Combined Electric Power Generating Systems

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Contents

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 repesents 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 repesents 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.

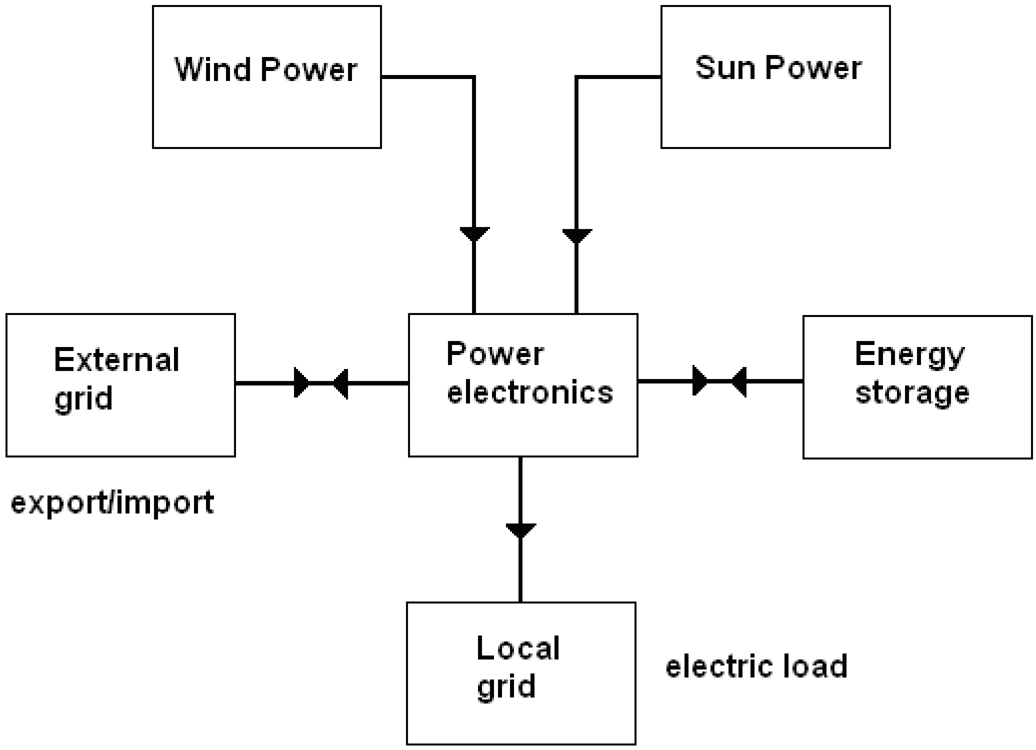


Figure 2.1-1 The principle of the power systems. The arrows show the energy flow

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 to 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 to 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.

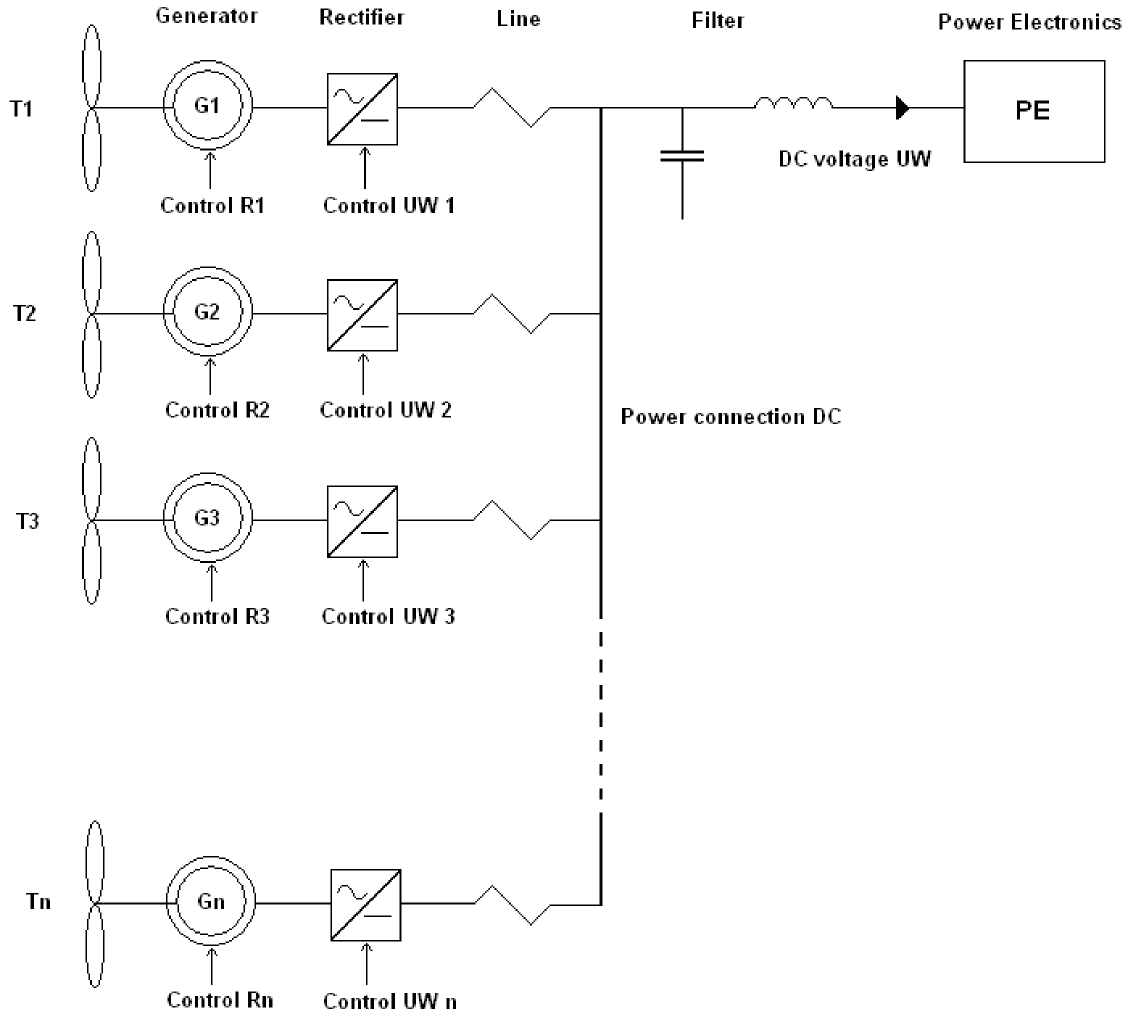


Figure 2.1-1 Wind power systems (1, 2, 3, …., n) connected to a total *Wind Power* block. The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1.

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.

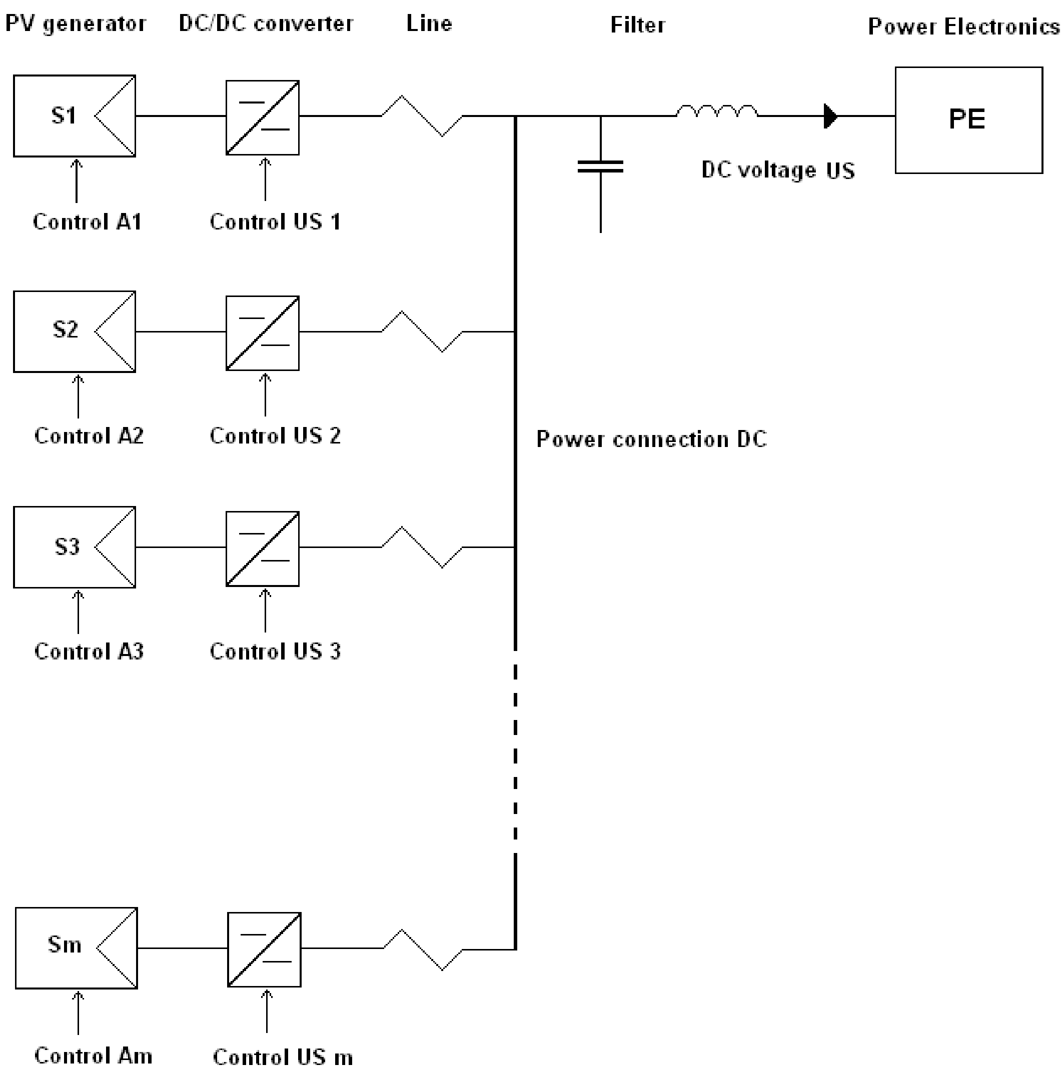


Figure 2.2-1 Sun power systems (1, 2, 3, …., m) connected to a total *Sun Power* block. The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1.

2.3 Local grid

The *Local grid* (Figure 2.1-1) act 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"* referes 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).

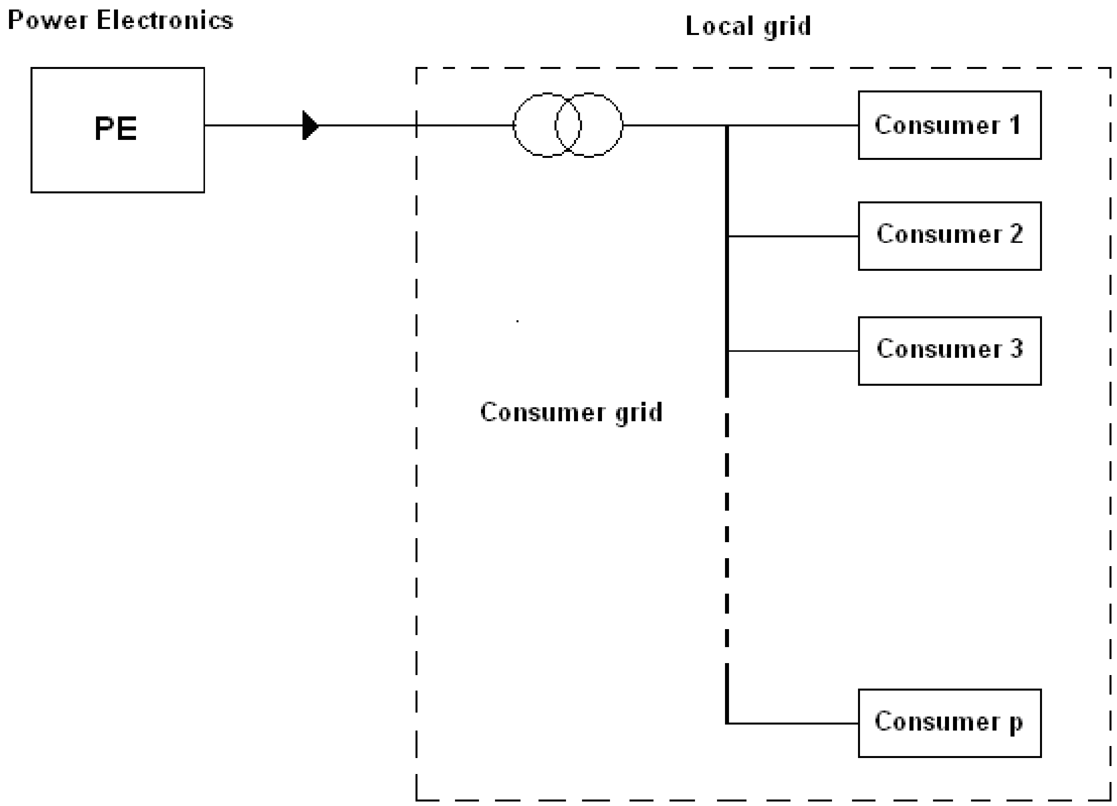


Figure 2.3-1 The principle of the isolated system representing a consumer grid with no connection to any other power supplier (besides the *Combined Power System*). The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1. The power flow direction is: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

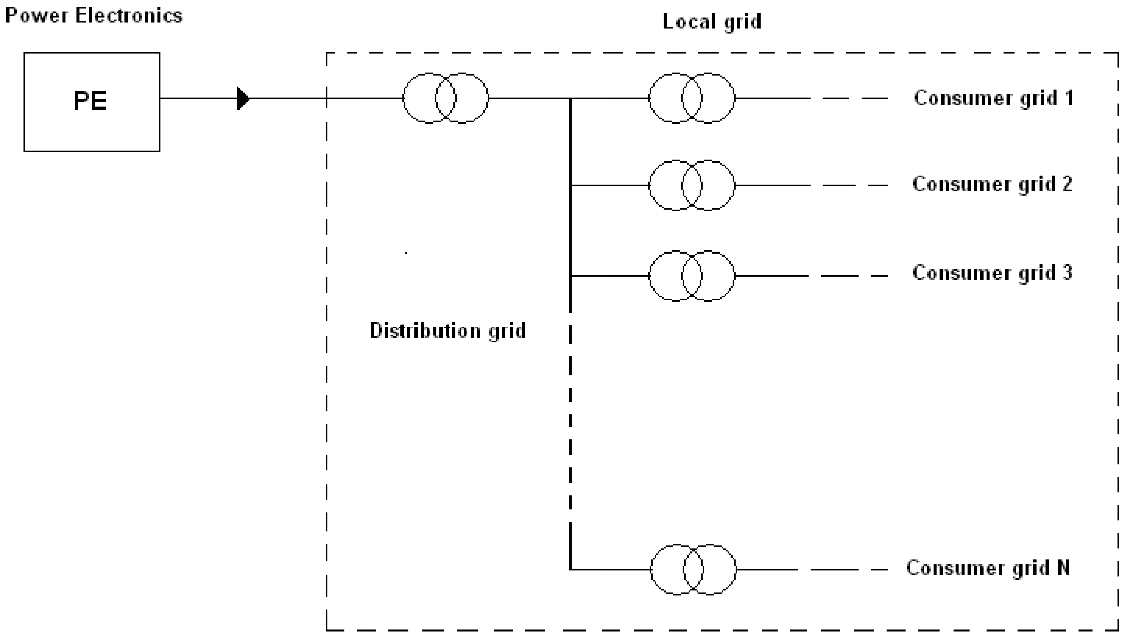


Figure 2.3-2 The principle of the isolated system representing a distribution grid with no connection to any other power supplier (besides the *Combined Power System*). The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1. The power flow direction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

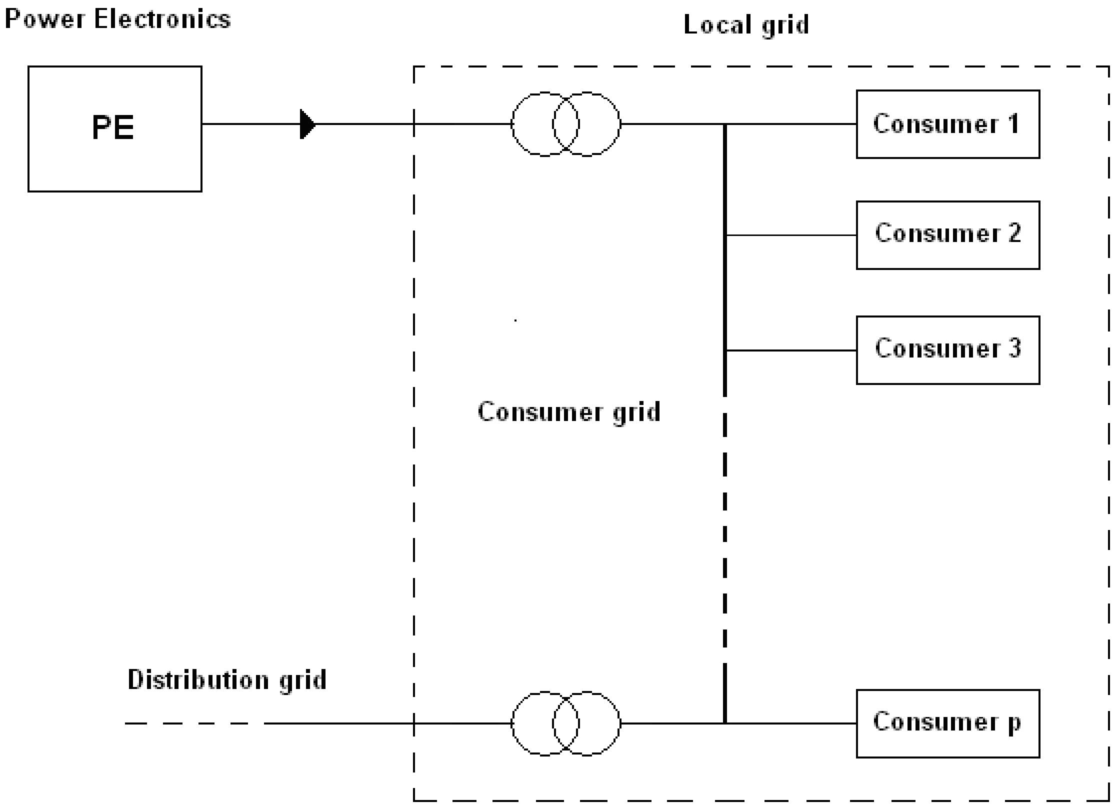


Figure 2.3-3 The principle of the not isolated system representing a consumer grid, that besides connection to the *Combined Power System*, also is connected to a distribution grid. The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1. The power flow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

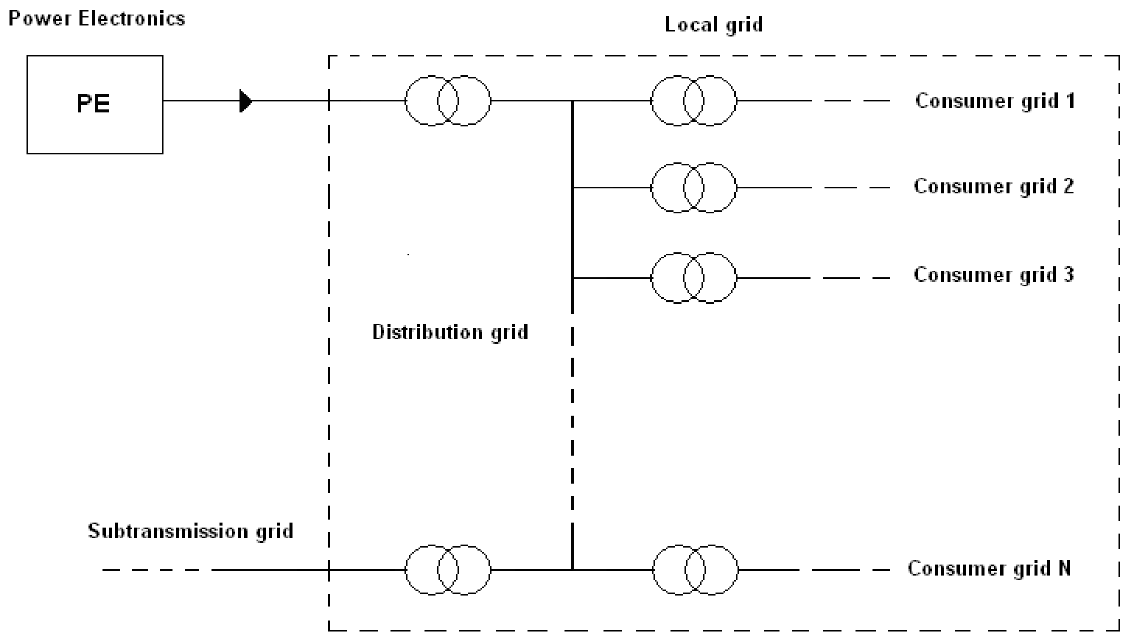


Figure 2.3-4 The principle of the not isolated system representing a distribution grid, that besides connection to the *Combined Power System*, also is connected to a subtransmission grid. The block *Power Electronics* (PE) represents the corresponding *Power Electronics* block in Figure 2.1-1. The power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

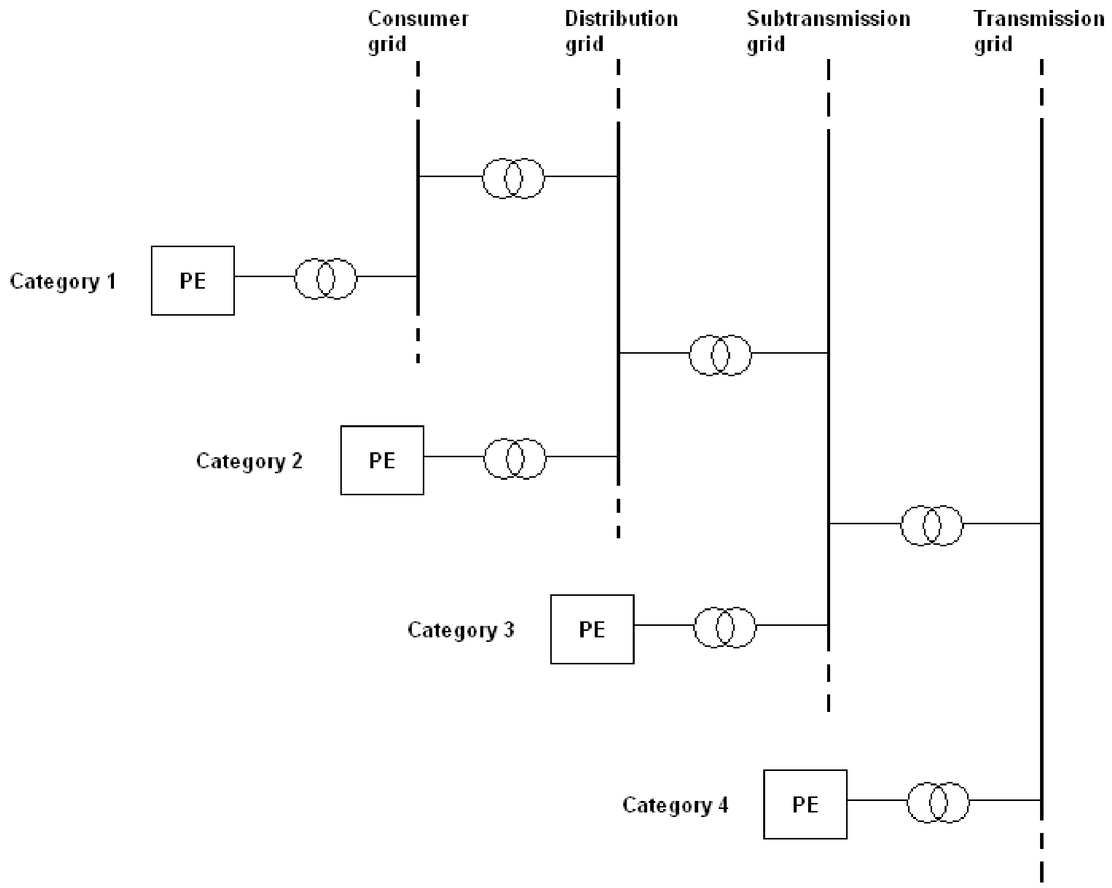


Figure 0-1 Four categories of *External grids* representing connection to four different kind of grids, consumer-,distribution, subtransmission, respectively transmission grid. The category in question is depending on the capacity of the *Combined Power System* and kind of *Local grid.* The power flow direction is: “from PE to external grid” when exporting power and “from external grid to PE” when importing power.

