a distribution grid or a subtransmission grid. The only power supply is realized by the *Combined Power System* (with connection by PE).

![Figure 2.3-1](image)

Figure 2.3-1 The principle of the isolated system representing a consumer grid with no connection to any other power supplier (besides the *Combined Power System*). The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1. The power flow direction is: “from *PE* to the *Local grid*.”
Figure 2.3-2 The principle of the isolated system representing a distribution grid with no connection to any other power supplier (besides the Combined Power System). The block Power Electronics (PE) represents the corresponding Power Electronics block in Figure 2.1-1. The power flow direction is: “from PE to the Local grid”.

2.3.2 Not Isolated systems

The principle of the not isolated system is illustrated in Figure 2.3-3 (consumer grid) and Figure 2.3-4 (distribution grid). The system consists of a grid with connection to another power supplier (besides the Combined Power System).
Figure 2.3-3 The principle of the not isolated system representing a consumer grid, that besides connection to the Combined Power System, also is connected to a distribution grid. The block Power Electronics (PE) represents the corresponding Power Electronics block in Figure 2.1-1. The power flow direction is: “from PE to the Local grid”.

Power Electronics

Local grid

Consumer 1
Consumer 2
Consumer 3

Consumer grid

Consumer p

Distribution grid
Figure 2.3-4 The principle of the not isolated system representing a distribution grid, that besides connection to the Combined Power System, also is connected to a subtransmission grid. The block Power Electronics (PE) represents the corresponding Power Electronics block in Figure 2.1-1. The power flow direction is: “from PE to the Local grid”.

2.4 External grid

The External grid (Figure 2.1-1) has two tasks: Supplier of deficit energy and Load of surplus energy and is in principle divided into four categories, according to Figure 0-1. What category that will be used, is depending on the the kind of Local grid. See Table 0-1.
Four categories of External grids representing connection to four different kind of grids, consumer-, distribution, subtransmission, respectively transmission grid. The category in question is depending on the capacity of the Combined Power System and kind of Local grid. The power flow direction is: “from PE to external grid” when exporting power and “from external grid to PE” when importing power.

<table>
<thead>
<tr>
<th>Kind of Local grid</th>
<th>Category of External grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer grid, isolated</td>
<td>1 or 2</td>
</tr>
<tr>
<td>Consumer grid, not isolated</td>
<td>2 or 3</td>
</tr>
<tr>
<td>Distribution grid, isolated</td>
<td>2 or 3</td>
</tr>
<tr>
<td>Distribution grid, not isolated</td>
<td>3 or 4</td>
</tr>
</tbody>
</table>

Table 0-1 Category of External grid for different kind of Local grids
2.5 Energy storage

The energy storage will act as an energy buffer, with the purpose to balance the energy production to the energy consumption at an optimal way. This means that importing of energy via the external grid often shall be minimized. On the other hand, this minimizing process is a question of energy storage capacity, and may be very tricky with influence of different parameters (economy, technology, statistics, environment and so on).

As the optimizing regarding the energy storage capacity is depending on a lot of parameters, it is a good solution to use simulations as a platform for this process. The developed simulation system, that is described in chapter 3, is very suitable for this activity.

The energy storage system is very schematically illustrated in Figure 2.5-1. The figure shows two blocks:

- Energy storage. This block consists of all facilities that are needed to store the electric energy in a suitable form (chemical, mechanical, potential) and to make this stored energy ready for later use in electric form. The feeding voltage (DC) to / from the energy storage is marked $U_{storage}$.

- Storage sensor. This block consists of a charge detector and a signal adapter to transmit information about the charge level in the storage. This signal is marked $S_{storage\ control}$.

![Diagram of energy storage system]

Figure 2.5-1 The energy storage system is controlled by the signal $S_{storage\ control}$
Three kind of energy storages have been defined:

- Battery system
- Hydro system
- Hydrogen system

2.6 **Power electronics**

The Power electronic system (PE) is aimed to control the energy flows between the blocks according to Figure 2.1-1.

Figure 2.6-1 illustrates the principle of the unit. The Power electronic unit is divided into five main parts, “Capacitor device, Energy storage device, Local grid device, External grid device and PE-Logic device”. See chapter 2.6.1 to 2.6.5. The flow designations are defined in Table 2.6-1.
Figure 2.6-1  Block diagram of the Power electronic unit

<table>
<thead>
<tr>
<th>Flow designation</th>
<th>Kind of flow</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW</td>
<td>Power</td>
<td>Feeding voltage (DC) from Wind power system to PE (Capacitor device)</td>
</tr>
<tr>
<td>US</td>
<td>&quot;-&quot;</td>
<td>Feeding voltage (DC) from Sun power system to PE (Capacitor device)</td>
</tr>
<tr>
<td>UB</td>
<td>&quot;-&quot;</td>
<td>Internal feeding voltage (DC) from/to Capacitor device to/from Energy storage device</td>
</tr>
<tr>
<td>UL</td>
<td>&quot;-&quot;</td>
<td>Internal feeding voltage (DC) from Capacitor device to Local grid device</td>
</tr>
<tr>
<td>UE</td>
<td>S pw</td>
<td>S ps</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>Data signal</td>
<td></td>
</tr>
</tbody>
</table>
### S export

-“-“

Signal from PE-Logic device to External grid device. Information: Activate DC/AC converter for supplying energy from PE to external grid (export energy)

### S import

-“-“

Signal from PE-Logic device to External grid device. Information: Activate AC/DC converter for supplying energy from external grid to PE (import energy)

### S storage control

-“-“

Signal from the Energy storage system to PE-Logic device. Information: current storage level (Ws) in the energy storage system

<table>
<thead>
<tr>
<th>Working Condition</th>
<th>Definition *)</th>
<th>Resulting power flow (see Figure 2.6-2 to Figure 2.6-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Net power &gt; 0 and battery_charge &lt; charge_level_max</td>
<td>Store energy to the energy storage</td>
</tr>
<tr>
<td>2</td>
<td>Net power &lt; 0 and battery_charge &gt; charge_level_min</td>
<td>Load energy from the energy storage</td>
</tr>
<tr>
<td>3</td>
<td>Net power &gt; 0 and battery_charge = charge_level_max</td>
<td>Export energy to the external grid</td>
</tr>
<tr>
<td>4</td>
<td>Net power &lt; 0 and battery_charge = charge_level_min</td>
<td>Import energy from the external grid</td>
</tr>
</tbody>
</table>

Table 2.6-1 Definition of flow designations for the Power electronic unit

The energy flow between the blocks according to Figure 2.1-1 is based on four defined working conditions. See Table 2.6-2.

Table 2.6-2 Definition of the four working conditions
*) The net power is the gross power minus the loaded power from the local grid, where the gross power is the sum of the electrical power generated by the Wind power generator(s) and the Sun power generator(s).

The battery_charge corresponds to the energy level in the energy storage.

The charge_level_max and the charge_level_min correspond to the maximum respectively the minimum recommended charge level in the energy storage.

The working conditions are illustrated in Figure 2.6-2 to Figure 2.6-5.

![Energy Flow Diagram](image)

Figure 2.6-2 Energy flow for “Condition 1”.
Figure 2.6-3 Energy flow for "Condition 2".

Figure 2.6-4 Energy flow for "Condition 3".
2.6.1 Capacitor device

The Capacitor device acts as a kind of temporary reservoir and distribution centre regarding the energy flow. It consists of:

- a large capacitor for temporary storing of energy. It connects the five main energy lines: produced wind energy, produced sun energy, energy storage, local grid (load) and external grid (export/import).
- Two power sensors to detect and deliver information about the current produced power.
The voltages UW, US, UB, UL and UE in Figure 2.6-6 are in principle equal regarding the level. In the following text this voltages are also is named the Capacitor device voltage, UC.

### 2.6.2 Energy storage device

The Energy storage device is an adapter unit between the Capacitor device and the Energy storage system. It consists of:

- two DC/DC converters, which are working in opposite directions, depending on the intended working principle:
  - Charging the Energy storage system. The lower DC/DC converter in Figure 2.6-7 is activated by the signal $S_{\text{charge}}$. The Capacitor device voltage ($UB = UC$) is adapted to the energy storage voltage ($U_{\text{storage}}$).
Discharging the Energy storage system. The upper DC/DC converter in Figure 2.6-7 is activated by the signal $S_{\text{discharge}}$. The energy storage voltage ($U_{\text{storage}}$) is adapted to the Capacitor device voltage ($UB = UC$).

![Diagram of Energy storage device with DC/DC converters and power direction arrows.](image)

Figure 2.6-7 Energy storage device. Note: $UB = UC$

### 2.6.3 Local grid device

The Local grid device is an adapter unit between the Capacitor device and the Local grid. It consists of:

- A DC/AC converter. It is activated by the signal $S_{\text{local grid}}$ to support the local grid. The Capacitor device voltage ($UL = UC$) is adapted to the local grid voltage.

- A power sensor to detect and deliver information about the current power to the local grid (signal $S_{p\text{ local grid}}$).
2.6.4 **External grid device**

The External grid device is an adapter unit between the Capacitor device and the External grid. It consists of:

- One DC/AC converter. It is activated by the signal $s_{\text{export}}$ to support the external grid with exported energy. The Capacitor device voltage ($UE = UC$) is adapted to the External grid voltage.

- One AC/DC converter. It is activated by the signal $s_{\text{import}}$ to support PE with imported energy. The External grid voltage is adapted to the Capacitor voltage ($UE = UC$).

- Two power sensors to detect and deliver information about the current exported / imported power to / from the external grid (signal $s_{p \text{ export}} / s_{p \text{ import}}$).
2.6.5 PE-Logic device

The PE-Logic device is the logical unit in PE. The following tasks are controlled by this unit:

- Working conditions. These are controlled by the input signals $S_{pw}$, $S_{ps}$, $S_{p \ local \ grid}$ (result in $Net \ power$) and $S_{storage \ control}$ (result in battery_charge). Together with information about the constants $charge_{level\_max}$ and $charge_{level\_min}$, the appropriate working conditions are determined (see Table 2.6-2). The resulting output signals, based on the current working condition, are $S_{charge}$ (working condition 1), $S_{discharge}$ (working condition 2), $S_{export}$ (working condition 3) and $S_{import}$ (working condition 4).

- Different kind of statistical calculations about the energy production and the energy consumption and different kind of control signals for operator presentation. These are based on the signals $S_{pw}$, $S_{ps}$, $S_{p \ local \ grid}$, $S_{p \ import}$, $S_{p \ export}$ and $S_{control \ 1}$. The output signals are according to Figure 2.6-10 marked with $S_{control \ 2}$.
Figure 2.6-10  PE-Logic device
3 SYSTEM SIMULATION

A simulation system has been developed for performance evaluation of complexed combinations of electric power systems, where wind and sun are energy sources regarding the electric power generation process. The total system is built up by the following parts:

- Wind speed generation (statistical)
- Extinction coefficient generation (statistical)
- Sun irradiance generation (based on the extinction coefficient, local and time dependence and statistical cloud dependence)
- Wind speed to electricity generation (wind generator model)
- Sun irradiance to electricity generation (sun generator model)
- Local grid load (statistical)
- Energy storage
- External grid (for export/import)

The simulation could be processed for an optional number of simulation sequences. A number of 50 to 100 sequences is recommended.

The simulation program, named “Combined_System”, that is developed for analysis of a complexed “Combined Electric Power Generating Systems” according to Figure 2.1-1 consists of a lot of modules. In order to put in adequate examples of parameters to the modules, measurements followed by analyses have been performed regarding:

- Different wind conditions
- Different sun conditions
- Different load conditions

The results of these measurements and analyses are presented in chapter 4 (Wind Power), chapter 5 (Sun Power) and chapter 6 (Electric Load).

The modules that build up the simulation system follow in Table 2.6-1.
<table>
<thead>
<tr>
<th>Modules in the Simulation System</th>
<th>Function</th>
<th>See chapter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind_make</td>
<td>Generate stochastic wind rates to the wind turbines</td>
<td>3.1</td>
</tr>
<tr>
<td>Wind_turbine</td>
<td>Generate electric power from one or a number of wind turbines as a result of the stochastic wind rates</td>
<td>3.2</td>
</tr>
<tr>
<td>Extinction_make</td>
<td>Generate stochastic extinction coefficients to calculate the sun intensity</td>
<td>3.3</td>
</tr>
<tr>
<td>Sun_intensity</td>
<td>Generate to solar cells incoming sun radiation as a result of the extinction coefficients and the sun position relatively the solar cells panels</td>
<td>3.4</td>
</tr>
<tr>
<td>Sun_panel_generator</td>
<td>Generate electric power from a number of solar cells panels as a result of the calculated incoming sun radiation</td>
<td>3.5</td>
</tr>
<tr>
<td>Load_make</td>
<td>Generate a stochastic load on the local grid</td>
<td>3.6</td>
</tr>
<tr>
<td>Connect_Gen_load</td>
<td>Connection of the local grid to the generators (wind and sun). Generate gross power and a net power</td>
<td>3.7</td>
</tr>
<tr>
<td>Battery_Distribution</td>
<td>Connection of the combination energy storage – external grid to the combination local grid - generators (wind and sun)</td>
<td>3.8</td>
</tr>
<tr>
<td>Power_evaluate</td>
<td>Evaluate the result of a simulation process</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Table 2.6-1  The simulation system is built up by 9 modules
Figure 2.6-1 The flow chart of the current simulation system. The total simulation process consists of a number (50 to 100 is recommended) of sequences. Evaluation of the simulation is based on statistics from the total number of sequences.
3.1 Module “Wind_make”

3.1.1 Principle

Wind_make is a program module with the purpose to generate a wind rate vector. The wind rate values, in the following named v_wind, are generated as results of 1) weather variations and 2) turbulences. The total \( v_{\text{wind}} = \text{Level}_W + \text{Level}_T \), where \( \text{Level}_W \) is a result of weather and \( \text{Level}_T \) is a result of turbulence. See Figure 3.1-1.

\[ \begin{align*}
\text{v_wind} & \\
\uparrow & \\
\left\{ \begin{array}{l}
\text{Level}_T \quad (\text{turbulence}) \\
\text{Level}_W \quad (\text{weather situation})
\end{array} \right.
\end{align*} \]

Figure 3.1-1 The wind rate is built up by two components, Level_W and Level_T

The simulation sequence consists of an optional number of simulation steps (Sim_step_total). The sequence is divided into a number of W-cycles, where each cycle is characterized of a “constant” weather situation. See Figure 3.1-2.
A total simulation sequence consists of a number (N) of W-cycles each of them representing a certain weather situation.

As mentioned above, the W-cycle contributes with a dominating “base” component to the wind speed. This base component is named Level_W. This is stochastically generated by a “Weibull distribution” according to:

**Equation 3.1-1:**

$$\text{Level}_W = W(A,B)$$

Where $W$ is a Weibull process and $A$ respectively $C$ are the “Weibull parameters”. A new generation is performed for every W-cycle.

There is a “soft” transition from one W-cycle to another. That means that the final value of Level_W is on hand not until 50% of the time for the W-cycle in question.

The number of simulation steps in a W-cycle, $\text{Sim\_step\_W\_total}$, is stochastically generated in two steps according to:

**Step 1**

**Equation 3.1-2:**

$$\text{Sim\_step\_W\_total\_prel} = N(\text{Sim\_step\_W\_My}, \text{Sim\_step\_W\_Sigma})$$
Where $Sim_{step\_W\_total\_prel}$ is a first preliminary number of simulation steps, $N$ is a normal process and $Sim_{step\_W\_My}$ and $Sim_{step\_W\_Sigma}$ are input parameters corresponding to mean value respectively standard deviation of simulation steps per W-cycle.

Step 2

$Sim_{step\_W\_total\_prel}$ is then adapted to the statistic mean value of simulation steps per T-cycle, $Sim_{step\_T\_My}$, according to:

**Equation 3.1-3:**

$$T_{cycles\_total} = \text{ceil}(Sim_{step\_W\_total\_prel} / Sim_{step\_T\_My}),$$

Where ceil rounds the argument to the nearest integer upwards.

**Equation 3.1-4:**

$$Sim_{step\_W\_total} = T_{cycles\_total} * Sim_{step\_T\_My}$$

Where $Sim_{step\_W\_total}$ is the final value of simulation steps in the W-cycle in question.

Each W-cycle consists of a number of T-cycles. See **Figure 3.1-3**.

---

**Figure 3.1-3**

Every W-cycle is divided into a number (M) of T-cycles each of them representing a certain turbulence situation.
Each T-cycle depends on an individual turbulence situation, that is varied from T-cycle to T-cycle. The contribution, Level_T, to the total wind speed, v_wind (see above), is generated by a “Normal distribution” according to:

**Equation 3.1-5:**

\[ \text{Level}_T = N(\text{Level}_T_{My}, \text{Level}_T_{Sigma}) \]

where \( \text{Level}_T_{My} \) and \( \text{Level}_T_{Sigma} \) are input parameters corresponding to mean value respectively standard deviation of turbulence contribution. \( \text{Level}_T_{My} \) is normaly zero as the turbulence normaly is fluctuating around the zero level.

The generated value of Level_T, is linearly distributed during the first half of the T-cycle. During the second half of the T-cycle the level returns to zero. See **Figure 3.1-4**.

Figure 3.1-4  Distribution of Level_T during the T-cycle

The number of simulation steps for a single T-cycle, \( \text{Sim}_\text{step}_\text{T}_{total} \), is stochastically generated by a “Normal distribution” according to:

**Equation 3.1-6:**

\[ \text{Sim}_\text{step}_\text{T}_{total} = N(\text{Sim}_\text{step}_\text{T}_{My}, \text{Sim}_\text{step}_\text{T}_{Sigma}) \]

Where \( \text{Sim}_\text{step}_\text{T}_{My} \) and \( \text{Sim}_\text{step}_\text{T}_{Sigma} \) are input parameters corresponding to mean value respectively standard deviation of number of simulation steps for the T-cycles.
3.1.2 Input parameters

The input parameters of the routine are specified in Table 3.1-1.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Sim_step_total</td>
<td>The total number of simulation steps per sequence (Sim_step_total = 43200</td>
</tr>
<tr>
<td></td>
<td>corresponds to a simulation sequence over a time of 30 days if Sim_step_sec = 60)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Sim_step_W_My</td>
<td>Mean value of the number of simulation steps per W-cycle (Sim_step_W_My =</td>
</tr>
<tr>
<td></td>
<td>4320 corresponds to a mean value of 3 days (3 times 24 hours) if Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Sim_step_W_Sigma</td>
<td>Standard deviation of the number of simulation steps per W-cycle</td>
</tr>
<tr>
<td>Sim_step_T_My</td>
<td>Mean value of the number of simulation steps per T-cycle (Sim_step_T_My =</td>
</tr>
<tr>
<td></td>
<td>10 corresponds to a mean value of 10 minutes if Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Sim_step_T_Sigma</td>
<td>Standard deviation of the number of simulation steps per T-cycle</td>
</tr>
<tr>
<td>A</td>
<td>Weibull parameter (scale parameter)</td>
</tr>
<tr>
<td>C</td>
<td>Weibull parameter (shape parameter)</td>
</tr>
<tr>
<td>Level_T_Sigma_proc</td>
<td>Standard deviation of Level _T in percent of Level_W</td>
</tr>
<tr>
<td>v_wwind_H</td>
<td>Upper limit of the wind speed</td>
</tr>
<tr>
<td>v_wwind_L</td>
<td>Lower limit of the wind speed</td>
</tr>
<tr>
<td>Wind_speed_file</td>
<td>The name of a Wind speed file (string) to store the wind speed vector and</td>
</tr>
<tr>
<td></td>
<td>the above parameters in this table</td>
</tr>
</tbody>
</table>

Table 3.1-1 Input parameters for routine “Wind_make”

3.1.3 Examples

Table 3.1-2 gives an example of used parameters in a simulation.
A statistically example when using input parameters according to Table 3.1-2 follows in Figure 3.1-5 (the total sequence of 720 hours), Figure 3.1-6 (the first 24 hours) and Figure 3.1-7 (the first 2.4 hours).

Have a look at Figure 3.1-6 and Figure 3.1-7 it can be observed that the turbulence contribution is oscillating around a base level, “above named “Level_W”, of about 4.7 metres per second. This base level is a result of stochastic generation by a Weibull distribution with the parameters A = 7.0 (scale parameter) and C = 2.0 (shape parameter).

For every new W-cycle a new generation of “Level_W” is performed. The resulting variations of base level during the simulation could be seen in Figure 3.1-5.

In Figure 3.1-8 different Weibull density functions are illustrated as functions of different Weibull parameters.

The turbulence contribution is stochastically generated by a Normal (Gauss) distribution. In the current example there has been used a standard deviation (Level_T_Sigma_proc) of 30 %. That means that the standard deviation in question is 30 % of the current base level (“Level_W”), in this case 30 % of about 4.7. As we normally suppose that the turbulence is symmetric around the base level, the stochastically mean level is zero. Figure 3.1-6 and Figure 3.1-7 illustrate the turbulence effect. The top-/bottom level of the triangles (that corresponds to the turbulence contribution), illustrated in Figure 3.1-7, is the level (“Level_T”) that is generated as a result of “Level_T_Sigma_proc”. Figure 3.1-9 gives some examples of Normal density functions with varying standard deviations; 20 %, 30 % and 50 % of “Level_W”. These examples assume a base level of 4.7 m/s (corresponding to the situation in Figure 3.1-7).

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used value in the example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>60</td>
</tr>
<tr>
<td>Sim_step_total</td>
<td>43200</td>
</tr>
<tr>
<td>Sim_step_W_My</td>
<td>4320</td>
</tr>
<tr>
<td>Sim_step_W_Sigma</td>
<td>1500</td>
</tr>
<tr>
<td>Sim_step_T_My</td>
<td>10</td>
</tr>
<tr>
<td>Sim_step_T_Sigma</td>
<td>3</td>
</tr>
<tr>
<td>A</td>
<td>7.0</td>
</tr>
<tr>
<td>C</td>
<td>2.0</td>
</tr>
<tr>
<td>Level_T_Sigma_proc</td>
<td>30.0</td>
</tr>
<tr>
<td>v_wind_H</td>
<td>20.0</td>
</tr>
<tr>
<td>v_wind_L</td>
<td>0.0</td>
</tr>
<tr>
<td>Wind_speed_file</td>
<td>‘Wind_1’</td>
</tr>
</tbody>
</table>

Table 3.1-2 An example of used input parameters for routine “Wind_make”
Figure 3.1-5 Simulated Wind speed for $A = 7$ and $C = 2$.
The total sequence is 720 hours
Figure 3.1-6  Simulated Wind speed for $A = 7$ and $C = 2$. The first 24 hours

Figure 3.1-7  Simulated Wind speed for $A = 7$ and $C = 2$. The first 2.4 hours
Figure 3.1-8 Examples of different Weibull Density Functions

Figure 3.1-9 Normal density functions with varying standard deviations, relating to the parameter “Level_T_Sigma_proc” and the value of “Level_W” = 4.7 m/s. The 30 % curve corresponds to the choseed “Level_T_Sigma_proc” in the simulation according to the example
As mentioned above the length of the time intervals corresponding to each W-cycle and T-cycle are continuously and stochastically generated during the simulation. **Figure 3.1-10** and **Figure 3.1-11** illustrate the Normal density functions that are in questions for these processes.

![Normal Density Functions with different standard deviations](image)

**Figure 3.1-10** Normal density functions with varying standard deviations, relating to the parameter “Sim_step_W_Sigma”. The “Sigma = 1500 steps” curve corresponds to the current the simulation in the example.
Normal density functions with varying standard deviations, relating to the parameter “Sim_step_T_Sigma”. The “Sigma = 3 steps” curve corresponds to the current the simulation in the example.

3.2 Module “Wind_turbine”

3.2.1 Principle

Wind_turbine is a module with the purpose to simulate the electric power generation by one or more wind power turbine(s). The wind rate vector that is generated by the function Wind_make is used as one of the input parameters. To calculate the current wind power the following equation is used (see e.g. Error! Reference source not found.):

\[
P_w = C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot V^3
\]

Where

\(P_w\) : wind power (W)

\(C_p\) : power coefficient
\[ \rho : \text{the air density (} \frac{kg}{m^3} \text{)} \]

\[ A : \text{rootor sweeping area (} m^2 \text{)} \text{ as a result of rootor diameter according to:} \]

**Equation 3.2-2:** \[ A = D_r^2 \cdot \frac{\pi}{4} \]

\[ D_r : \text{rootor diameter (} m \text{)} \]

\[ V : \text{wind speed (} \frac{m}{s} \text{)} \]

\[ \rho \text{ is calculated according to:} \]

**Equation 3.2-3:** \[ \rho = \frac{1.293 \cdot \text{Pair}}{1 + 0.00367 \cdot T_{air} \cdot 1013} \]

Where

\[ T_{air} \text{ is the air temperature in } ^\circ C \]

And

\[ \text{Pair is the air pressure in } mbar \]

The power coefficient \( Cp \) is a function of a parameter \( \lambda \), the so called “tip speed ratio” (\% \) according to:

**Equation 3.2-4:** \[ \lambda = \frac{V_t}{V} \]

Where

\[ V_t \text{ is the wing tip speed (} \frac{m}{s} \text{)} \]

The relation between \( Cp \) and \( \lambda \) is in the routine calculated by a polynom of grade 5 according to:

**Equation 3.2-5:** \[ Cp = 1.142515 - 1.253909 \lambda + 0.478158 \lambda^2 - 0.07554 \lambda^3 + 0.005426 \lambda^4 - 1.4623 \cdot 10^{-4} \lambda^5 \]
This is a result of a polynom adaptation of the relation between $C_p$ and $\lambda$ that is valid at Chalmers Test Wind Turbine at Hönö. See Figure 3.2-1. For measured values see Error! Reference source not found.]. Figure 3.2-1 shows the measured and adapted curves.