Kind of Local grid	***Category of External grid***
Consumer grid, isolated	1 or 2
Consumer grid, not isolated	2 or 3
Distribution grid, isolated	2 or 3
Distribution grid, not isolated	3 or 4

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*.

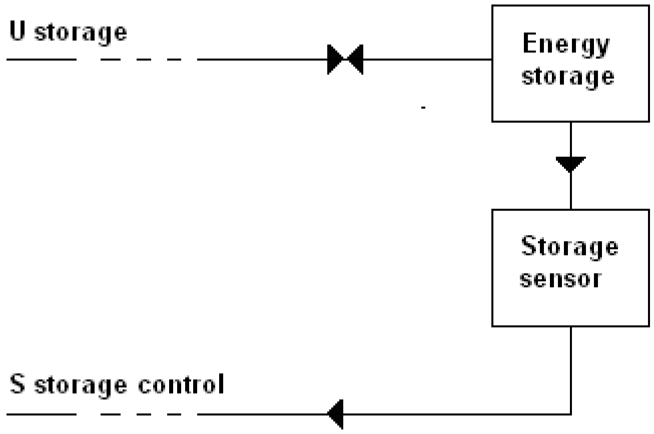


Figure 2.5-1 The energy storage system is controlled by the signal *S storage control*

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 illustratres 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-Locic device”. See chapter 2.6.1 to 2.6.5. The flow designations are defined in Table 2.6-1.

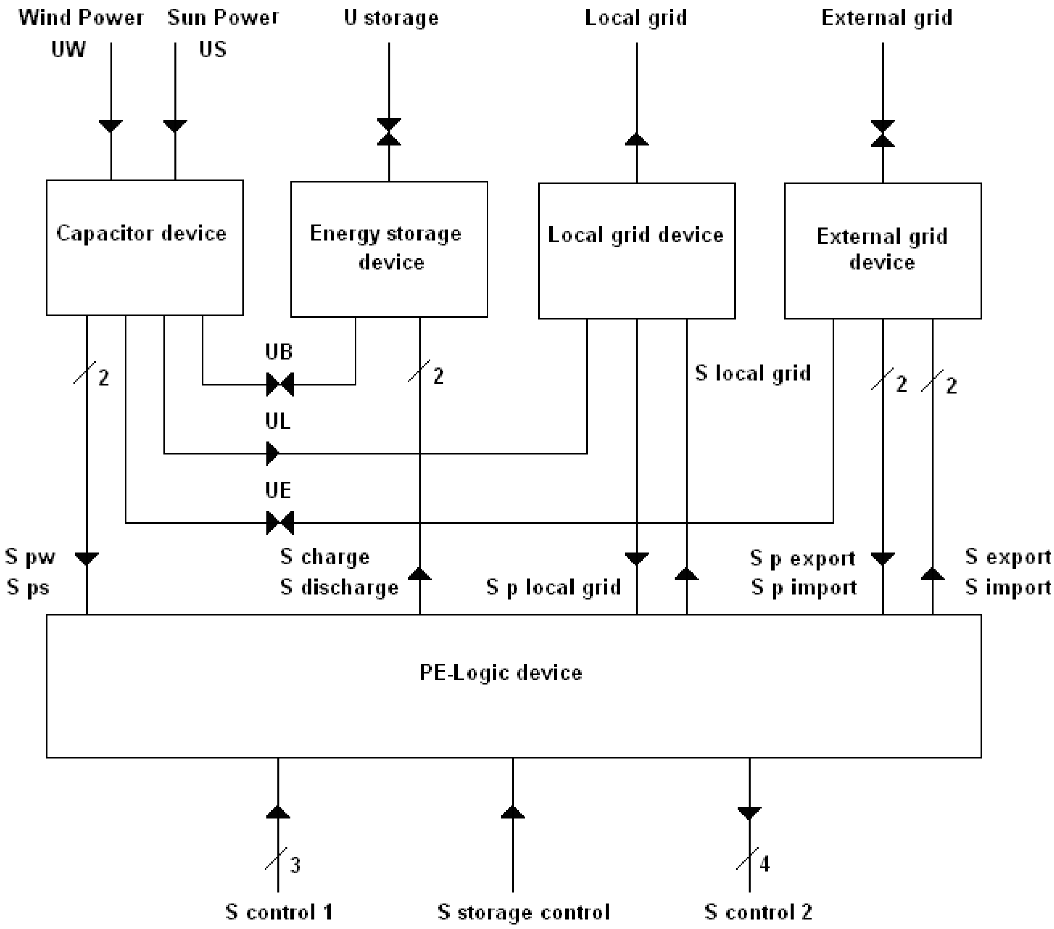


Figure 2.6-1 Block diagram of the Power electronic unit

Flow designation	***Kind of flow***	***Description***
UW	Power	Feeding voltage (DC) from Wind power system to PE (Capacitor device)
US	-"-	Feeding voltage (DC) from Sun power system to PE (Capacitor device)
UB	-"-	Internal feeding voltage (DC) from/to Capacitor device to/from Energy storage device
UL	-"-	Internal feeding voltage (DC) from Capacitor device to Local grid device

UE	-"-	Internal feeding voltage (DC) from/to Capacitor device to/from External grid device
S pw	Data signal	Signal from Capacitor device to PE-Logic device. Information: current produced wind power (W)
S ps	-"-	Signal from Capacitor device to PE-Logic device. Information: current produced sun power (W)
S charge	-"-	Signal from PE-Logic device to Energy storage device. Information: Activate DC/DC converter for supplying energy from PE to the Energy storage system
S discharge	-"-	Signal from PE-Logic device to Energy storage device. Information: Activate DC/DC converter for supplying energy from the Energy storage system to PE
S p local grid	-"-	Signal from Local grid device to PE-Logic device. Information: current delivered power (W) to the local grid
S local grid	-"-	Signal from PE-Logic device to Local grid device. Information: Activate DC/AC converter for supplying energy from PE to local grid
S p export	-"-	Signal from External grid device to PE-Logic device. Information: current exported power (W) to the external grid
S p import	-"-	Signal from External grid device to PE-Logic device. Information: current imported power (W) from the external grid

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 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.

Working Condition	***Definition *)***	***Resulting power flow (see Figure 2.6-2 to Figure 2.6-5)***
1	Net power > 0 and battery_charge < charge_level_max	Store energy to the energy storage
2	Net power < 0 and battery_charge > charge_level_min	Load energy from the energy storage
3	Net power > 0 and battery_charge = charge_level_max	Export energy to the external grid
4	Net power < 0 and battery_charge = charge_level_min	Import energy from the external grid

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 gerator(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.

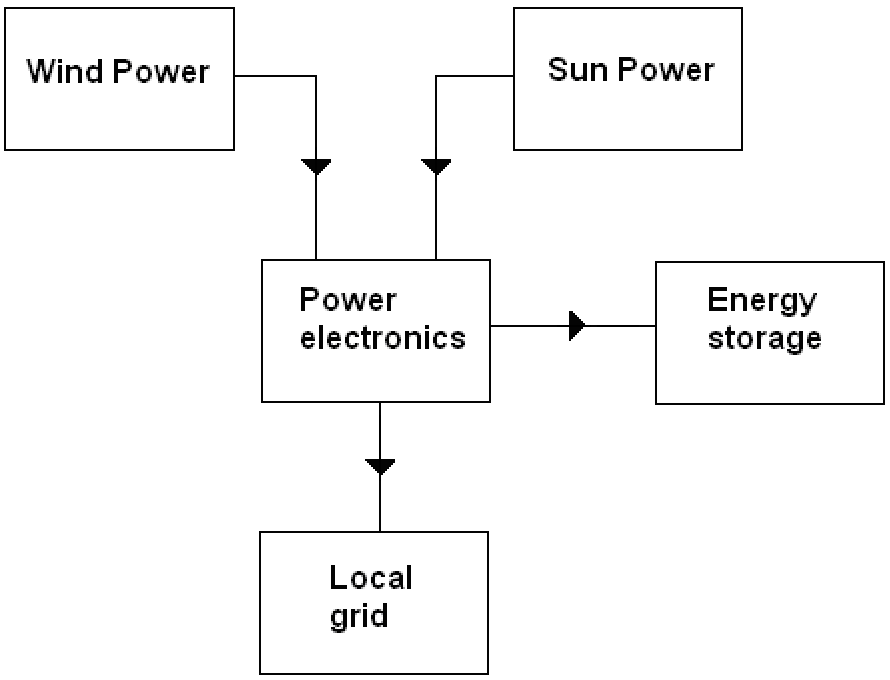


Figure 2.6-2 Energy flow for “*Condition 1*”.

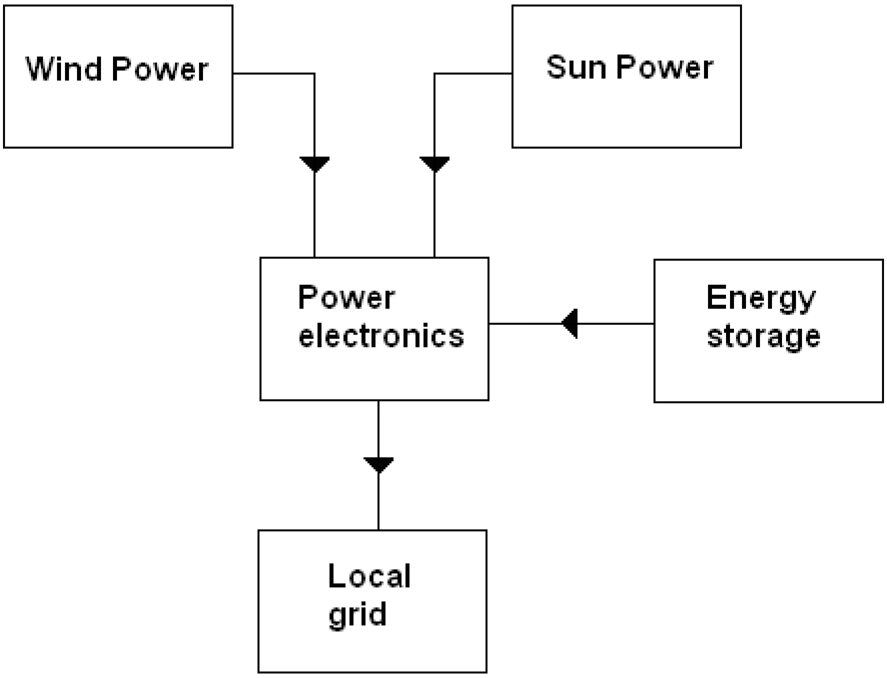


Figure 2.6-3 Energy flow for “*Condition 2*”.

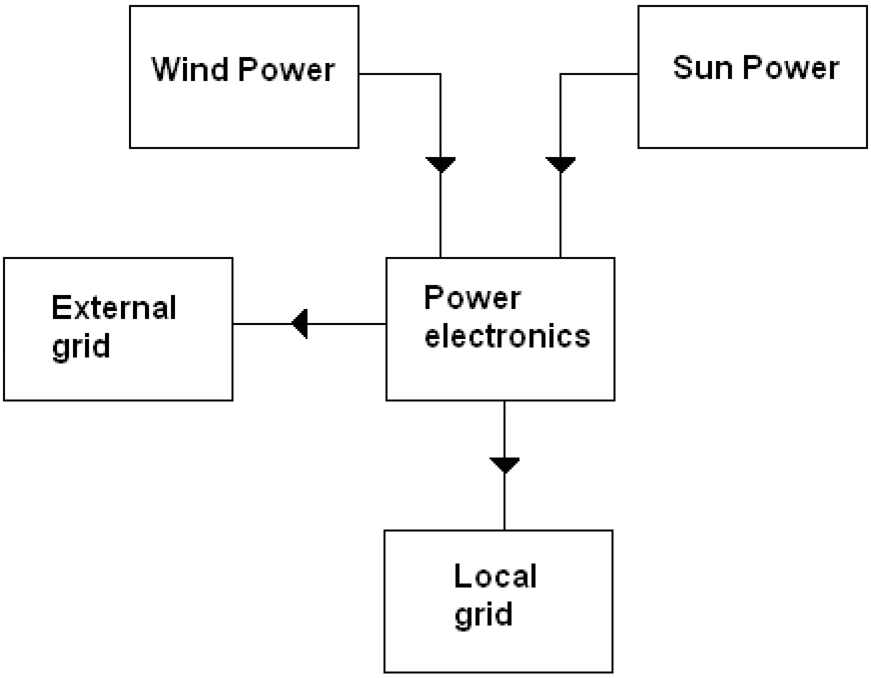


Figure 2.6-4 Energy flow for “*Condition 3* ”.

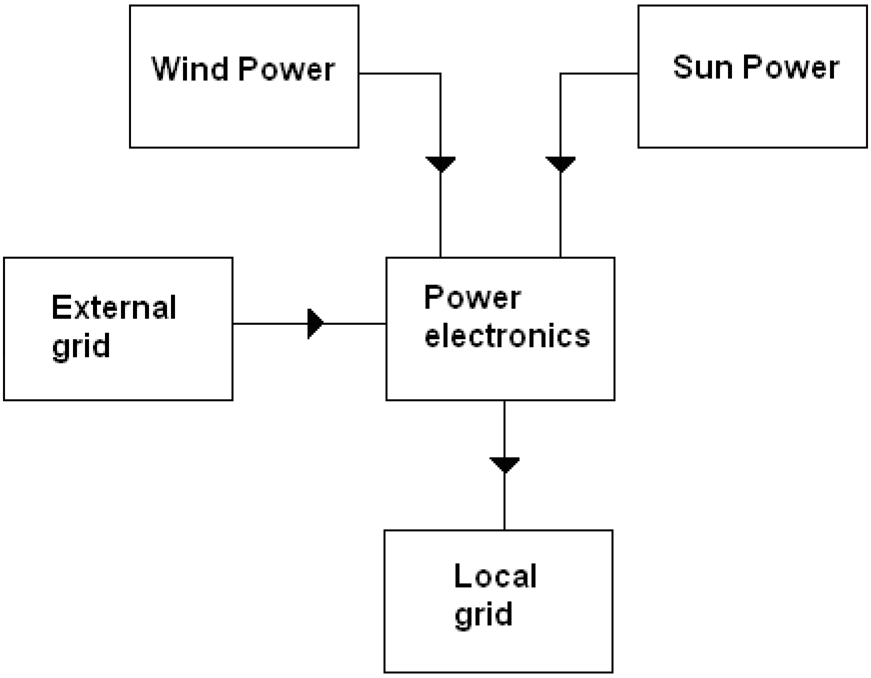


Figure 2.6-5 Energy flow for “*Condition 4”*.

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.

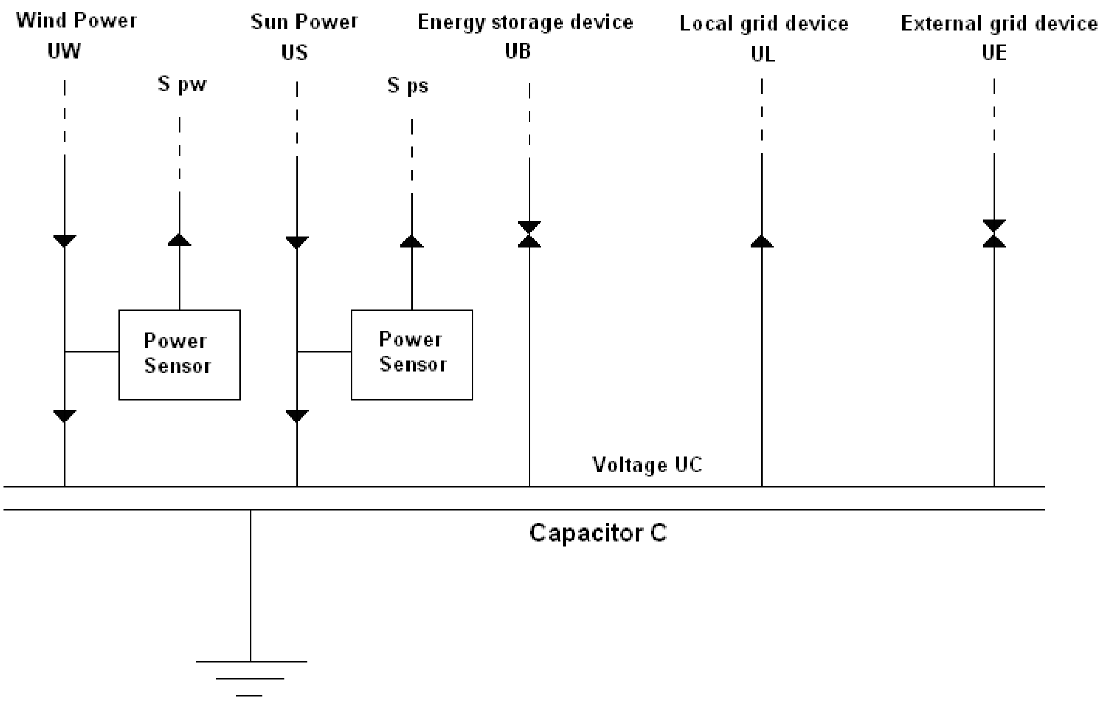


Figure 2.6-6 Capacitor device

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 charge*. The Capacitor device voltage (UB = UC) is adapted to the energy storage voltage (U storage).

– Discharging the Energy storage system. The upper DC/DC converter in Figure 2.6-7 is activated by the signal *S discharge*. The energy storage voltage (U storage) is adapted to the Capacitor device voltage (UB = UC).

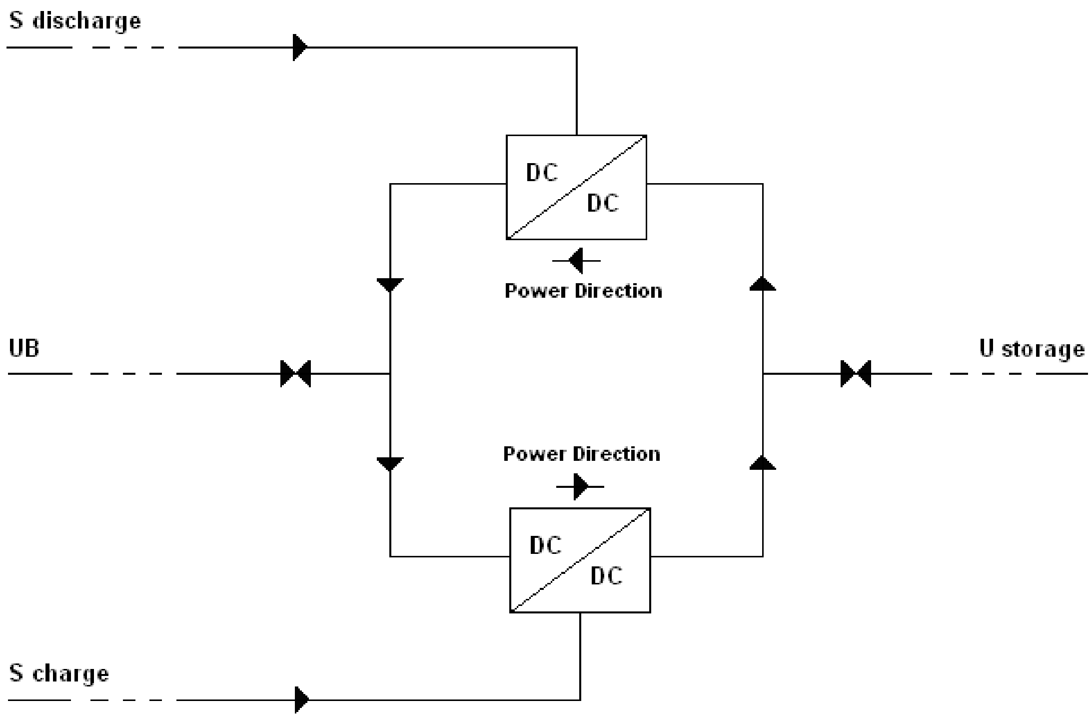


Figure 2.6-7 Energy storage device. Note: UB = UC

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 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 local grid*).