![Graph showing measured and adapted curves](image)

Figure 3.2-1 The relation between $C_p$ and $\lambda$ at Chalmers Test Wind Turbine at Hönö. The figure shows the measured respectively the polynom adapted relations

The routine presumes that the turbine, for a given wind speed, will regulate the rotation speed to get that $\lambda$ that results in maximum $C_p$ - value.

The rotation speed is limited by an optional input parameter. That means that the turbine regulation regarding $\lambda$ only will adjust the rotation speed to give $C_p$ - max up to a certain wind speed. If this wind speed is exceeded the $\lambda$ - value will be less than the value that corresponds to $C_p$ - max.
**Figure 3.2-2** illustrates an example of the relation between wind speed and rotor speed. The rotor speed is limited at 85 rpm. Below this limit the control system adjust the rotor speed to get a $\lambda$-value that results in $C_p$ - max. When the rotor speed limit is exceeded the $\lambda$-value decreases continuously according to **Figure 3.2-3**. This will on the other hand decrease the $C_p$ - value (following the relation according to **Figure 3.2-1**) as is shown in **Figure 3.2-4**.

**Figure 3.2-5** presents the electrical output power as a function of current wind speed. The electrical output power could be limited by an input parameter. The figure gives two examples. The solid curve represents the case with a limit of 35 kW. The dashed part gives the power without any limit.

Other input parameters that have been used in the current examples is (see also paragraph 3.2.2):

Number of wind turbines:   1

$\lambda_{REF}$ : 9.0

Where $\lambda_{REF}$ is the $\lambda$-value that gives $C_p$ - max

Mechanical and electrical efficiency $\eta$:  0.85

Where $\eta$ is defined according to the following:

**Equation 3.2-6:**  

$P_E = P_W \cdot \eta$

$P_E$ : Electrical power

$P_W$ : Wind power according to Equation 3.2-1

$T_{air}$ :  15 °C (see Equation 3.2-3)

$P_{air}$ :  1013 mbar (see Equation 3.2-3)

$D_R$ :  13.5 m (see Equation 3.2-2)
Maximum and minimum windrates

- If the wind rate exceeds a certain defined maximum level ($v_{\text{wind\_max}}$) the turbine(s) is (are) stopped, resulting in no output power.

- If the wind rate is lower than a certain defined minimum level ($v_{\text{wind\_min}}$) the turbine(s) does (do) not produce any output power.

Figure 3.2-2 The rotor speed is limited. In this example at 85 rpm
As the rotor speed is limited (85 rpm) the $\lambda$ - value will decrease for rotor speeds that exceed the limit.

As $\lambda$ is decreased for rotor speeds exceeding the rotor speed limit the consequence will be a decreasing $C_p$ - value.
Figure 3.2-5 Resulted electric power as a function of wind speed. The dashed part of the curve corresponds to the circumstances when the electric power is not limited.
### 3.2.2 Input parameters

The input parameters of the module are specified in Table 3.2-1.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>v_wind_vector</td>
<td>Vector with wind rates (per simulation step)</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td></td>
</tr>
<tr>
<td>Turb_numbers</td>
<td>Number of wind turbines</td>
</tr>
<tr>
<td>lambda_ref</td>
<td>The $\lambda$-value that gives $C_p$ - max</td>
</tr>
<tr>
<td>max_power</td>
<td>Limit for electrical output power from one turbine (W)</td>
</tr>
<tr>
<td>rotor_speed_max</td>
<td>Rotation speed limit for the turbine (rpm)</td>
</tr>
<tr>
<td>eta</td>
<td>Mechanical and electrical efficiency</td>
</tr>
<tr>
<td>t_air</td>
<td>The air temperature (°C)</td>
</tr>
<tr>
<td>p_air</td>
<td>The air pressure (mbar)</td>
</tr>
<tr>
<td>d_rootor</td>
<td>Rotor diameter (m)</td>
</tr>
<tr>
<td>v_wind_max</td>
<td>Maximum allowed wind rate (m/s) for function. If this wind rate is exceeded, the wind turbine(s) is (are) stopped</td>
</tr>
<tr>
<td>v_wind_max</td>
<td>Minimum wind rate (m/s) to result in power</td>
</tr>
</tbody>
</table>

Table 3.2-1 Input parameters for module “Wind_turbine”
3.2.3 Examples

Table 3.2-2 gives an example of used parameters in a simulation.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used value in the example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turb_numbers</td>
<td>2</td>
</tr>
<tr>
<td>lambda_ref</td>
<td>9.0</td>
</tr>
<tr>
<td>max_power</td>
<td>50 000</td>
</tr>
<tr>
<td>rotor_speed_max</td>
<td>85</td>
</tr>
<tr>
<td>aeta</td>
<td>0.85</td>
</tr>
<tr>
<td>t_air</td>
<td>15.0</td>
</tr>
<tr>
<td>p_air</td>
<td>1013.0</td>
</tr>
<tr>
<td>d_rootor</td>
<td>13.5</td>
</tr>
<tr>
<td>v_wind_max</td>
<td>25</td>
</tr>
<tr>
<td>v_wind_min</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 3.2-2 An example of used input parameters for module “Wind_turbine”

A statistically example when using input parameters according to Table 3.2-2 follows in Figure 3.2-6 (wind speed, a sequence of 24 hours) and Figure 3.2-7 (electrical output power, a sequence of 24 hours) respectively Figure 3.2-8 (wind speed, the first 2.4 hours of the sequence) and Figure 3.2-9 (electrical output power, the first 2.4 hours of the sequence).
Figure 3.2-6  Wind speed vs time in the current example

Figure 3.2-7  Electric power with wind speeds according to Figure 3.2-6 and Table 3.2-2
Figure 3.2-8 Wind speed vs time. The first 2.4 hours in the current example

Figure 3.2-9 Electric power with wind speeds according to Figure 3.2-8 and Table 3.2-2
3.3 Module “Extinction_make”

3.3.1 Principle

Extinction_make is a module with the purpose to generate an extinction vector. For definition of the parameter “Extinction” (or “Extinction coefficient”) see 3.4.1, Error! Reference source not found. and Error! Reference source not found.

The extinction values, in the following named Ext_T, are generated as results of 1) low frequency variations and 2) high frequency variations. The total Ext_T = Ext_L + Ext_H, where Ext_L is the low frequency contribution and Ext_H is the high frequency contribution. See Figure 3.3-1.

![Diagram](https://via.placeholder.com/150)

**Figure 3.3-1** The extinction is built up by two components, Ext_L and Ext_H

The simulation sequence consists of an optional number of simulation steps (Sim_step_total). The sequence is divided into a number of L-cycles, where each cycle is characterized of a “constant” weather situation. See Figure 3.3-2.
A total simulation sequence consists of a number (M) of L-cycles each of them representing a certain weather situation.

Ext_L is stochastically generated by a “Normal distribution” according to:

\[ Ext_L = N(Ext_L_My, Ext_L_Sigma) \]

Where \( Ext_L_My \) and \( Ext_L_Sigma \) are input parameters corresponding to mean value respectively standard deviation of the low frequency component.

A new generation is performed for every new L-cycle.

There is a “soft” transition from one L-cycle to another. That means that the final value of Ext_L is on hand not until 50 % of the time for the L-cycle in question.

The number of simulation steps in an L-cycle, \( \text{Sim}_\text{step}_L_\text{total} \), is stochastically generated in two steps according to:

**Step 1**

\[ \text{Sim}_\text{step}_L_\text{total}_\text{prel} = N(\text{Sim}_\text{step}_L_\text{My}, \text{Sim}_\text{step}_L_\text{Sigma}) \]

Where \( \text{Sim}_\text{step}_L_\text{total}_\text{prel} \) is a first preliminary number of simulation steps, \( N \) is a normal process and \( \text{Sim}_\text{step}_L_\text{My} \) and \( \text{Sim}_\text{step}_L_\text{Sigma} \) are input parameters corresponding to mean value respectively standard deviation of simulation steps per L-cycle.

**Step 2**

\( \text{Sim}_\text{step}_L_\text{total}_\text{prel} \) is then adapted to the statistic mean value of simulation steps per T-cycle, \( \text{Sim}_\text{step}_T_\text{My} \), according to:
\[ H\_cycles\_total = \text{ceil}\left(\frac{Sim\_step\_L\_total\_prel}{Sim\_step\_H\_My}\right), \]

Where \text{ceil} rounds the argument to the nearest integer upwards.

Finally:

\[ Sim\_step\_L\_total = H\_cycles\_total \times Sim\_step\_H\_My \]

Where \textit{Sim\_step\_L\_total} is the final value of simulation steps in the L-cycle in question.

Each L-cycle consists of a number of H-cycles. See \textbf{Figure 3.3-3}.

![Figure 3.3-3](image)

\textit{Figure 3.3-3} Every L-cycle is divided into a number (N) of H-cycles each of them representing a certain extinction variation

Each H-cycle depends on an individual extinction situation, that is varied from H-cycle to H-cycle. The contribution, \textit{Ext\_H}, to the total extinction, \textit{Ext\_T} (see above), is generated by a “Normal distribution” according to:

\[ Ext\_H = N(Ext\_H\_My, Ext\_H\_Sigma) \]

where \textit{Ext\_H\_My} and \textit{Ext\_H\_Sigma} are input parameters corresponding to mean value respectively standard deviation of high frequency contribution.

The generated value of \textit{Ext\_H} could be distributed according to two alternative methods:
Alternative 1 (step distribution)

The total value of Ext_H is distributed direct at start of the H-cycle and change to a new value direct at start of the next H-cycle. See Figure 3.3-4.

Alternative 2 (triangular distribution)

The value is linearly distributed during the first half of the H-cycle. During the second half of the H-cycle the level returns to zero. See Figure 3.3-5.
Figure 3.3-5 Distribution of Ext_H during the H-cycle at “Triangular distribution”

The number of simulation steps for a single H-cycle, Sim_step_H_total, is stochastically generated by a “Normal distribution” according to:

\[ \text{Sim}_\text{step}_\text{H}\_\text{total} = N(\text{Sim}_\text{step}_\text{H}_\text{My}, \text{Sim}_\text{step}_\text{H}_\text{Sigma}) \]

Where Sim_step_H_My and Sim_step_H_Sigma are input parameters corresponding to mean value respectively standard deviation of number of simulation steps for the H-cycles.

As the H-cycles very often will be used to simulate temporary cloud variations, the H-cycles are to be repeated according to defined stochastic processes. These processes are controlled by a parameter, in the routine named “H_limit”. This parameter will, based on a “Normal distribution”, result in defined possibilities of starting a H-cycle at a given time point. The principle to set the possibility of starting up a H-cycle (at a given time point) is explained by help of the example in Figure 3.3-6. The figure illustrates the so called “Standardized Normal Distribution”. In the figure “H_limit” has been assigned the value 1.5. The possibility to start up a H-cycle at a given time point, in the following named \( P_H \), corresponds to the blacked areas in the figure. In other words:

\[ P_H(\text{H_limit}) = 2 \cdot (1 - F(\text{H_limit})) \]

Where

\( F(x) \) is the integrated distributed function of a standardized Normal random variable.
$H_{\text{limit}} = 1.5$ results in $P_H = 13.36\%$.

Suppose that there (as an example) is a cloudiness of $\frac{2}{8}$. A good modeling of this regarding parameter “$H_{\text{limit}}$” is the following:

Cloudiness: $\frac{2}{8} = 0.25$

This corresponds to a possibility for cloud of about 25\%.

The inverse of $P_H(H_{\text{limit}}) = 25\%$ results in $H_{\text{limit}} = 1.15$

Following this principle for other values of the cloudiness results in the relation between $H_{\text{limit}}$ and cloudiness according to Table 3.3-1.

Figure 3.3-7 shows $P_H$ as a function of $H_{\text{limit}}$.

![The standardized normal distribution](image)

Figure 3.3-6 The parameter H-limit is in this example 1.5. $P_H$ corresponds to the blacked areas, that is the same as 13.36\% of the total area
Figure 3.3-7  $P_H$ as a function of $H_{limit}$

<table>
<thead>
<tr>
<th>Cloudiness</th>
<th>P(cloud) (%)</th>
<th>$H_{limit}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>12.5</td>
<td>1.534</td>
</tr>
<tr>
<td>2/8</td>
<td>25.0</td>
<td>1.150</td>
</tr>
<tr>
<td>3/8</td>
<td>37.5</td>
<td>0.887</td>
</tr>
<tr>
<td>4/8</td>
<td>50.0</td>
<td>0.674</td>
</tr>
<tr>
<td>5/8</td>
<td>62.5</td>
<td>0.489</td>
</tr>
<tr>
<td>6/8</td>
<td>75.0</td>
<td>0.319</td>
</tr>
<tr>
<td>7/8</td>
<td>87.5</td>
<td>0.157</td>
</tr>
<tr>
<td>8/8</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3.3-1  $H_{limit}$ as a function of cloudiness

For further information about the extinction model see [2].
### 3.3.2 Input parameters

The input parameters of the routine are specified in Table 3.3-2.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Sim_step_total</td>
<td>The total number of simulation steps per sequence (Sim_step_total = 43200corresponds to a simulation sequence overa time of 30 days if Sim_step_sec = 60)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Sim_step_L_My</td>
<td>Mean value of the number of simulation steps per L-cycle (Sim_step_L_My = 4320corresponds to a mean value of 3 days (3times 24 hours) if Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Sim_step_L_Sigma</td>
<td>Standard deviation of the number of simulation steps per L-cycle</td>
</tr>
<tr>
<td>Sim_step_H_My</td>
<td>Mean value of the number of simulation steps per H-cycle (Sim_step_H_My = 10corresponds to a mean value of 10 minutesif Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Sim_step_H_Sigma</td>
<td>Standard deviation of the number of simulation steps per H-cycle</td>
</tr>
<tr>
<td>Ext_L_My</td>
<td>Mean value of the low frequency contribution of the extinction coefficient</td>
</tr>
<tr>
<td>Ext_L_Sigma</td>
<td>Standard deviation of the low frequency contribution of the extinction coefficient</td>
</tr>
<tr>
<td>Ext_H_My</td>
<td>Mean value of the high frequency contribution of the extinction coefficient</td>
</tr>
<tr>
<td>Ext_H_Sigma</td>
<td>Standard deviation of the high frequency contribution of the extinction coefficient</td>
</tr>
<tr>
<td>Ext_T_High</td>
<td>Upper limit for the total extinction value</td>
</tr>
<tr>
<td>Ext_T_Low</td>
<td>Lower limit for the total extinction value</td>
</tr>
<tr>
<td>H_limit</td>
<td>Parameter to control the possibility that a single H-cycle shall be processed. See above</td>
</tr>
</tbody>
</table>
| Ext_H_onestep        | Parameter to control the distribution of Ext_H during a H-cycle. Ext_H_onestep = 1 results in “step
Extinction_file

The name of an Extinction file (string) to store the extinction vector and the above parameters in this table

### Table 3.3-2
<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used value in the examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>60</td>
</tr>
<tr>
<td>Sim_step_total</td>
<td>1440</td>
</tr>
<tr>
<td>Sim_step_L_My</td>
<td>240</td>
</tr>
<tr>
<td>Sim_step_L_Sigma</td>
<td>60</td>
</tr>
<tr>
<td>Sim_step_H_My</td>
<td>10</td>
</tr>
<tr>
<td>Sim_step_H_Sigma</td>
<td>4</td>
</tr>
<tr>
<td>Ext_L_My</td>
<td>0.4</td>
</tr>
<tr>
<td>Ext_L_Sigma</td>
<td>0.2</td>
</tr>
<tr>
<td>Ext_H_My</td>
<td>3.</td>
</tr>
<tr>
<td>Ext_H_Sigma</td>
<td>1.</td>
</tr>
<tr>
<td>Ext_T_High</td>
<td>10.</td>
</tr>
<tr>
<td>Ext_T_Low</td>
<td>0.32</td>
</tr>
<tr>
<td>H_limit</td>
<td>1.534 alt 0.674</td>
</tr>
<tr>
<td>Ext_H_onestep</td>
<td>1 alt 0</td>
</tr>
<tr>
<td>Extinction_file</td>
<td>‘Ext_1’</td>
</tr>
</tbody>
</table>

### Table 3.3-3
Examples of used input parameters for module “Extinction_make”

#### 3.3.3 Examples

Table 3.3-3 gives examples of used parameters in a simulation.
The example according to Table 3.3-3 has some alternatives regarding parameters $H_{limit}$ and $Ext_{H\_onestep}$. The different results are illustrated in Figure 3.3-8, Figure 3.3-9 (the first to hours), Figure 3.3-10 (the total simulation of 24 hours) and Figure 3.3-11 (the total simulation of 24 hours).

**Figure 3.3-8**

- $H_{limit} = 1.534$ (corresponding to a cloudiness of 1/8)
- $Ext_{H\_onestep} = 0$ (“Triangular distribution” of the H-cycle)
Figure 3.3-9 \[ H_{\text{limit}} = 1.534 \] (corresponding to a cloudiness of 1/8)
\[ \text{Ext}_H_{\text{onestep}} = 1 \] (“Step distribution” of the H-cycle)

Figure 3.3-10 \[ H_{\text{limit}} = 1.534 \] (corresponding to a cloudiness of 1/8)
\[ \text{Ext}_H_{\text{onestep}} = 0 \] (“Step distribution” of the H-cycle)
Figure 3.3-11  \( H_{\text{limit}} = 0.674 \) (corresponding to a cloudiness of 4/8)
\( Ext\_H_{\text{onestep}} = 1 \) ("Step distribution" of the H-cycle)

3.4 Module "Sun_intensity"

3.4.1 Principle

Sun_intensity is a program module with the purpose to generate an irradiance vector. The term "sun irradiance" refers in this case to the sun power density (W per square meter) that is coming in to a defined surface, in the following named Measuring surface, at earth level, that have a specified direction to the sun.

The irradiance values, in the following named Radiation, are generated as results of:

- The sun angle to zenith
- The angle relative to the sun of the surface in question
- The transmission properties of the atmosphere
- Properties regarding clear view between the sun and the surface in question

The sun position (angle to zenith and angle to south) is calculated as a result of the following:
The local position (latitude and longitude)

- The date
- The time

The angle between the direction to the sun and the normal of the measuring surface is calculated as a function of the sun position and specified angle values regarding the surface normal to south and to zenith.

The transmission properties of the atmosphere is calculated by use of the extinction vector, that is generated by the routine “Extinction_make” (see chapter 3.3).

Properties regarding clear view between the sun and the measuring surface. This depends on the sun position relative to different objects that could block the view between the sun and the surface in question. This also includes the time interval when the sun is below the horizon.

To calculate the effective irradiance against the measuring surface the following calculation sequence is:

**Equation 3.4-1**

\[ UT = start\_hour + \frac{time\_counter}{60} \cdot count\_interval \]  

(in hours + decimals)

Where:

- **start_hour**: start hour for the simulation (0 if the simulation will start at midnight)
- **count_interval**: simulation interval per step. This parameter is specified in minutes or parts of a minute
- **time_counter**: the simulation step in question. This parameter will step from 1 up to an upper limit named **time_counter_limit**

\[ time\_counter\_limit = 60 \cdot (stop\_hour − start\_hour)/count\_interval \]

Where

- **stop_hour**: stop hour for the simulation (24 if the simulation is to be performed during 24 hours, 240 if the simulation is to be performed during 10 days, and so on)
Equation 3.4-2

\[ d = 367 \cdot y - \text{floor} \left( 7 \cdot (y + \text{floor} \left( \frac{(m + 9)}{12} \right)) / 4 \right) + \text{floor} \left( \frac{275 \cdot m}{9} \right) + D - 730530 + UT / 24 \]

Where

\( y \): the year in question (e.g. 2006)
\( m \): the month in question (month number)
\( D \): date (day number in the month)

This specification of \( d \) results in that day 0 will occur at 2000, Jan 01, 00.00 (or 1999, Dec 31, 24.00).

Note: floor(x) rounds “x” down to the nearest integer.

Equation 3.4-3

\[ ecl = 23.4393 - 3.563e - 7 \cdot d \]

Where

\( ecl \): “the obliquity of the ecliptic”, i.e. the “tilt” of the Earth’s axis of rotation (currently ca 23.4 degrees and slowly decreasing)

Orbital elements of the Sun

These elements is partly used in the calculation of the sun position:

\( N \): longitude of the ascending node
\( i \): inclination to the ecliptic (plane of the Earth’s orbit)
\( w \): argument of perihelion
\( a \): semi-major axis, or mean distance from Sun
\( e \): eccentricity (0=circle, 0-1=ellipse, 1=parabola)
\( M \): mean anomaly (0 at perihelion; increase uniformly with time)

In this case the following is on hand:
Compute the eccentric anomaly $E$ from the mean anomaly $M$ and from the eccentricity $e$ ($E$ and $M$ in degrees):

**Equation 3.4-4**

$$E = M + e \cdot \left( \frac{180}{\pi} \right) \cdot \sin \left( \frac{M}{180} \pi \right) \cdot \left( 1.0 + e \cdot \cos \left( \frac{M}{180} \pi \right) \right)$$

Compute the Sun’s distance $r$ and its true anomaly $v$ from:

**Equation 3.4-5**

$$X_v = r \cdot \cos \left( \frac{v}{180} \pi \right) = \cos \left( \frac{E}{180} \pi \right) - e$$

**Equation 3.4-6**

$$Y_v = r \cdot \sin \left( \frac{v}{180} \pi \right) = \sqrt{1.0 - e^2} \cdot \sin \left( \frac{E}{180} \pi \right)$$

**Equation 3.4-7**

$$v = a \tan2(Y_v, X_v) \cdot \frac{180}{\pi} \quad \text{(degrees)}$$

**Equation 3.4-8**

$$r = \sqrt{X_v^2 + Y_v^2}$$

Note: $\tan2$ is a function that converts a coordinate pair to the correct angle in all four quadrants.

Compute the Sun’s true longitude, $l_{\text{sun}}$:
Equation 3.4-9
\[ lonsun = v + w \] (degrees)

Convert lonsun and r to ecliptic rectangular geocentric coordinates \( Xs \) and \( Ys \)

Equation 3.4-10
\[ Xs = r \cdot \cos \left( \frac{lonsun}{180} \pi \right) \]

Equation 3.4-11
\[ Ys = r \cdot \sin \left( \frac{lonsun}{180} \pi \right) \]

As the Sun is in the ecliptic plane, \( Zs \) is zero. \( Xs \) and \( Ys \) is the Sun’s position in a coordinate system in the plane of the ecliptic.

Convert to equatorial, rectangular, geocentric coordinates:

Equation 3.4-12
\[ Xe = Xs \]

Equation 3.4-13
\[ Ye = Ys \cdot \cos \left( \frac{ecl}{180} \pi \right) \]

Equation 3.4-14
\[ Ze = Ys \cdot \sin \left( \frac{ecl}{180} \pi \right) \]

Compute the Sun’s Right Ascension (RA) and Declination (Dec):

Equation 3.4-15
\[ RA = a \tan 2(Ye, Xe) \cdot \frac{180}{\pi} \] (degrees)
Equation 3.4-16

\[ Dec = a \tan 2 \left( Z \epsilon, \frac{\sqrt{X e^2 + Y e^2}}{\pi} \right) \left( \frac{180}{\pi} \right) \] (degrees)

Compute the Sun’s mean longitude, \( L \):

Equation 3.4-17

\[ L = M + w \] (degrees)

Compute “the Sidereal Time at Greenwich”, \( GMST_0 \), at 00:00 “Universal Time”:

Equation 3.4-18

\[ GMST_0 = L + 180 \] (degrees)

\( GMST_0 \) is expressed in degrees to simplify the computations. \( GMST_0 = 360 \) degrees corresponds to 24 hours, i.e. each hour corresponds to 15 degrees.