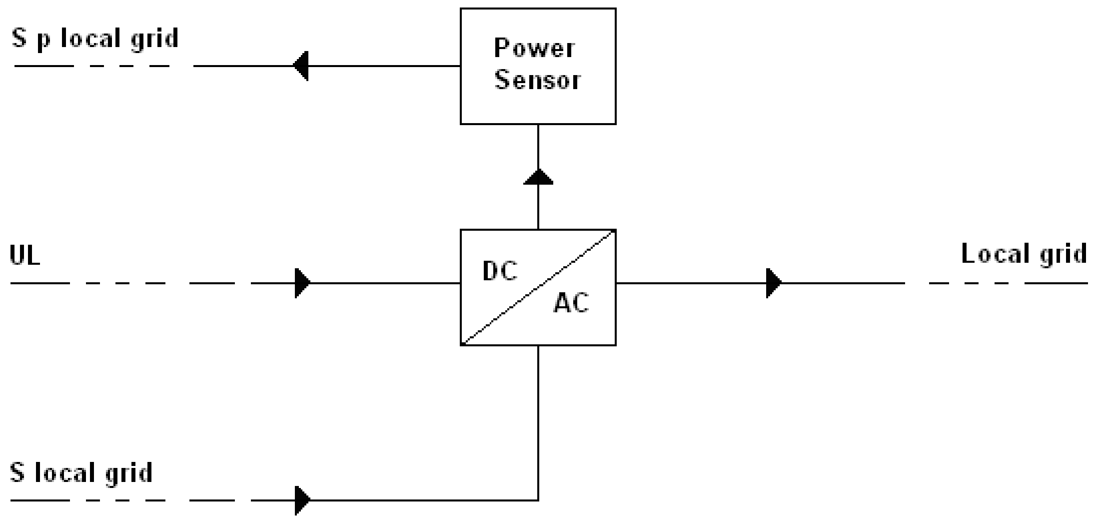


Figure 2.6-8 Local grid device. Note: UL = UC

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 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 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 export / S p import*).

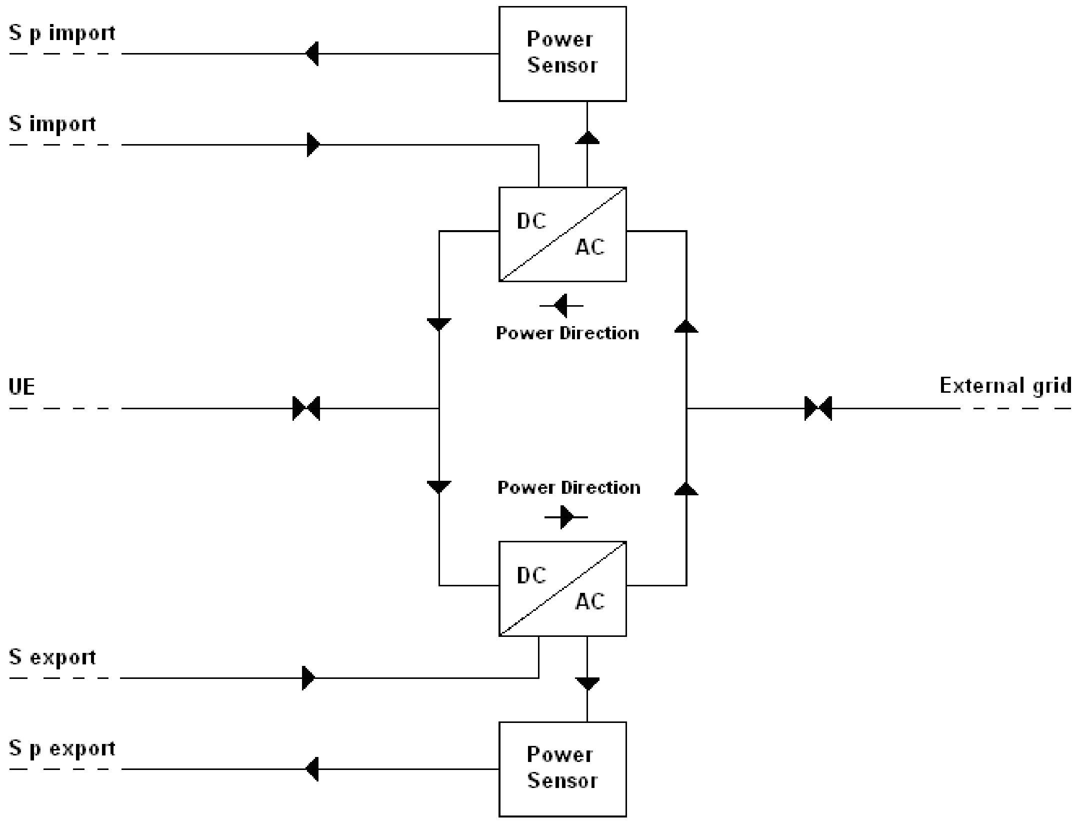


Figure 2.6-9 External grid device. Note: UE = UC

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*.

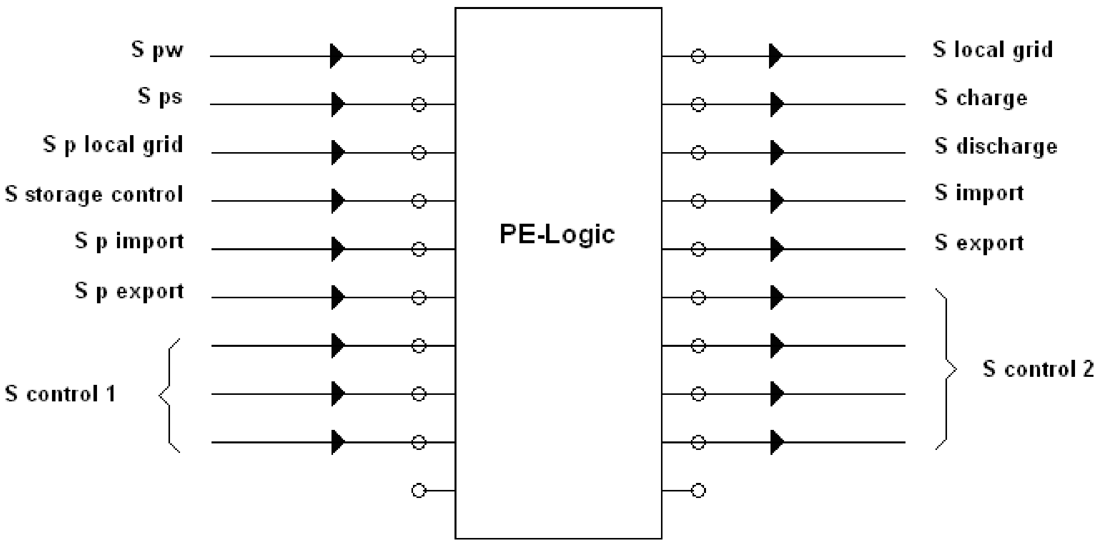


Figure 2.6-10 PE-Logic device

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.

Modules in the Simulation System	**Function**	**See chapter**
Wind_make	Generate stochastic wind rates to the wind turbines	3.1
Wind_turbine	Generate electric power from one or a number of wind turbines as a result of the stochastic wind rates	3.2
Extinction_make	Generate stochastic extinction coefficients to calculate the sun intensity	3.3
Sun_intensity	Generate to solar cells incoming sun radiation as a result of the extinction coefficients and the sun position relatively the solar cells panels	3.4
Sun_panel_generator	Generate electric power from a number of solar cells panels as a result of the calculated incoming sun radiation	3.5
Load_make	Generate a stochastic load on the local grid	3.6
Connect_Gen_load	Connection of the local grid to the generators (wind and sun). Generate gross power and a net power	3.7
Battery_Distribution	Connection of the combination *energy storage – externa grid* to the combination *local grid - generators (wind and sun)*	3.8
Power_evaluate	Evaluate the result of a simulation process	3.9

Table 2.6-1 The simulation system is built up by 9 modules

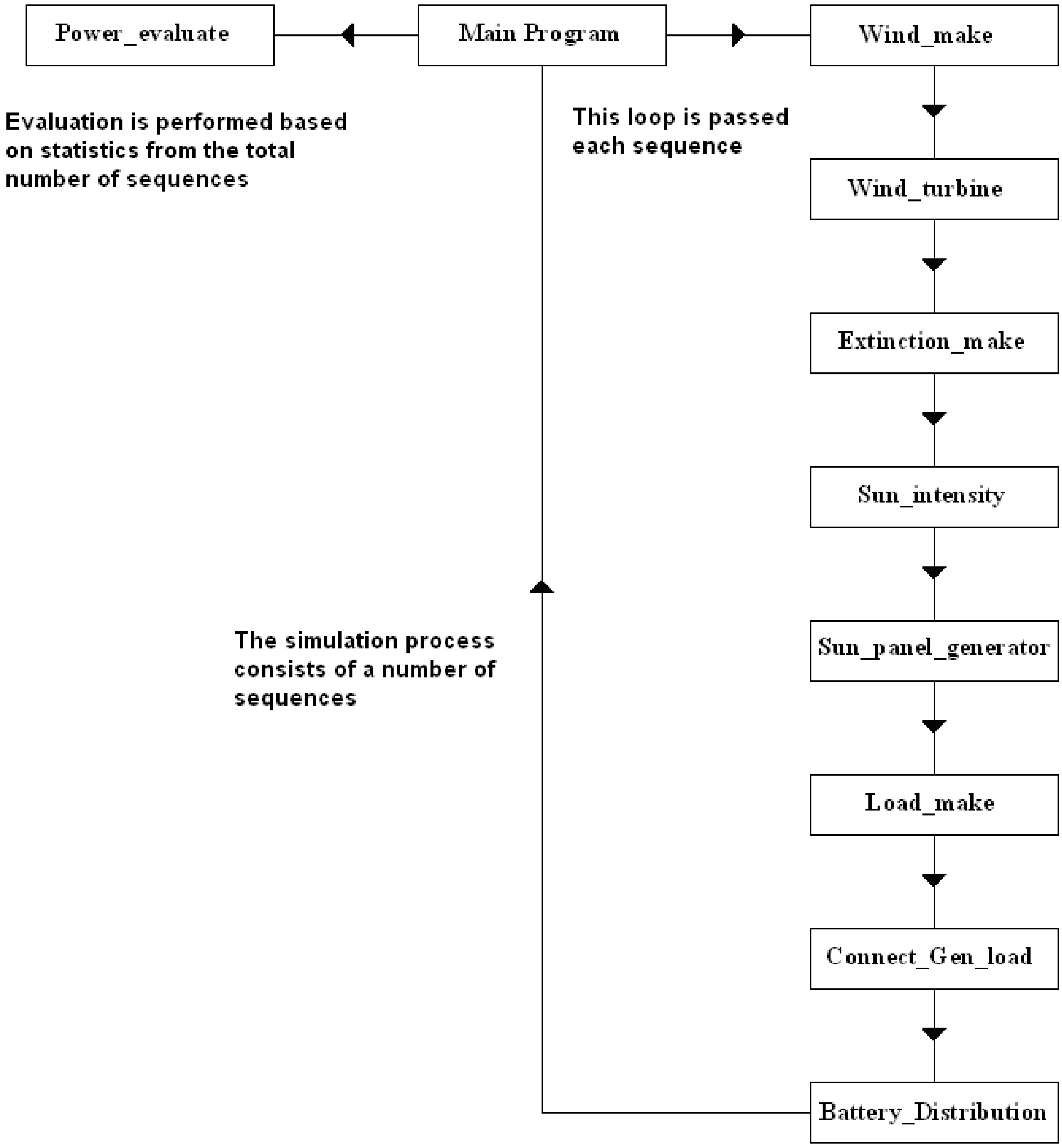


Figure 2.6-1 The flow chart of the current simulation system. The total simulation process consists of a number (50 to 100 is recommended) of sequences. Evaluation of the simulation is based on statistics from the total number of sequences.

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_wind = Level_W + Level_T, where Lewel_W is a result of weather and Level_T is a result of turbulence. See Figure 3.1-1.

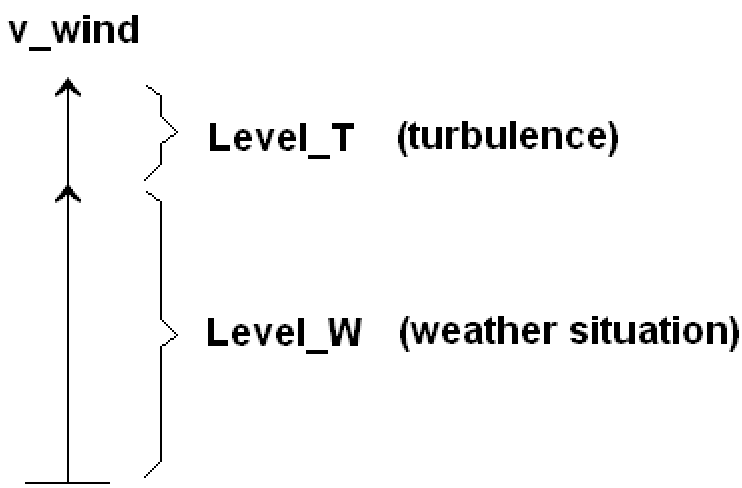


Figure 3.1-1 The wind rate is built up by two components, Level_W and Level_T

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.

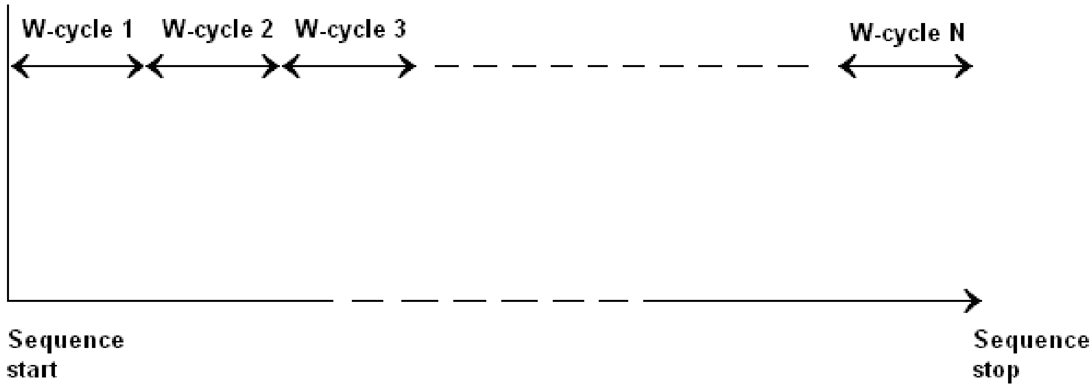


Figure 3.1-2 **A total simulation sequence consists of a number (N) of W-cycles each of them representing a sertain weather situation**

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 stochasticly generated by a “Weibull distribution” according to:

Equation 3.1-1:

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 valuel 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, *Sim_step_W_total*, is stochasticly generated in two steps according to:

<u>Step 1</u>

Equation 3.1-2:

Sim_step_W_total_prel = N(Sim_step_W_My ,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.

<u>Step 2</u>

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 = 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**.

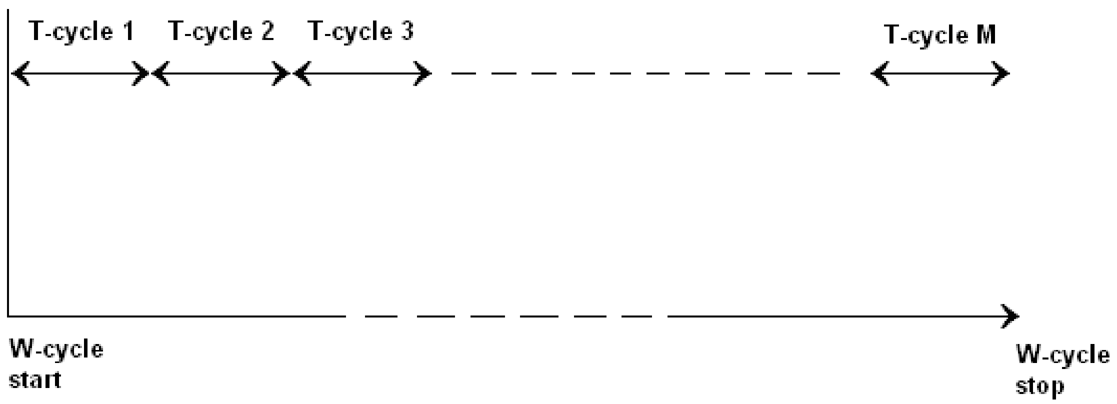


Figure 3.1-3 Every W-cycle is divided into a number (M) of T-cycles each of them representing a sertain turbulence situation

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:

Level_T = N (Level_T_My , Level_T_Sigma)

where *Level_T_My* and *Level_T_Sigma* are input parameters corresponding to mean value respectively standard deviation of turbulence contribution. *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**.

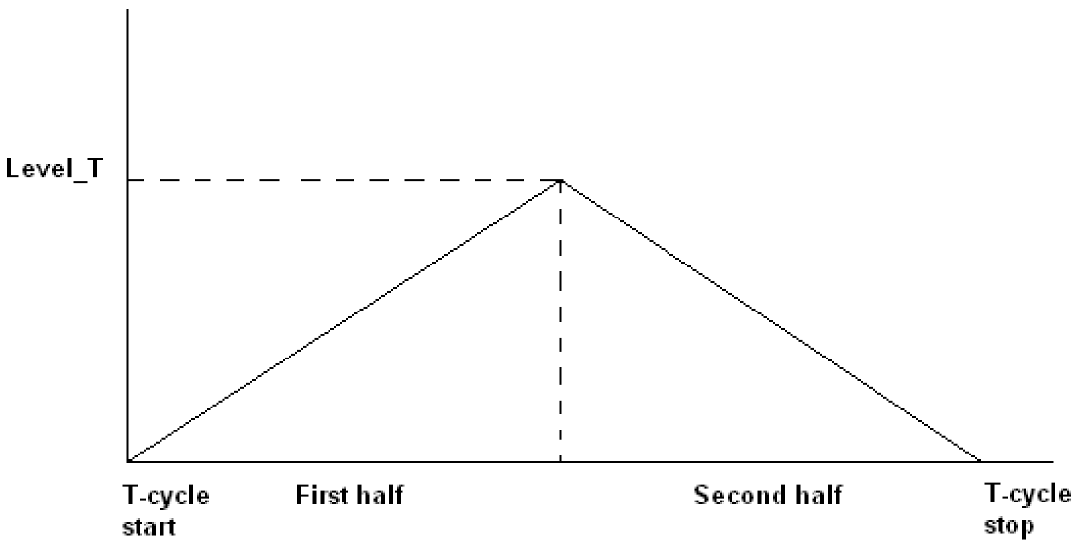


Figure 3.1-4 Distribution of Level_T during the T-cycle

The number of simulation steps for a single T-cycle, *Sim_step_T_total*, is stochasticly generated by a "Normal distribution" according to:

Equation 3.1-6:

Sim_step_T_total = N (Sim_step_T_My, Sim_step_T_Sigma)

Where *Sim_step_T_My* and *Sim_step_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**.

Parameter name	**Purpose**
Sim_step_sec Input via function argument from Main Program	Time interval in seconds per simulation step (60 is a standard value)
Sim_step_total Input via function argument from Main Program	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)
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)
Level_T_Sigma_proc	Standard deviation of Level _T in percent of Level_W
v_wind_H	Upper limit of the wind speed
v_wind_L	Lower limit of the wind speed
Wind_speed_file	The name of a *Wind speed file* (string) to store the wind speed vector and the above parameters in this 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.

Parameter name	Used value in the example
Sim_step_sec	60
Sim_step_total	43200
Sim_step_W_My	4320
Sim_step_W_Sigma	1500
Sim_step_T_My	10
Sim_step_T_Sigma	3
A	7.0
C	2.0
Level_T_Sigma_proc	30.0
v_wind_H	20.0
v_wind_L	0.0
Wind_speed_file	'Wind_1'

Table 3.1-2 An example of used input parameters for routine “Wind_make”

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 normaly 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**).