Compute “the Local Sidereal Time, \( LST \):

Equation 3.4-19

\[ LST = GMST_0 + UT \cdot 15.0 + long \] (degrees)

Where

\( UT : \) "Universal Time" expressed in hours + decimals

\( Long : \) local longitude in degrees. East longitude counts as positive and west longitude as negative
Compute “the Sun’s Local Hour Angle, LHA, i.e. the angle the Earth has turned since the Sun last was in the south:

**Equation 3.4-20**

$LHA = LST - RA$

Compute the Sun’s altitude above the horizon, $\alpha$:

**Equation 3.4-21**

$$\sin_\alpha = \cos\left(\frac{\text{Dec}}{180} \pi\right) \cdot \cos\left(\frac{\text{lat}}{180} \pi\right) \cdot \cos\left(\frac{\text{LHA}}{180} \pi\right) + \sin\left(\frac{\text{Dec}}{180} \pi\right) \cdot \sin\left(\frac{\text{lat}}{180} \pi\right)$$

Where

$\text{lat}$: the latitude in question

**Equation 3.4-22**

$$\alpha = \arcsin(\sin_\alpha)$$

(radians)

Compute the Sun’s azimuth, $az$

**Equation 3.4-23**

$$\cos_\text{az} = \frac{\cos\left(\frac{\text{Dec}}{180} \pi\right) \cdot \sin\left(\frac{\text{lat}}{180} \pi\right) \cdot \cos\left(\frac{\text{LHA}}{180} \pi\right) - \sin\left(\frac{\text{Dec}}{180} \pi\right) \cdot \cos\left(\frac{\text{lat}}{180} \pi\right)}{\cos(\alpha)}$$

**Equation 3.4-24**

$$az = \arccos(\cos_\text{az})$$

(radians)
Compute the “atmospheric depth” as a function of the Sun’s altitude above the horizon, $\alpha$:

**Equation 3.4-25**

$$M_{\text{atm}} = \frac{1}{\sin(\alpha)}$$

Where

$M_{\text{atm}}$ : the atmospheric depth relative to the depth when the Sun is in zenith

$$\alpha = \frac{\pi}{2}$$

Compute the atmospheric transmission, $\tau$:

**Equation 3.4-26**

$$\tau = \exp\left(-\text{Extinction} \cdot M_{\text{atm}}\right)$$

Where

Extinction : extinction coefficient for the atmospheric depth when the Sun is in zenith

Compute the Sun irradiation that is incoming to the measuring surface:

**Equation 3.4-27**

$$\text{Radiation}_A = \tau \cdot \text{Radiation}_{\text{ref}}$$

Where

Radiation$_{\text{ref}}$ : Sun irradiation before passing the atmosphere
Radiation_\text{A} \text{: Sun irradiation after passing the atmosphere}

Compute the angle, \( \beta \), between the direction to the Sun and the measuring surface normal (the surface that corresponds to the solar cell panel):

**Equation 3.4-28**

\[
\cos \beta = \sin(\alpha) \cdot \cos \left( \frac{S_{\text{rel}}}{180} \pi \right) + \cos(\alpha) \cdot \sin \left( \frac{S_{\text{rel}}}{180} \pi \right) \cdot \cos \left( \pi - \frac{S_{\text{rel}}}{180} \pi \right)
\]

Where

- \( S_{\text{rel}} \): the normal angle of the measuring surface relative to zenith
- \( S_{\text{rel}} \): the normal angle of the measuring surface relative to south

**Equation 3.4-29**

\[
\beta = \arccos(\cos \beta)
\]

Compute the "effective irradiation" from the Sun against the measuring surface as a function of the angle \( \beta \):

**Equation 3.4-30**

\[
\text{Radiation}_B = \text{Radiation}_A \cdot \cos \beta
\]

Where

- \( \text{Radiation}_A \): to the surface incoming irradiation
- \( \text{Radiation}_B \): effective part of irradiation
**Function for “Sun Tracking”**

There is a function in the routine that simulates so called “Sun Tracking”. This means that the measuring surface follows the Sun position, i.e. the angle, \( \beta \), is assigned the value zero. To get “Sun Tracking” activated the parameter “Tracking” should be assigned the value 1.

**Properties regarding clear view between the sun and the measuring surface**

If there is no clear view between the sun and the measuring surface the calculated irradiance is assigned the value zero. Two equations should be fulfilled for clear view:

**Equation 3.4-31** \( \alpha \geq \alpha_{\min} \)

**Equation 3.4-32** \( \alpha_{\min} \leq \alpha \leq \alpha_{\max} \)

Where

\( \alpha \): Sun’s altitude above the horizon

\( \alpha_{\min} \): under limit for the altitude of the Sun to be visible

\( \alpha_{\max} \): upper limit for the azimuth of the Sun to be visible

\( \alpha_{\min} \): under limit for the azimuth of the Sun to be visible

**3.4.2 Input parameters**

The input parameters of the module are specified in Table 3.4-1.
<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Sim_step_total</td>
<td>The total number of simulation steps per sequence (Sim_step_total = 43200 corresponds to a simulation sequence over a time of 30 days if Sim_step_sec = 60)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Ext_T_vector</td>
<td>Vector with extinction coefficients (per simulation step)</td>
</tr>
<tr>
<td></td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>y</td>
<td>Start year for simulation</td>
</tr>
<tr>
<td>m</td>
<td>Start month for simulation</td>
</tr>
<tr>
<td>D</td>
<td>Start date for simulation</td>
</tr>
<tr>
<td>long</td>
<td>Longitude</td>
</tr>
<tr>
<td>lat</td>
<td>Latitude</td>
</tr>
<tr>
<td>start_hour</td>
<td>Start hour for simulation</td>
</tr>
<tr>
<td>Surface_rel_S</td>
<td>The normal of the measuring surface relative to south (degrees). If no “tracking”</td>
</tr>
<tr>
<td>Surface_rel_Z</td>
<td>The normal of the measuring surface relative to zenith (degrees). If no “tracking”</td>
</tr>
<tr>
<td>Radiation_ref</td>
<td>The sun irradiance before passing the atmosphere (W/m²)</td>
</tr>
<tr>
<td>azimuth_min</td>
<td>Under limit for the azimuth of the Sun to be visible</td>
</tr>
<tr>
<td>azimuth_max</td>
<td>Upper limit for the azimuth of the Sun to be visible</td>
</tr>
<tr>
<td>alpha_min</td>
<td>Under limit for the altitude of the Sun to be visible</td>
</tr>
<tr>
<td>Tracking</td>
<td>If “Tracking” = 1 then the measuring surface follows the Sun position (“sun tracking”)</td>
</tr>
</tbody>
</table>

Table 3.4-1  Input parameters for module “Sun_intensity”
### 3.4.3 Examples

Table 3.4-2 gives examples of used parameters in a simulation.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used value in the examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>60</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td></td>
</tr>
<tr>
<td>Sim_step_total</td>
<td>1440 (corresponds to 24 hours simulation per sequence)</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td>525600 (corresponds to 365 days simulation per sequence)</td>
</tr>
<tr>
<td>y</td>
<td>2006</td>
</tr>
<tr>
<td>m</td>
<td>3, 6, 12</td>
</tr>
<tr>
<td>D</td>
<td>21</td>
</tr>
<tr>
<td>long</td>
<td>11.97, 20.22, 36.83</td>
</tr>
<tr>
<td>lat</td>
<td>57.72, 67.85, -1.28</td>
</tr>
<tr>
<td>start_hour</td>
<td>0</td>
</tr>
<tr>
<td>Surface_rel_S</td>
<td>0.</td>
</tr>
<tr>
<td>Surface_rel_Z</td>
<td>45.</td>
</tr>
<tr>
<td>Radiation_ref</td>
<td>1367.</td>
</tr>
<tr>
<td>azimuth_min</td>
<td>-90.</td>
</tr>
<tr>
<td>azimuth_max</td>
<td>90.</td>
</tr>
<tr>
<td>alpha_min</td>
<td>0.</td>
</tr>
<tr>
<td>Tracking</td>
<td>0, 1</td>
</tr>
</tbody>
</table>

Table 3.4-2 Examples of used input parameters for module “Sun_intensity”
3.4.3.1 Different localities and seasons

Table 3.4-3 and Table 3.4-4 specifies three localities respectively three seasons that have been compared regarding different conditions for Sun irradiation. Some results follow in Figure 3.4-1, Figure 3.4-2 and Figure 3.4-3 and Table 3.4-5, Table 3.4-6, and Table 3.4-7. In the figures follow the Sun irradiation as a function of time during the day. The tables give the integrated irradiation during the day. In these examples the extinction coefficient consequently has been assumed to 0.3126. This extinction value results in an irradiance at sea level of 1000 W/m², if the Sun is at zenith (Radiation_ref = 1367 according to Table 3.4-2).

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude (degrees)</th>
<th>Longitude (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nairobi</td>
<td>-1.283</td>
<td>36.833</td>
</tr>
<tr>
<td>Kiruna</td>
<td>67.850</td>
<td>20.217</td>
</tr>
<tr>
<td>Göteborg</td>
<td>57.710</td>
<td>11.968</td>
</tr>
</tbody>
</table>

Table 3.4-3 The different places that have been studied regarding Sun irradiation

Note! To get a more clear curve illustration, the time scale in the figures have been adapted to local time in Göteborg.

<table>
<thead>
<tr>
<th>Season</th>
<th>Month</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td>June</td>
<td>20</td>
</tr>
<tr>
<td>Autumn</td>
<td>September</td>
<td>20</td>
</tr>
<tr>
<td>Winter</td>
<td>December</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 3.4-4 The different seasons that have been studied regarding Sun irradiation
Figure 3.4-1  Effective irradiance for alternating localities.
Date: 20 June 2006. See Table 3.4-5

<table>
<thead>
<tr>
<th>Curve identifier</th>
<th>Locality</th>
<th>Integration (kWh / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'.…….'</td>
<td>Nairobi</td>
<td>8.42</td>
</tr>
<tr>
<td>'.-.-.-.-.'</td>
<td>Kiruna</td>
<td>11.77</td>
</tr>
<tr>
<td>'_____.'</td>
<td>Göteborg</td>
<td>11.11</td>
</tr>
</tbody>
</table>

Table 3.4-5  Curve identifier and integrated irradiances. 20 June.
Figure 3.4-2 Effective irradiance for alternating localities.
Date: 20 September 2006. See Table 3.4-6

<table>
<thead>
<tr>
<th>Curve identifier</th>
<th>Locality</th>
<th>Integration (kWh / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'……..'</td>
<td>Nairobi</td>
<td>8.89</td>
</tr>
<tr>
<td>'.-.-.-.'</td>
<td>Kiruna</td>
<td>4.60</td>
</tr>
<tr>
<td>'_____.'</td>
<td>Göteborg</td>
<td>6.20</td>
</tr>
</tbody>
</table>

Table 3.4-6 Curve identifier and integrated irradiances. 20 September
Figure 3.4-3 Effective irradiance for alternating localities.
Date: 20 December 2006. See Table 3.4-7

<table>
<thead>
<tr>
<th>Curve identifier</th>
<th>Locality</th>
<th>Integration (kWh / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'……..'</td>
<td>Nairobi</td>
<td>8.61</td>
</tr>
<tr>
<td>'.-.-.-.'</td>
<td>Kiruna</td>
<td>0</td>
</tr>
<tr>
<td>'_____.'</td>
<td>Göteborg</td>
<td>0.54</td>
</tr>
</tbody>
</table>

Table 3.4-7 Curve identifier and integrated irradiance. 20 December.
Note! Sun not over the horizon in Kiruna
### 3.4.3.2 Integrating irradiances per month and summed over 12 month

For calculated integrated irradiances See Table 3.4-8 and Figure 3.4-4.

<table>
<thead>
<tr>
<th>Month</th>
<th>Integrated irradiance (kWh/m²) Nairobi</th>
<th>Integrated irradiance (kWh/m²) Göteborg</th>
<th>Integrated irradiance (kWh/m²) Kiruna</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>260.36</td>
<td>32.06</td>
<td>0.16</td>
</tr>
<tr>
<td>February</td>
<td>264.96</td>
<td>91.08</td>
<td>27.43</td>
</tr>
<tr>
<td>Mars</td>
<td>266.68</td>
<td>165.52</td>
<td>111.65</td>
</tr>
<tr>
<td>April</td>
<td>263.51</td>
<td>244.25</td>
<td>218.98</td>
</tr>
<tr>
<td>May</td>
<td>257.33</td>
<td>302.48</td>
<td>304.27</td>
</tr>
<tr>
<td>June</td>
<td>253.12</td>
<td>330.93</td>
<td>348.99</td>
</tr>
<tr>
<td>July</td>
<td>255.08</td>
<td>318.29</td>
<td>328.74</td>
</tr>
<tr>
<td>Augusty</td>
<td>261.27</td>
<td>269.22</td>
<td>254.84</td>
</tr>
<tr>
<td>September</td>
<td>266.08</td>
<td>197.15</td>
<td>153.59</td>
</tr>
<tr>
<td>Oktober</td>
<td>266.05</td>
<td>117.67</td>
<td>53.70</td>
</tr>
<tr>
<td>November</td>
<td>261.92</td>
<td>47.57</td>
<td>2.42</td>
</tr>
<tr>
<td>December</td>
<td>258.61</td>
<td>18.41</td>
<td>0</td>
</tr>
<tr>
<td>Total year</td>
<td>3135</td>
<td>2135</td>
<td>1805</td>
</tr>
</tbody>
</table>

Table 3.4-8 Integrated irradiance per month and summed over 12 month
3.4.3.3 Toplevels of irradiances over a year

Calculated toplevels of irradiances over a year for Göteborg, Kiruna and Nairobi are illustrated in Figure 3.4-5, Figure 3.4-6 and Figure 3.4-7.
Figure 3.4-5  Top level irradiance vs day over a year. Göteborg

Figure 3.4-6  Top level irradiance vs day over a year. Kiruna
3.4.3.4 Different angles between measuring surface and zenith respectively ”Sun Tracking”

Figure 3.4-8 (June) and Figure 3.4-10 (September) illustrate the dependence on the effective irradiance when the measuring surface relative zenith alternates. The angle between the measuring surface (normal) and South has been assigned to zero. Figure 3.4-9 (June) and Figure 3.4-11 (September) show the corresponding results if “Sun Tracking” is used. The integrated irradiances follow in Table 3.4-9 (June) and Table 3.4-10 (September).

The locality in these calculations has been Göteborg.

In could bee interesting to compare the results between $Surface_{rel,Z} = 0$ respectively $Surface_{rel,Z} = 90$ from the two sesons. In June $Surface_{rel,Z} = 0$ is much to prefere before $Surface_{rel,Z} = 90$ while in September $Surface_{rel,Z} = 90$ is much to prefere before $Surface_{rel,Z} = 0$. This is of course an effect of the lower Sun altitude over the horizon in September compared with in June.

An imported point to observe is the great power increase that is on hand by using “Sun Tracking”.

Figure 3.4-7 Top level irradiance vs day over a year. Nairobi
Figure 3.4-8 Effective irradiance for alternating angle of the measuring surface relative zenith. 20 June 2006. Göteborg. See Table 3.4-9

<table>
<thead>
<tr>
<th>Curve identifier (Figure 3.4-8)</th>
<th>Surface_rel_Z</th>
<th>Integration (kWh / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘…….’</td>
<td>0</td>
<td>6.91</td>
</tr>
<tr>
<td>‘-.-.-.’</td>
<td>45</td>
<td>6.89</td>
</tr>
<tr>
<td>‘__ __’</td>
<td>75</td>
<td>4.74</td>
</tr>
<tr>
<td>‘_____’</td>
<td>90</td>
<td>3.23</td>
</tr>
<tr>
<td>See Figure 3.4-9</td>
<td>‘Sun Tracking’</td>
<td>11.11</td>
</tr>
</tbody>
</table>

Table 3.4-9 Integrated irradiance for different surface angles rel zenith. 20 June 2006. Göteborg
Figure 3.4-9  Effective irradiance if “Sun Tracking” is used. 20 June 2006. Göteborg
Figure 3.4-10  Effective irradiance for alternating angle of the measuring surface relative zenith. 20 September 2006. Göteborg. See Table 3.4-10

<table>
<thead>
<tr>
<th>Curve identifier (Figure 3.4-10)</th>
<th>Surface_rel_Z</th>
<th>Integration (kWh / m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'……..'</td>
<td>0</td>
<td>2.71</td>
</tr>
<tr>
<td>'-.-.-.-'</td>
<td>45</td>
<td>4.79</td>
</tr>
<tr>
<td>'___ __'</td>
<td>75</td>
<td>4.63</td>
</tr>
<tr>
<td>'______'</td>
<td>90</td>
<td>4.07</td>
</tr>
<tr>
<td>See Figure 3.4-11</td>
<td>“Sun Tracking”</td>
<td>6.20</td>
</tr>
</tbody>
</table>

Table 3.4-10  Integrated irradiance for different surface angles rel zenith. 20 September 2006. Göteborg
3.5 Module “Sun_panel_generator”

3.5.1 Principle

“Sun_panel_generator” is a program module that generates the electric power from a number of solar panels that are radiated by sun irradiation. The program function has as input an irradiation vector, named “Radiation_vector” that is generated by the routine “Sun_Intensity”. The output from the routine “Sun_panel_generator” is a vector, called “P_sun_el_vector”, with electric power values for the different time steps. The calculation is according the following (for further details see Error! Reference source not found. and Error! Reference source not found.):
Equation 3.5-1:

\[
P_{\text{sun_el_vector}}(\text{time_step}) = \text{Radiation\_vector}(\text{time\_step}) \cdot \text{Sun\_panel\_area} \cdot \cdot \cdot \text{Power\_factor\_cells} \cdot \text{Power\_factor\_MPP} \cdot \text{Power\_factor\_electr} / 1000 \quad (kW)
\]

Where:

- \( P_{\text{sun_el_vector}} \): vector with generated power from the solar cells generator (kW)
- \( \text{time\_step} \): current time step (dimension less)
- \( \text{Radiation\_vector} \): vector with irradiation values \((W / m^2)\)
- \( \text{Sun\_panel\_area} \): total solar cell area \((m^2)\)
- \( \text{Power\_factor\_cells} \): The efficiency of the solar cells (radiated power to electric power) \((0 - 1)\)
- \( \text{Power\_factor\_MPP} \): The efficiency to adapt the working point to the most effective one, called Maximum Power Point \((0 - 1)\). A perfect adaption results in \( \text{Power\_factor\_MPP} = 1 \)
- \( \text{Power\_factor\_electr} \): The efficiency of the power electronics \((0 - 1)\)

3.5.2 Input parameters

The input parameters of the routine are specified in Table 3.5-1.
<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation_vector</td>
<td>Vector with irradiation (effective to the solar cells) (per simulation step)</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td></td>
</tr>
<tr>
<td>Power_factor_cells</td>
<td>The efficiency of the solar cells (radiated power to electric power) (0 - 1)</td>
</tr>
<tr>
<td>Power_factor_MPP</td>
<td>The efficiency to adapt the working point to the most effective one, called Maximum Power Point (0 – 1). A perfect adaption, results in Power_factor_MPP = 1</td>
</tr>
<tr>
<td>Power_factor_electr</td>
<td>The efficiency of the power electronics (0 – 1)</td>
</tr>
<tr>
<td>Sun_panel_area</td>
<td>total solar cell area (m²)</td>
</tr>
</tbody>
</table>

Table 3.5-1 Input parameters for module “Sun_panel_generator”

3.5.3 Examples

Table 3.5-2 gives an example of used parameters in a simulation.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used value in the example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power_factor_cells</td>
<td>0.15</td>
</tr>
<tr>
<td>Power_factor_MPP</td>
<td>0.95</td>
</tr>
<tr>
<td>Power_factor_electr</td>
<td>0.95</td>
</tr>
<tr>
<td>Sun_panel_area</td>
<td>800</td>
</tr>
</tbody>
</table>

Table 3.5-2 Examples of used parameters in a simulation.

The resulted output power from the Sun power generator with values according to Table 3.5-1 and irradiances as in Figure 3.5-1 follow in Figure 3.5-2.
Figure 3.5-1  An example of irradiances during a period of 24 hours

Figure 3.5-2  The resulted power from the sun power generator when using the parameters in Table 3.5-2 together with the irradiances according to Figure 3.5-1
3.6 Module “Load_make”

3.6.1 Principle

3.6.1.1 Common

“Load_make” is a program module that generates a stochastic model of a grid load that is connected to the Wind generator(s), the Sun generator(s) and the energy storage. This load corresponds to the load of the local grid.

3.6.1.2 Base values and day time points

The routine works with 6 separated day time points, TP_0 – TP_5. TP_0 is defined as midnight (0 or 24). TP_1 – TP_5 should be defined as input values. The routine also uses 4 primary base power levels, A_prim, B_prim, C_prim and D_prim, that are related to the time points according to:

- A_prim: base power at TP_0
- B_prim: base power at TP_1 to TP_2
- C_prim: base power at TP_3 to TP_4
- D_prim: base power at TP_5

That means that the primary base levels follow the following sequence for a 24 hours cycle:

A_prim(at TP_0) – B_prim (at TP_1) – B_prim (at TP_2) – C_prim(at TP_3) – C_prim(at TP_4) – D_prim(at TP_5) – A_prim back to a new 24 hours cycle, TP_0.

The shifts between the 4 base power levels are performed linearly.

3.6.1.3 Stochastic variations

3.6.1.3.1 Low frequency variations

The 4 primary base power levels undergo a stochastic variation according a Normal (Gauss) process. This stochastic variation are performed once per 24 hours cycle. This variation is named “the low frequency” variation. The statistic parameters are named “L_My_L” and “L_sigma_L” (the first L stands for Load and the second stands for Low), representing the mean value respectively the standard deviation in the Normal distribution. The so called “Load_factor” that is achieved by the Normal distribution and that is generated once per 24 hours cycle is used as a factor for all base levels. This means that the base levels are updated every new 24 hours cycle according to Equation 3.6-1 to Equation 3.6-4:
The values of A, B, C and D are the real (used) base values during the present 24 hours cycle. The next coming 24 hours cycle will result in a new set of base levels (from the original levels of A_prim, B_prim, C_prim and D_prim) and so on.

**Figure 3.6-1** illustrates the principle of building up the base power structure during a 24 hours cycle.

![Diagram of power shifts](image)

Figure 3.6-1 An illustration of the base power shifts between the different time points during a 24 hours cycle

### 3.6.1.3.2 High frequency variations

For each simulation step a “Normal distributed noise” is added to the present level that is achieved by the base levels. This “high frequency” variation has the statistic parameters “L_My_H” and “L_sigma_H” (the L stands for Load and the H stands for High), representing the mean value respectively the standard deviation in the Normal distribution.
An example of this “Power Noise” effect is illustrated in Figure 3.6-2 (no “Power Noise added) and Figure 3.6-3 (“Power Noise” added).

Figure 3.6-2  An example with no power noise added to the base levels
3.6.1.4 Load Category a respectively b

The load model works with 2 categories of loads:

- Category a
- Category b

The simulation starts with category a. This category will be modeled corresponding to a specified number of days, “a_limit”. After this is completed, follows simulation with category b. This category is modeled corresponding to a specified number of days, “b_limit”. This sequence is then repeated as long as the total simulation continues. The dividing into 2 separated categories is useful when modelling for example the power consumption in e.g. an industry area. In this case it could be a large difference between the power profile during the working week compared with the weekend.

The effect of this separating into 2 categories is illustrated in Figure 3.6-4. The figure shows the load during 10 days. The first 5 days correspond to a working week. Then follow 2 days corresponding to the weekend, and so on.
3.6.2 Input parameters

The input parameters of the module are specified in Table 3.6-1.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_total</td>
<td>The total number of simulation steps per sequence (Sim_step_total = 43200 corresponds to a simulation sequence over a time of 30 days if Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td></td>
</tr>
<tr>
<td>Sim_step_sec</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td></td>
</tr>
<tr>
<td>a_limit</td>
<td>Number of days for modeling according category a, before change to category b.</td>
</tr>
</tbody>
</table>
The simulation always starts with category a.

Table 3.6-1 Input parameters for module “Load_make”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>b_limit</td>
<td>Number of days for modeling according category b, before change to category a. The simulation always starts with category a.</td>
</tr>
<tr>
<td>A_prim_a</td>
<td>This relates to load category a. For further definition see above.</td>
</tr>
<tr>
<td>B_prim_a</td>
<td>““.</td>
</tr>
<tr>
<td>C_prim_a</td>
<td>““.</td>
</tr>
<tr>
<td>D_prim_a</td>
<td>““.</td>
</tr>
<tr>
<td>A_prim_b</td>
<td>This relates to load category b. For further definition see above.</td>
</tr>
<tr>
<td>B_prim_b</td>
<td>““.</td>
</tr>
<tr>
<td>C_prim_b</td>
<td>““.</td>
</tr>
<tr>
<td>D_prim_c</td>
<td>““.</td>
</tr>
<tr>
<td>TP_1_a</td>
<td>This relates to load category a. For further definition see above.</td>
</tr>
<tr>
<td>TP_2_a</td>
<td>““.</td>
</tr>
<tr>
<td>TP_3_a</td>
<td>““.</td>
</tr>
<tr>
<td>TP_4_a</td>
<td>““.</td>
</tr>
<tr>
<td>TP_5_a</td>
<td>““.</td>
</tr>
<tr>
<td>TP_1_b</td>
<td>This relates to load category b. For further definition see above.</td>
</tr>
<tr>
<td>TP_2_b</td>
<td>““.</td>
</tr>
<tr>
<td>TP_3_b</td>
<td>““.</td>
</tr>
<tr>
<td>TP_4_b</td>
<td>““.</td>
</tr>
<tr>
<td>TP_5_b</td>
<td>““.</td>
</tr>
<tr>
<td>L_My_H_a</td>
<td>This relates to load category a. For further definition see above.</td>
</tr>
<tr>
<td>L_Sigma_H_a</td>
<td>““.</td>
</tr>
<tr>
<td>L_My_L_a</td>
<td>This relates to load category a. For further definition see above.</td>
</tr>
<tr>
<td>L_Sigma_L_a</td>
<td>““.</td>
</tr>
<tr>
<td>L_My_H_b</td>
<td>This relates to load category b. For further definition see above.</td>
</tr>
<tr>
<td>L_Sigma_H_b</td>
<td>““.</td>
</tr>
<tr>
<td>L_My_L_b</td>
<td>This relates to load category b. For further definition see above.</td>
</tr>
<tr>
<td>L_Sigma_L_b</td>
<td>““.</td>
</tr>
<tr>
<td>Load_power_file</td>
<td>The name of a Load power file (string) to store the load vector and the above parameters</td>
</tr>
</tbody>
</table>
3.6.3 Examples

Table 3.6-2 gives examples of used parameters in a simulation.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used values in the example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_total</td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>Sim_step_sec</td>
<td>Input via function argument from Main Program</td>
</tr>
<tr>
<td>a_limit</td>
<td>5</td>
</tr>
<tr>
<td>b_limit</td>
<td>2</td>
</tr>
<tr>
<td>A_prim_a</td>
<td>10 (kW)</td>
</tr>
<tr>
<td>B_prim_a</td>
<td>5 &quot;&quot;</td>
</tr>
<tr>
<td>C_prim_a</td>
<td>65 &quot;&quot;</td>
</tr>
<tr>
<td>D_prim_a</td>
<td>20 &quot;&quot;</td>
</tr>
<tr>
<td>A_prim_b</td>
<td>10 &quot;&quot;</td>
</tr>
<tr>
<td>B_prim_b</td>
<td>5 &quot;&quot;</td>
</tr>
<tr>
<td>C_prim_b</td>
<td>20 &quot;&quot;</td>
</tr>
<tr>
<td>D_prim_b</td>
<td>20 &quot;&quot;</td>
</tr>
<tr>
<td>TP_1_a</td>
<td>2 (hour)</td>
</tr>
<tr>
<td>TP_2_a</td>
<td>6 &quot;&quot;</td>
</tr>
<tr>
<td>TP_3_a</td>
<td>10 &quot;&quot;</td>
</tr>
<tr>
<td>TP_4_a</td>
<td>18 &quot;&quot;</td>
</tr>
<tr>
<td>TP_5_a</td>
<td>22 &quot;&quot;</td>
</tr>
<tr>
<td>TP_1_b</td>
<td>2 (hour)</td>
</tr>
<tr>
<td>TP_2_b</td>
<td>6 &quot;&quot;</td>
</tr>
<tr>
<td>TP_3_b</td>
<td>10 &quot;&quot;</td>
</tr>
<tr>
<td>TP_4_b</td>
<td>18 &quot;&quot;</td>
</tr>
<tr>
<td>TP_5_b</td>
<td>22 &quot;&quot;</td>
</tr>
<tr>
<td>L_My_H_a</td>
<td>0.0</td>
</tr>
<tr>
<td>L_Sigma_H_a</td>
<td>0.04</td>
</tr>
<tr>
<td>L_My_L_a</td>
<td>1.0</td>
</tr>
<tr>
<td>L_Sigma_L_a</td>
<td>0.15</td>
</tr>
<tr>
<td>L_My_H_b</td>
<td>0.0</td>
</tr>
<tr>
<td>L_Sigma_H_b</td>
<td>0.02</td>
</tr>
<tr>
<td>L_My_L_b</td>
<td>1.0</td>
</tr>
<tr>
<td>L_Sigma_L_b</td>
<td>0.10</td>
</tr>
<tr>
<td>Load_power_file</td>
<td>‘Load_1’</td>
</tr>
</tbody>
</table>

Table 3.6-2 Examples of used input parameters for module “Load_make”
The simulation result regarding the generated load power based on parameters according to Table 3.6-2 follows in Figure 3.6-5.

Figure 3.6-5  The loaded power for a simulation sequence of 30 days. Input parameters according to Table 3.6-2
3.7 Module “Connect_Gen_load”

3.7.1 Principle

“Connect_Gen_load” is a program module that models the electrical connection of the Windpower and Sunpower generators to a loaded (local) grid. Two separated types of power levels have been defined:

- Gross power
- Net power

3.7.1.1 Gross power

The *gross power* is the sum of the electrical power generated by the Wind power generator(s) and the Sun power generator(s).

The sum of the electrical power generated by the Wind power generator(s) and the Sun power generator(s) (the gross power) is for each single simulation step loaded in a vector named “*P_generation_vector*”.

3.7.1.2 Net power

The *net power* is the *gross power* minus the *loaded power* from the loaded grid.

The *net power* is for each single simulation step loaded in a vector named “*P_buffer_vector*”. 
3.7.2 Input parameters

The input parameters of the module are specified in Table 3.7-1.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_wind_el_vector</td>
<td>Vector with electric power generated by the wind generator(s) (for each single simulation step)</td>
</tr>
<tr>
<td>(Input via function argument from Main Program)</td>
<td></td>
</tr>
<tr>
<td>P_sun_el_vector</td>
<td>Vector with electric power generated by the sun generator(s) (for each single simulation step)</td>
</tr>
<tr>
<td>(Input via function argument from Main Program)</td>
<td></td>
</tr>
<tr>
<td>P_load_vector</td>
<td>Vector with electric loaded power (from the consumer grid) (for each single simulation step)</td>
</tr>
<tr>
<td>(Input via function argument from Main Program)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.7-1 Input parameters for module “Connect_Gen_load”

3.7.3 Examples

3.7.3.1 Example 1 (24 hours simulation)

The following example is based on a single simulation during a time sequence of 24 hours. Assumptions according to the following was done:

- Local area: Göteborg
- Time: 20 June
- Cloudiness: 1/8
- Weibull parameters: $A = 7$, $C = 2$
- Number of wind generators corresponding to “Hönö”: 3
- Solar panel area: 500 m²
- Sun Tracking: yes
One single sample of simulation resulted in the following:

- Mean wind rate: 7.6 m/sec
- Standard deviation wind rate: 1.3 m/sec
- Mean extinction coefficient: 0.41
- Standard deviation extinction coefficient: 0.13

The loaded power was simulated as shown in **Figure 3.7-1**.

![Figure 3.7-1](image)

**Figure 3.7-1**  Loaded power. Example 1

Based on above defined conditions, gross- respectively net power according to **Figure 3.7-2** respectively **Figure 3.7-3** were obtained. **Figure 3.7-4** and **Figure 3.7-5** show the separated wind- and sun power that were generated.
Figure 3.7-2  Generated gross power. Example 1

Figure 3.7-3  Generated net power. Example 1
Figure 3.7-4  Generated Wind power. Example 1

Figure 3.7-5  Generated Sun power. Example 1
3.7.3.2  Example 2 (10 days simulation)

This example is based on a single simulation during a time sequence of 10 days (240 hours). The other assumptions agree with example 1.

One single sample of simulation resulted in the following:

- Mean wind rate: 3.5 m/sec
- Standard deviation wind rate: 1.8 m/sec
- Mean extinction coefficient: 0.40
- Standard deviation extinction coefficient: 0.13

The loaded power was simulated as shown in Figure 3.7-6.

![Figure 3.7-6](image)

Figure 3.7-6  Loaded power. Example 2

Based on above defined conditions, gross- respectively net power according to Figure 3.7-7 respectively Figure 3.7-8 were obtained. Figure 3.7-9 and Figure 3.7-10 show the separated wind- and sun power that were generated.
Figure 3.7-7  Generated gross power. Example 2

Figure 3.7-8  Generated net power. Example 2
Figure 3.7-9  Generated Wind power. Example 2

Figure 3.7-10  Generated Sun power. Example 2
3.8 Module “Battery_Distribution”

3.8.1 Principle

“Battery_Distribution” is a program module that models the electrical function of the energy storage (battery) and the external grid. The module get inputs from the module “Connect_Gen_load”. Two separated modes have been defined:

- Storing / loading of energy to / from the energy storage
- Exporting / importing of energy to / from the external grid

3.8.1.1 Storing / Loading of energy to / from the energy storage

This mode is in question if one of the following 2 conditions are fulfilled:

**Condition 1:**

\[ a) \text{ Net power } > 0 \text{ (see paragraph 3.7.1.2) } \]

And

\[ b) \text{ battery}\_\text{charge(time}\_\text{step}) < \text{charge}\_\text{level}\_\text{max} \]

**Condition 2:**

\[ a) \text{ Net power } < 0 \text{ (see paragraph 3.7.1.2) } \]

And

\[ b) \text{ battery}\_\text{charge(time}\_\text{step}) > \text{charge}\_\text{level}\_\text{min} \]

where

- \( \text{battery}\_\text{charge(time}\_\text{step}) \): current battery charge
- \( \text{charge}\_\text{level}\_\text{max} \): maximum allowed charge level in the energy storage
- \( \text{charge}\_\text{level}\_\text{min} \): minimum allowed charge level in the energy storage
*time_step*: current simulation step

If “**Condition 1**” is fulfilled then the energy corresponding to the Net power multiplied with the time step of one simulation step, *time_step*, shall be **stored** in the energy storage. This energy is the part of produced energy that for the current simulation step not is consumed by the ordinary (consumer) grid load (*Load_make*. See paragraph 3.6). There is in other word a surplus energy on hand according to:

\[
\text{Surplus \_energy} = \text{Net \_Power} \times \text{time \_step}
\]

If “**Condition 2**” is fulfilled then the energy corresponding to the absolute value of the Net power multiplied with the time step of one simulation step shall be **loaded** from the energy storage. This energy is the part of consumed energy (by the consumer grid) that for the current simulation step not is produced by the ordinary generators (*Wind_turbine* see paragraph 3.2 together with *Sun_panel_generator* see paragraph 3.5). There is in other word a deficiency of energy on hand according to:

\[
\text{Deficiency \_energy} = |\text{Net \_Power}| \times \text{time \_step}
\]

Some other parameters regarding the energy storage

- Efficiency of storing (*charge_factor*)
- Efficiency of loading (*load_factor*)
- Maximum power for storing / loading (*power_max_batt*)
- Charge level in the energy storage at simulation start (*charge_level_init*)
- Self-discharge (*discharge_self*)

Figure 3.8-1 and Figure 3.8-2 illustrate the energy flow for “**Condition 1**” and “**Condition 2**”. Compare chapter 2.6 and Figure 2.6-2 and Figure 2.6-3.
Figure 3.8-1  Energy flow for “Condition 1”.

Figure 3.8-2  Energy flow for “Condition 2”.
3.8.1.2 Exporting / importing of energy to / from the external grid

This mode is in question if non of the conditions in paragraph 3.8.1.1, Condition 1 and Condition 2, is fulfilled. Two conditions are then in question, named Condition 3 and condition 4:

**Condition 3:**
Condition 1.a is fulfilled
Condition 1.b is not fulfilled
Then export of generated surplus energy to the distribution grid shall be realized.

**Condition 4:**
Condition 2.a is fulfilled
Condition 2.b is not fulfilled
Then import of deficit energy from the distribution grid shall be realized.

The external grid is limited regarding maximum power for export / import by a parameter named \textit{power\_max\_distr}.

**Figure 3.8-3** and **Figure 3.8-4** illustrate the energy flow for “Condition 3” and “Condition 4”. Compare chapter 2.6 and Figure 2.6-4 and Figure 2.6-5.

For further information regarding the questions about energy storage see chapter 2.5.
Figure 3.8-3  Energy flow for “Condition 3”.

Figure 3.8-4  Energy flow for “Condition 4”.
3.8.2 Input parameters

The input parameters of the module are specified in Table 3.8-1.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_buffer_vector (Input via function argument from Main Program)</td>
<td>See paragraph 3.7.1.2.</td>
</tr>
<tr>
<td>Sim_step_sec (Input via function argument from Main Program)</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td>charge_factor</td>
<td>Storage efficiency (part of unit) of the energy storage</td>
</tr>
<tr>
<td>load_factor</td>
<td>Loading efficiency (part of unit) of the energy storage</td>
</tr>
<tr>
<td>charge_level_init</td>
<td>Charge level in the energy storage at simulation start (kWh)</td>
</tr>
<tr>
<td>charge_level_min</td>
<td>Minimum allowed charge level in the energy storage (kWh)</td>
</tr>
<tr>
<td>charge_level_max</td>
<td>Maximum allowed charge level in the energy storage (kWh)</td>
</tr>
<tr>
<td>discharge_self</td>
<td>The energy storage self-discharge per 24 hours in % of charge_level_max</td>
</tr>
<tr>
<td>power_max_batt</td>
<td>Maximum power for storing / loading (kW) of the battery</td>
</tr>
<tr>
<td>power_max_distr</td>
<td>Maximum power for export / import (kW)</td>
</tr>
</tbody>
</table>

Table 3.8-1 Input parameters for module “Battery_Distribution”

3.8.3 Examples

Table 3.8-2 gives examples of used input parameters in a simulation.

Figure 3.8-5 shows the used input regarding Net Power vs time (P_buffer_vector).
<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Used value in the example</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_buffer_vector</td>
<td>See Figure 3.8-5.</td>
</tr>
<tr>
<td>(Input via function argument from Main Program)</td>
<td></td>
</tr>
<tr>
<td>Sim_step_sec</td>
<td>60</td>
</tr>
<tr>
<td>(Input via function argument from Main Program)</td>
<td></td>
</tr>
<tr>
<td>charge_factor</td>
<td>0.8</td>
</tr>
<tr>
<td>load_factor</td>
<td>0.9</td>
</tr>
<tr>
<td>charge_level_init</td>
<td>800</td>
</tr>
<tr>
<td>charge_level_min</td>
<td>600</td>
</tr>
<tr>
<td>charge_level_max</td>
<td>1000</td>
</tr>
<tr>
<td>discharge_self</td>
<td>0.5</td>
</tr>
<tr>
<td>power_max_batt</td>
<td>100</td>
</tr>
<tr>
<td>power_max_distr</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 3.8-2  Examples of used input parameters for module “Battery_Distribution”

The output results regarding *Battery charge, Net Power relative maximum storing / loading power, Net Power relative maximum export / import power, Imported Power and Exported Power* are shown in Figure 3.8-6 - Figure 3.8-10.

![Figure 3.8-5 The Net Power vs Time (P_buffer_vector)](image-url)
Figure 3.8-6  Battery charge vs Time

Figure 3.8-7  Net Power relative maximum storing / loading power vs Time
Figure 3.8-8  Net Power relative maximum export / import power vs Time

Figure 3.8-9  Imported Power vs Time
3.9 Module “Power_evaluate”

3.9.1 Principle

“Power_evaluate” is a program module that evaluates the result of a simulation process of a combined energy system that consists of the following building blocks:

- Wind power generators
- Sun power generators
- Local grid (loaded grid)
- Energy storage (battery system)
- External grid (for export / import of energy)

The module presumes input data as a result of a number of repeating simulation sequences, where each sequence is a defined time period, e.g. a month. The total simulation process is a repetition, e.g. 100 times, of this sequence.
The following parameters are calculated (Table 3.9-1):

- Generated electric Wind Energy ($E_{\text{Wind}}$)
- Generated electric Sun Energy ($E_{\text{Sun}}$)
- Total generated (Wind + Sun) electric energy ($E_{\text{Gen}}$)
- Exported electric energy ($E_{\exp}$)
- Imported electric energy ($E_{\imp}$)
- Loaded (by the local grid) energy ($E_{\text{Load}}$)
- The difference between Exported and Imported electric energy ($D_{\exp \imp}$)
- The quotient $E_{\text{Wind}} / E_{\text{Gen}}$ ($\text{Rel}_{\text{Wind Gen}}$)
- The quotient $E_{\text{Sun}} / E_{\text{Gen}}$ ($\text{Rel}_{\text{Sun Gen}}$)
- The quotient $E_{\text{Gen}} / E_{\text{Load}}$ ($\text{Rel}_{\text{Gen Load}}$)
- The quotient $E_{\exp} / E_{\text{Gen}}$ ($\text{Rel}_{\text{Exp Gen}}$)
- The quotient $E_{\imp} / E_{\text{Load}}$ ($\text{Rel}_{\text{Imp Load}}$)
- The quotient $D_{\exp \imp} / E_{\text{Gen}}$ ($\text{Rel}_{\text{DEI Gen}}$)
- The quotient $E_{\text{Battery}} / E_{\text{Load \_day}}$ ($\text{Rel}_{\text{Battery \_Load \_day}}$). See comment below

Table 3.9-1  Parameters that are calculated

Comment regarding “The quotient $E_{\text{Battery}} / E_{\text{Load \_day}}$”

$E_{\text{Battery}}$: maximum energy capacity of the battery system

$E_{\text{Load \_day}}$: loaded (by the local grid) electric mean energy per 24 hours

All the above listed parameters all calculated according to:

- *per simulation sequence*. These values are stored in an Evaluation file. See Table 3.9-2.
• mean value and standard deviation for the total simulation process. These values are displayed after the simulation. As an example see paragraph 3.9.3.

### 3.9.2 Input parameters

The input parameters of the routine are specified in **Table 3.9-2**.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_wind_el_vector (Input via function argument from Main Program)</td>
<td>Vector with electric wind power (per simulation step) (kW)</td>
</tr>
<tr>
<td>P_sun_el_vector (Input via function argument from Main Program)</td>
<td>Vector with electric sun power (per simulation step) (kW)</td>
</tr>
<tr>
<td>P_load_vector (Input via function argument from Main Program)</td>
<td>Vector with electric load (local) (per simulation step) (kW)</td>
</tr>
<tr>
<td>E_export_vector (Input via function argument from Main Program)</td>
<td>Vector with export energy (per simulation step) (kWh)</td>
</tr>
<tr>
<td>E_import_vector (Input via function argument from Main Program)</td>
<td>Vector with import energy (per simulation step) (kWh)</td>
</tr>
<tr>
<td>Sim_step_sec (Input via function argument from Main Program)</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td>charge_level_max (Input via function argument from Main Program)</td>
<td>Maximum allowed charge level in the energy storage (kWh)</td>
</tr>
<tr>
<td>N_sim_turns (Input via function argument from Main Program)</td>
<td>Number of simulation sequences in a total simulation</td>
</tr>
<tr>
<td>sim_turn (Input via function argument from Main Program)</td>
<td>Current simulation sequence</td>
</tr>
<tr>
<td>Evaluation_file</td>
<td>Name of an evaluation file (string) to store the parameters listed in <strong>Table 3.9-1</strong> (per sequence) in vectors</td>
</tr>
</tbody>
</table>

**Table 3.9-2** Input parameters for module “Power_evaluate”
### 3.9.3 Examples

The following list is an example of simulation results regarding mean values (My) and standard deviations (Sigma) based on 100 sequences:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>My</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_Wind (kWh)</td>
<td>3.464e+003</td>
<td>1.230e+003</td>
</tr>
<tr>
<td>E_Sun (kWh)</td>
<td>4.204e+003</td>
<td>3.471e+002</td>
</tr>
<tr>
<td>E_Gen (kWh)</td>
<td>7.668e+003</td>
<td>1.294e+003</td>
</tr>
<tr>
<td>E_Load (kWh)</td>
<td>7.924e+003</td>
<td>3.831e+002</td>
</tr>
<tr>
<td>E_Exp (kWh)</td>
<td>6.455e+002</td>
<td>5.594e+002</td>
</tr>
<tr>
<td>E_Imp (kWh)</td>
<td>1.517e+003</td>
<td>7.729e+002</td>
</tr>
<tr>
<td>D_Exp_Imp (kWh)</td>
<td>-8.713e+002</td>
<td>1.145e+003</td>
</tr>
<tr>
<td>Rel_Wind_Gen</td>
<td>4.371e-001</td>
<td>1.007e-001</td>
</tr>
<tr>
<td>Rel_Sun_Gen</td>
<td>5.629e-001</td>
<td>1.007e-001</td>
</tr>
<tr>
<td>Rel_Gen_Load</td>
<td>9.690e-001</td>
<td>1.662e-001</td>
</tr>
<tr>
<td>Rel_Exp_Gen</td>
<td>7.700e-002</td>
<td>6.076e-002</td>
</tr>
<tr>
<td>Rel_Imp_Load</td>
<td>1.906e-001</td>
<td>9.563e-002</td>
</tr>
<tr>
<td>Rel_DEI_Gen</td>
<td>-1.432e-001</td>
<td>1.884e-001</td>
</tr>
<tr>
<td>Rel_Battery_Load</td>
<td>1.265e+000</td>
<td>6.117e-002</td>
</tr>
</tbody>
</table>

**Figure 3.9-1 - Figure 3.9-10** give some information about the circumstances that have been present, during the simulation process. The figures in question illustrate only the different parameters for **one single** sequence (the first) but give a hint about the present situation.
Figure 3.9-1  Wind speed vs Time

Figure 3.9-2  Wind power vs Time
Figure 3.9-3  Extinction vs Time

Figure 3.9-4  Sun power vs Time
Figure 3.9-5  Gross power vs Time

Figure 3.9-6  Load power vs Time
Figure 3.9-7 Net power vs Time

Figure 3.9-8 Battery charge vs Time
Figure 3.9-9  Imported power vs Time

Figure 3.9-10  Exported power vs Time
3.10 Future Developed Simulation System

A future simulation system is planned. The principle is to complete the current system with the following features:

- Modelles of hydro power generators
- Modelles of wave power generators
- Locally separated generators that are working in separated grids but connected in large main grids

Figure 3.10-1 illustrates the principle structure of a power system that could be analysed by a future developed simulation system.

Figure 3.10-1 The base structure of the power system that could be analysed with a future simulation system that is completed with some features according the above list
The following abbreviations have been used in Figure 3.10-1:

HW a: Power production with the combination Hydro and Wave (unit number a)

WS b: Power production with the combination Wind and Sun (unit number b)

I: International grid

T: Transmission grid (voltage >130 kV)

ST c: Subtransmission grid (region grid) (voltage >10 kV to 130 kV) (unit number c)

D d: Distribution grid (voltage 10 kV) (unit number d)

C WS de: Consumer grid connected to distribution grid d (unit e)

4 WIND POWER

4.1 Introduction

This chapter deals with the problem to, based on measurements, at an appropriate manner analyse some available wind speed data regarding relevant input parameters for a specific stochastic wind speed model. The present wind speed model is developed as a module to the complete simulation model according to chapter 3.

The wind speed data is collected during 4 periods according to:

1) 27 – 29 May 2007 (72 hours)
2) 2 – 4 June 2007 (72 hours)
3) 9 – 11 June 2007 (72 hours)
4) 17 – 21 June 2007 (120 hours)

The measurements were realized at Chalmers wind power system at Hönö. The measurement point was about 20 m over the sea level.

Each period is analysed separately in respect of the model parameters.
4.2 Measurement results

The measurement results from the 4 periods in question (see paragraph 4.1) are illustrated in Figure 4.2-1 to Figure 4.2-8. The wind speed data is presented as mean values during sampling intervals of 1 minute respectively 1 hour. As can be seen there is a significant difference depending on which sampling period that is used. If a sampling period of 1 hour is in question, then the turbulence contributions are effectively eliminated. On the other hand if 1 minute is used as sampling period these “high frequency” contributions are important parts of the result. The dividing into so called “low frequency” respectively “high frequency” contributions is used in the present wind speed model. See chapter 3.
Figure 4.2-1  Measured wind speed. Period 1.
Mean value during a sampling period of 1 minute

Figure 4.2-2  Measured wind speed. Period 1.
Mean value during a sampling period of 1 hour
Figure 4.2-3  Measured wind speed. Period 2.
Mean value during a sampling period of 1 minute

Figure 4.2-4  Measured wind speed. Period 2.
Mean value during a sampling period of 1 hour
Figure 4.2-5  Measured wind speed. Period 3.
Mean value during a sampling period of 1 minute

Figure 4.2-6  Measured wind speed. Period 3.
Mean value during a sampling period of 1 hour
Figure 4.2-7 Measured wind speed. Period 4. Mean value during a sampling period of 1 minute

Figure 4.2-8 Measured wind speed. Period 4. Mean value during a sampling period of 1 hour
4.3 Evaluation of measurements

4.3.1 Common

The evaluation is focused on parameters to be used in the stochastic model named "Wind_make". This model is described in paragraph 3.1 and in reference Error! Reference source not found.].

4.3.2 Wind_make

Wind_make is a program function (subroutine) with the purpose to generate stochastic wind speed data. The resulted data values are collected in a vector.