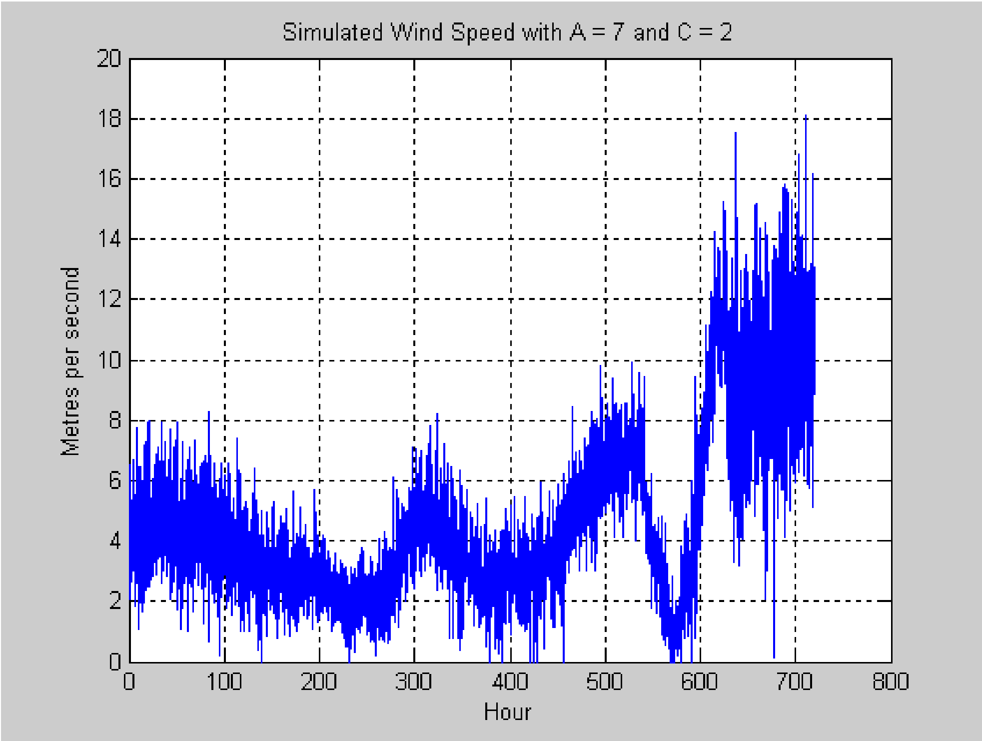


Figure 3.1-5 Simulated Wind speed for A = 7 and C = 2.
The total sequence is 720 hours

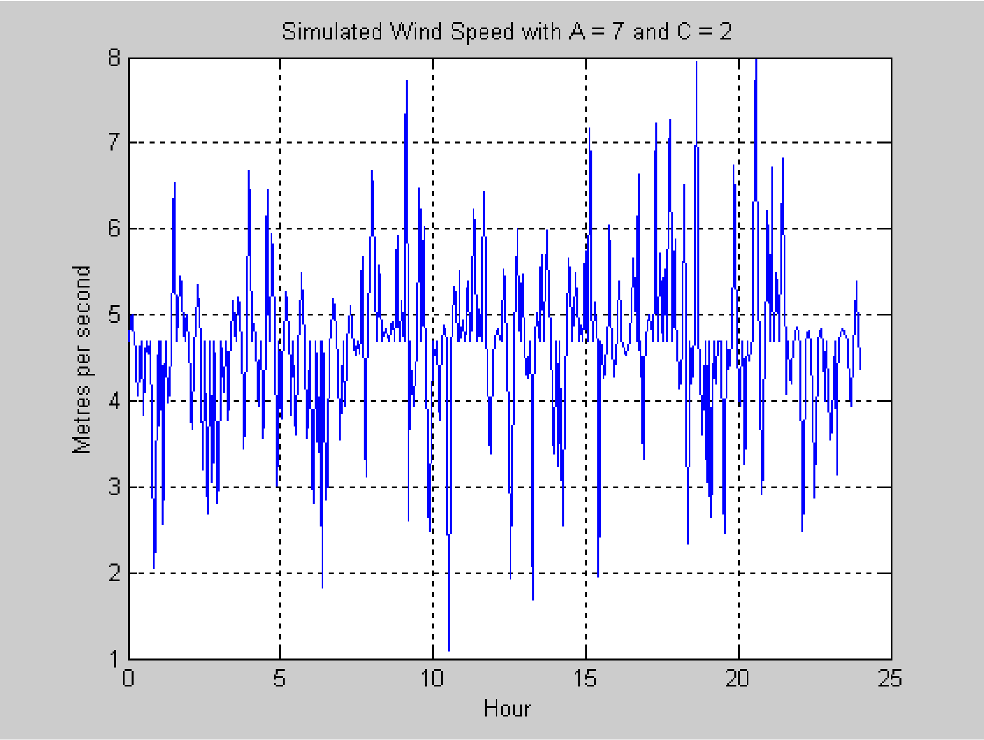


Figure 3.1-6 Simulated Wind speed for A = 7 and C = 2. The first 24 hours

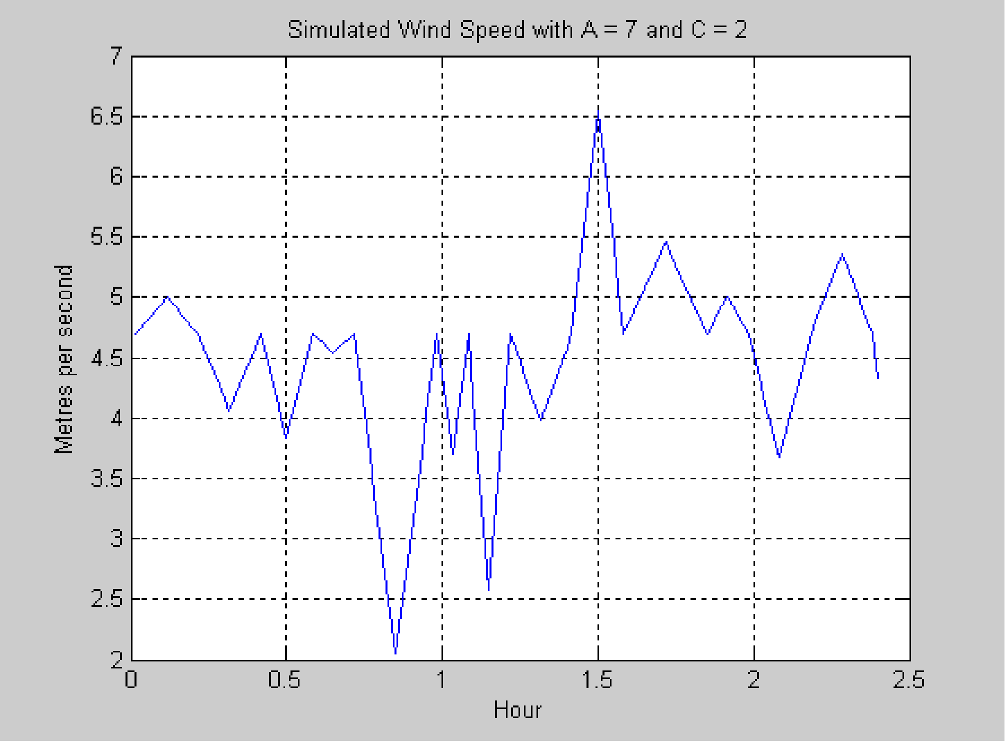


Figure 3.1-7 Simulated Wind speed for A = 7 and C = 2. The first 2.4 hours

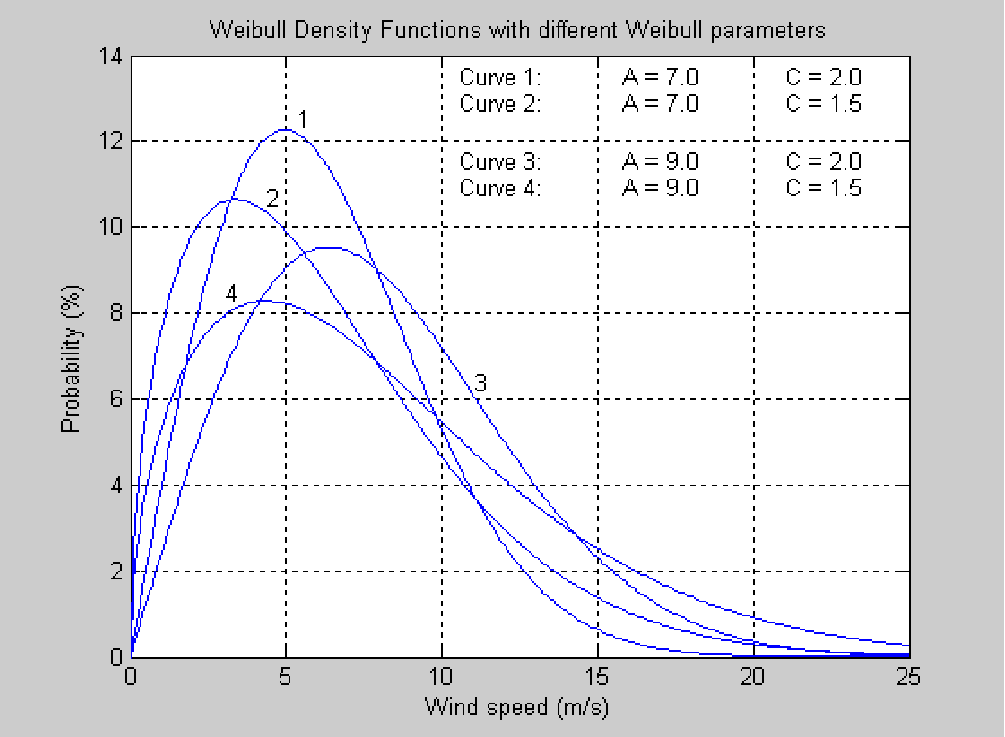


Figure 3.1-8 Examples of different Weibull Density Functions

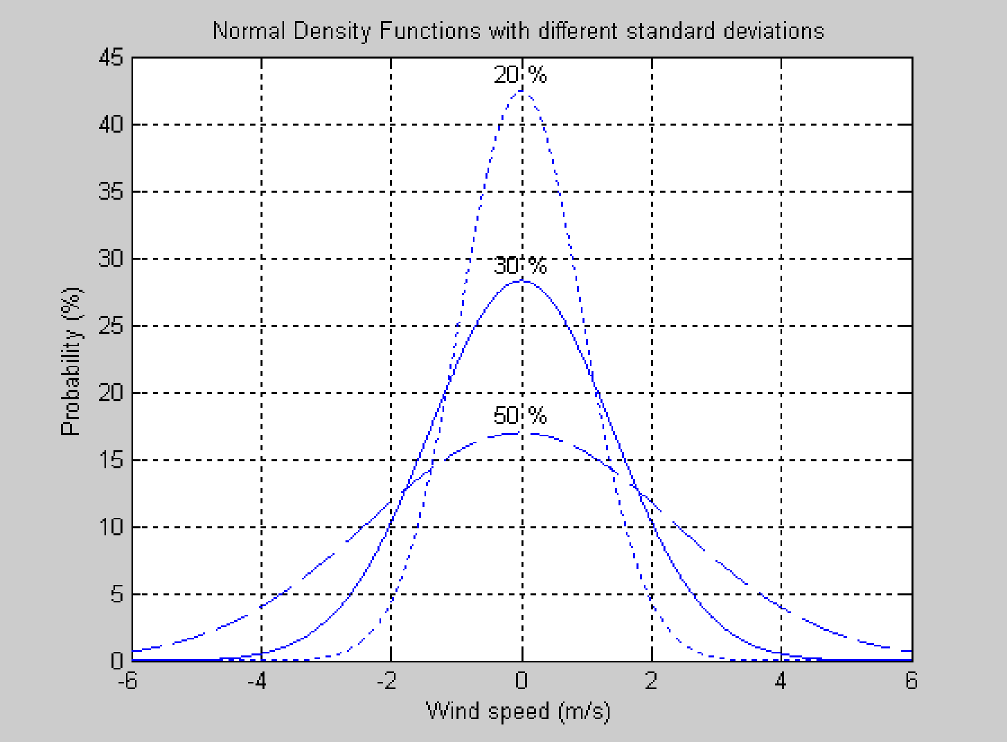


Figure 3.1-9 Normal density functions with varying standard deviations, relating to the parameter "Level_T_Sigma_proc" and the value of "Level_W" = 4.7 m/s. The 30 % curve corresponds to the chosed "Level_T_Sigma_proc" in the simulation according to the example

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.

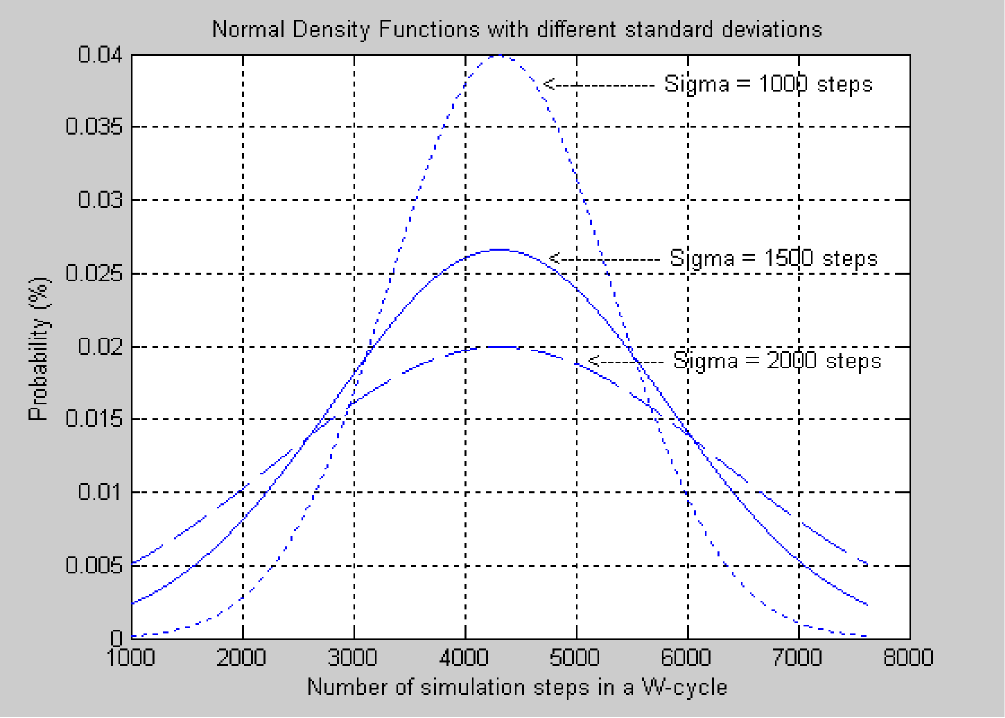


Figure 3.1-10 Normal density functions with varying standard deviations, relating to the parameter “Sim_step_W_Sigma”. The “Sigma = 1500 steps” curve corresponds to the current the simulation in the example

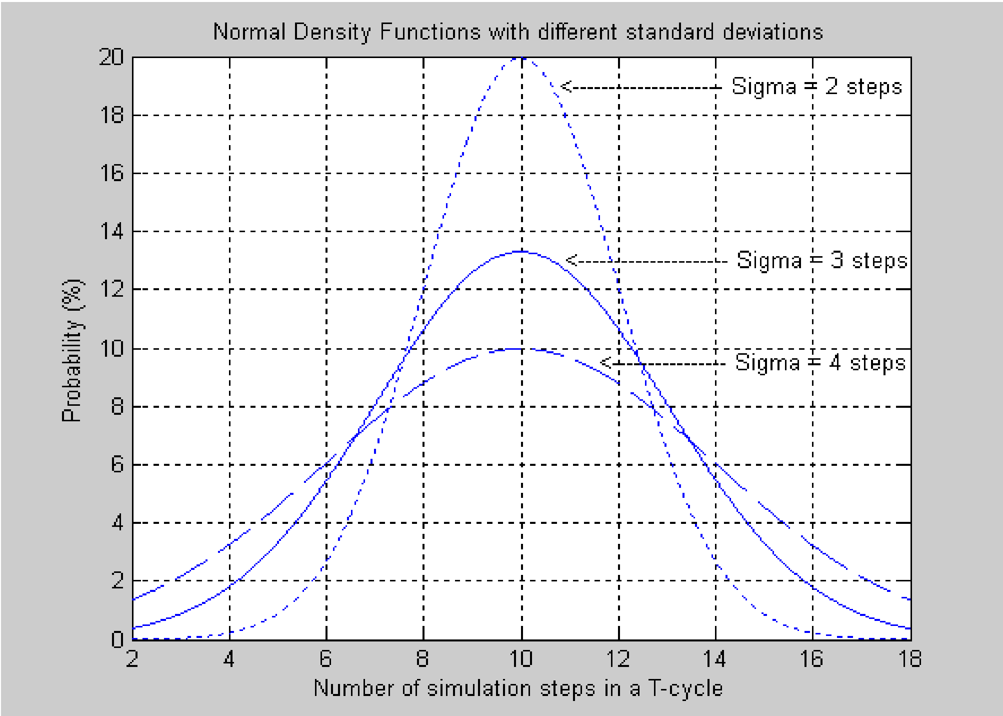


Figure 3.1-11 Normal density functions with varying standard deviations, relating to the parameter "Sim_step_T_Sigma". The "Sigma = 3 steps" curve corresponds to the current the simulation in the example

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.**]):

Equation 3.2-1: $$Pw = Cp \cdot \frac{1}{2} \cdot \rho \cdot A \cdot V^3$$

Where

Pw: wind power (W)

Cp: power coefficient

ρ: the air density ($\frac{kg}{m^3}$)

A: rootor sweeping area (m^2) as a result of rootor diameter according to:

Equation 3.2-2: $$A = D_R^{\ 2} \cdot \frac{\pi}{4}$$

D_R: rootor diameter (m)

V: wind speed ($\frac{m}{s}$)

ρ is calculated according to:

Equation 3.2-3: $$\rho = \frac{1.293}{1 + 0.00367 \cdot Tair} \cdot \frac{Pair}{1013}$$

Where

$Tair$ is the air temperature in $°C$

And

$Pair$ is the air pressure in $mbar$

The power coefficient Cp is a function of a parameter λ, the so called "tip speed ratio" (%) according to:

Equation 3.2-4: $$\lambda = \frac{Vt}{V}$$

Where

Vt is the wing tip speed ($\frac{m}{s}$)

The relation between Cp and λ is in the routine calculated by a polynom of grade 5 according to:

Equation 3.2-5:

$$Cp = 1.142515 - 1.253909\lambda + 0.478158 \cdot \lambda^2 - 0.07554 \cdot \lambda^3 + 0.005426 \cdot \lambda^4 - 1.4623 \cdot 10^{-4} \cdot \lambda^5$$

This is a result of a polynom adaptation of the relation between Cp and λ 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.

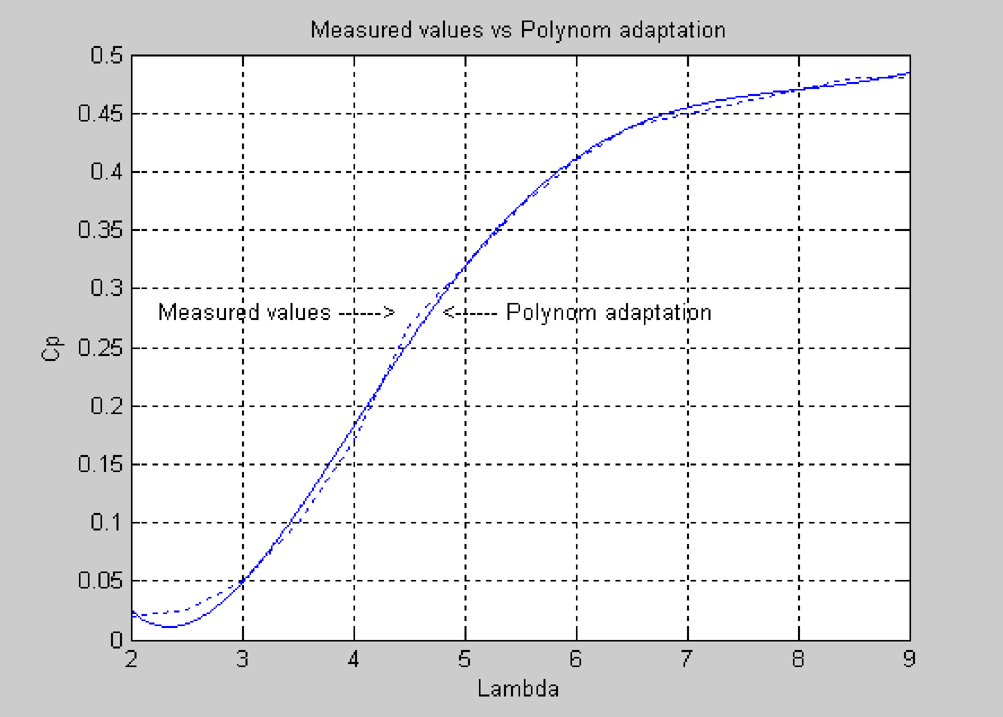


Figure 3.2-1 The relation between Cp and λ at Chalmers Test Wind Turbine at Hönö. The figure shows the measured respectively the polynom adapted relations

The routine presumes that the turbine, for a given wind speed, will regulate the rotation speed to get that λ that results in maximum Cp - value.

The rotation speed is limited by an optional input parameter. That means that the turbine regulation regarding λ only will adjust the rotation speed to give Cp - max up to a certain wind speed. If this wind speed is exceeded the λ - value will be less than the value that corresponds to Cp - 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 λ-value that results in Cp - max. When the rotor speed limit is exceeded the λ-value decreases continuously according to **Figure 3.2-3**. This will on the other hand decrease the Cp - 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

λ_{REF}: 9.0

Where λ_{REF} is the λ-value that gives Cp - max

Mechanical and electrical efficiency η: 0.85

Where η 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

$Tair$: 15 $°C$ (see Equation 3.2-3)

$Pair$: 1013 $mbar$ (see Equation 3.2-3)

D_R: 13.5 m (see Equation 3.2-2)

<u>Maximum and minimum windrates</u>

- If the wind rate exceeds a certain defined maximum level (*v_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_wind_min*) the turbine(s) does (do) not produce any output power.