The wind speed values, in the following named v_wind, are generated as results of 1) weather variations and 2) turbulences. The total v_wind = Level_W + Level_T, where Level_W is a result of the weather situation and Level_T is a result of turbulence. Level_W is also named “the low frequency component” and Level_T “the high frequency component”. See Figure 4.3-1

\[ v_{wind} \]

\[ \begin{align*}
\text{Level}_W & \quad (\text{weather situation}) \\
\text{Level}_T & \quad (\text{turbulence})
\end{align*} \]

Figure 4.3-1 The wind speed is built up by two components, Level_W and Level_T.
Wind_make is used as a module in the total simulation program according to chapter 3. A simulation sequence consists of an optional number of simulation steps (Sim_step_total). Each simulation sequence is, in respect of the module Wind_make, divided into a number of W-cycles, where each cycle is characterized by a “specific” weather situation. See Figure 4.3-2.

![Diagram of W-cycles](image)

Figure 4.3-2 A total simulation sequence consists of a number (N) of W-cycles, each of them representing a specific weather situation.

The W-cycle contributes with a dominating “base” component to the wind speed. This base component, named Level_W, is stochastically generated by a “Weibull distribution” according to:

**Equation 4.3-1:**

\[ \text{Level}_W = W(A, C) \]

Where \( W \) is a Weibull process and \( A \) respectively \( C \) are the “Weibull parameters”.

The Weibull distribution has the density function according to:

**Equation 4.3-2:**

\[
W(A, C) = \frac{C}{A} \left( \frac{S}{A} \right)^{C-1} e^{-\left( \frac{S}{A} \right)^C}
\]

Where:

\( S \): Level_W
A,C: Weibull parameters

The probability that “Level_W” not exceeds “S” follows by Equation 4.3-3.

**Equation 4.3-3:**

\[
P(\text{Level}_W \leq S) = \int_0^S W(A,C)dS = \]

\[
= \int_0^S \frac{C}{A} \left( \frac{S}{A} \right)^{C-1} \left( \frac{S}{A} \right)^C dS = 1 - e^{\left( \frac{S}{A} \right)^C}
\]

A new generation is performed for every W-cycle.

There is a “soft linear” transition from one W-cycle to another. That means that the new value of Level_W is gradually and linearly assigned over the total W-cycle time in question. **Figure 4.3-3** illustrates how the “low frequency component is gradually and linearly shifted during the time interval corresponding to the W-cycle in question.

![Figure 4.3-3](image)

**Figure 4.3-3**  
**Level_W is linearly assigned during the different W-cycle times**

- **Level_W(Tn):** Level_W stochastically generated at time point Tn
- **W-cycle(Tn):** W-cycle between time points Tn and Tn+1
As may be seen in Figure 4.3-3 the different levels are delayed and get their final values at the end of respective W-cycle. For example: Level_W (Tn+1) is stochastically generated at time point Tn+1 and is then linearly distributed during the total W-cycle (Tn+1). Level_W (Tn+2) is stochastically generated at time point Tn+2 and is then linearly distributed during the total W-cycle (Tn+2), and so on.

The number of simulation steps in a W-cycle, Sim_step_W_total, is stochastically generated according to Equation 4.3-4.

**Equation 4.3-4:**

\[ \text{Sim}_\text{step}_W_{\text{total}} = N(\mu, \sigma) \]

Where:

- \( N \): a normal process
- \( \mu \): an assigned mean value of simulation steps per W-cycle (Sim_step_W_My)
- \( \sigma \): an assigned standard deviation of simulation steps per W-cycle (Sim_step_W_Sigma)

The Normal distribution follows according to Equation 4.3-5.

**Equation 4.3-5:**

\[ N(\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \]

Each W-cycle consists of a number of T-cycles. See Figure 4.3-4.

Figure 4.3-4: Every W-cycle is divided into a number (M) of T-cycles each of them representing a certain turbulence situation.
Each T-cycle depends on an individual turbulence situation, that is varied from T-cycle to T-cycle. The contribution, Level_T, to the total wind speed, v_wind (see above), is generated by a “Normal distribution” according to:

**Equation 4.3-6:**

\[ \text{Level}_T = N(\mu, \sigma) \]

Where:
- \( N \): a normal process
- \( \mu \): an assigned mean value of turbulence contribution per W-cycle (Level_T_My). Level_T_My is normally assigned to zero, as the turbulence is proposed to fluctuate around the zero level.
- \( \sigma \): an assigned standard deviation of turbulence contribution per W-cycle (Level_T_Sigma)

The generated value of Level_T, is linearly distributed during the first half of the T-cycle. During the second half of the T-cycle the level returns to zero. See **Figure 4.3-5**.
The number of simulation steps for a single T-cycle, $Sim_{-}step_{-}T_{-}total$, is stochastically generated by a “Normal distribution” according to:

**Equation 4.3-7:**

$$Sim_{-}step_{-}T_{-}total = N (\mu, \sigma)$$

Where:

$N$: a normal process  
$\mu$: an assigned mean value of number of simulation steps per T-cycle  
($Sim_{-}step_{-}T_{-}My$)  
$\sigma$: an assigned standard deviation of number of simulation steps per T-cycle  
($Sim_{-}step_{-}T_{-}Sigma$)

The input parameters to the module follow in **Table 4.3-1**.

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_sec</td>
<td>Time interval in seconds per simulation step (60 is a standard value)</td>
</tr>
<tr>
<td>Input via function argument from Main Program</td>
<td></td>
</tr>
</tbody>
</table>
| Sim_step_total               | The total number of simulation steps per sequence  
($Sim_{-}step_{-}total = 43200$ corresponds to a simulation sequence over a time of 30 days if $Sim_{-}step_{-}sec = 60$) |
| Input via function argument from Main Program |                                                         |
| Sim_step_W_My                | Mean value of the number of simulation steps per W-cycle  
($Sim_{-}step_{-}W_{-}My = 4320$ corresponds to a mean value of 3 days (3 times 24 hours) if $Sim_{-}step_{-}sec = 60$) |
| Sim_step_W_Sigma             | Standard deviation of the number of simulation steps per W-cycle       |
| Sim_step_T_My                | Mean value of the number of simulation steps per T-cycle  
($Sim_{-}step_{-}T_{-}My = 10$ corresponds to a mean value of 10 minutes if $Sim_{-}step_{-}sec = 60$) |
| Sim_step_T_Sigma             | Standard deviation of the number of simulation steps per T-cycle       |
| A                            | Weibull parameter (scale parameter)                                     |
| C                            | Weibull parameter (shape parameter)                                     |
### Input parameters for module “Wind_make”

<table>
<thead>
<tr>
<th>Parameter name</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_W_My</td>
<td>Mean value of the number of simulation steps per W-cycle (Sim_step_W_My = 4320 corresponds to a mean value of 3 days (3 times 24 hours) if Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Sim_step_W_Sigma</td>
<td>Standard deviation of the number of simulation steps per W-cycle</td>
</tr>
<tr>
<td>Sim_step_T_My</td>
<td>Mean value of the number of simulation steps per T-cycle (Sim_step_T_My = 10 corresponds to a mean value of 10 minutes if Sim_step_sec = 60)</td>
</tr>
<tr>
<td>Sim_step_T_Sigma</td>
<td>Standard deviation of the number of simulation steps per T-cycle</td>
</tr>
<tr>
<td>A</td>
<td>Weibull parameter (scale parameter)</td>
</tr>
<tr>
<td>C</td>
<td>Weibull parameter (shape parameter)</td>
</tr>
<tr>
<td>Level_T_Sigma_proc</td>
<td>Standard deviation of Level _T in percent of Level_W</td>
</tr>
</tbody>
</table>

Table 4.3-1

The parameters according to Table 4.3-2 will be evaluated based on the measurements presented in paragraph 4.1 and 4.2.
4.3.3 Methods for evaluation

There are some important criterions that are to be fulfilled when the parameters in Table 4.3-2 are adapted to the measurements in question. The adaption is in principle performed by model simulations and varying some model parameters in order to get a good similarity between measurements and simulated results. There are some characteristics that will be used in the evaluation process. These characteristic parameters are:

- Energy band
- Discrete Frequency Function
- Mean value of the kinetic wind energy
- Mean value and Standard deviation of the wind rate
- Maximum and Minimum value of the wind rate

4.3.3.1 Energy Band

The kinetic wind energy spectrum is divided into a number of discrete energy bands. These bands are defined according to Equation 4.3-8, Equation 4.3-9 and Equation 4.3-10. See also paragraph 4.3.3.2.

Equation 4.3-8:

\[
Band(1) = \sum_n W_n(V)
\]

Where:

- \( Band(1) \): integrated normalized energy in lowest band. The principle of normalized energy follows in paragraph 4.3.3.2.
- \( W_n(V) \): normalised kinetic wind energy as a function of wind rate \( V \), time point \( n \). \( W_n(V) \) is for \( Band(1) \) defined as \( W_n < k_1 \cdot W_{\text{mean}} \), \( k_1 = k_{\min} \)
- \( W_{\text{mean}} \): normalised mean energy of the process
- \( k_{\min} \): defined parameter. In this study \( k_{\min} = 0.2 \)
Equation 4.3-9:

\[ Band(n) = \sum_n W_n(V) \quad n = 2, 3, \ldots, N-1 \]

Where:

* Band(n): integrated normalized energy in band n.

* \( W_n(V) \): normalised kinetic wind energy as a function of wind rate \( V \), time point \( n \). \( W_n(V) \) is for \( Band(n) \) defined as \( k_{n-1} \cdot W_{\text{mean}} \leq W_n(V) < k_n \cdot W_{\text{mean}} \),

\[ k_n = k_{\text{min}} + (n-1) \cdot k_{\text{band}}, \quad n = 2, 3, \ldots, N-1 \]

* \( N \): number of bands. \textbf{In this study} \( N = 52 \)

* \( k_{\text{band}} \): defined parameter. \textbf{In this study} \( k_{\text{band}} = 0.2 \)

Equation 4.3-10:

\[ Band(N) = \sum_n W_n(V) \]

Where:

* Band(N): integrated normalized energy in highest band.

* \( W_n(V) \): normalised kinetic wind energy as a function of wind rate \( V \), time point \( n \). \( W_n(V) \) is for \( Band(N) \) defined as \( k_{N-1} \cdot W_{\text{mean}} \leq W_n(V) \),

\[ k_{N-1} = k_{\text{min}} + (N-1) \cdot k_{\text{band}} \]

4.3.3.2 Normalised Energy

A definition of what in this paper is named the \textit{Normalised Energy} follows in Equation 4.3-11.
Equation 4.3-11:

\[ W_{\text{Normalised}}(V) = \frac{W(V) \cdot \Delta V}{\int_{V_{\text{min}}}^{V_{\text{max}}} W(V) \, dV} \]

Where:

- \( W_{\text{Normalised}}(V) \): normalized (kinetic) energy per m\(^2\) (perpendicular to the wind direction) at the wind rate \( V \)
- \( W(V) \): measured or simulated kinetic wind energy per second and per m\(^2\) (perpendicular to the wind direction) at the wind rate \( V \)
- \( V \): a defined wind speed
- \( \Delta V \): a small wind rate region quite around \( V \)
- \( V_{\text{min}} \): minimum wind rate of the process
- \( V_{\text{max}} \): maximum wind rate of the process

If the function \( W_{N}(V) \) is regarded in a specific wind rate region, for instance an energy band, it could be defined according to Equation 4.3-12:

Equation 4.3-12:

\[ W_{N}(b) = \frac{\int_{V_{\text{Band}}(b)}^{V_{\text{Band}}(b)+d_{\text{Band}}(b)} W(V) \, dV}{\int_{V_{\text{min}}}^{V_{\text{max}}} W(V) \, dV} \]

Where:

- \( W_{N}(b) \): normalized (kinetic) energy per m\(^2\) (perpendicular to the wind direction) in the energy band \( b \)
- \( V_{\text{Band}}(b) \): a function that gives the lower wind rate limit for energy band \( b \)
$d_{\text{Band}}(b)$: a function that gives the wind rate interval for energy band $b$

Equation 4.3-12 could be expressed according to Equation 4.3-13.

**Equation 4.3-13:**

$$W_N(b) = \frac{\int_{V_{\min}}^{V_{\max}} C \cdot V^3 \cdot f(V) \, dV}{\int_{V_{\min}}^{V_{\max}} V^3 \cdot f(V) \, dV}$$

Where:

- $C$: \(\frac{1}{2} \rho\), where $\rho$ is the air density (kg/m$^3$). If $\rho$ could be assumed to be constant, then the parameter $C$ is a constant

- $f(V)$: a continuous function that gives the relative frequency of the wind speed $V$

Equation 4.3-13 could be expressed in an *approximative and discretised* form according to Equation 4.3-14.

**Equation 4.3-14:**

$$W_N(b) = \frac{\sum_{V(b)}^{V(b)+d_{\text{Band}}(b)} V^3 \cdot g(V)}{\sum_{V_{\min}}^{V_{\max}} V^3 \cdot g(V)}$$
Where:

\[ W_N(b) : \] normalized (kinetic) energy per \( m^2 \) (perpendicular to the wind direction) in the energy band \( b \)

\[ g(V) : \] a discrete frequency function that gives the frequency (number) of measured/calculated samples with different wind rates \( V \). In this study these samples are counted over a time period of 72 hours respectively 120 hours, corresponding to the 4 periods according to paragraph 4.1.

4.3.3.3 Mean value of the kinetic wind energy

The mean value of the kinetic wind energy from all energy bands results in a good measure regarding a specific wind situation. This parameter is compared in respect of simulated results and corresponding measure values.

4.3.3.4 Mean value and Standard deviation of the wind rate

The mean value and standard deviation of the wind rate (\( V_\mu \) and \( V_\sigma \)) is based on the total number of samples during the measuring/simulation interval (period). It is defined according to Equation 4.3-15 and Equation 4.3-16.

**Equation 4.3-15:**

\[
V_\mu = \frac{\sum_{k=1}^{N} M(k)}{N}
\]

Where:

\( V_\mu \): mean value of wind rate during the period in question

\( M(k), N \): measurement/simulation value regarding wind rate at time point \( k \)

\( N \): number of time points
Equation 4.3-16:

\[ V\sigma = \sqrt{\frac{\sum_{k=1}^{N} (M(k) - V\mu)^2}{N - 1}} \]

Where:

- \( V\sigma \): standard deviation of the wind rate during the period in question
- \( V\mu, M(k), N \): see Equation 4.3-15

### 4.3.3.5 Maximum and Minimum value of the wind rate

The Maximum and Minimum value of the wind rate (\( V_{\text{max}} \) and \( V_{\text{min}} \)) is based on the total number of samples during the measuring/simulation interval (period). It is defined according to Equation 4.3-17 and Equation 4.3-18.

**Equation 4.3-17:**

\[ V_{\text{max}} = \max \{ M(k) \}, k = 1 \rightarrow N \]

Where:

- \( M(k), N \): see Equation 4.3-15

**Equation 4.3-18:**

\[ V_{\text{min}} = \min \{ M(k) \}, k = 1 \rightarrow N \]

Where:

- \( M(k), N \): see Equation 4.3-15
4.4 Simulations

As is mentioned in 4.3.3 the parameters in Table 4.3-2 are adapted to the measurements by model simulations and varying some model parameters in order to get a good similarity between measurements and simulated results. In Table 4.4-1 and Table 4.4-2 the adapted results from simulations are collected for the 4 measuring periods in question. The tables give recommended (nominal) values for the model parameters.

<table>
<thead>
<tr>
<th>Measuring period (see paragraph 4.1)</th>
<th>Weather variation</th>
<th>Turbulence variation</th>
<th>Turbulance level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sim_step_W_My</td>
<td>Sim_step_W_Sigma</td>
<td>Sim_step_T_My</td>
</tr>
<tr>
<td>1</td>
<td>300</td>
<td>100</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>100</td>
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<tr>
<td>3</td>
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<td>100</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>100</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4.4-1 Resulting nominal model parameters after comparing measuring results with simulation results

<table>
<thead>
<tr>
<th>Measuring period (see paragraph 4.1)</th>
<th>Weibull parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>4.80</td>
</tr>
<tr>
<td>2</td>
<td>5.80</td>
</tr>
<tr>
<td>3</td>
<td>3.30</td>
</tr>
<tr>
<td>4</td>
<td>3.80</td>
</tr>
</tbody>
</table>

Table 4.4-2 Resulting nominal model parameters after comparing measuring results with simulation results
4.4.1 Measuring period 1

Date: 27 – 29 May 2007 (72 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 4.4-2 - Figure 4.4-8 and in Table 4.4-3 and Table 4.4-4 the comparisons are presented.

Comments regarding figures and tables

Figure 4.4-2 - Figure 4.4-5 The graphs give the correlation between the Energy Bands and corresponding wind rates. The following model parameters have been altered:

- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 4.8 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 3.12 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 35 % gives the best adaption to the measurement result
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3,1)° gives the best adaption to the measurement result.

Figure 4.4-6 The graphs give the correlation between the Energy Bands and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). Simulation with nominal parameters is compared with measurement result.

Figure 4.4-7 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific Wind rate Bands (defined by wind rates) and the Wind rate Bands in question. (Frequency function vs wind rate band). See Figure 4.4-1 and Equation 4.4-1. The figure illustrates 52 Wind rate Bands, separated with 0.2 m/s. The equation defines the correlation between Wind rate Bands and Wind rates. Simulation with nominal parameters is compared with measurement result.

Figure 4.4-8 and Figure 4.4-9 The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 1
Table 4.4-3 lists the resulting Quotient of Relative Mean Energy between simulation and measurement during period 1. As can be noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 4.4-4 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement results.

*) mean value: 3, standarddeviation: 1

<table>
<thead>
<tr>
<th>band</th>
<th>value</th>
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<td>band 52</td>
<td>10.2 m/s</td>
</tr>
<tr>
<td>band 51</td>
<td>10.0 m/s</td>
</tr>
<tr>
<td>band 5</td>
<td>1.0 m/s</td>
</tr>
<tr>
<td>band 4</td>
<td>0.8 m/s</td>
</tr>
<tr>
<td>band 3</td>
<td>0.6 m/s</td>
</tr>
<tr>
<td>band 2</td>
<td>0.4 m/s</td>
</tr>
<tr>
<td>band 1</td>
<td>0.2 m/s</td>
</tr>
</tbody>
</table>

Figure 4.4-1 "Wind rate Bands" 1 to 52. The Wind rate Bands are defined according to Equation 4.4-1.
Equation 4.4-1:

Wind rate Band $N$, $N=1 \rightarrow 51$: $(N-1) \cdot 0.2 \text{ m/s} \leq \text{wind rate} < N \cdot 0.2 \text{ m/s}$

Wind rate Band 52: \[ \text{wind rate} \geq 10.2 \text{ m/s} \]

Figure 4.4-2 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)
Figure 4.4-3  Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

Figure 4.4-4  Wind rate vs Energy Band with altering Turbulence level. (C, A and Turbulence variation are fixed nominal)
Figure 4.4-5  Wind rate vs Energy Band with altering Turbulence variation. (C, A and Turbulence are fixed nominal)

Figure 4.4-6  Normalised energy distribution vs energy band
Figure 4.4-7  Frequency function vs wind rate band

Figure 4.4-8  Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 1
Figure 4.4-9  Measured wind speed. Period 1
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Value</th>
<th>Relative Mean Energy:</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>Simulated Result</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement Result</td>
</tr>
<tr>
<td>A</td>
<td>4.0</td>
<td>0.5785</td>
</tr>
<tr>
<td>(C, Turbulence and Turbulence variation nominal)</td>
<td><strong>4.8</strong> (nominal)</td>
<td><strong>1.0029</strong></td>
</tr>
<tr>
<td></td>
<td>5.6</td>
<td>1.6157</td>
</tr>
<tr>
<td>C</td>
<td>2.5</td>
<td>1.0934</td>
</tr>
<tr>
<td>(A, Turbulence and Turbulence variation nominal)</td>
<td><strong>3.12</strong> (nominal)</td>
<td><strong>1.0029</strong></td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>0.9854</td>
</tr>
<tr>
<td>Turbulence</td>
<td>20 %</td>
<td>0.8523</td>
</tr>
<tr>
<td>(C, A and Turbulence variation nominal)</td>
<td>30 %</td>
<td>0.9254</td>
</tr>
<tr>
<td></td>
<td><strong>35 %</strong> (nominal)</td>
<td><strong>1.0029</strong></td>
</tr>
<tr>
<td></td>
<td>40 %</td>
<td>1.1278</td>
</tr>
<tr>
<td></td>
<td>50 %</td>
<td>1.7211</td>
</tr>
<tr>
<td>Turbulence variation</td>
<td>(3,1) (nominal)</td>
<td><strong>1.0029</strong></td>
</tr>
<tr>
<td>(C, A and Turbulence nominal)</td>
<td>(5,2)</td>
<td>0.9432</td>
</tr>
<tr>
<td></td>
<td>(10,3)</td>
<td>0.9707</td>
</tr>
</tbody>
</table>

Table 4.4-3 Relative Mean Energy vs variation of some parameters

<table>
<thead>
<tr>
<th>Mean (m/s)</th>
<th>Standarddev. (m/s)</th>
<th>Maximum (m/s)</th>
<th>Minimum (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3</td>
<td>4.4</td>
<td>1.8 1.6</td>
<td>10.6 12.0</td>
</tr>
</tbody>
</table>

Table 4.4-4 Statistical parameters regarding wind rate. Measurements vs simulations
4.4.2 Measuring period 2

Date: 2 – 4 June 2007 (72 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 4.4-10 - Figure 4.4-20 and in Table 4.4-5 and Table 4.4-6 the comparisons are presented.

Comments regarding figures and tables:

Figure 4.4-10 - Figure 4.4-13 The graphs give the correlation between the Energy Bands and corresponding wind rates. The following model parameters have been altered:

- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 5.8 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 3.6 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 15 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)\(^3\) gives the best adaption to the measurement result.

Figure 4.4-14 - Figure 4.4-17 The graphs give the correlation between the Energy Bands and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). The following model parameters have been altered:

- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 3.6 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 15 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)\(^3\) gives the best adaption to the measurement result.

Figure 4.4-18 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific Wind rate Bands (defined by wind rates) and the Wind rate Bands in question. (Frequency function vs wind rate band). See Figure 4.4-1 and Equation 4.4-1. The figure illustrates 52 Wind rate Bands, separated with 0.2 m/s. The equation defines the correlation between Wind rate Bands and Wind rates. Simulation with nominal parameters is compared with measurement result.
The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 2.

Table 4.4-5 lists the resulting Quotient of Relative Mean Energy between simulation and measurement during period 2. As can bee noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 4.4-6 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement result.

*) mean value: 3, standarddeviation: 1
Figure 4.4-11  Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

Figure 4.4-12  Wind rate vs Energy Band with altering Turbulence level. (A, C and Turbulence variation are fixed nominal)
Figure 4.4-13  Wind rate vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

Figure 4.4-14  Normalised Energy Distribution vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)
Figure 4.4-15  Normalised Energy Distribution vs Energy Band with altering Turbulence. (A, C and Turbulence variation are fixed nominal)

Figure 4.4-16  Normalised Energy Distribution vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)
Figure 4.4-17  Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

Figure 4.4-18  Frequency Function vs Wind Rate Band (see Figure 4.4-1). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)
Figure 4.4-19  Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 2.

Figure 4.4-20  Measured wind speed. Period 2
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Value</th>
<th>Relative Mean Energy:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulated Result</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement Result</td>
</tr>
<tr>
<td><strong>A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C, Turbulence and Turbulence variation nominal)</td>
<td>5.00</td>
<td>0.6468</td>
</tr>
<tr>
<td></td>
<td><strong>5.80</strong> (nominal)</td>
<td><strong>1.0169</strong></td>
</tr>
<tr>
<td></td>
<td>6.60</td>
<td>1.5680</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>3.00</td>
<td>1.0764</td>
</tr>
<tr>
<td>(A, Turbulence and Turbulence variation nominal)</td>
<td><strong>3.60</strong> (nominal)</td>
<td><strong>1.0169</strong></td>
</tr>
<tr>
<td></td>
<td>4.20</td>
<td>1.0342</td>
</tr>
<tr>
<td><strong>Turbulence</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C, A and Turbulence variation nominal)</td>
<td>5 %</td>
<td>0.9863</td>
</tr>
<tr>
<td></td>
<td>10 %</td>
<td>1.0219</td>
</tr>
<tr>
<td></td>
<td><strong>15 %</strong> (nominal)</td>
<td><strong>1.0169</strong></td>
</tr>
<tr>
<td></td>
<td>20 %</td>
<td>1.0635</td>
</tr>
<tr>
<td></td>
<td>25 %</td>
<td>1.0817</td>
</tr>
<tr>
<td><strong>Turbulence variation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C, A and Turbulence nominal)</td>
<td><strong>(3,1)</strong> (nominal)</td>
<td><strong>1.0169</strong></td>
</tr>
<tr>
<td></td>
<td>(5,2)</td>
<td>1.0262</td>
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<td></td>
<td>(10,3)</td>
<td>1.0214</td>
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Table 4.4-5 Relative Mean Energy vs variation of some parameters

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<tr>
<th>Mean (m/s)</th>
<th>Standarddev. (m/s)</th>
<th>Maximum (m/s)</th>
<th>Minimum (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>5.2</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 4.4-6 Statistical parameters regarding wind rate. Measurements vs simulations
4.4.3 Measuring period 3

Date: 9 – 11 June 2007 (72 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 4.4-21 - Figure 4.4-28 and in Table 4.4-7 and Table 4.4-8 the comparisons are presented.

Comments regarding figures and tables:

Figure 4.4-21 - Figure 4.4-24 The graphs give the correlation between the Energy Bands and corresponding wind rates. The following model parameters have been altered:
- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 3.30 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 2.40 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 25 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1)° gives the best adaption to the measurement result.

Figure 4.4-25 The graphs give the correlation between the Energy Bands and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). Simulation with nominal parameters is compared with measurement result.

Figure 4.4-26 The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific Wind rate Bands (defined by wind rates) and the Wind rate Bands in question. (Frequency function vs wind rate band). See Figure 4.4-1 and Equation 4.4-1. The figure illustrates 52 Wind rate Bands, separated with 0.2 m/s. The equation defines the correlation between Wind rate Bands and Wind rates. Simulation with nominal parameters is compared with measurement result.

Figure 4.4-27 and Figure 4.4-28 The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 3.
Table 4.4-7 lists the resulting Quotient of Relative Mean Energy between simulation and measurement during period 3. As can be noted, simulation with the nominal parameters results in good adaption to the measurement result.

In Table 4.4-8 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaption between simulation results and measurement result.

*) mean value: 3, standard deviation: 1

Figure 4.4-21 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)
Figure 4.4-22  Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

Figure 4.4-23  Wind rate vs Energy Band with altering Turbulence level. (A,C, and Turbulence variation are fixed nominal)
Figure 4.4-24 Wind rate vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

Figure 4.4-25 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)
Figure 4.4-26  Frequency Function vs Wind Rate Band (see Figure 4.4-1). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)
Figure 4.4-27  Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 3.

Figure 4.4-28  Measured wind speed. Period 3
### Table 4.4-7
Relative Mean Energy vs variation of some parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parameter Value</th>
<th>Relative Mean Energy:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Simulated Result</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Measurement Result</td>
</tr>
<tr>
<td>A (C, Turbulence and Turbulence variation nominal)</td>
<td>3.00</td>
<td>0.7123</td>
</tr>
<tr>
<td></td>
<td>3.30 (nominal)</td>
<td>0.9962</td>
</tr>
<tr>
<td></td>
<td>3.60</td>
<td>1.2358</td>
</tr>
<tr>
<td>C (A, Turbulence and Turbulence variation nominal)</td>
<td>2.00</td>
<td>1.1330</td>
</tr>
<tr>
<td></td>
<td>2.40 (nominal)</td>
<td>0.9962</td>
</tr>
<tr>
<td></td>
<td>2.80</td>
<td>0.9099</td>
</tr>
<tr>
<td>Turbulence (C, A and Turbulence variation nominal)</td>
<td>5 %</td>
<td>0.9398</td>
</tr>
<tr>
<td></td>
<td>15 %</td>
<td>0.9674</td>
</tr>
<tr>
<td></td>
<td>20 % (nominal)</td>
<td>0.9962</td>
</tr>
<tr>
<td></td>
<td>25 %</td>
<td>1.0033</td>
</tr>
<tr>
<td></td>
<td>35 %</td>
<td>1.1718</td>
</tr>
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<td>Turbulence variation (C, A and Turbulence nominal)</td>
<td>(3,1) (nominal)</td>
<td>0.9962</td>
</tr>
<tr>
<td></td>
<td>(5,2)</td>
<td>0.9341</td>
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<tr>
<td></td>
<td>(10,3)</td>
<td>0.9607</td>
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### Table 4.4-8
Statistical parameters regarding wind rate. Measurements vs simulations with nominal parameters

<table>
<thead>
<tr>
<th>Mean (m/s)</th>
<th>Standarddev. (m/s)</th>
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<th>Minimum (m/s)</th>
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<td>2.7</td>
<td>2.9</td>
<td>1.4 1.1</td>
<td>7.6 7.3</td>
</tr>
</tbody>
</table>

Table 4.4-7 Relative Mean Energy vs variation of some parameters

Table 4.4-8 Statistical parameters regarding wind rate. Measurements vs simulations with nominal parameters
4.4.4 Measuring period 4

Date: 17 – 21 June 2007 (120 hours)

Simulations with varying model parameters have been performed. The results have been compared with the corresponding measurement results. In Figure 4.4-29 - Figure 4.4-38 and in Table 4.4-9 and Table 4.4-10 the comparisons are presented.

Comments regarding figures and tables:

**Figure 4.4-29 - Figure 4.4-33** The graphs give the correlation between the Energy Bands and corresponding wind rates. The following model parameters have been altered:
- Weibull parameter A (parameter C, Turbulence and Turbulence variation are fixed nominal). A = 3.80 gives the best adaption to the measurement result.
- Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal). C = 2.50 gives the best adaption to the measurement result.
- Turbulence level (parameter A, parameter C and Turbulence variation are fixed nominal). Turbulence level = 25 % gives the best adaption to the measurement result.
- Turbulence variation (parameter A, parameter C and Turbulence level are fixed nominal). Turbulence variation = (3, 1) gives the best adaption to the measurement result.

**Figure 4.4-34 - Figure 4.4-35** The graphs give the correlation between the Energy Bands and corresponding energy in relation to the total energy (%). (Normalised energy distribution vs energy band). Weibull parameter C (parameter A, Turbulence and Turbulence variation are fixed nominal) have been altered. C = 2.50 gives the best adaption to the measurement result.

**Figure 4.4-36** The graphs give the correlation between the frequency of samples (% of total samples of the process) in specific Wind rate Bands (defined by wind rates) and the Wind rate Bands in question. (Frequency function vs wind rate band). See Figure 4.4-1 and Equation 4.4-1. The figure illustrates 52 Wind rate Bands, separated with 0.2 m/s. The equation defines the correlation between Wind rate Bands and Wind rates. Simulation with nominal parameters is compared with measurement result.

**Figure 4.4-37 - Figure 4.4-38** The graphs give the resulted simulated wind speed (nominal model parameters) and the corresponding measured wind speed for period 4.
Table 4.4-9 lists the resulting Quotient of Relative Mean Energy between simulation and measurement during period 4. As can be noted, simulation with the nominal parameters results in good adaptation to the measurement result.

In Table 4.4-10 some statistical parameters are compared regarding measurements and simulations. The conclusion is that there are good adaptation between simulation results and measurement result.

*) mean value: 3, standarddeviation: 1
Figure 4.4-30  Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

Figure 4.4-31  Wind rate vs Energy Band with altering Turbulence. (A, C, and Turbulence variation are fixed nominal)
Figure 4.4-32  Wind rate vs Energy Band with altering Turbulence variation. (A, C, Turbulence are fixed nominal)

Figure 4.4-33  Wind rate vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation). 3 separated simulation sequences are compared
Figure 4.4-34 Normalised Energy Distribution vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

Figure 4.4-35 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation). 3 separated simulation sequences are compared
Figure 4.4-36  Frequency Function vs Wind Rate Band (see Figure 4.4-1). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)
Figure 4.4-37  Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 4.

Figure 4.4-38  Measured wind speed. Period 4
<table>
<thead>
<tr>
<th>Parameter (C, Turbulence and Turbulence variation nominal)</th>
<th>Parameter Value</th>
<th>Relative Mean Energy:</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.80</td>
<td>0.4111</td>
</tr>
<tr>
<td></td>
<td>3.80 (nominal)</td>
<td>1.0328 (1.0359, 1.0587)</td>
</tr>
<tr>
<td></td>
<td>4.40</td>
<td>1.5980</td>
</tr>
<tr>
<td>C (A, Turbulence and Turbulence variation nominal)</td>
<td>2.00</td>
<td>1.1971</td>
</tr>
<tr>
<td></td>
<td>2.50 (nominal)</td>
<td>1.0328 (1.0359, 1.0587)</td>
</tr>
<tr>
<td></td>
<td>3.20</td>
<td>0.9766</td>
</tr>
<tr>
<td>Turbulence (C, A and Turbulence variation nominal)</td>
<td>5 %</td>
<td>0.9875</td>
</tr>
<tr>
<td></td>
<td>15 %</td>
<td>1.0149</td>
</tr>
<tr>
<td></td>
<td>20 % (nominal)</td>
<td>1.0328 (1.0359, 1.0587)</td>
</tr>
<tr>
<td></td>
<td>25 %</td>
<td>1.1075</td>
</tr>
<tr>
<td></td>
<td>35 %</td>
<td>1.1687</td>
</tr>
<tr>
<td>Turbulence variation (C, A and Turbulence nominal)</td>
<td>(3,1) (nominal)</td>
<td>1.0328 (1.0359, 1.0587)</td>
</tr>
<tr>
<td></td>
<td>(5,2)</td>
<td>1.0310</td>
</tr>
<tr>
<td></td>
<td>(10,3)</td>
<td>1.0101</td>
</tr>
</tbody>
</table>

Table 4.4-9 Relative Mean Energy vs variation of some parameters

<table>
<thead>
<tr>
<th>Mean (m/s)</th>
<th>Standarddev. (m/s)</th>
<th>Maximum (m/s)</th>
<th>Minimum (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>3.4 (3.4, 3.4)</td>
<td>1.4</td>
<td>1.2 (1.2, 1.2)</td>
</tr>
</tbody>
</table>

Table 4.4-10 Statistical parameters regarding wind rate. Measurements vs simulations with nominal parameters
4.5 Conclusion

To adapt the model parameters to the measurement data the following principle is recommended:

- *Sim_step_W_My*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. In the previous examples according to period 1 – 4, *Sim_step_W_My* consistently has been assigned to the value 300.

- *Sim_step_W_Sigma*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. In the previous examples according to period 1 – 4, *Sim_step_W_Sigma* consistently has been assigned to the value 100.

- *Sim_step_T_My*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. See Figure 4.4-5, Figure 4.4-13, Figure 4.4-16, Figure 4.4-24 and Figure 4.4-32 and Table 4.4-3, Table 4.4-5, Table 4.4-7 and Table 4.4-9. In the previous examples according to period 1 – 4, *Sim_step_T_My* consistently has been assigned to the value 3.

- *Sim_step_T_Sigma*. The parameter is estimated by using a visual comparison between the measurement and simulation regarding the period of time. This parameter is not very critical and it is good enough to make a rough estimation. See Figure 4.4-5, Figure 4.4-13, Figure 4.4-16, Figure 4.4-24 and Figure 4.4-32 and Table 4.4-3, Table 4.4-5, Table 4.4-7 and Table 4.4-9. In the previous examples according to period 1 – 4, *Sim_step_T_Sigma* consistently has been assigned to the value 1.

- *Level_T_Sigma_proc*. The parameter is estimated by comparing measurements with simulations in the following routines:

  a) The graphs that give the correlation between the *Wind rate vs Energy Band* (see Figure 4.4-4, Figure 4.4-12, Figure 4.4-23 and Figure 4.4-31).

  b) The graphs that give the correlation between the *Normalised Energy Distribution vs Energy Band* (see Figure 4.4-15). The present judgement is that this point can be cancelled if point a) is realized.

  c) *Relative Mean Energy* (see Table 4.4-3, Table 4.4-5, Table 4.4-7 and Table 4.4-9)

  d) The statistic parameters *meanvalue, standarddeviation, maximum and minimum* (see Table 4.4-4, Table 4.4-6, Table 4.4-8 and Table 4.4-10)
- Weibull parameter $A$. The parameter is estimated by comparing measurements with simulations in the following routines:

a) The graphs that give the correlation between the Wind rate vs Energy Band (see Figure 4.4-2, Figure 4.4-10, Figure 4.4-21 and Figure 4.4-29)

c) Relative Mean Energy (see Table 4.4-3, Table 4.4-5, Table 4.4-7 and Table 4.4-9)

d) The statistic parameters meanvalue, standarddeviation, maximum and minimum (see Table 4.4-4, Table 4.4-6, Table 4.4-8 and Table 4.4-10)

- Weibull parameter $C$. The parameter is estimated by comparing measurements with simulations in the following routines:

a) The graphs that give the correlation between the Wind rate vs Energy Band (see Figure 4.4-3, Figure 4.4-11, Figure 4.4-22 and Figure 4.4-30). The present judgement is that this point can be canceled if point b) is realized.

b) The graphs that give the correlation between the Normalised Energy Distribution vs Energy Band (see Figure 4.4-14 and Figure 4.4-34).

c) Relative Mean Energy (see Table 4.4-3, Table 4.4-5, Table 4.4-7 and Table 4.4-9)

d) The statistic parameters meanvalue, standarddeviation, maximum and minimum (see Table 4.4-4, Table 4.4-6, Table 4.4-8 and Table 4.4-10)

The present judgement is that it is sufficient only to realize point b) and point c). Point a) and point d) can be canceled without any effect on the quality of the result. However it is interesting to have a check on the statistic parameters meanvalue, standarddeviation, maximum and minimum.

Table 4.5-1 gives a summary of the estimation routines.
<table>
<thead>
<tr>
<th>Model parameter</th>
<th>Estimation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sim_step_W_My</td>
<td>Visual comparison between the measurement and simulation regarding the period of time</td>
</tr>
<tr>
<td>Sim_step_W_Sigma</td>
<td>-“-</td>
</tr>
<tr>
<td>Sim_step_T_My</td>
<td>-“-</td>
</tr>
<tr>
<td>Sim_step_T_Sigma</td>
<td>-“-</td>
</tr>
</tbody>
</table>
| Level_T_Sigma_proc | Comparison between the measurement and simulation regarding:  
|                  | - Wind rate vs Energy Band  
|                  | - (Normalised Energy Distribution vs Energy Band)  
|                  | - Relative Mean Energy  
|                  | - Meanvalue, standarddeviation, maximum and minimum |
| A                | Comparison between the measurement and simulation regarding:  
|                  | - Wind rate vs Energy Band  
|                  | - Relative Mean Energy  
|                  | - Meanvalue, standarddeviation, maximum and minimum |
| C                | Comparison between the measurement and simulation regarding:  
|                  | - (Wind rate vs Energy Band)  
|                  | - Normalised Energy Distribution vs Energy Band  
|                  | - Relative Mean Energy  
|                  | - Meanvalue, standarddeviation, maximum and minimum |

Table 4.5-1 Summary of the parameter estimation routines

4.6 Future work

As future work the following is suggested:

- analysis based on measurements representing strong varying whether conditions (e.g. wind rates from a few metres per second up to at least 20 metres per second)

- a deeper theoretical analysis regarding different statistical relations
5 SUN POWER

5.1 Introduction

This chapter deals with the problem to realize a useful stochastic model of how the extinction coefficients, regarding the wave length region corresponding to the working area for silicon photovoltaic solarcells, will vary as a consequence of how different meteorological parameters undergo variations. As the weather situation is depending on stochastic variations, then also the extinction coefficients will vary stochastically. See paragraph 3.3 (Module “Extinction_make”) for information about the use of extinction coefficient in combination with simulation. Equation 5.1-1 to Equation 5.1-6 give some important relations regarding the questions around the extinction coefficient.

Equation 5.1-1:

\[ \tau = \exp(-Ext \cdot M) \]

Equation 5.1-2:

\[ S = S_0 \cdot \tau \]

Equation 5.1-3:

\[ M = \frac{h}{h_0} \]

Equation 5.1-4:

\[ S_M = S \cdot \cos \beta + S_{diff} \]

Where:

\( \tau \): the atmospheric transmission \((0 - 1)\)

\( Ext \): the extinction coefficient (in the wave length region of silicon photovoltaic solarcells)
\[ M: \text{ the relative atmospheric depth (i.e. the distance to pass through the atmosphere by the Sun radiation). It is related to the depth when the Sun is in zenith} \]

\[ h: \text{ the atmospheric depth} \]

\[ h_0: \text{ the atmospheric depth for } \alpha = \frac{\pi}{2} \]

\[ \alpha: \text{ the Sun’s altitude above the horizon} \]

\[ S: \text{ irradiance (W/m}^2\text{) after the radiation (in the wave length region of silicon photovoltaic solarcells) has passed the atmosphere in question} \]

\[ S_0: \text{ irradiance (W/m}^2\text{) before the radiation (in the wave length region of silicon photovoltaic solarcells) has passed the atmosphere in question} \]

\[ S_{diff}: \text{ diffuse irradiance component against a measuring surface (solar panel). The diffuse component is a result of atmospheric scattering and reflections against surrounding objects} \]

\[ S_M: \text{ effective irradiance (W/m}^2\text{) against a measuring surface (solar panel)} \]

\[ \beta: \text{ the angle between the surface normal of the measuring surface (solar panel) and the direction to Sun} \]

\( \cos \beta \) could be calculated by the following expression:

**Equation 5.1-5:**

\[ \cos \beta = \sin \alpha \cdot \cos \Omega_z + \cos \alpha \cdot \sin \Omega_z \cdot \cos (\theta - \Omega_s) \]

Where

\[ \Omega_z: \text{ the normal angle of the measuring surface relative to zenith} \]

\[ \Omega_s: \text{ the normal angle of the measuring surface relative to south} \]

\[ \theta: \text{ the Sun’s azimuth} \]

\[ \alpha: \text{ the Sun’s altitude above the horizon} \]

\( \alpha \) and \( \theta \) are calculated according to paragraph 3.4 (Module “Sun_intensity”).
See Figure 5.1-1 for some illustration of the above parameters.

![Diagram of atmospheric layers and radiation reduction](image)

Figure 5.1-1 The radiation is reduced as an effect of the atmospheric influence

From Figure 5.1-1 it could be established the following relation between $M$ and $\alpha$:

**Equation 5.1-6:**

$$M = \frac{1}{\sin \alpha}$$

From Equation 5.1-1 it could be observed that the transmission will decrease if the extinction is increasing. If the transmission is 1 ($Ext \cdot M = 0$) then there is no atmospheric reduction of the incoming Sun irradiance.

The extinction is dependent of the meteorological conditions regarding:

- Temperature
- Air pressure
- Humidity
- Rain
- Snow
- Visibility
- Cloudiness
- Varying conditions regarding aerosols in the air
- Varying conditions regarding the composition of different molecules in the air

All together there are a lot of parameters that have influences on the extinction in question.

The model that is suggested in this document, presumes so called “typical cases”, for instance:

- Ordinary summer in Sweden (a mixture of different meteorological conditions)
- Cloudy day with a clodiness of ¼
- Sunny day

And so on

Each such “typical cases” will be assigned model parameters (stochastic parameters) that serve as inputs to the model. Outputs from the model are extinction coefficients that in a statistic point of view are representative for the “typical cases” in question. See Figure 5.1-2 that shows the principle of the model that is suggested.

The reason to use “typical cases” is to get a model process that is practical to handle.
5.2 Modeling of the extinction coefficient

The principle for the model is described in paragraph 3.3 (Module “Extinction_make”).

5.3 Measurements

Measurements to get statistic foundations to make a survey of the extinction coefficient have been performed during the period 21/6 - 7/9 – 2006.

The principle for the measurement arrangement follows by Figure 5.3-1.

There are 3 solar cell panels connected in series by the connection box. Each solar cell panel consists of 72 series connected solar cells. The result of this arrangement is that there are 216 series connected cells at the output of the connection box. The current $I_S$ in Figure 5.3-1 corresponds to the “short circuit current” of the solar cells. As there are so many solar cells that co-operates, two advantages are at hand:

- Small effects regarding the voltage drops in the connection wires
- A good representative value (mean value of a large number cells) regarding the short circuit current in question
The principle for the measurement arrangement. The connection box connects the three solar cells panels in series. This results in 216 series connected solar cells.

The equivalent circuit of a solar cell.
The short circuit current is a good measure of the Sun irradiance. See Figure 5.3-2 that shows the equivalent circuit of the solar cell. As the resistance $R_S$ in Figure 5.3-2 is quite small (about 15 m$\Omega$) the maximum voltage drop over this resistance (i.e. at short circuit) normally is less than 60 mV. This voltage corresponds to the voltage $U_S$. A short circuited cell output (i.e. $U_L = 0$) will result in $U_S = U_{diod}$. If $U_{diod}$ is in the region of maximum 60 mV, then the diod current $I_{diod}$ is very small (in the order of a few mA) compared with the short circuit current (normally in the order of amperes). This results in:

**Equation 5.3-1:**

$$I_{SC} = I_L \text{ at short circuited cell output.}$$

I.e.

$$I_{SC} = I_S \quad \text{(see Figure 5.3-1 and Figure 5.3-2).}$$

$$I_{SC} = G \cdot S_M,$$

Where

$G$: a scale factor (Am$^2$/W)

$S_M$: Effective Sun irradiance (W/m$^2$)

Or

**Equation 5.3-2:**

$$I_S = G \cdot S_M$$

According to Equation 5.1-1, Equation 5.1-2 and Equation 5.1-4:

$$\tau = \exp(-Ext \cdot M)$$

$$S = S_0 \cdot \tau$$

And

$$S_M = S \cdot \cos \beta + S_{diff}$$

This gives:

**Equation 5.3-3:**

$$I_S = G \cdot S_0 \cdot \exp(-Ext \cdot M) \cdot \cos \beta + G \cdot S_{diff} = I_M \cdot \exp(-Ext \cdot M) \cdot \cos \beta + Idiff$$
Where

\( I_M \): A reference current (A), that corresponds to the short circuit current for a Sun irradiance of \( S_0 \).

\( Idiff \): A current component (A), that corresponds to the contribution from diffuse irradiance

\( I_S \): Short circuited current (A)

Equation 5.3-3 gives the extinction coefficient.

**Equation 5.3-4:**

\[
Ext = \frac{-\ln\left(\frac{I_S - Idiff}{I_M \cdot \cos \beta}\right)}{M}
\]

If \( Ext, Idiff \) and \( I_M \) are known then it is possible to calculate a value for \( I_S \) for a given geographic position (latitude and longitude), a given normal angle of the measuring surface relative to zenith and south and a given time point (date and hour) according to:

**Equation 5.3-5:**

\[
I_S = \exp(-Ext \cdot M) \cdot I_M \cdot \cos \beta + Idiff
\]
5.4 Measurement results

Measurements to get statistic foundations to make a survey of the extinction coefficient have been performed during the period 21/6 - 7/9 – 2006. Figure 5.4-1 to Figure 5.4-8 give some examples of the short circuit current from the measurements during the period in question. The main reason for the measurement campaign was to collect information about the short circuit current. To get some idea about the voltage variations, some days however, were used for “no load” voltage measuring. An example of this follows in Figure 5.4-9.

Figure 5.4-1  Short circuit current 060626
Figure 5.4-2  Short circuit current 060721

Figure 5.4-3  Short circuit current 060806
Figure 5.4-4  Short circuit current 060816

Figure 5.4-5  Short circuit current 060819
Figure 5.4-6  Short circuit current 060827

Figure 5.4-7  Short circuit current 060904
Figure 5.4-8  Short circuit current 060907

Figure 5.4-9  No load voltage 060714
5.5 Analysis of the measurements

5.5.1 The extinction coefficient

The extinction coefficient is defined according to Equation 5.1-1. This is more and less a good approximation of the so called “Beers law”, that gives the transmission for the electromagnetic radiation in a very narrow wave length region in combination with a homogeneous transmission media. This is not on hand in the present application. So it must be pointed out that there is an approximation to use one single extinction coefficient to describe the transmission circumstances in this case. However the estimation is that the present approximation will result in a tool with a precision good enough for statistic prediction of the potential to get electric power when using solar cells at different geographic locations and times of the year. Future validations will give more answers about these questions.

The calculations of the extinction coefficients are based on Equation 5.3-4. The following parameters have then been used:

\( I_{\text{diff}} \):
The parameter corresponds to the resulted current component from the diffuse irradiance. The measured short circuited current at time point 16.30 has been used as value. The chosed time point will ensure that there is only diffuse radiation that hit the solar cells.

\( I_M \):
The parameter corresponds to the short circuit current for a Sun irradiance of \( S_0 \) (Sun irradiance outside the atmosphere) and \( \cos \beta = 1 \). This value has been predicted to 5 A.

\( \cos \beta \):
The parameter corresponds to cosinus of the angle between the surface normal of the measuring surface (solar panel) and the direction to Sun. It is calculated as a result of the Sun altitude and azimuth and on the normal angle of the measuring surface relative to zenith and south. The Sun altitude and azimuth are calculated according to the description in paragraph 3.4 (Module “Sun_intensity”). The normal angle of the measuring surface relative to zenith is 90°. The normal angle of the measuring surface relative to south is - 30°. The equation to calculate \( \cos \beta \) follows by Equation 5.1-5.

\( M \):
The parameter corresponds to the relative atmospheric depth. It is calculated according to Equation 5.1-6 and the description in paragraph 3.4 (Module “Sun_intensity”).

The measurements consists of collected data in intervals of 1 minute during the period from 21/6 to 7/9 2006.
The mean values and standard deviations of the extinction coefficients between 9 am to 15 pm (Swedish summer time) for the first 30 short circuit measurement days are given in Table 5.5-1.