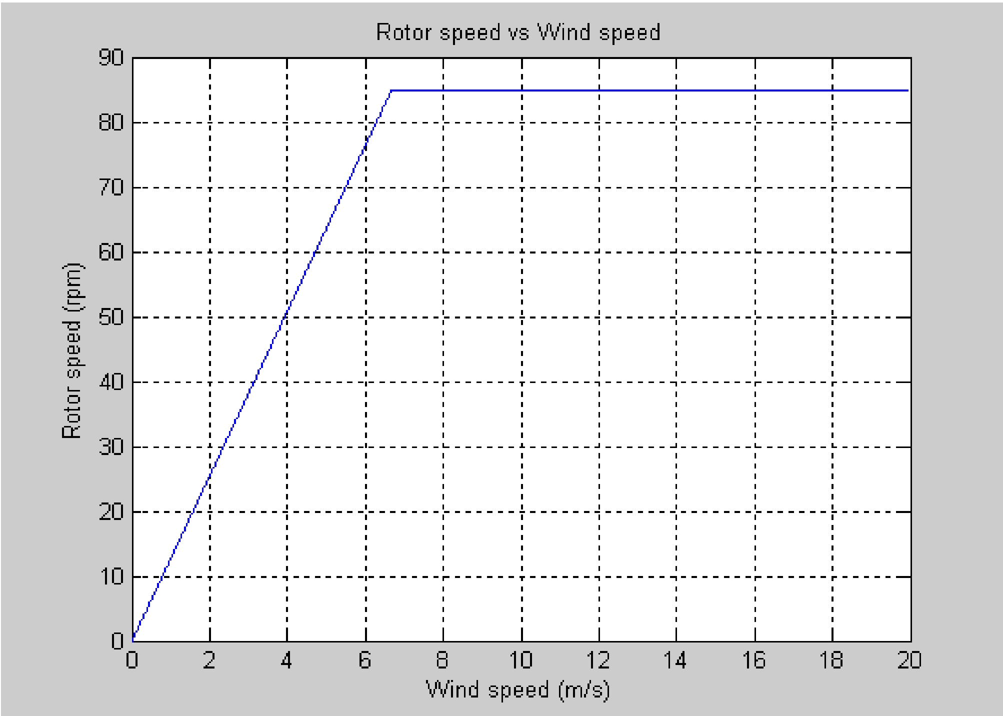


Figure 3.2-2 The rotor speed is limited. In this example at 85 rpm

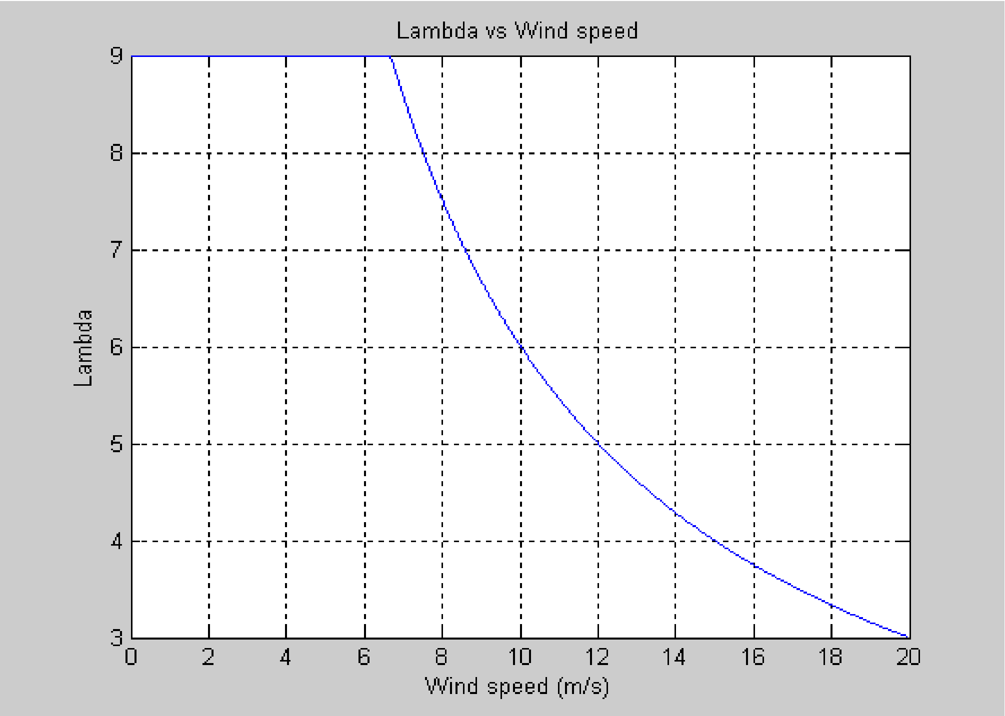


Figure 3.2-3 As the rotor speed is limited (85 rpm) the λ - value will decrease for rotor speeds that exceeds the limit

Figure 3.2-4 As λ is decreased for rotor speeds exceeding the rotor speed limit the consequence will be a decreasing Cp - value

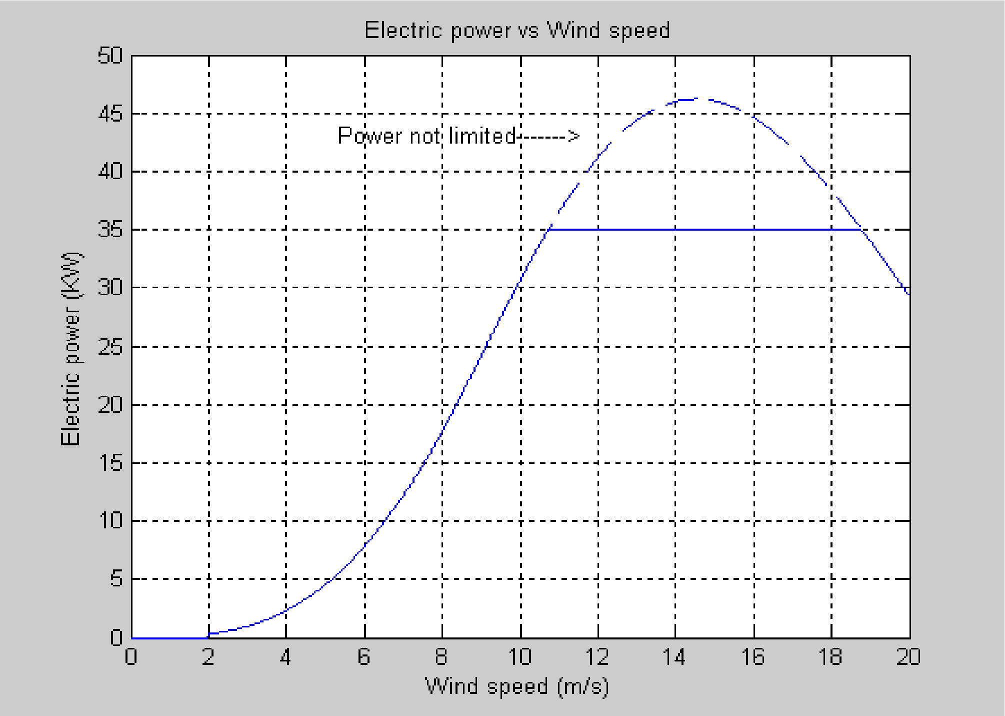


Figure 3.2-5 Resulted electric power as a function of wind speed. The dashed part of the curve corresponds to the circumstances when the electric power is not limited

3.2.2 Input parameters

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

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

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.

Parameter name	Used value in the example
Turb_numbers	2
lambda_ref	9.0
max_power	50 000
rotor_speed_max	85
aeta	0.85
t_air	15.0
p_air	1013.0
d_rootor	13.5
v_wind_max	25
v_wind_min	2

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).

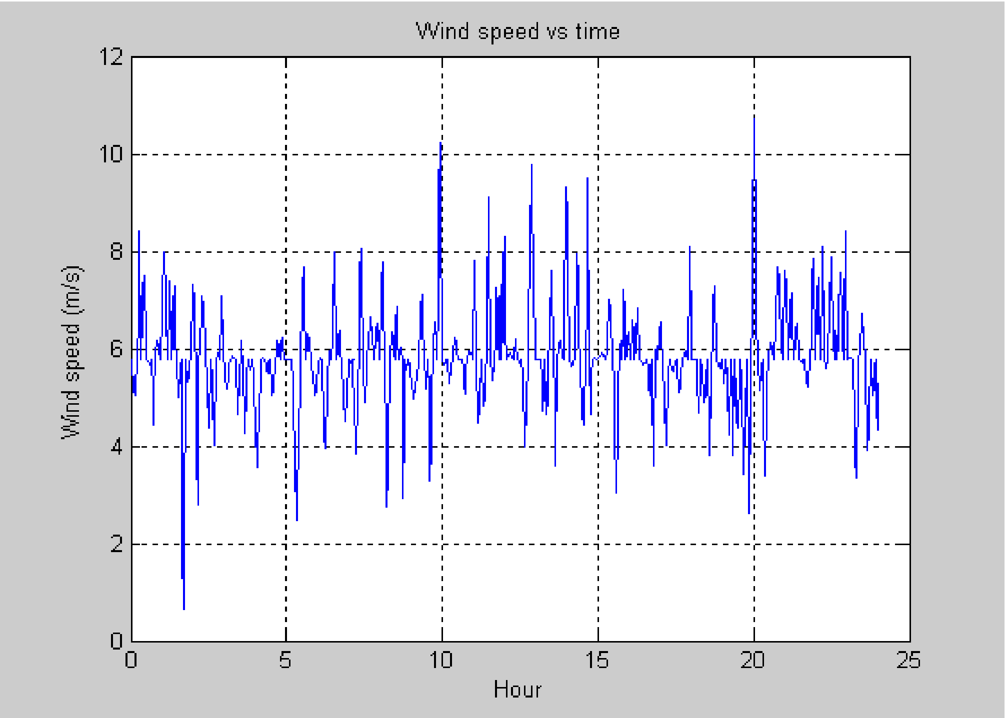


Figure 3.2-6 Wind speed vs time in the current example

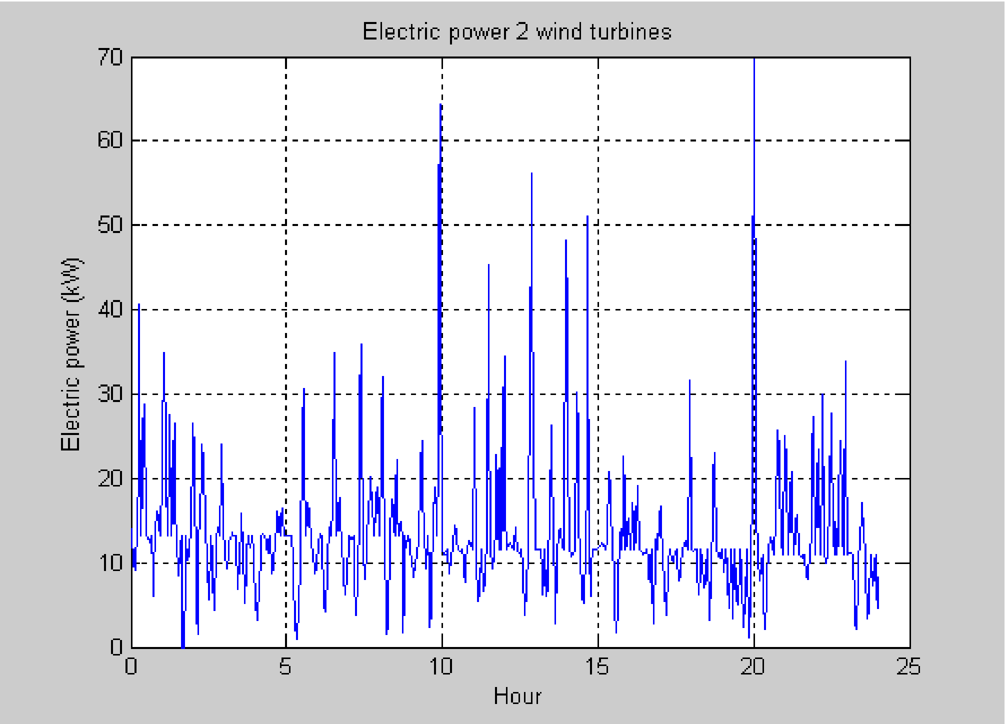


Figure 3.2-7 Electric power with wind speeds according to Figure 3.2-6 and Table 3.2-2

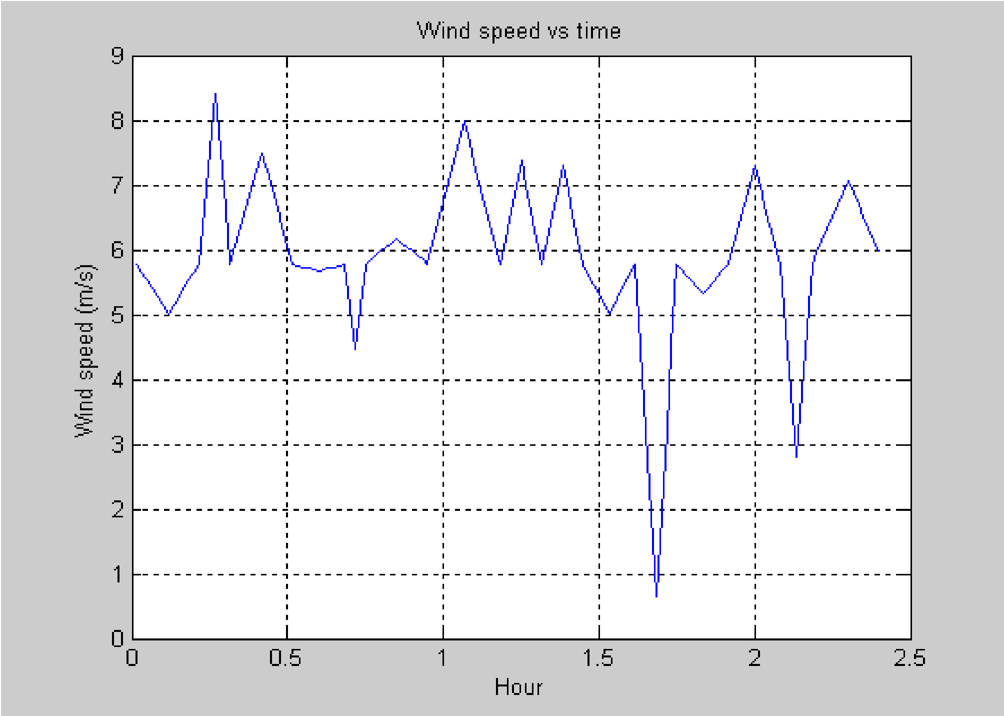


Figure 3.2-8 Wind speed vs time. The first 2.4 hours in the current example

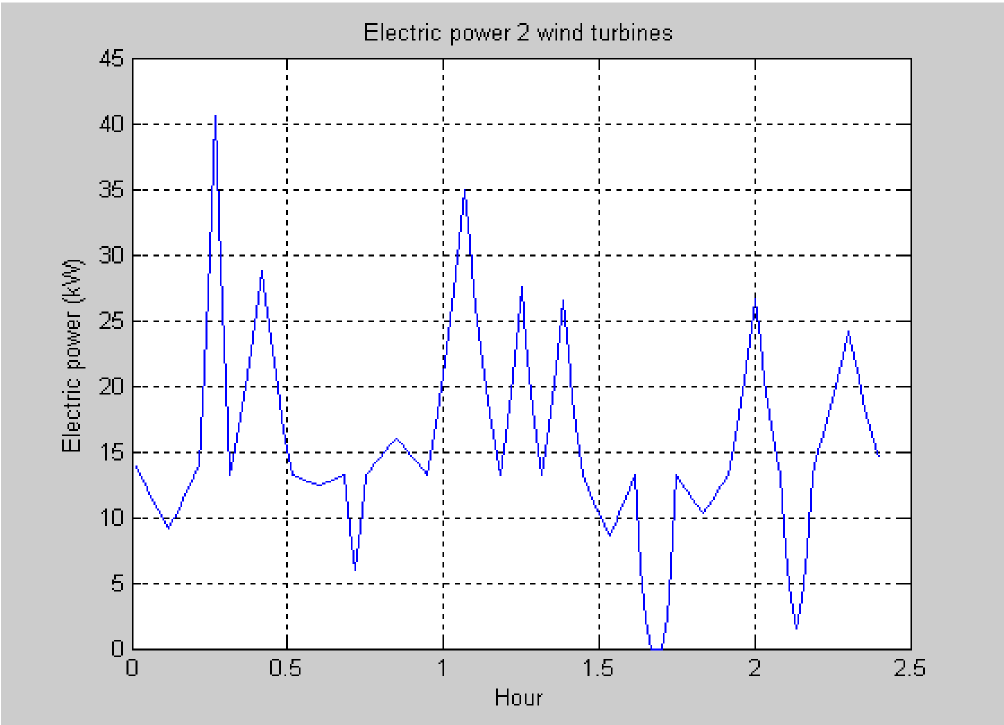


Figure 3.2-9 Electric power with wind speeds according to Figure 3.2-8 and Table 3.2-2

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**.

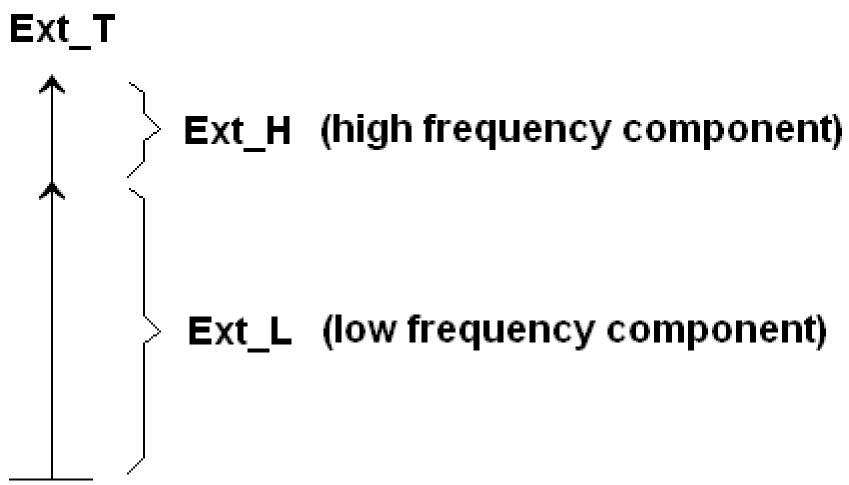


Figure 3.3-1 The extinction is built up by two components, Ext_L and Ext_H

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**.

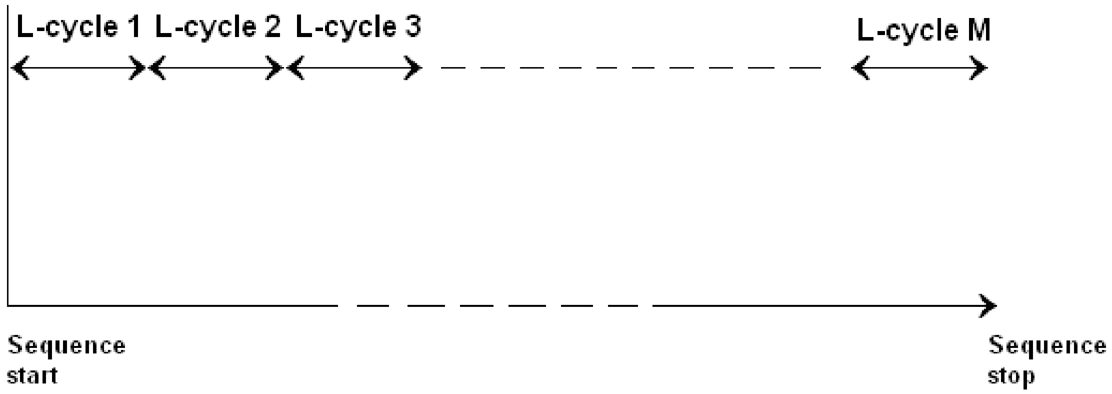


Figure 3.3-2 A total simulation sequence consists of a number (M) of L-cycles each of them representing a certain weather situation

Ext_L is stochasticly 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, *Sim_step_L_total*, is stochasticly generated in two steps according to:

<u>Step 1</u>

Sim_step_L_total_prel = N(Sim_step_L_My ,Sim_step_L_Sigma)

Where *Sim_step_L_total_prel* is a first preliminary number of simulation steps, *N* is a normal process and *Sim_step_L_My* and *Sim_step_L_Sigma* are input parameters corresponding to mean value respectively standard deviation of simulation steps per L-cycle.

<u>Step 2</u>

Sim_step_L_total_prel is then adapted to the statistic mean value of simulation steps per T-cycle, *Sim_step_T_My*, according to:

H_cycles_total = ceil(Sim_step_L_total_prel / Sim_step_H_My),

Where ceil rounds the argument to the nearest integer upwards.

Finally:

*Sim_step_L_total = H_cycles_total * Sim_step_H_My*

Where *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 **Figure 3.3-3**.

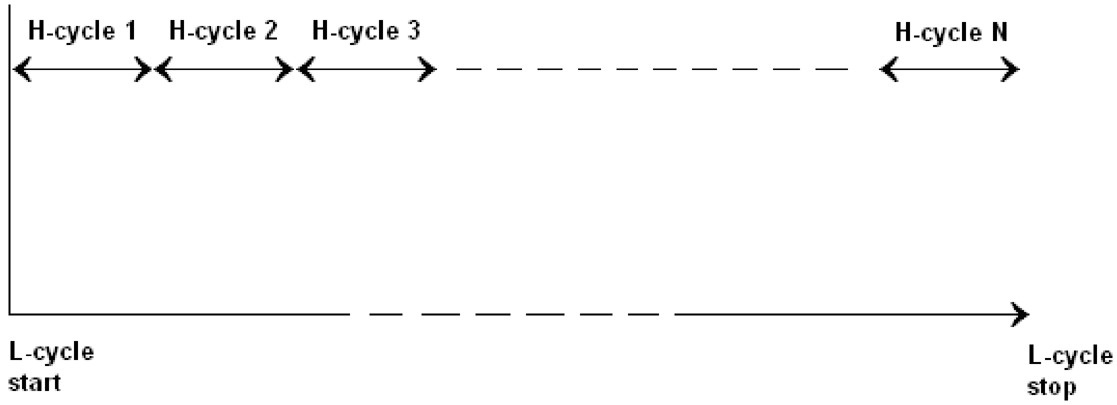


Figure 3.3-3 Every L-cycle is divided into a number (N) of H-cycles each of them representing a certain extinction variation

Each H-cycle depends on an individual extinction situation, that is varied from H-cycle to H-cycle. The contribution, Ext_H, to the total extinction, Ext_T (see above), is generated by a "Normal distribution" according to:

Ext_H = N (Ext_H_My , Ext_H_Sigma)

where *Ext_H_My* and *Ext_H_Sigma* are input parameters corresponding to mean value respectively standard deviation of high frequency contribution.

The generated value of *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**.

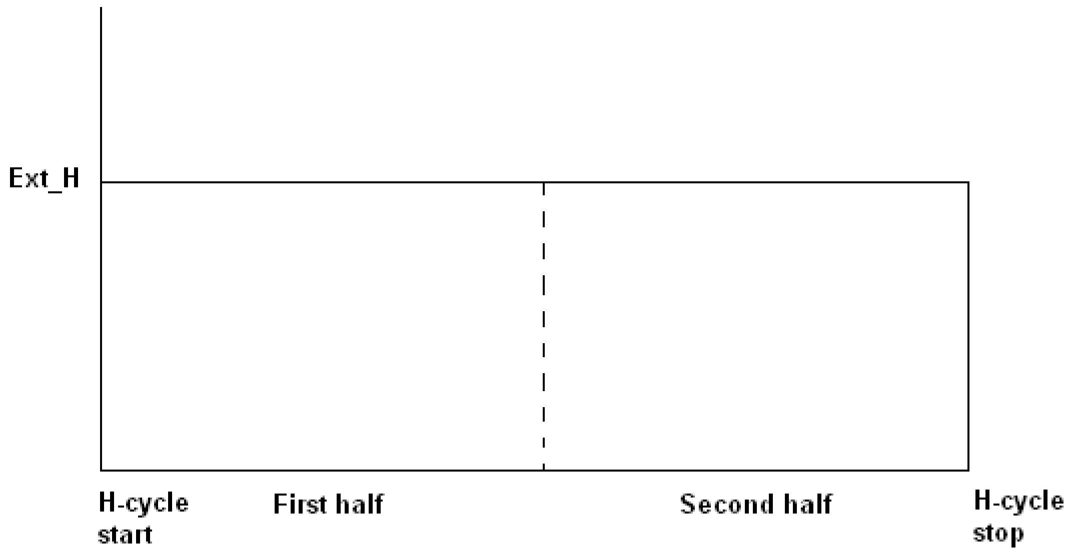


Figure 3.3-4 Distribution of Ext_H during the H-cycle at “Step distribution”

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**.