Figure 5.5-1 illustrates the extinction coefficient profile, based on the measurements, during the period in question. 71 days in this period were used for “short circuit” measurements, giving basic data for extinction calculations. 4 days were used for “no load” measurements giving information about the top voltage profile. 4 days were not used for regular measurements.

In Figure 5.5-1 it could be noted that the “envelope” (the top values) of the extinction coefficient describes a falling curve, i.e. the maximum extinction is reduced during the time period in question.

Note. Days with extinction coefficient = 0 in Figure 5.5-1 represent “no load” measurements alternatively “no regular measurements”.

Figure 5.5-1 Profile of the extinction coefficient, based on the measurements, during the period from 21/6 to 7/9 2006.
<table>
<thead>
<tr>
<th>Measuring day (number)</th>
<th>Date</th>
<th>Cloudiness (mean value)</th>
<th>Mean value of extinction coefficient 9 am to 15 pm</th>
<th>Standard deviation of extinction coefficient 9 am to 15 pm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2006-06-21</td>
<td>5 – 6/8</td>
<td>1.82</td>
<td>1.12</td>
</tr>
<tr>
<td>2</td>
<td>-22</td>
<td>5 – 6/8</td>
<td>1.58</td>
<td>1.18</td>
</tr>
<tr>
<td>3</td>
<td>-23</td>
<td>5 – 6/8</td>
<td>2.03</td>
<td>1.09</td>
</tr>
<tr>
<td>4</td>
<td>-24</td>
<td>3 – 4/8</td>
<td>0.94</td>
<td>0.70</td>
</tr>
<tr>
<td>5</td>
<td>-25</td>
<td>5 – 6/8</td>
<td>1.98</td>
<td>0.62</td>
</tr>
<tr>
<td>6</td>
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<td>2.08</td>
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<td>7</td>
<td>-27</td>
<td>7 – 8/8</td>
<td>2.42</td>
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</tr>
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<td>8</td>
<td>-28</td>
<td>5 – 6/8</td>
<td>1.96</td>
<td>1.18</td>
</tr>
<tr>
<td>9</td>
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<td>1 – 2/8</td>
<td>0.65</td>
<td>0.56</td>
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<td>-30</td>
<td>3 – 4/8</td>
<td>0.99</td>
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<td>0.46</td>
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<td>0.48</td>
<td>0.02</td>
</tr>
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<td>7 – 8/8</td>
<td>2.27</td>
<td>1.54</td>
</tr>
<tr>
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<td>7 – 8/8</td>
<td>2.42</td>
<td>1.42</td>
</tr>
<tr>
<td>26</td>
<td>-23</td>
<td>5 – 6/8</td>
<td>1.60</td>
<td>1.10</td>
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<td>28</td>
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<td>5 – 6/8</td>
<td>1.49</td>
<td>0.96</td>
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<td>30</td>
<td>-27</td>
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<td>0.53</td>
<td>0.08</td>
</tr>
<tr>
<td>Mean value:</td>
<td></td>
<td></td>
<td>1.35</td>
<td>0.85</td>
</tr>
</tbody>
</table>

Table 5.5-1  Mean values and standard deviations of extinction coefficients during 9 am to 15 pm for the first 30 measuring days of short circuited current
5.5.2 Probability function of the extinction coefficient

The following analysis presumes that the extinction coefficients are distributed according a so called lognormal distribution function. That implies that the natural logarithm of the extinction coefficients are normal distributed.

The mean values (μ) and standard deviations (σ) of the natural logarithm of the extinction coefficients between 9 am to 15 pm (Swedish summer time) for the first 30 short circuit measurement days are given in Table 5.5-2.

The total mean value of the statistical parameters (μ and σ) in Table 5.5-2 is

μtot = -0.8863 and σtot = 0.9652

Presuming these values gives the lognormal density function according to Figure 5.5-2.

![Lognormal Density Function](image)

Figure 5.5-2 The extinction coefficient density function with μtot = -0.8863 and σtot = 0.9652
<table>
<thead>
<tr>
<th>Measuring day (number)</th>
<th>Date</th>
<th>Cloudiness (mean value)</th>
<th>Mean value of nat log for extinction coefficient 9 am to 15 pm $\mu$</th>
<th>Standard deviation of nat log for extinction coefficient 9 am to 15 pm $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2006-06-21</td>
<td>5 – 6/8</td>
<td>0.0602</td>
<td>1.0661</td>
</tr>
<tr>
<td>2</td>
<td>-22</td>
<td>5 – 6/8</td>
<td>-0.5869</td>
<td>1.6811</td>
</tr>
<tr>
<td>3</td>
<td>-23</td>
<td>5 – 6/8</td>
<td>-0.1390</td>
<td>2.2193</td>
</tr>
<tr>
<td>4</td>
<td>-24</td>
<td>3 – 4/8</td>
<td>-1.0329</td>
<td>1.4186</td>
</tr>
<tr>
<td>5</td>
<td>-25</td>
<td>5 – 6/8</td>
<td>0.4247</td>
<td>0.4587</td>
</tr>
<tr>
<td>6</td>
<td>-26</td>
<td>5 – 6/8</td>
<td>0.5209</td>
<td>0.3211</td>
</tr>
<tr>
<td>7</td>
<td>-27</td>
<td>7 – 8/8</td>
<td>0.7211</td>
<td>0.2264</td>
</tr>
<tr>
<td>8</td>
<td>-28</td>
<td>5 – 6/8</td>
<td>-0.8158</td>
<td>2.5341</td>
</tr>
<tr>
<td>9</td>
<td>-29</td>
<td>1 – 2/8</td>
<td>-2.0478</td>
<td>1.4178</td>
</tr>
<tr>
<td>10</td>
<td>-30</td>
<td>3 – 4/8</td>
<td>-1.8986</td>
<td>2.8009</td>
</tr>
<tr>
<td>11</td>
<td>-07-01</td>
<td>0 – 1/8</td>
<td>-2.0920</td>
<td>0.2162</td>
</tr>
<tr>
<td>12</td>
<td>-02</td>
<td>0 – 1/8</td>
<td>-2.0284</td>
<td>0.3451</td>
</tr>
<tr>
<td>13</td>
<td>-03</td>
<td>0 – 1/8</td>
<td>-1.9814</td>
<td>0.2419</td>
</tr>
<tr>
<td>14</td>
<td>-04</td>
<td>0 – 1/8</td>
<td>-1.8449</td>
<td>0.2668</td>
</tr>
<tr>
<td>15</td>
<td>-05</td>
<td>0 – 1/8</td>
<td>-1.6916</td>
<td>0.2056</td>
</tr>
<tr>
<td>16</td>
<td>-06</td>
<td>0 – 1/8</td>
<td>-1.7998</td>
<td>0.1313</td>
</tr>
<tr>
<td>17</td>
<td>-07</td>
<td>7 – 8/8</td>
<td>0.1217</td>
<td>1.2163</td>
</tr>
<tr>
<td>18</td>
<td>-08</td>
<td>5 – 6/8</td>
<td>0.0141</td>
<td>1.3137</td>
</tr>
<tr>
<td>19</td>
<td>-09</td>
<td>5 – 6/8</td>
<td>0.0854</td>
<td>0.7732</td>
</tr>
<tr>
<td>20</td>
<td>-10</td>
<td>5 – 6/8</td>
<td>-0.1951</td>
<td>1.7054</td>
</tr>
<tr>
<td>21</td>
<td>-11</td>
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<td>-2.2442</td>
<td>0.0905</td>
</tr>
<tr>
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<td>-2.2309</td>
<td>0.0792</td>
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<tr>
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<td>0 – 1/8</td>
<td>-2.5169</td>
<td>0.8713</td>
</tr>
<tr>
<td>24</td>
<td>-14</td>
<td>0 – 1/8</td>
<td>-1.2291</td>
<td>0.2951</td>
</tr>
<tr>
<td>25</td>
<td>-15</td>
<td>7 – 8/8</td>
<td>0.2460</td>
<td>1.3772</td>
</tr>
<tr>
<td>26</td>
<td>-16</td>
<td>5 – 6/8</td>
<td>-0.3687</td>
<td>1.5807</td>
</tr>
<tr>
<td>27</td>
<td>-17</td>
<td>5 – 6/8</td>
<td>-0.1083</td>
<td>1.5530</td>
</tr>
<tr>
<td>28</td>
<td>-18</td>
<td>0 – 1/8</td>
<td>-0.7527</td>
<td>2.1293</td>
</tr>
<tr>
<td>29</td>
<td>-19</td>
<td>0 – 1/8</td>
<td>-2.0537</td>
<td>0.1183</td>
</tr>
<tr>
<td>30</td>
<td>-20</td>
<td>0 – 1/8</td>
<td>-1.5838</td>
<td>0.3016</td>
</tr>
</tbody>
</table>

Mean value of mean values: -0.8863  0.9652

Table 5.5-2  Mean values and standard deviations of the natural logarithm for extinction coefficients during 9 am to 15 pm for the first 30 measuring days of short circuited current
5.5.3 Comparisons between measured and calculated short circuit values

Figure 5.5-3 to Figure 5.5-32 illustrate some calculated short circuit currents together with corresponding measured results from the 30 first measurement days. The solid curves (___) correspond to measured values. The dashed (-->) and dashed-dotted (_ _) curves are calculated values with different extinction koefficients. The calculations are based on Equation 5.3-5.

The dashed (-->) curves are based on the extinction coefficient = 0.3126. This value has been assumed as the under limit of a realistic extinction coefficient. The value is based on calculations according to Equation 5.1-1, Equation 5.1-2 and Equation 5.1-3, with the following parameters:

\[ M: \ 1 \text{ (corresponding to the Sun in zenith)} \]
\[ S: \ 1000 \text{ W/m}^2 \]
\[ S_0: \ 1367 \text{ W/m}^2 \]

The dashed-dotted (_ _) curves are based on the extinction coefficients according to the mean value of extinction coefficient between 9 am to 15 pm for the measurement day in question. See Table 5.5-1.

![Figure 5.5-3](image.png)

Figure 5.5-3 Measured and calculated short circuit current 060621
___: measured, _ : 0.3126, _ . _ : 1.8242
Figure 5.5-4  Measured and calculated short circuit current 060622
____: measured, _ _ : 0.3126, _ . _: 1.5760

Figure 5.5-5  Measured and calculated short circuit current 060623
____: measured, _ _ : 0.3126, _ . _: 2.0317
Figure 5.5-6 Measured and calculated short circuit current 060624
- measured, _ _: 0.3126, _ . _: 0.9449

Figure 5.5-7 Measured and calculated short circuit current 060625
- measured, _ _: 0.3126, _ . _: 1.9826
Figure 5.5-8  Measured and calculated short circuit current 060626
 - : measured, - : 0.3126, - : 2.0771

Figure 5.5-9  Measured and calculated short circuit current 060627
 - : measured, - : 0.3126, - : 2.4233
Figure 5.5-10  Measured and calculated short circuit current 060628
_____ : measured, _ _ : 0.3126, _ _ _ : 1.9638

Figure 5.5-11  Measured and calculated short circuit current 060629
_____ : measured, _ _ : 0.3126, _ _ _ : 0.6486
Figure 5.5-12  Measured and calculated short circuit current 060630
_____: measured, _ _: 0.3126, _ _ _: 0.9933

Figure 5.5-13  Measured and calculated short circuit current 060701
_____: measured, _ _: 0.3126, _ _ _: 0.4393
Figure 5.5-14  Measured and calculated short circuit current 060702
___: measured, _ _: 0.3126, _ _ _: 0.4615

Figure 5.5-15  Measured and calculated short circuit current 060703
___: measured, _ _: 0.3126, _ _ _: 0.4553
Figure 5.5-16  Measured and calculated short circuit current 060704
_____ : measured, _-_: 0.3126, -._: 0.4769

Figure 5.5-17  Measured and calculated short circuit current 060705
_____ : measured, _-_: 0.3126, -._: 0.5008
Figure 5.5-18 Measured and calculated short circuit current 060706
---: measured, _ _: 0.3126, _ _ _: 0.4792

Figure 5.5-19 Measured and calculated short circuit current 060707
---: measured, _ _: 0.3126, _ _ _: 2.2706
Figure 5.5-20  Measured and calculated short circuit current 060708
____: measured, _ _: 0.3126, _ . _: 1.9575

Figure 5.5-21  Measured and calculated short circuit current 060709
____: measured, _ _: 0.3126, _ . _: 1.7162
Figure 5.5-22 Measured and calculated short circuit current 060710
_____ : measured, __ : 0.3126, ___ : 1.8421

Figure 5.5-23 Measured and calculated short circuit current 060718
_____ : measured, __ : 0.3126, ___ : 0.4189
Figure 5.5-24  Measured and calculated short circuit current 060719
---: measured, _ _: 0.3126, _ _ _: 0.4203

Figure 5.5-25  Measured and calculated short circuit current 060720
---: measured, _ _: 0.3126, _ _ _: 0.4144
Figure 5.5-26  Measured and calculated short circuit current 060721
-----: measured, _ _ : 0.3126, _ _ : 3.8493

Figure 5.5-27  Measured and calculated short circuit current 060722
-----: measured, _ _ : 0.3126, _ _ : 2.4203
Figure 5.5-28  Measured and calculated short circuit current 060723
____: measured, __: 0.3126, _._: 1.6010

Figure 5.5-29  Measured and calculated short circuit current 060724
____: measured, __: 0.3126, _._: 1.9856
Figure 5.5-30  Measured and calculated short circuit current 060725
___: measured, -: 0.3126, -. -. : 1.4888

Figure 5.5-31  Measured and calculated short circuit current 060726
___: measured, -: 0.3126, -. -. : 0.4417
Figure 5.5-32 Measured and calculated short circuit current 060727
__: measured, _ __: 0.3126, _ _ _: 0.5288

5.5.4 Extinction coefficient - Short circuit current. Some illustrations

Figure 5.5-33 to Figure 5.5-38 illustrate the relation between the extinction coefficient and the corresponding short circuit current during some measurement days. As can be observed is that a relative high extinction coefficient (low atmospheric transmission) results in a low short circuit current. A low extinction coefficient (high atmospheric transmission) results in a high short circuit current.
Figure 5.5-33 Extinction coefficient (lower curve) and short circuited current (upper curve) vs Time. 060705

Figure 5.5-34 Extinction coefficient (lower curve) and short circuited current (upper curve) vs Time. 060706
Figure 5.5-35  Extinction coefficient (lower curve) and short circuited current (upper curve) vs Time. 060719

Figure 5.5-36  Extinction coefficient (upper curve) and short circuited current (lower curve) vs Time. 060626
Figure 5.5-37  Extinction coefficient (upper curve) and short circuited current (lower curve) vs Time. 060627

Figure 5.5-38  Extinction coefficient (upper curve) and short circuited current (lower curve) vs Time. 060721
6 ELECTRIC LOAD

6.1 Introduction

This paper deals with the electric power consumption, where the load consists of the sum of different kind of companies. The aim of the study is to find out a suitable mathematic model that could be used for statistic evaluations of the power consumption when a region consisting of a mix of different companies is on hand. The model is based on results from a measurement campaign with a specific region as measurement object.

Company region: Almås, Lindome
Companies and power consumption according to Table 6.1-1.
Measurement interval: 05-10-25 to 05-11-29

<table>
<thead>
<tr>
<th>Company</th>
<th>Power consumption (kWh/year)</th>
<th>Fuse (A)</th>
<th>Voltage (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HB LINDOME</td>
<td>220929</td>
<td>315</td>
<td>10</td>
</tr>
<tr>
<td>HB LINDOME</td>
<td>266298</td>
<td>200</td>
<td>10</td>
</tr>
<tr>
<td>MÖLNDAL KOMMUN</td>
<td>22900</td>
<td>35</td>
<td>0.4</td>
</tr>
<tr>
<td>MÖLNDAL KOMMUN</td>
<td>111900</td>
<td>100</td>
<td>0.4</td>
</tr>
<tr>
<td>SVENSK VÅTRUMSTEKNIK I GÖTEBORG</td>
<td>19400</td>
<td>63</td>
<td>0.4</td>
</tr>
<tr>
<td>BILHUSET I LINDOME AB</td>
<td>121600</td>
<td>63</td>
<td>0.4</td>
</tr>
<tr>
<td>BILHUSET I LINDOME AB</td>
<td>13100</td>
<td>25</td>
<td>0.4</td>
</tr>
<tr>
<td>BILHUSET I LINDOME AB</td>
<td>3000</td>
<td>16</td>
<td>0.4</td>
</tr>
<tr>
<td>BILHUSET I LINDOME AB</td>
<td>15300</td>
<td>16</td>
<td>0.4</td>
</tr>
<tr>
<td>GISSELS ENTREPRENAD AB</td>
<td>41400</td>
<td>35</td>
<td>0.4</td>
</tr>
<tr>
<td>TRIAGON SNICKERI AB</td>
<td>45700</td>
<td>63</td>
<td>0.4</td>
</tr>
<tr>
<td>R SEGERS FASTIGHETSKONTOR</td>
<td>67500</td>
<td>80</td>
<td>0.4</td>
</tr>
<tr>
<td>STÅLMARIN AB</td>
<td>45600</td>
<td>35</td>
<td>0.4</td>
</tr>
<tr>
<td>HULTHEMS FASTIGHET O FÖRSÄLJNING</td>
<td>102000</td>
<td>35</td>
<td>0.4</td>
</tr>
<tr>
<td>STIGS RÖRLÄGGERI AB</td>
<td>9300</td>
<td>25</td>
<td>0.4</td>
</tr>
<tr>
<td>STURE JONSSONS PLÅTLAGERI</td>
<td>11300</td>
<td>25</td>
<td>0.4</td>
</tr>
<tr>
<td>MKS INPLASTNING</td>
<td>6600</td>
<td>25</td>
<td>0.4</td>
</tr>
<tr>
<td>VAGOTT KB</td>
<td>150500</td>
<td>125</td>
<td>0.4</td>
</tr>
<tr>
<td>Total Consumption (kWh/year):</td>
<td>1274327</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1-1 Name and power consumption for the companies that were involved during the measurement campaign in question
**Figure 6.1-1** illustrates the total power consumption for the company area during the measurement interval in question.

**Figure 6.1-2** illustrates the total power consumption during seven days. The interval 00.00 o’clock, 26/10 to 00.00 o’clock, 2/11 has been taken as an example. As can be observed there are two days with extremely small consumption. These days correspond to the weekend days, Saturday respectively Sunday.
Figure 6.1-1 illustrates that the consumption regarding the weekend differs from week to week. This indicates that there probably are some varying industrial activities in operation during the weekends.

Figure 6.1-2 The power consumption for the studied company area during a sample period of seven days.
Figure 6.1-3 illustrates the total power consumption for the company area during a sample period of 24 hours. The example in question is typical regarding the power profile as a function of time for a working day. There are two main time points; “The start of the working day” and “The end of the working day”. In the figure the start point is about 06.30 and the end about 18.00. Between these two time points there are two other time points. Namely “The time point when the start up is finished” respectively “The time point when the end of the working day begins”. From Figure 6.1-3 it could be noticed that the corresponding time points are about 08.30 respectively 15.00. Figure 6.1-4 shows the principle to model this type of load. See paragraph 3.6 (Module “Load_make”).

Comparing Figure 6.1-3 with Figure 6.1-4 results in the following corresponding points:

“The start of the working day” → TP_2
“The end of the working day” → TP_5

The time points between these points, namely:

“The time point when the start up is finished” → TP_3
“The time point when the end of the working day begins” → TP_4

According to above this gives:

TP_2 ≈ 06.30
TP_5 ≈ 18.00
TP_3 ≈ 08.30
TP_4 ≈ 15.00
Figure 6.1-3  The power consumption for the studied company area during a sample period of 24 hours (26/10, 00.00 – 27/10, 00.00)

Figure 6.1-4  An illustration of the base power shifts between the different time points during a 24 hours cycle
6.2 Measurement results. Some typical examples

Figure 6.2-1 to Figure 6.2-5 illustrate the power consumption for the first five days during the measurement period in question. The first three days are working days. The last two days are weekend days. The examples are typical for the power consumption of this type of load.

Figure 6.2-1 Power consumption 26/10, 00.00 – 27/10, 00.00. Working day
Figure 6.2-2  Power consumption 27/10, 00.00 – 28/10, 00.00. Working day

Figure 6.2-3  Power consumption 28/10, 00.00 – 29/10, 00.00. Working day
Figure 6.2-4  Power consumption 29/10, 00.00 – 30/10, 00.00. Weekend day

Figure 6.2-5  Power consumption 30/10, 00.00 – 31/10, 00.00. Weekend day
6.3 Evaluation of measurements

6.3.1 Common

The evaluation is focused on parameters to be used in a stochastic model named "Load_make". This model is described in point 6.3.2 and in 3.6 (Module "Load_make").

6.3.2 Load_make

"Load_make" is a program module that generates a stochastic model of a grid load. The module works with 6 separated day time points, TP_0 – TP_5. TP_0 is defined as midnight (0 or 24). TP_1 – TP_5 are input values. The module also uses 4 primary base power levels, A_prim, B_prim, C_prim and D_prim, that are related to the time points according to:

- A_prim: base power at TP_0
- B_prim: base power at TP_1 to TP_2
- C_prim: base power at TP_3 to TP_4
- D_prim: base power at TP_5

That means that the primary base levels follow the following sequence for a 24 hours cycle:

A_prim(at TP_0) – B_prim (at TP_1) – B_prim (at TP_2) – C_prim(at TP_3) –
- C_prim(at TP_4) – D_prim(at TP_5) – A_prim(back to a new 24 hours cycle, TP_0).

The shifts between the 4 base power levels are linearly performed.

The principle is illustrated in Figure 6.3-1.
The 4 primary base power levels undergo a stochastic variation, according a normal process. This stochastic variation are performed once per 24 hours cycle. This variation is named “the low frequency” noise”. The statistic parameters are named “L_My_L” and “L_Sigma_L” (the first L stands for Load and the second stands for Low), representing the mean value respectively the standard deviation in the Normal distribution. The so called “Load_factor” that is achieved by the Normal distribution and that is generated once per 24 hours cycle, is used as a factor for all base levels. This means that the base levels are updated every new 24 hours cycle according to Equation 6.3-1 to Equation 6.3-4.

**Equation 6.3-1**  \[ A = A_{\text{prim}} \cdot \text{Load} \cdot \text{factor} \]

**Equation 6.3-2**  \[ B = B_{\text{prim}} \cdot \text{Load} \cdot \text{factor} \]

**Equation 6.3-3**  \[ C = C_{\text{prim}} \cdot \text{Load} \cdot \text{factor} \]

**Equation 6.3-4**  \[ D = D_{\text{prim}} \cdot \text{Load} \cdot \text{factor} \]
The values of A, B, C and D are the real (used) base values during the present 24 hours cycle. The next coming 24 hours cycle will result in a new set of base levels (from the original levels of A_prim, B_prim, C_prim and D_prim) and so on.

For each simulation step a “Normal distributed noise” is added to the present level (that is achieved by the base level in question). This “high frequency noise” has the statistic parameters “$L_{My_H}$” and “$L_{Sigma_H}$” (the L stands for Load and the H stands for High), representing the mean value respectively the standard deviation in the Normal distribution.

An example of this “Power Noise” effect is illustrated in Figure 6.3-2 (no “High frequency Noise added) and Figure 6.3-3 (“High frequency Noise” added).

![Figure 6.3-2](image)

Figure 6.3-2 An example with no high frequency noise added to the base levels.
Figure 6.3-3  An example with high frequency noise added to the base levels. The standard deviation “$L_{\sigma_H}$” (in this example) is 10 % of present base level. The noise mean value “$L_{My_H}$” is zero.

The load model works with 2 categories of loads:

- Category a
- Category b

The simulation starts with category a. This category is modeled corresponding to a specified number of days, “$a_{\text{limit}}$”. When these days are completed, simulation of category b will be continued. This category is modeled corresponding to a specified number of days, “$b_{\text{limit}}$”. This sequence, category a to category b and so on, is repeated as long as the total simulation continues. The dividing into 2 separated categories is useful when modelling for example the power consumption in e.g. an industry area. In this case it could be a large difference between the power profile during the working week compared with the weekend.

The effect of this separating into 2 categories is illustrated in Figure 6.3-4. The figure shows the load during 10 days. The first 5 days correspond to a working week. Then follow 2 days corresponding to the weekend, and so on.
6.3.3 The measured power consumption profile

To calculate a representative mean value regarding the daily consumption profile of the 24 working days respectively the 10 weekend days during the measurement period the measure samples are organized in 2 matrixes. One matrix for the working days and one matrix for the weekend days. The rows correspond to the specific days and the columns to the specific time points in question. I.e. index (n,m) stands for day number n (working day number n respectively weekend day number n) and time point number m.

The matrixes $M^W$ and $M^{WE}$ are defined in Equation 6.3-5 and Equation 6.3-6.