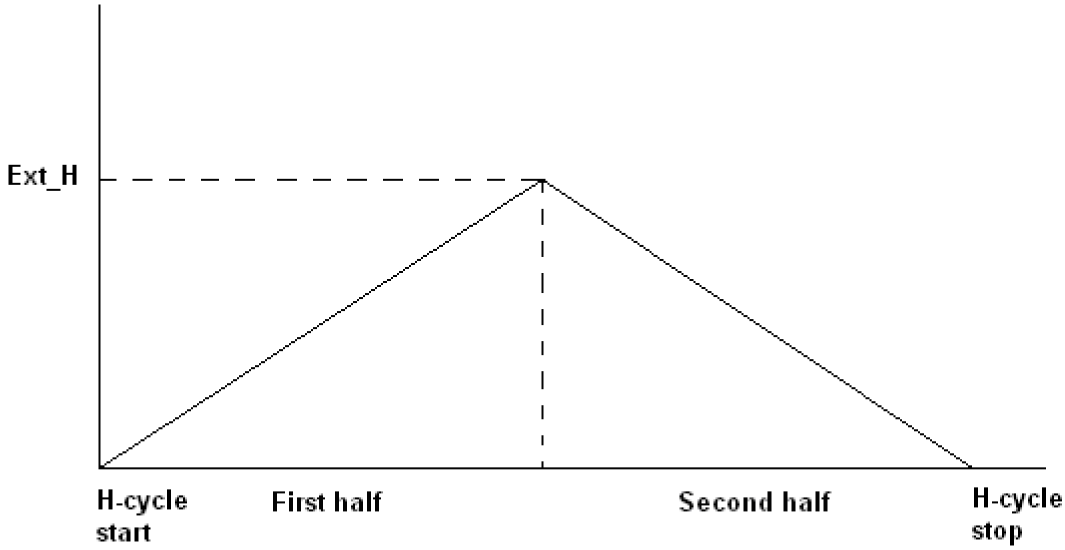


Figure 3.3-5 Distribution of Ext_H during the H-cycle at "Triangular distribution"

The number of simulation steps for a single H-cycle, *Sim_step_H_total*, is stochasticly generated by a "Normal distribution" according to:

Sim_step_H_total = N (Sim_step_H_My, Sim_step_H_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:

$$P_H(\mathrm{H\_limit}) = 2 \cdot (1 - F(\mathrm{H\_limit}))$$

Where

$F(x)$ is the integrated distributed function of a standardized Normal random variable.

H_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_limit"* is the following:

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

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

The inverse of $P_H(\text{H\_limit}) = 25\ \%$ results in *H_limit* = 1.15

Following this principle for other values of the cloudiness results in the relation between *H_limit* and cloudiness according to **Table 3.3-1**.

Figure 3.3-7 shows P_H as a function of *H_limit*.

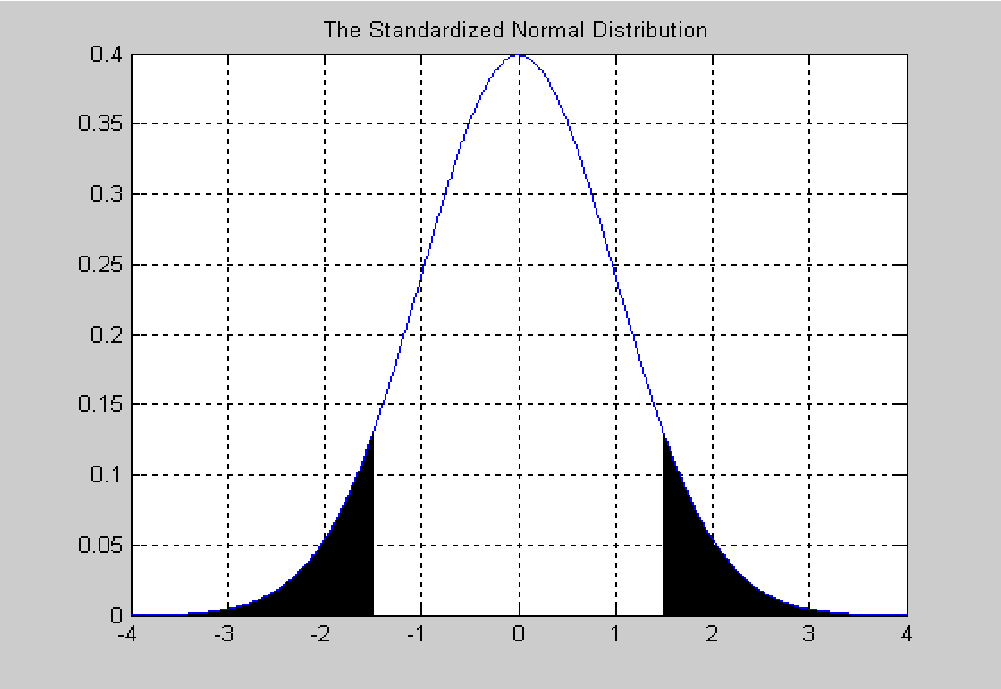


Figure 3.3-6 The parameter H-limit is in this example 1.5. P_H corresponds to the blacked areas, that is the same as 13.36 % of the total area

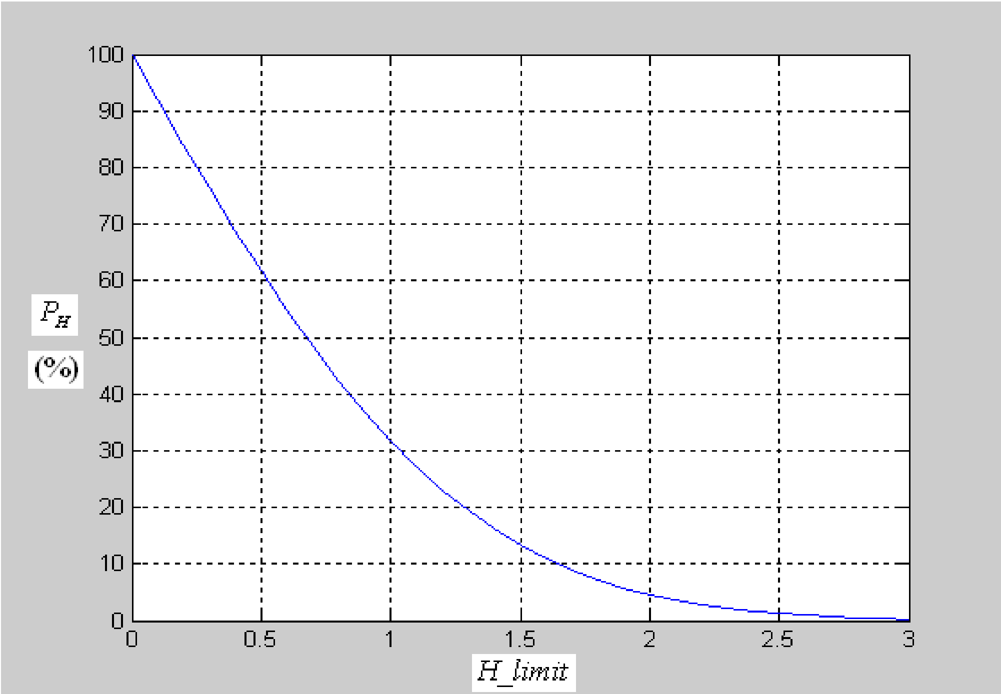


Figure 3.3-7 P_H as a function of *H_limit*

Cloudiness	P(cloud) (%)	*H_limit*
1/8	12.5	1.534
2/8	25.0	1.150
3/8	37.5	0.887
4/8	50.0	0.674
5/8	62.5	0.489
6/8	75.0	0.319
7/8	87.5	0.157
8/8	100	0

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**.

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

	distribution" Ext_H_onestep $\neq 1$ results in "triangular distribution"
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 Input parameters for module "Extinction_make"

3.3.3 Examples

Table 3.3-3 gives examples of used parameters in a simulation.

Parameter name	**Used value in the examples**
Sim_step_sec	60
Sim_step_total	1440
Sim_step_L_My	240
Sim_step_L_Sigma	60
Sim_step_H_My	10
Sim_step_H_Sigma	4
Ext_L_My	0.4
Ext_L_Sigma	0.2
Ext_H_My	3.
Ext_H_Sigma	1.
Ext_T_High	10.
Ext_T_Low	0.32
H_limit	1.534 alt 0.674
Ext_H_onestep	1 alt 0
Extinction_file	'Ext_1'

Table 3.3-3 Examples of used input parameters for module "Extinction_make"

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).

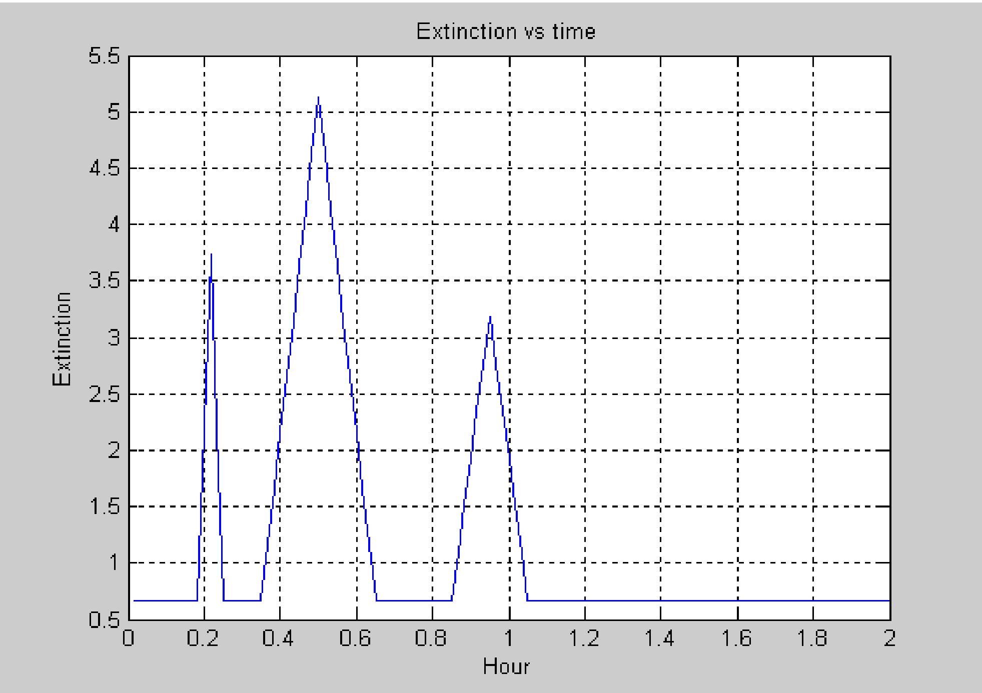


Figure 3.3-8 *H_limit* = 1.534 (corresponding to a cloudiness of 1/8)
Ext_H_onestep = 0 ("Triangular distribution" of the H-cycle)

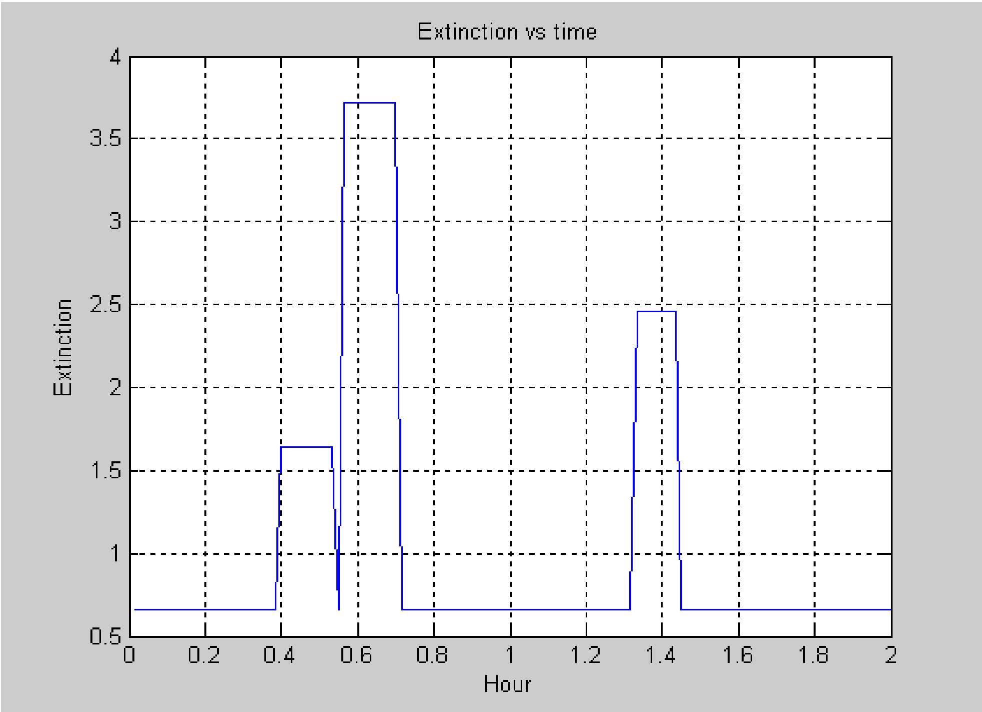


Figure 3.3-9 *H_limit* = 1.534 (corresponding to a cloudiness of 1/8)
Ext_H_onestep = 1 ("Step distribution" of the H-cycle)

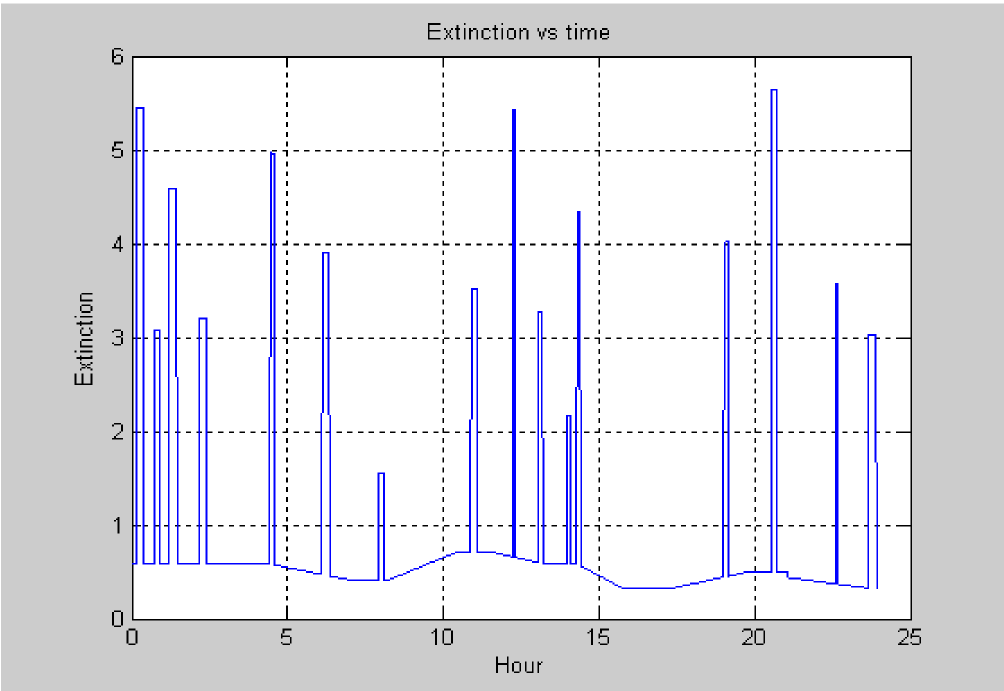


Figure 3.3-10 *H_limit* = 1.534 (corresponding to a cloudiness of 1/8)
Ext_H_onestep = 0 ("Step distribution" of the H-cycle)

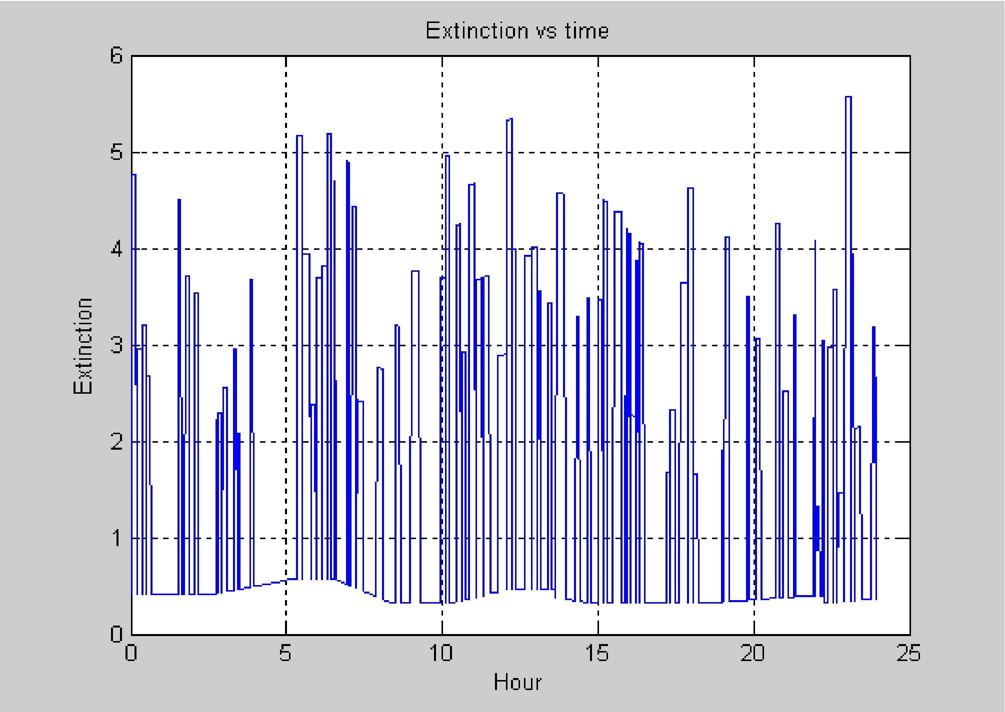


Figure 3.3-11 *H_limit* = 0.674 (corresponding to a cloudiness of 4/8)
Ext_H_onestep = 1 ("Step distribution" of the H-cycle)

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.

<u>To calculate the effective irradiance against the measuring surface the following calculation sequence is</u>:

Equation 3.4-1

$UT = start\_hour + time\_counter / 60 \cdot count\_interval$ (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 uper 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

$$d = 367 \cdot y - floor\left(7 \cdot \left(y + floor\left((m+9)/12\right)\right)/4\right) + floor\left(275 \cdot m/9\right) + D - 730530 + UT/24$$

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)

<u>Orbital elements of the Sun</u>

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:

$N = 0.0$

$i = 0.0$

$w = 282.9404 + 4.70935e-5 \cdot d$

a = 1.0

$e = 0.016709 - 1.151e-9 \cdot d$

$M = 356.0470 + 0.9856002585 \cdot d$

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

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

Equation 3.4-6

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

Equation 3.4-7

$$v = a\tan 2(Yv, Xv) \cdot \frac{180}{\pi} \qquad \text{(degrees)}$$

Equation 3.4-8

$$r = \sqrt{Xv^2 + Yv^2}$$

Note: *atan2* is a function that converts a coordinate pair to the correct angle in all four quadrants.

Compute the Sun's true longitude, *lonsun*:

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

$$Dec = a\tan 2(Ze, \sqrt{Xe^2 + Ye^2}) \cdot \frac{180}{\pi}$$ (degrees)

Compute the Sun's mean longitude, *L*:

Equation 3.4-17

$$L = M + w$$ (degrees)

Compute "the Sidereal Time at Greenwich", *GMST0*, at 00:00 "Universal Time":

Equation 3.4-18

$$GMST0 = L + 180$$ (degrees)

GMST0 is expressed in degrees to simplify the computations. GMST0 = 360 degrees corresponds to 24 hours, i.e. each hour corresponds to 15 degrees.

Compute "the Local Sidereal Time, *LST*:

Equation 3.4-19

$$LST = GMST0 + UT \cdot 15.0 + long$$ (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

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

Where

lat : the latitude in question

Equation 3.4-22

$$alpha = \arcsin(\sin\_alpha) \qquad \text{(radians)}$$

Compute the Sun's azimuth, *az*

Equation 3.4-23

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

Equation 3.4-24

$$az = \arccos(\cos\_az)) \qquad \text{(radians)}$$

Compute the “atmospheric depth” as a function of the Sun’s altitude above the horizon, *alpha*:

Equation 3.4-25

$$M\_atm = \frac{1}{\sin(alpha)}$$

Where

M_atm : the atmospheric depth relative to the depth when the Sun is in zenith ($alpha = \frac{\pi}{2}$)

Compute the atmospheric transmission, τ :

Equation 3.4-26

$$\tau = \exp(-Extinction \cdot M\_atm)$$

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

$$Radiation\_A = \tau \cdot Radiation\_ref$$

Where

Radiation_ref : Sun irradiation before passing the atmosphere

Radiation_A : 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

$$cos\_beta = \sin(alpha)\cdot\cos\left(\frac{Srf\_rel\_Z}{180}\pi\right) + \cos(alpha)\cdot\sin\left(\frac{Srf\_rel\_Z}{180}\pi\right)\cdot\cos\left(az - \frac{Srf\_rel\_S}{180}\pi\right)$$

Where

Srf_rel_Z : the normal angle of the measuring surface relative to zenith

Srf_rel_S : the normal angle of the measuring surface relative to south

Equation 3.4-29

$$beta = \arccos(cos\_beta) \qquad \text{(radians)}$$

Compute the ”effective irradiation” from the Sun against the measuring surface as a function of the angle *beta*:

Equation 3.4-30

$$Radiation\_B = Radiation\_A \cdot cos\_beta$$

Where

Radiation_A : to the surface incoming irradiation

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.

<u>Properties regarding clear view between the sun and the measuring surface</u>

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 $azimuth\_\min \leq az \leq azimuth\_\max$

Where

alpha : Sun's altitude above the horizon

alpha_min : under limit for the altitude of the Sun to be visible

azimuth_min : under limit for the azimuth of the Sun to be visible

azimuth_max : upper 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.

Parameter name	**Purpose**
Sim_step_sec Input via function argument from Main Program	Time interval in seconds per simulation step (60 is a standard value)
Sim_step_total Input via function argument from Main Program	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)
Ext_T_vector Input via function argument from Main Program	Vector with extinction coefficients (per simulation step)
y	Start year for simulation
m	Start month for simulation
D	Start date for simulation
long	Longitude
lat	Latitude
start_hour	Start hour for simulation
Surface_rel_S	The normal of the measuring surface relative to south (degrees). If no “tracking”
Surface_rel_Z	The normal of the measuring surface relative to zenith (degrees). If no “tracking”
Radiation_ref	The sun irradiance before passing the atmosphere (W/m^2)
azimuth_min	Under limit for the azimuth of the Sun to be visible
azimuth_max	Upper limit for the azimuth of the Sun to be visible
alpha_min	Under limit for the altitude of the Sun to be visible
Tracking	If “Tracking” = 1 then the measuring surface follows the Sun position (“sun tracking”)

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.

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

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/m^2 , if the Sun is at zenith (Radiation_ref = 1367 according to Table 3.4-2).