The mean values of the columns in each matrix results in vectors $\bar{P}^W$ and $\bar{P}^{WE}$ according to Equation 6.3-7 to Equation 6.3-12. These vectors represent the mean values of the daily consumption profile for the working day respectively the weekend day. See Figure 6.3-5 and Figure 6.3-6. The corresponding profiles of the standard deviations are illustrated in Figure 6.3-7 and Figure 6.3-8.
The measure samples for the working days are organised in a matrix $M^W$ with 24 rows (corresponding to the number of working days) and 48 columns (corresponding to the number of samples per day). Element $M^W_{m,n}$ corresponds to the measure sample for working day $m$ and time point $n$. 

Equation 6.3-5:
Equation 6.3-6:

\[
M^{WE} = \begin{bmatrix}
M^{WE}_{1,1} & M^{WE}_{1,2} & M^{WE}_{1,n} & M^{WE}_{1,n+1} & M^{WE}_{1,48} \\
M^{WE}_{2,1} & M^{WE}_{2,2} & M^{WE}_{2,n} & M^{WE}_{2,n+1} & M^{WE}_{2,48} \\
M^{WE}_{m,1} & M^{WE}_{m,2} & M^{WE}_{m,n} & M^{WE}_{m,n+1} & M^{WE}_{m,48} \\
M^{WE}_{m+1,1} & M^{WE}_{m+1,2} & M^{WE}_{m+1,n} & M^{WE}_{m+1,n+1} & M^{WE}_{m+1,48} \\
M^{WE}_{10,1} & M^{WE}_{10,2} & M^{WE}_{10,n} & M^{WE}_{10,n+1} & M^{WE}_{10,48}
\end{bmatrix}
\]

The measure samples for the weekend days are organised in a matrix \( M^{WE} \) with 10 rows (corresponding to the number of weekend days) and 48 columns (corresponding to the number of samples per day). Element \( M^{WE}_{m,n} \) corresponds to the measure sample for weekend day \( m \) and time point \( n \).
Equation 6.3-7:

\[ P_n^W = \frac{\sum_{m=1}^{24} M_{m,n}^W}{24} \]

\( n = 1 \) to \( 48 \)

Equation 6.3-8:

\[ P_{49}^W = P_1^W \]

comment: time 0 equivalent with time 24

Equation 6.3-9:

\[ P_n^{WE} = \frac{\sum_{m=1}^{10} M_{m,n}^{WE}}{10} \]

\( n = 1 \) to \( 48 \)

Equation 6.3-10:

\[ P_{49}^{WE} = P_1^{WE} \]

comment: time 0 equivalent with time 24

Equation 6.3-11:

\[ \overline{P^W} = [P_1^W \quad P_2^W \quad P_3^W \quad \vdots \quad P_n^W \quad P_{n+1}^W \quad P_{49}^W] \]

The vector \( \overline{P^W} \) is built up by the mean values of the columns in the matrix \( \overline{M^W} \). The vector represent the mean value of the daily consumption profile for the working day. See Figure 6.3-5.
Equation 6.3-12:

\[
\overline{P^{WE}} = \begin{bmatrix}
P_1^{WE} & P_2^{WE} & P_3^{WE} \\
P_n^{WE} & P_{n+1}^{WE} & P_{49}^{WE}
\end{bmatrix}
\]

The vector \(\overline{P^{WE}}\) is built up by the mean values of the columns in the matrix \(M^{WE}\). The vector represent the mean value of the daily consumption profile for the weekend day. See Figure 6.3-6

![Figure 6.3-5](image-url)  
The power consumption mean value profile for a working day
Figure 6.3-6   The power consumption mean value profile for a weekend day

Figure 6.3-7   The power consumption standard deviation profile for a working day
6.3.4 Model parameters

As a result of the measurements the following model parameters will be estimated (see also paragraph 6.3.2:

- TP_1 – TP_5 (TP_0 is by definition assigned as midnight)
- A_prim, B_prim, C_prim and D_prim
- L_My_L and L_Sigma_L
- L_My_H and L_Sigma_H

As can be established by Figure 6.3-5 and Figure 6.3-6 there are quite different model parameters for a working day compared with a weekend day.
6.3.4.1 Working Days

6.3.4.1.1 TP_1 to TP_5

From the mean value result according to Figure 6.3-5 the time points TP_1 to TP_5 are estimated as:

TP_1: 1
TP_2: 6
TP_3: 10
TP_4: 17
TP_5: 21

6.3.4.1.2 A_prim, B_prim, C_prim and D_prim

The used principle to calculate A_prim, B_prim, C_prim and D_prim follows according to Equation 6.3-13 to Equation 6.3-27:

Equation 6.3-13:
\[ C\_\text{prim} = \mu P_{34} \]

Where:
\( \mu P_{34} \): power mean value in the time region TP_3 to TP_4 (Equation 6.3-14)

Equation 6.3-14:
\[
\mu P_{34} = \frac{\sum_{n=pos\_TP\_3}^{pos\_TP\_4} P_n^w}{pos\_TP\_4 - pos\_TP\_3 + 1}
\]

Where:
\( P^w_n \): element \( n \) in power vector \( \overline{P^w} \) (Equation 6.3-11)

\( \text{pos}_{\text{TP}_3}, \text{pos}_{\text{TP}_4} \): the vector positions (n-values) corresponding to the time points \( \text{TP}_3 \) respectively \( \text{TP}_4 \) in vector \( \overline{P^w} \)

**Equation 6.3-15:**

\[
D_{\text{prim}} = 2 \cdot \mu_{P_{45}} - C_{\text{prim}}
\]

Where:

\( \mu_{P_{45}} \): power mean value in the time region \( \text{TP}_4 \) to \( \text{TP}_5 \) (Equation 6.3-16)

The principle of Equation 6.3-15 is described in **Figure 6.3-9.**

![Diagram showing the principle of Equation 6.3-15](image)
Equation 6.3-16:

\[
\mu_{P_{45}} = \frac{\sum_{n=pos_{TP\_4}}^{pos_{TP\_5}} P_{n}^{W}}{pos_{TP\_5} - pos_{TP\_4} + 1}
\]

Where:

- \( P_{n}^{W} \): element \( n \) in power vector \( \bar{P}^{W} \) (Equation 6.3-11)
- \( pos_{TP\_4}, pos_{TP\_5} \): the vector positions (n-values) corresponding to the time points TP_4 respectively TP_5 in vector \( \bar{P}^{W} \)

Equation 6.3-17:

\[ A_{\_prim\_1} = P_{49}^{W} \]

Where:

- \( A_{\_prim\_1} \): a first calculated value of \( A_{\_prim} \)
- \( P_{49}^{W} \): element 49 in power vector \( \bar{P}^{W} \) (Equation 6.3-11)

Equation 6.3-18:

\[ A_{\_prim\_2} = 2 \cdot \mu_{P_{56}} - D_{\_prim} \]

Where:

- \( A_{\_prim\_2} \): a second calculated value of \( A_{\_prim} \)
- \( \mu_{P_{56}} \): the power mean value in the time region TP_5 to TP_6 (Equation 6.3-19)

The principle of Equation 6.3-18 corresponds to the principle of Equation 6.3-15 (see Figure 6.3-9).
Equation 6.3-19:

\[ \mu_{P_{56}} = \frac{\sum_{n=pos\_TP\_5}^{pos\_TP\_6} P_n^w}{pos\_TP\_6 - pos\_TP\_5 + 1} \]

Where:

- \( P_n^w \): element \( n \) in power vector \( \overline{P^w} \) (Equation 6.3-11)
- \( pos\_TP\_5, pos\_TP\_6 \): the vector positions (n-values) corresponding to the time points TP\_5 respectively TP\_6 in vector \( \overline{P^w} \)

Equation 6.3-20:

\[ A\_prim = \frac{(A\_prim\_1 + A\_prim\_2)}{2} \]

Where:

- \( A\_prim \): the final calculated value of \( A\_prim \)

Equation 6.3-21:

\[ B\_prim\_1 = 2 \cdot \mu_{P_{23}} - C\_prim \]

Where:

- \( B\_prim\_1 \): a first calculated value of \( B\_prim \)
- \( \mu_{P_{23}} \): the power mean value in the time region TP\_2 to TP\_3 (Equation 6.3-22)

The principle of Equation 6.3-21 corresponds to the principle of Equation 6.3-15 (see Figure 6.3-9).

Equation 6.3-22:

\[ \mu_{P_{23}} = \frac{\sum_{n=pos\_TP\_2}^{pos\_TP\_3} P_n^w}{pos\_TP\_3 - pos\_TP\_2 + 1} \]
Where:

\( P_n^w \): element \( n \) in power vector \( \overline{P^w} \)  (Equation 6.3-11)

\( pos_{TP\_2}, pos_{TP\_3} \): the vector positions (n-values) corresponding to the time points TP_2 respectively TP_3 in vector \( \overline{P^w} \)

**Equation 6.3-23:**

\[
B\_\text{prim}\_2 = 2 \cdot \mu P_{01} - A\_\text{prim}\_2
\]

Where:

\( B\_\text{prim}\_2 \): a second calculated value of \( B\_\text{prim} \)

\( \mu P_{01} \): the power mean value in the time region TP_0 to TP_1 (Equation 6.3-24)

The principle of Equation 6.3-23 corresponds to the principle of Equation 6.3-15 (see Figure 6.3-9).

**Equation 6.3-24:**

\[
\mu P_{01} = \frac{\sum_{n=pos_{TP\_0}}^{pos_{TP\_1}} P_n^w}{pos_{TP\_1} - pos_{TP\_0} + 1}
\]

Where:

\( P_n^w \): element \( n \) in power vector \( \overline{P^w} \)  (Equation 6.3-11)

\( pos_{TP\_0}, pos_{TP\_1} \): the vector positions (n-values) corresponding to the time points TP_0 respectively TP_1 in vector \( \overline{P^w} \)

**Equation 6.3-25:**

\[
B\_\text{prim}\_3 = \mu P_{12}
\]

Where:

\( B\_\text{prim}\_3 \): a third calculated value of \( B\_\text{prim} \)
\[ \mu_{P_{12}} : \text{the power mean value in the time region TP}_1 \text{ to TP}_2 \text{ (Equation 6.3-26)} \]

**Equation 6.3-26:**

\[
\mu_{P_{12}} = \frac{\sum_{n=pos_{TP}_1}^{pos_{TP}_2} P_n^w}{pos_{TP}_2 - pos_{TP}_1 + 1}
\]

Where:

- \( P_n^w \): element \( n \) in power vector \( P^w \) (Equation 6.3-11)

- \( pos_{TP}_1, pos_{TP}_2 \): the vector positions (n-values) corresponding to the time points \( TP_1 \) respectively \( TP_2 \) in vector \( P^w \)

**Equation 6.3-27:**

\[
B_{prim} = \frac{(B_{prim}_1 + B_{prim}_2 + 3 \cdot B_{prim}_3)}{5}
\]

Where:

- \( B_{prim} \): the final calculated value of \( B_{prim} \)

The weighting coefficient for \( B_{prim}_1, B_{prim}_2 \) and \( B_{prim}_3 \) is a result of adaption to get a good resulting modeled mean value of the total power during a 24 hours period compared with the measured mean value.

Equation 6.3-13 to Equation 6.3-27 used together with the suggested values of TP_1 to TP_5 according to paragraph 6.3.4.1.1 result in the following values of A_prim, B_prim, C_prim and D_prim:
A\_prim: 112.76 kW
B\_prim: 109.92 kW
C\_prim: 214.30 kW
D\_prim: 118.20 kW

Figure 6.3-10 illustrates the measured (mean value of 24 working days) power consumption profile (dashed) together with the model profile (solid) if TP\_1 to TP\_5 according to paragraph 6.3.4.1.1 and A\_prim, B\_prim, C\_prim and D\_prim according to the values above are used. To this model profile statistical variations (noise) shall be added. These parameters are treated in paragraph 6.3.4.1.3 (low frequency noise) and paragraph 6.3.4.1.4 (high frequency noise).
The mean power of the curves (24 hours) in Figure 6.3-10 is:

Measured power: 159.2 kW
Modelled power: 159.2 kW

6.3.4.1.3 L_My_L and L_Sigma_L

The used principle to calculate L_My_L and L_Sigma_L follows according to Equation 6.3-28 to Equation 6.3-32:

Equation 6.3-28:

$L_{My_L} = 1$

This is the standard value of this parameter as the stochastic variation is assumed as a relative variation around the mean value.

Equation 6.3-29:

$L_{Sigma_L} = \frac{\sigma(E^W)}{\mu(E^W)}$

Where:

$\sigma(E^W)$: the standard deviation of vector $E^W$ (Equation 6.3-30)

$\mu(E^W)$: the mean value of vector $E^W$ (Equation 6.3-31)

$E^W$: vector where the elements are defined according to Equation 6.3-32
Equation 6.3-30:

\[
\sigma(E^W) = \sqrt{\frac{\sum_{m=1}^{24} (E^W_m - \mu(E^W))^2}{23}}
\]

Equation 6.3-31:

\[
\mu(E^W) = \frac{\sum_{m=1}^{24} E^W_m}{24}
\]

Equation 6.3-32:

\[
E^W_m = \sum_{n=1}^{48} M^W_{m,n}
\]

Where:

\[
M^W_{m,n} : \quad \text{elements in matrix } M^W \text{ (Equation 6.3-5)}
\]

According to Equation 6.3-29, \( L_{\text{Sigma}_L} \) will be the relative standard deviation of the daily energy consumption.

Equation 6.3-29 results in:

\[
L_{\text{Sigma}_L} = 0.0957
\]
6.3.4.1.4  L_My_H and L_Sigma_H

The used principle to calculate L_My_L and L_Sigma_L follows according to Equation 6.3-33 to Equation 6.3-37:

**Equation 6.3-33:**

\[
L_{My_H} = 0
\]

This is the standard value of this parameter as the stochastic variation (power noise) is assumed to be symmetric around zero.

**Equation 6.3-34:**

\[
L_{Sigma_H} = \mu(C^W)
\]

Where:

\[
\mu(C^W) \quad \text{the mean value of vector } C^W \quad \text{according to Equation 6.3-35. The elements} \\
C^W_m \quad \text{in vector } C^W \quad \text{are defined according to Equation 6.3-36 and Equation} \\
6.3-37. \quad \text{This vector contains the relative standard deviation (the standard deviation relative to the mean value) of the power in the time interval} \\
TP_3 \quad \text{to TP_4 for each working day (1 to 24). Consequently} \\
L_{Sigma_H} \quad \text{is a measure of the mean value of the relative standard deviation for the power consumption.}
\]

**Equation 6.3-35:**

\[
\mu(C^W) = \frac{\sum_{m=1}^{24} C^W_m}{24}
\]
Equation 6.3-36:

\[ C_m^W = \sqrt{\frac{\sum_{n=\text{pos}_{TP_3}}^{\text{pos}_{TP_4}} (M_{m,n}^W - M^W \mu(m,3_4))^2}{M^W \mu(m,3_4)}} \]

\[ m = 1 \text{ to } 24 \]

Where:

- \( M_{m,n}^W \): element I matrix \( M^W \) (Equation 6.3-5)
- \( M^W \mu(m,3_4) \): see Equation 6.3-37

Equation 6.3-37:

\[ M^W \mu(m,3_4) = \frac{\sum_{n=\text{pos}_{TP_3}}^{\text{pos}_{TP_4}} M_{m,n}^W}{\text{pos}_{TP_4} - \text{pos}_{TP_3}} \]

Where:

- \( \text{Pos}_{TP_3}, \text{Pos}_{TP_4} \): the time positions (n-values) corresponding to the time points TP_3 respectively TP_4 in matrix \( M^W \)

Equation 6.3-34 results in:

\[ L_{\text{Sigma}_H} = 0.0458 \]
6.3.4.2 Weekend days

6.3.4.2.1 TP_1 to TP_5

From the mean value result according to Figure 6.3-6 the time points TP_1 to TP_5 are estimated as:

TP_1: 1
TP_2: 4
TP_3: 6
TP_4: 21
TP_5: 23

6.3.4.2.2 A_prim, B_prim, C_prim and D_prim

To calculate A_prim, B_prim, C_prim and D_prim the corresponding principle as described in paragraph 6.3.4.1.2 is used.

As the power vector $P^W$ shall be replaced by the power vector $P^{WE}$, the following changes must be done regarding some equations according to:

<table>
<thead>
<tr>
<th>Equation</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 6.3-14</td>
<td>$P_n^W \Rightarrow P_n^{WE}$</td>
</tr>
<tr>
<td>Equation 6.3-16</td>
<td>-“-</td>
</tr>
<tr>
<td>Equation 6.3-17</td>
<td>$P_{49}^W \Rightarrow P_{49}^{WE}$</td>
</tr>
<tr>
<td>Equation 6.3-19</td>
<td>$P_n^W \Rightarrow P_n^{WE}$</td>
</tr>
<tr>
<td>Equation 6.3-22</td>
<td>-“-</td>
</tr>
<tr>
<td>Equation 6.3-24</td>
<td>-“-</td>
</tr>
<tr>
<td>Equation 6.3-26</td>
<td>-“-</td>
</tr>
</tbody>
</table>
The calculations result in:

\[
\begin{align*}
A_{\text{prim}} & : 110.14 \text{ kW} \\
B_{\text{prim}} & : 107.73 \text{ kW} \\
C_{\text{prim}} & : 113.96 \text{ kW} \\
D_{\text{prim}} & : 113.75 \text{ kW}
\end{align*}
\]

**Figure 6.3-11** illustrates the measured (mean value of 10 weekend days) power consumption profile (dashed) together with the model profile (solid) if TP_1 to TP_5 according to paragraph 6.3.4.2.1 and \(A_{\text{prim}}, B_{\text{prim}}, C_{\text{prim}}\) and \(D_{\text{prim}}\) according to the values above are used. To the model profile in this figure statistical variations are added. These parameters are treated in paragraph 6.3.4.2.3 (low frequency variations) and paragraph 6.3.4.2.4 (high frequency variations).
The mean power of the curves (24 hours) in Figure 6.3-11 is:

- Measured power: 112.7 kW
- Modelled power: 112.6 kW

### 6.3.4.2.3  L\_My\_L and L\_Sigma\_L

To calculate L\_My\_L and L\_Sigma\_L the corresponding principle as described in paragraph 6.3.4.1.3 is used.

The following index changes shall be done regarding the equations:

<table>
<thead>
<tr>
<th>Equation</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 6.3-29</td>
<td>$E^W \Rightarrow E^{WE}$</td>
</tr>
<tr>
<td>Equation 6.3-30</td>
<td>$E^W \Rightarrow E^{WE}$, $E^W_m \Rightarrow E^{WE}_m$</td>
</tr>
<tr>
<td>Equation 6.3-31</td>
<td></td>
</tr>
<tr>
<td>Equation 6.3-32</td>
<td>$E^W_m \Rightarrow E^{WE}<em>m$, $M^W</em>{m,n} \Rightarrow M^{WE}_{m,n}$</td>
</tr>
</tbody>
</table>

The calculations result in:

- $L\_My\_L = 1$
- $L\_Sigma\_L = 0.1632$
6.3.4.2.4 L_My_H and L_Sigma_H

To calculate L_My_H and L_Sigma_H the corresponding principle as described in paragraph 6.3.4.1.4 is used.

The following index changes shall bee done regarding the equations:

<table>
<thead>
<tr>
<th>Equation</th>
<th>Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 6.3-34</td>
<td>(C^W \Rightarrow C^{WE})</td>
</tr>
<tr>
<td>Equation 6.3-35</td>
<td>(C^W \Rightarrow C^{WE}, C^W_m \Rightarrow C^{WE}_m)</td>
</tr>
<tr>
<td>Equation 6.3-36</td>
<td>(C^W_m \Rightarrow C^{WE}<em>m, M^W</em>{m,n} \Rightarrow M^{WE}_{m,n}, M^W\mu(m,3_4) \Rightarrow M^{WE}\mu(m,3_4))</td>
</tr>
<tr>
<td>Equation 6.3-37</td>
<td>(M^W\mu(m,3_4) \Rightarrow M^{WE}\mu(m,3_4), M^W_{m,n} \Rightarrow M^{WE}_{m,n})</td>
</tr>
</tbody>
</table>

The calculations result in:

\[L_My_H = 0\]
\[L_Sigma_H = 0.0755\]

6.3.4.3 Model parameters. Conclusion

Table 6.3-1 concludes the resulted statistical model parameters for the analysed electrical load.
<table>
<thead>
<tr>
<th>Model Parameter</th>
<th>Working day</th>
<th>Weekend day</th>
</tr>
</thead>
<tbody>
<tr>
<td>TP_1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>TP_2</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>TP_3</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>TP_4</td>
<td>17</td>
<td>21</td>
</tr>
<tr>
<td>TP_5</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td>A_prim</td>
<td>112.76 kW</td>
<td>110.14 kW</td>
</tr>
<tr>
<td>B_prim</td>
<td>109.92 kW</td>
<td>107.73 kW</td>
</tr>
<tr>
<td>C_prim</td>
<td>214.30 kW</td>
<td>113.96 kW</td>
</tr>
<tr>
<td>D_prim</td>
<td>118.20 kW</td>
<td>113.75 kW</td>
</tr>
<tr>
<td>L_My_L</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>L_Sigma_L</td>
<td>0.0957</td>
<td>0.1632</td>
</tr>
<tr>
<td>L_My_H</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>L_Sigma_H</td>
<td>0.0458</td>
<td>0.0755</td>
</tr>
</tbody>
</table>

Table 6.3-1 Statistical model parameters for the analysed electrical load

6.4 Simulations

Simulations have been performed based on the resulted parameters according to Table 6.3-1.

To illustrate the effect of the noise parameters (L_Sigma_L and L_Sigma_H) the simulations have been performed with a gradual change (increasing of the noise) according to Table 6.4-1.
Figure 6.4-6 gives the result with three in sequence coming weekend days while the simulations according to Figure 6.4-7 and Figure 6.4-8 have been performed on the condition that a week consists of 5 working days followed by 2 weekend days (i.e. a normal week).

It could be interesting to compare the power profile according to Figure 6.4-9 (measured profile) with Figure 6.4-8 (simulated profile).

<table>
<thead>
<tr>
<th>Figure</th>
<th>Day *)</th>
<th>Number of days</th>
<th>L_Sigma_L **)</th>
<th>L_Sigma_H **)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 6.4-1</td>
<td>W</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>No noise</td>
</tr>
<tr>
<td>Figure 6.4-2</td>
<td>W</td>
<td>1</td>
<td>0</td>
<td>M</td>
<td>“High frequency noise” included</td>
</tr>
<tr>
<td>Figure 6.4-3</td>
<td>W</td>
<td>3</td>
<td>M</td>
<td>M</td>
<td>“High- and low frequency noise” included</td>
</tr>
<tr>
<td>Figure 6.4-4</td>
<td>WE</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>No noise</td>
</tr>
<tr>
<td>Figure 6.4-5</td>
<td>WE</td>
<td>1</td>
<td>0</td>
<td>M</td>
<td>“High frequency noise” included</td>
</tr>
<tr>
<td>Figure 6.4-6</td>
<td>WE</td>
<td>3</td>
<td>M</td>
<td>M</td>
<td>“High- and low frequency noise” included</td>
</tr>
<tr>
<td>Figure 6.4-7</td>
<td>W</td>
<td>10</td>
<td>M</td>
<td>M</td>
<td>“High- and low frequency noise” included</td>
</tr>
<tr>
<td>Figure 6.4-8</td>
<td>W</td>
<td>34</td>
<td>M</td>
<td>M</td>
<td>“High- and low frequency noise” included</td>
</tr>
</tbody>
</table>

Table 6.4-1 Figure 6.4-1 to Figure 6.4-8 illustrate the simulated power profile with a gradual change (increasing) of the noise parameters

*) W: working day, WE: weekend day

**) M: the parameter is assigned to the suggested model value according to Table 6.3-1
Figure 6.4-1  
Simulated power profile. 1 working day. No noise

Figure 6.4-2  
Simulated power profile. 1 working day. High frequency noise
Figure 6.4-3  Simulated power profile. 3 working days. High- and low frequency noise

Figure 6.4-4  Simulated power profile. 1 weekend day. No noise
Figure 6.4-5  Simulated power profile. 1 weekend day. High frequency noise

Figure 6.4-6  Simulated power profile. 3 weekend days. High- and low frequency noise
Figure 6.4-7 Small  Simulated power profile. 10 days with a week consisting of 5 working days and 2 weekend days. High- and low frequency noise
Figures 6.4-8 and 6.4-9: Simulated and measured power profiles. 34 days with a week consisting of 5 working days and 2 weekend days. High- and low frequency noise have been observed.
6.5 Future work

The present analysis has been performed with an object where the electric energy consumption is quite small (about 1.3 GWh / year). In a future study it would be interesting to analyse objects according to the following list:

- larger industrial areas
- cities (including industrial areas)
- regions of cities

7 SIMULATIONS

7.1 Cases

Simulations are performed for 3 different conditions regarding the geographic environment:

- Kiruna
- Göteborg
- Nairobi
- The Sahara desert
- Greenland
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