Location	Latitude (degrees)	Longitude (degrees)
Nairobi	-1.283	36.833
Kiruna	67.850	20.217
Göteborg	57.710	11.968

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.

Season	Month	Date
Summer	June	20
Autumn	September	20
Winter	December	20

Table 3.4-4 The different seasons that have been studied regarding Sun irradiation

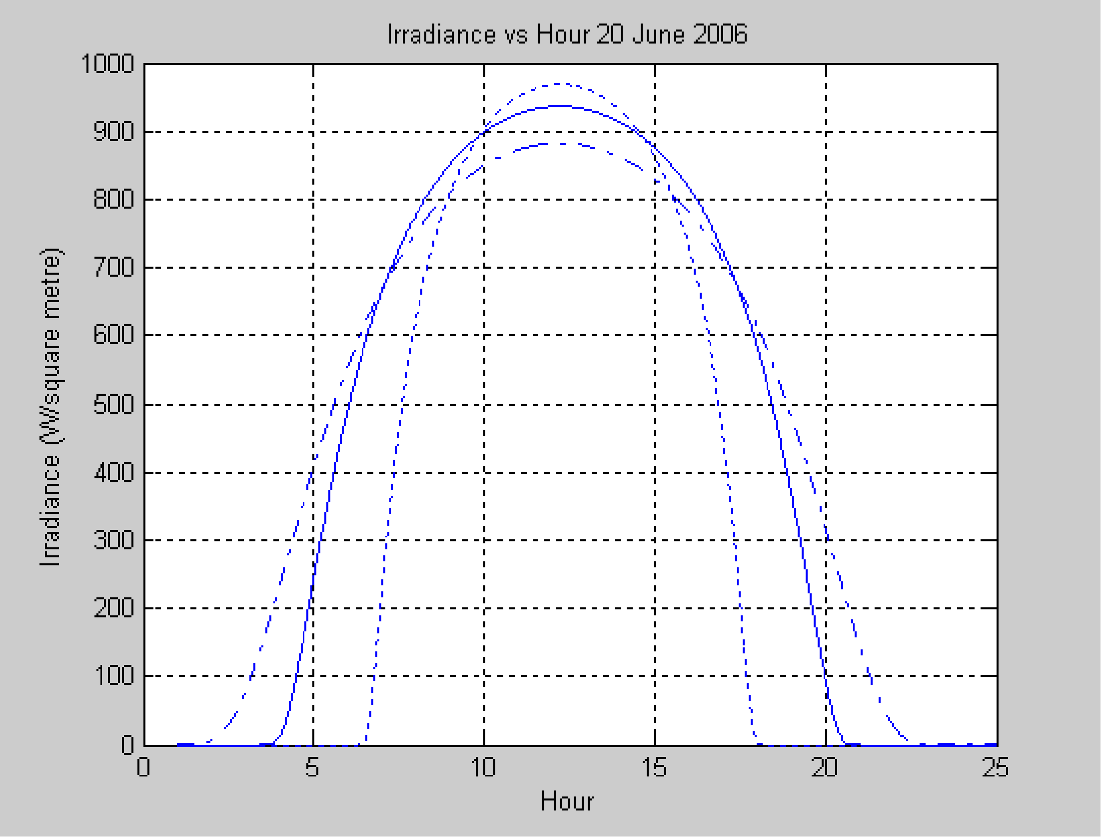


Figure 3.4-1 Effective irradiance for alternating localities. Date: 20 June 2006. See Table 3.4-5

Curve identifier	Locality	Integration (kWh / m^2)
'…….'	Nairobi	8.42
'-.-.-.-'	Kiruna	11.77
'______'	Göteborg	11.11

Table 3.4-5 Curve identifier and integrated irradiances. 20 June.

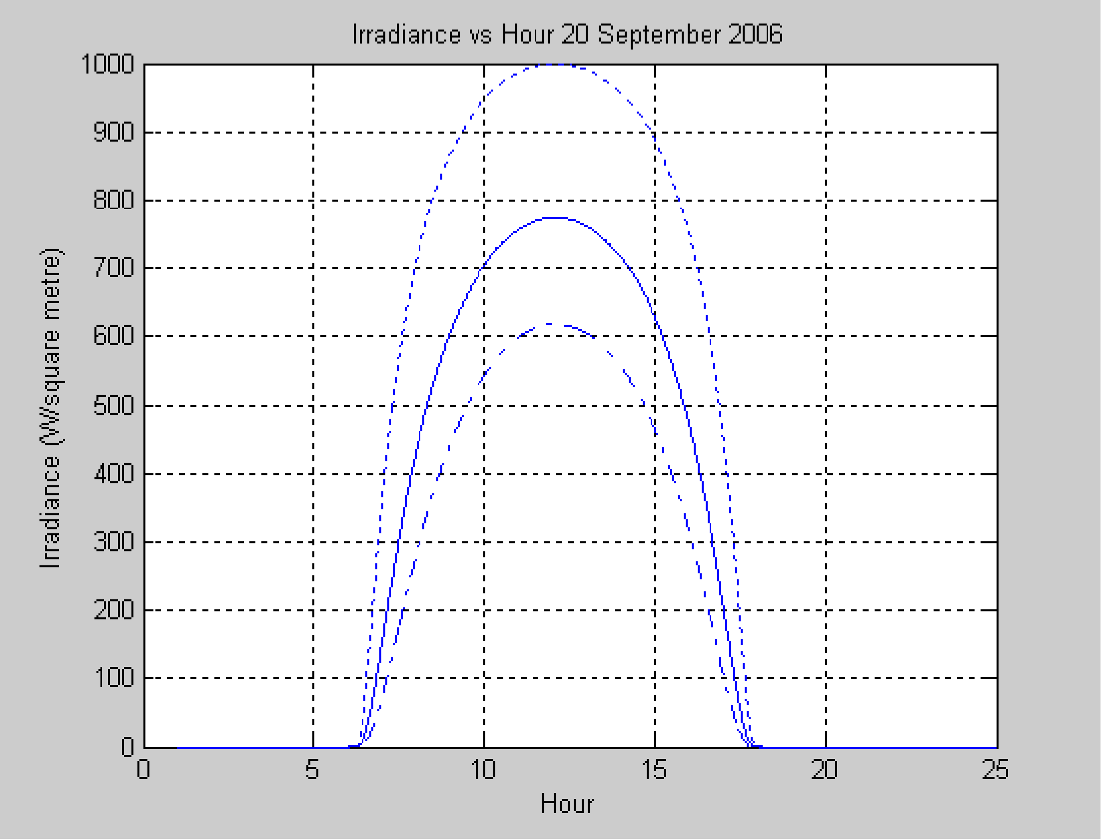


Figure 3.4-2 Effective irradiance for alternating localities.
Date: 20 September 2006. See Table 3.4-6

Curve identifier	Locality	Integration (kWh / m^2)
'.......'	Nairobi	8.89
'-.-.-.-'	Kiruna	4.60
'______'	Göteborg	6.20

Table 3.4-6 Curve identifier and integrated irradiances. 20 September

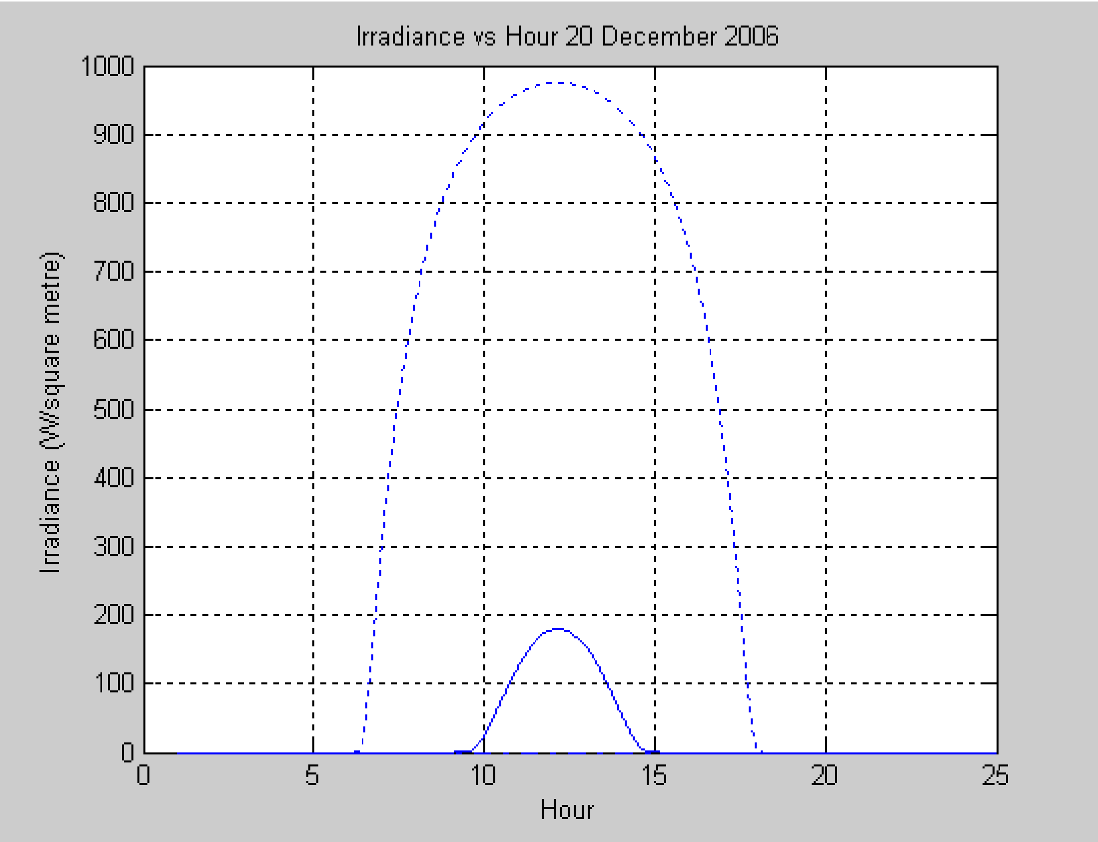


Figure 3.4-3 Effective irradiance for alternating localities.
Date: 20 December 2006. See Table 3.4-7

Curve identifier	Locality	Integration (kWh / m^2)
'…….'	Nairobi	8.61
'-.-.-.-'	Kiruna	0
'______'	Göteborg	0.54

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**.

Month	Integrated irradiance (kWh/m^2) Nairobi	Integrated irradiance (kWh/m^2) Göteborg	Integrated irradiance (kWh/m^2) Kiruna
January	260.36	32.06	0.16
February	264.96	91.08	27.43
Mars	266.68	165.52	111.65
April	263.51	244.25	218.98
May	257.33	302.48	304.27
June	253.12	330.93	348.99
July	255.08	318.29	328.74
Augusty	261.27	269.22	254.84
September	266.08	197.15	153.59
Oktober	266.05	117.67	53.70
November	261.92	47.57	2.42
December	258.61	18.41	0
Total year	3135	2135	1805

Table 3.4-8 Integrated irradiance per month and summed over 12month

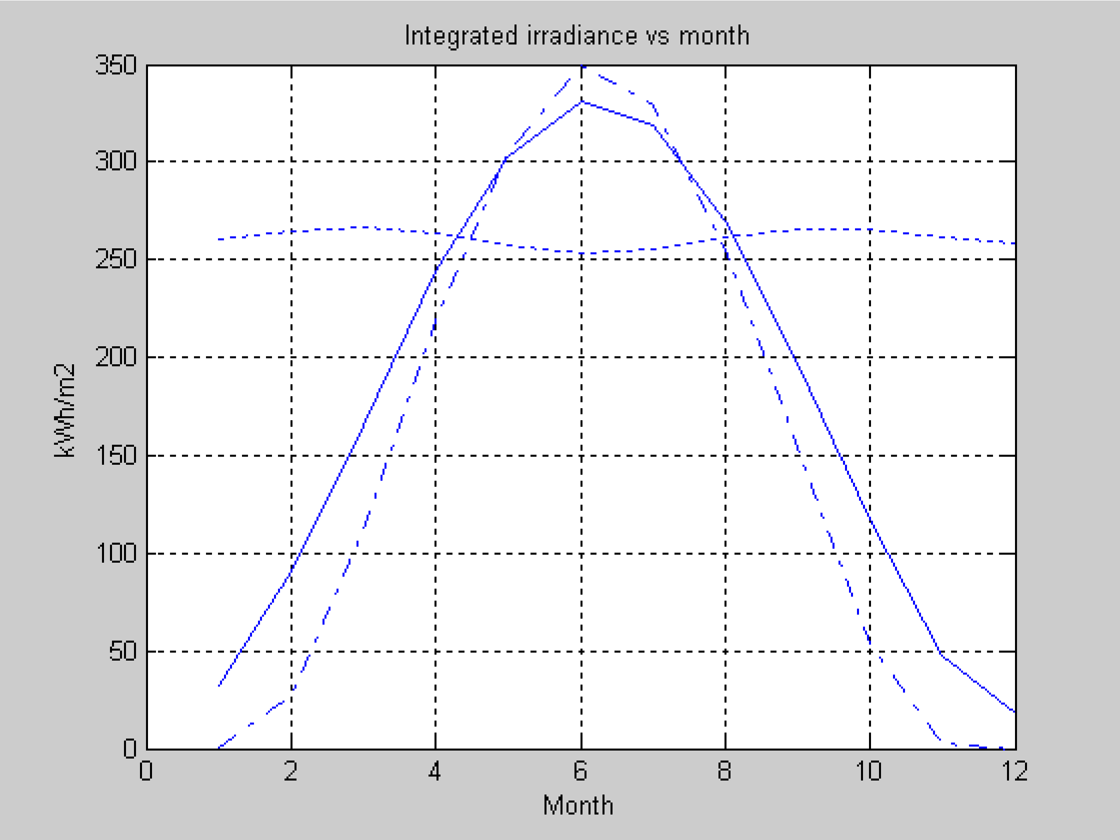


Figure 3.4-4 Integrated irradiance vs month

'.......'	Nairobi
'______'	Göteborg
'-.-.-.-'	Kiruna

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**.

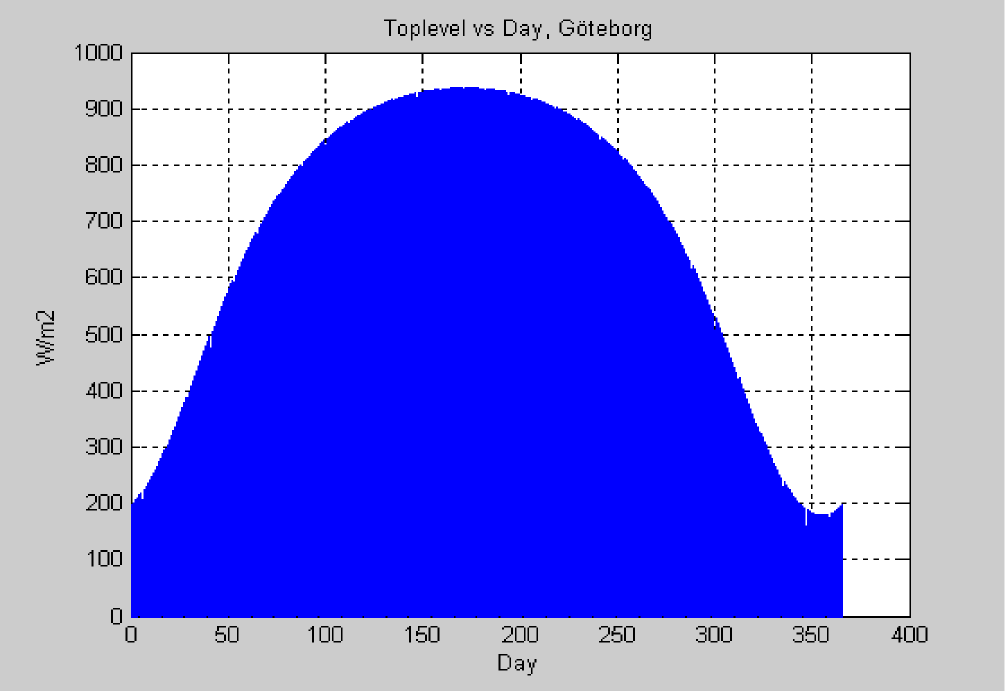


Figure 3.4-5 Top level irradiance vs day over a year. Göteborg

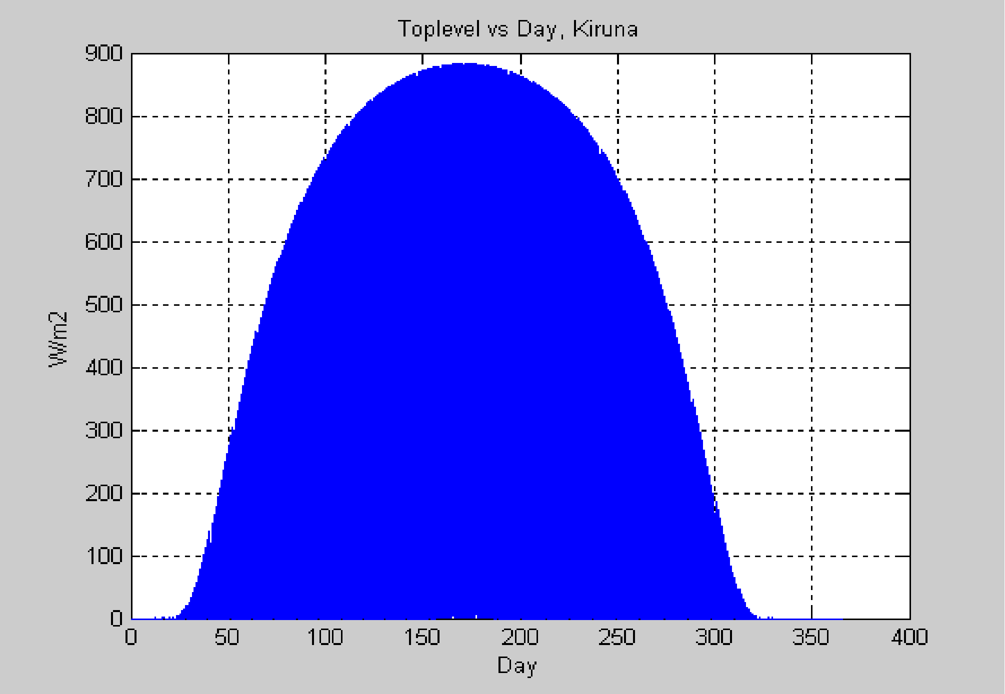


Figure 3.4-6 Top level irradiance vs day over a year. Kiruna

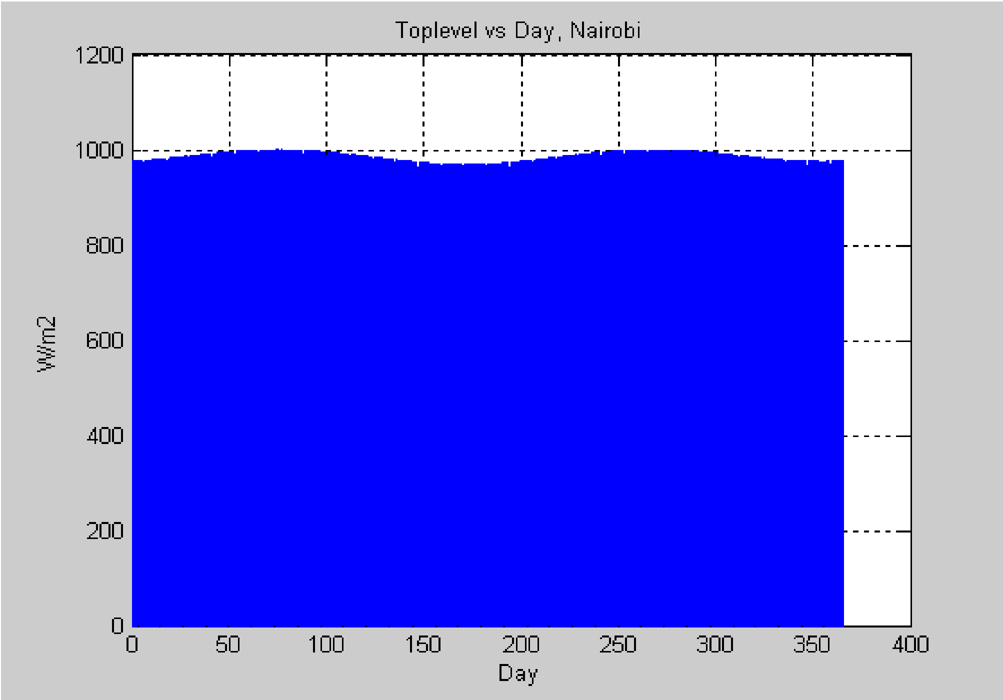


Figure 3.4-7 Top level irradiance vs day over a year. Nairobi

3.4.3.4 Different angles between measuring surface and zenit 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”.

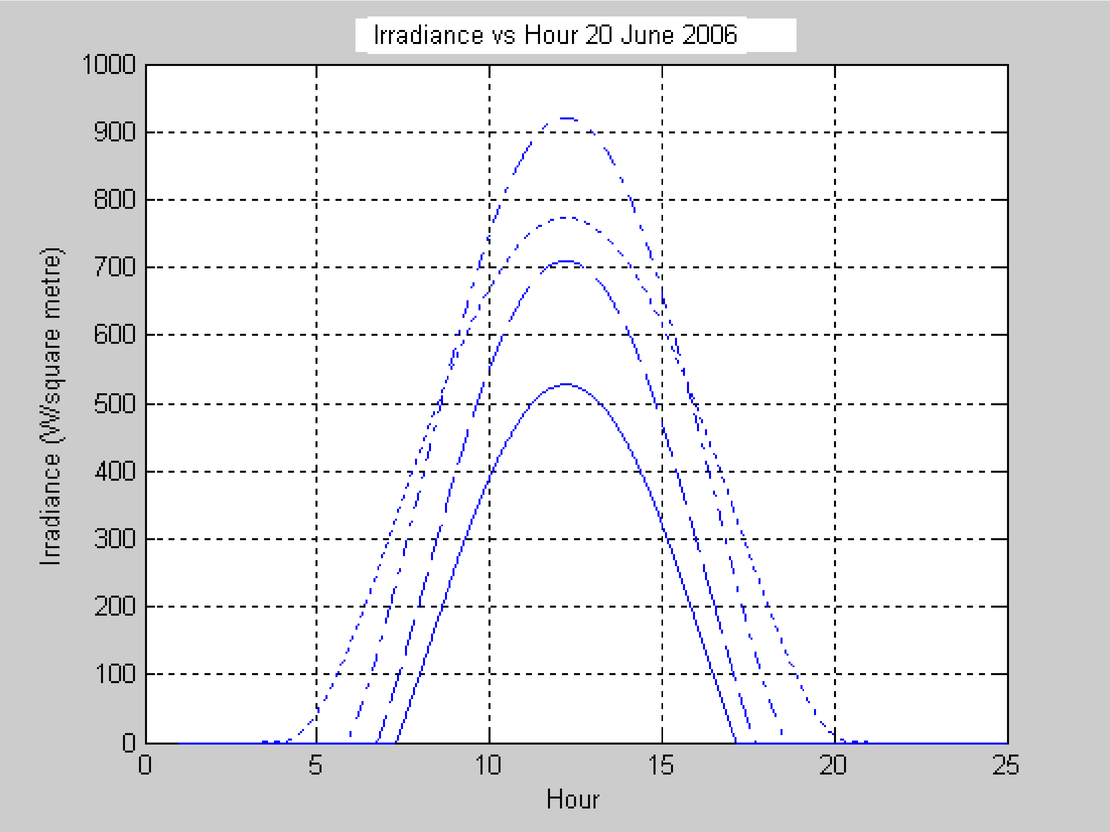


Figure 3.4-8 Effective irradiance for alternating angle of the measuring surface relative zenith. 20 June 2006. Göteborg. See Table 3.4-9

Curve identifier (**Figure 3.4-8**)	*Surface_rel_Z*	Integration (kWh / m^2)
'.......'	0	6.91
'-.-.-.-'	45	6.89
'__ __'	75	4.74
'______'	90	3.23
See **Figure 3.4-9**	“Sun Tracking”	11.11

Table 3.4-9 Integrated irradiance for different surface angles rel zenith. 20 June 2006. Göteborg

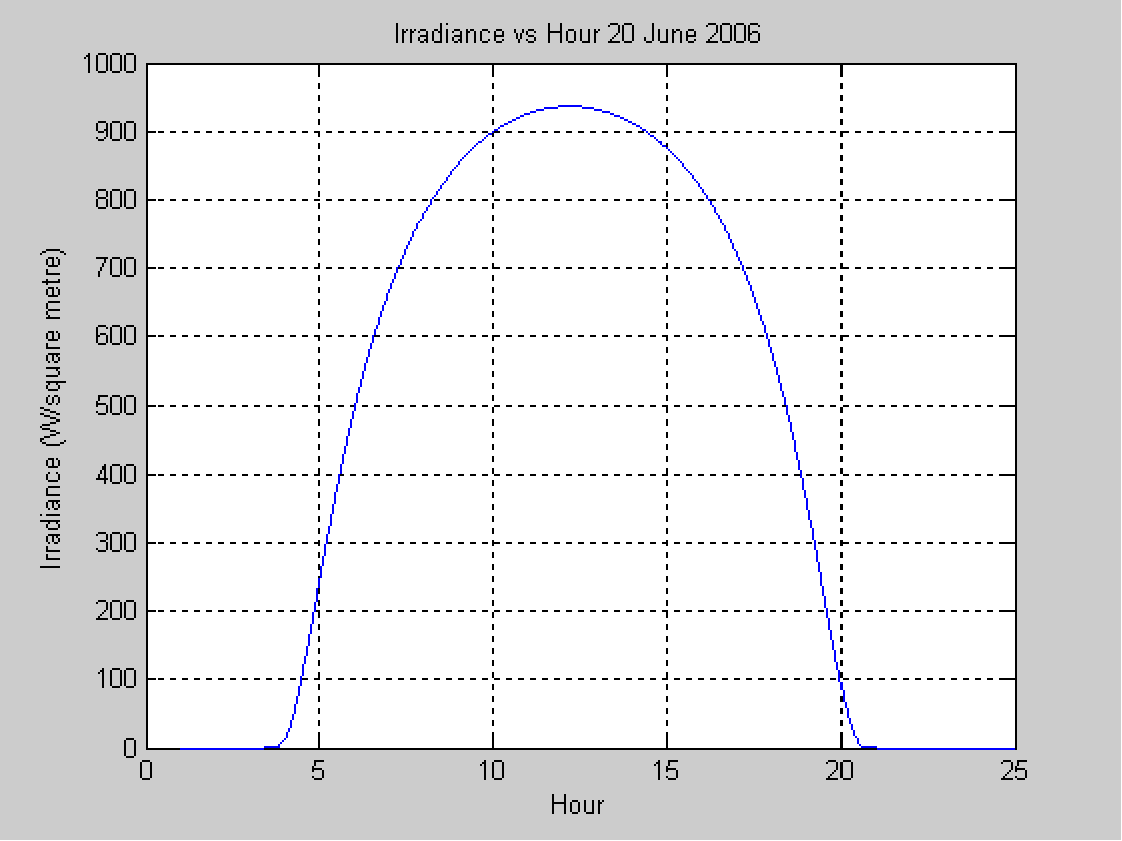


Figure 3.4-9 Effective irradiance if “Sun Tracking” is used. 20 June 2006. Göteborg

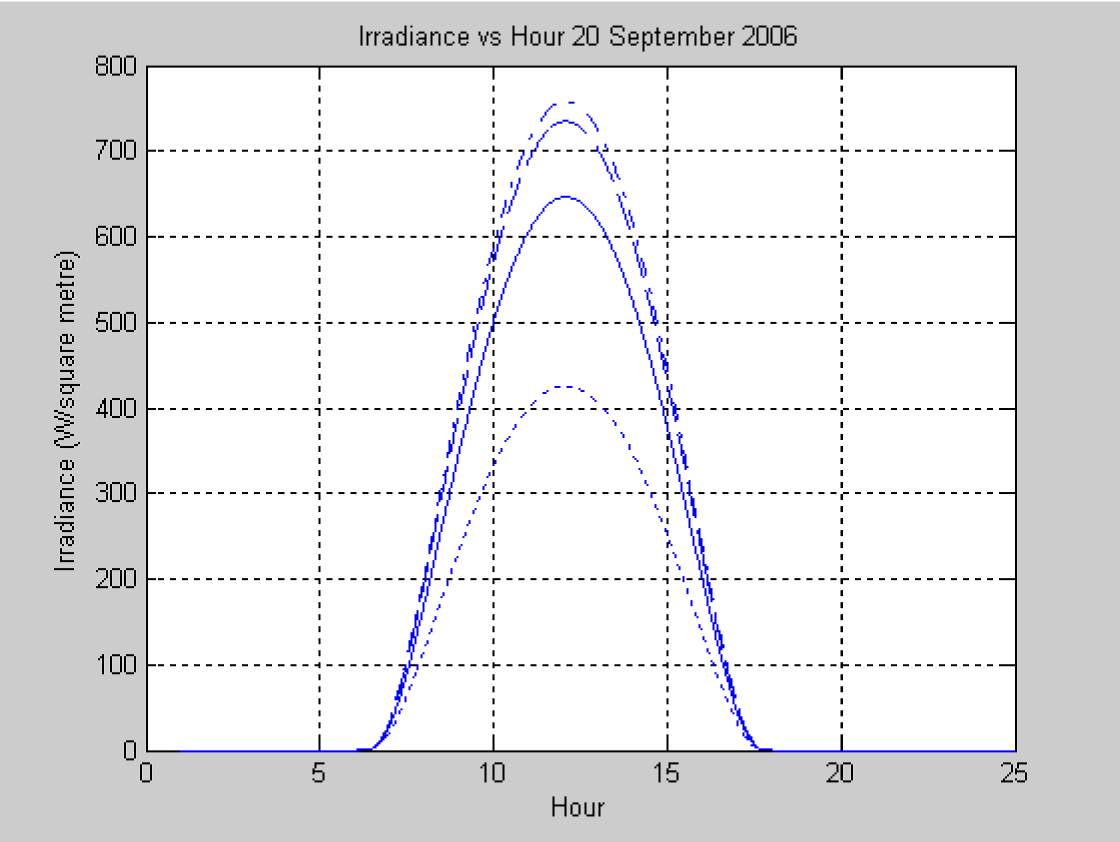


Figure 3.4-10 Effective irradiance for alternating angle of the measuring surface relative zenith. 20 September 2006. Göteborg. See Table 3.4-10

Curve identifier (**Figure 3.4-10**)	*Surface_rel_Z*	Integration (kWh / m^2)
'…….'	0	2.71
'-.-.-.-'	45	4.79
'__ __'	75	4.63
'______'	90	4.07
See **Figure 3.4-11**	"Sun Tracking"	6.20

Table 3.4-10 Integrated irradiance for different surface angles rel zenith. 20 September 2006. Göteborg

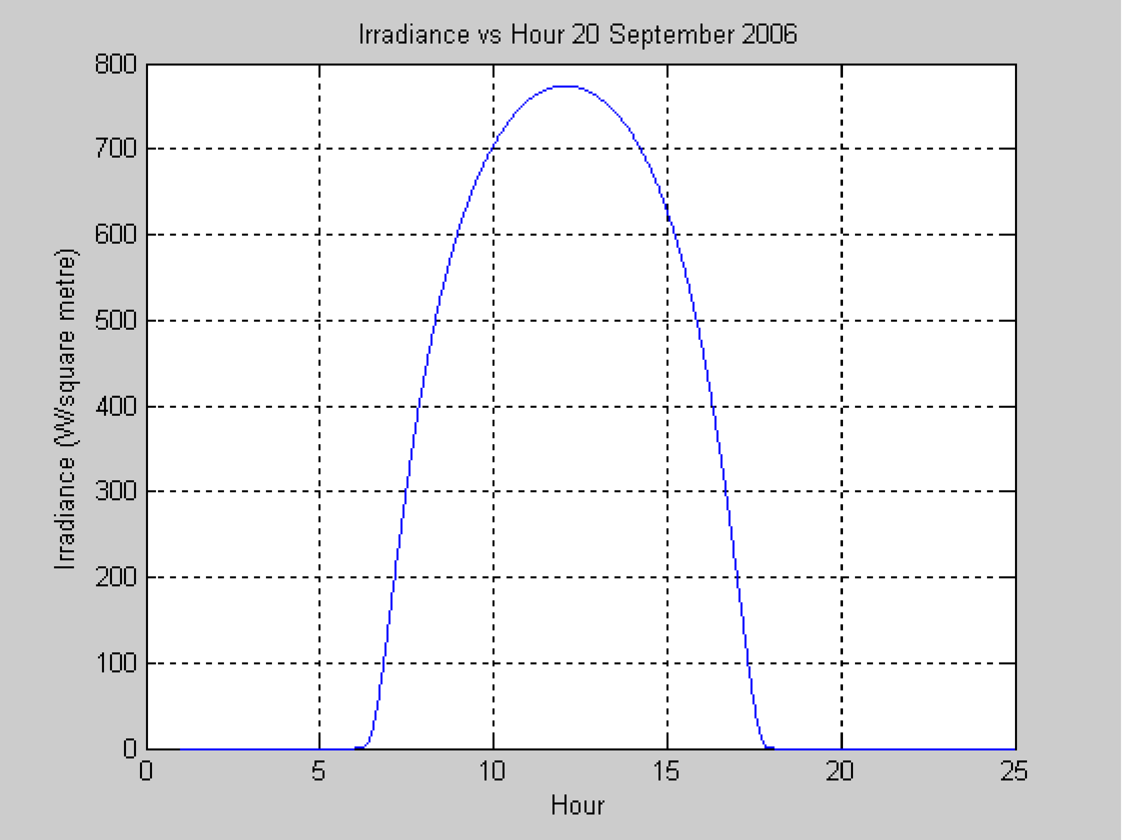


Figure 3.4-11 Effective irradiance if "Sun Tracking" is used. 20 September 2006. Göteborg

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:

$$P\_sun\_el\_vector(time\_step) = Radiation\_vector(time\_step) \cdot Sun\_panel\_area \cdot$$

$$\cdot Power\_factor\_cells \cdot Power\_factor\_MPP \cdot Power\_factor\_electr / 1000 \quad (kW)$$

Where:

P_sun_el_vector: vector with generated power from the solar cells generator (*kW*)

time_step: current time step (dimension less)

Radiation_vector: vector with irradiation values (W/m^2)

Sun_panel_area: total solar cell area (m^2)

Power_factor_cells: The efficiency of the solar cells (radiated power to electric power) (0 - 1)

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 *Power_factor_MPP* = 1

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**.

Parameter name	**Purpose**
Radiation_vector Input via function argument from Main Program	Vector with irradiation (effective to the solar cells) (per simulation step)
Power_factor_cells	The efficiency of the solar cells (radiated power to electric power) (0 - 1)
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 *Power_factor_MPP* = 1
Power_factor_electr	The efficiency of the power electronics (0 – 1)
Sun_panel_area	total solar cell area $\left(m^2\right)$

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.

Parameter name	**Used value in the example**
Power_factor_cells	0.15
Power_factor_MPP	0.95
Power_factor_electr	0.95
Sun_panel_area	800

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**.

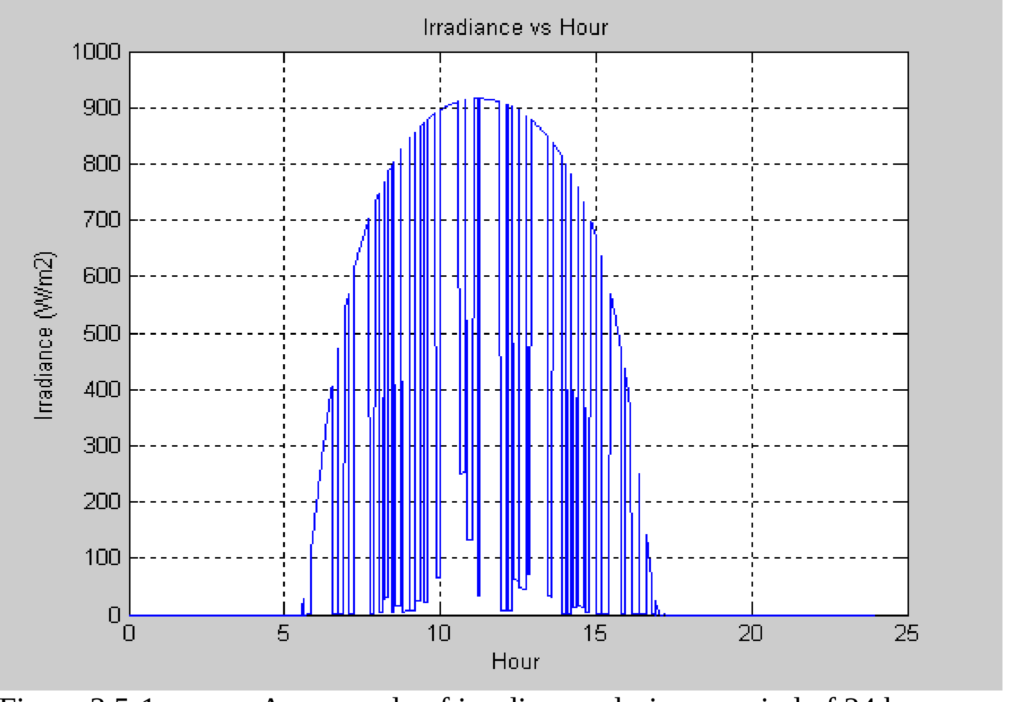


Figure 3.5-1 An example of irradiances during a period of 24 hours

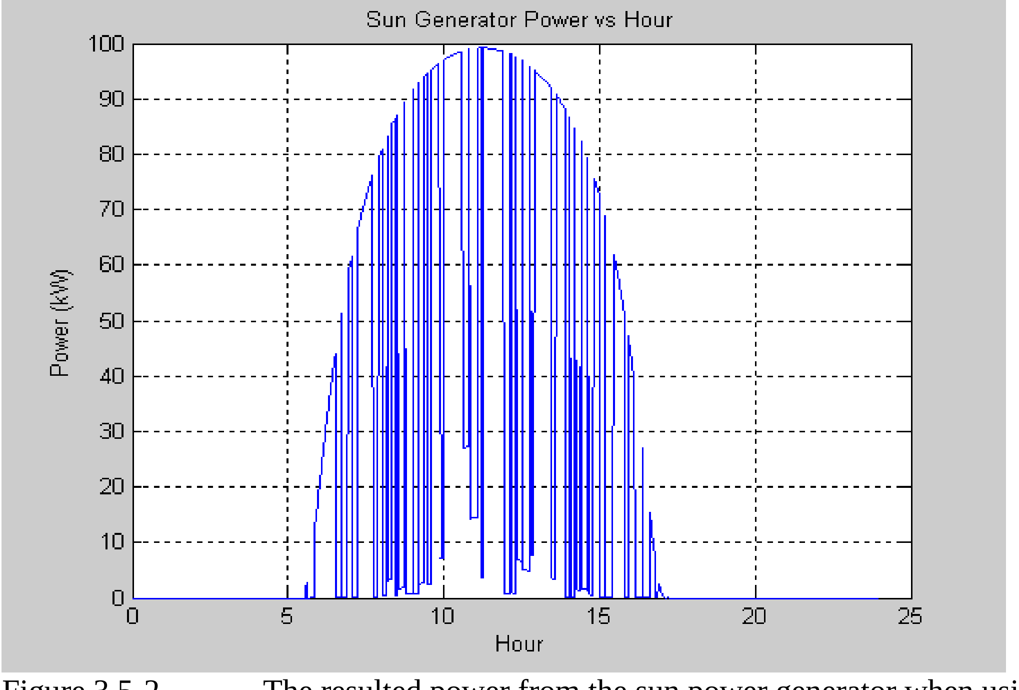


Figure 3.5-2 The resulted power from the sun power generator when using the parameters in Table 3.5-2 together with the irradiances according to Figure 3.5-1

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 lineary.

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:

Equation 3.6-1 $A = A\_prim \cdot Load\_factor$

Equation 3.6-2 $B = B\_prim \cdot Load\_factor$

Equation 3.6-3 $C = C\_prim \cdot Load\_factor$

Equation 3.6-4 $D = D\_prim \cdot Load\_factor$

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.

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

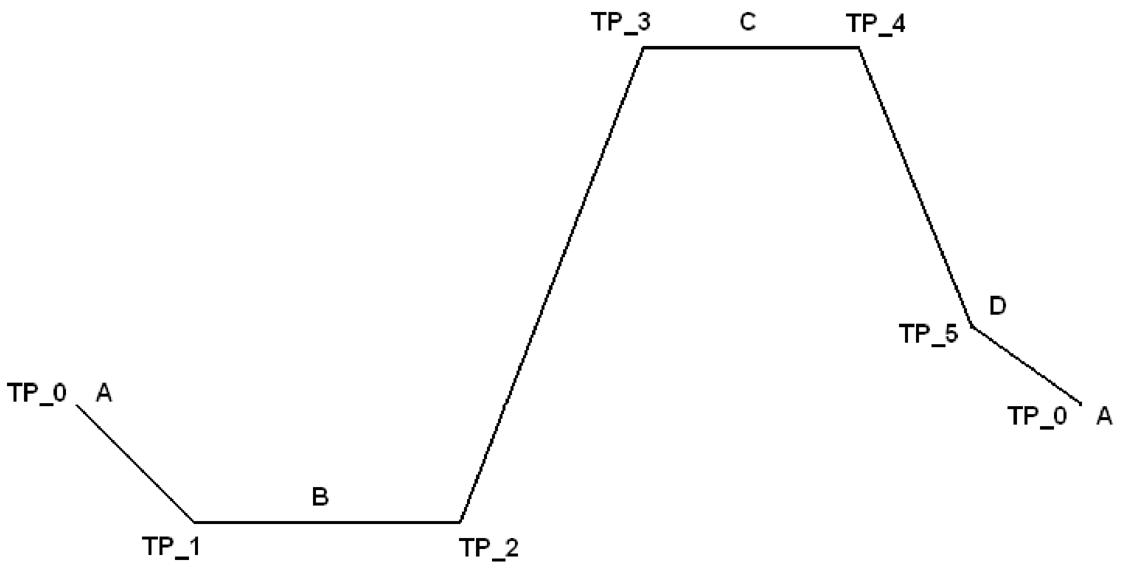


Figure 3.6-1 An illustration of the base power shifts between the different time points during a 24 hours cycle

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).

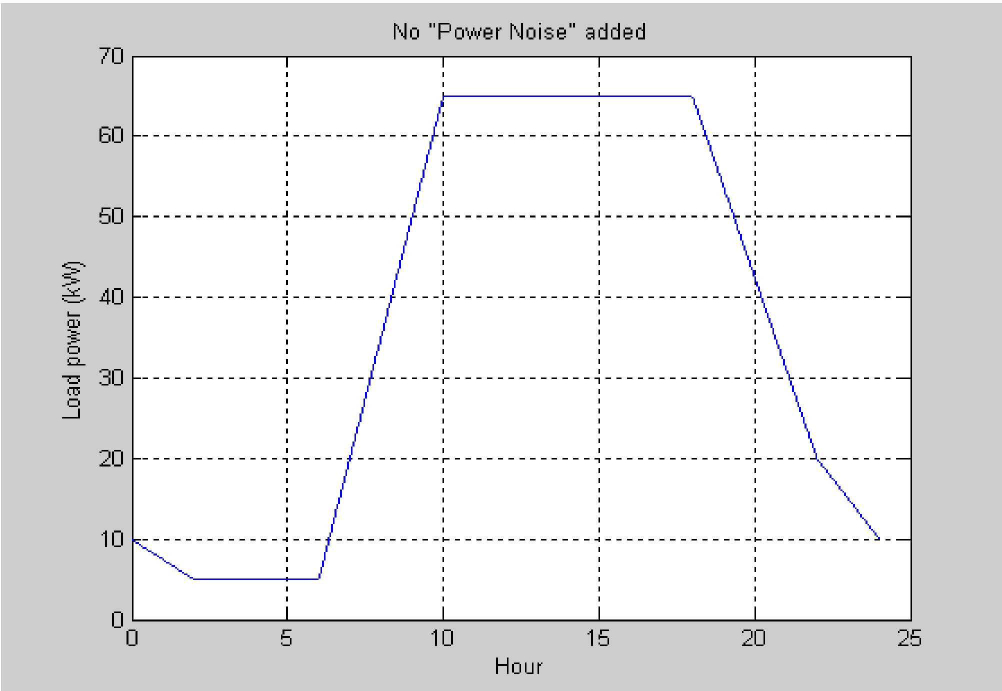


Figure 3.6-2 An example with **no** power noise added to the base levels

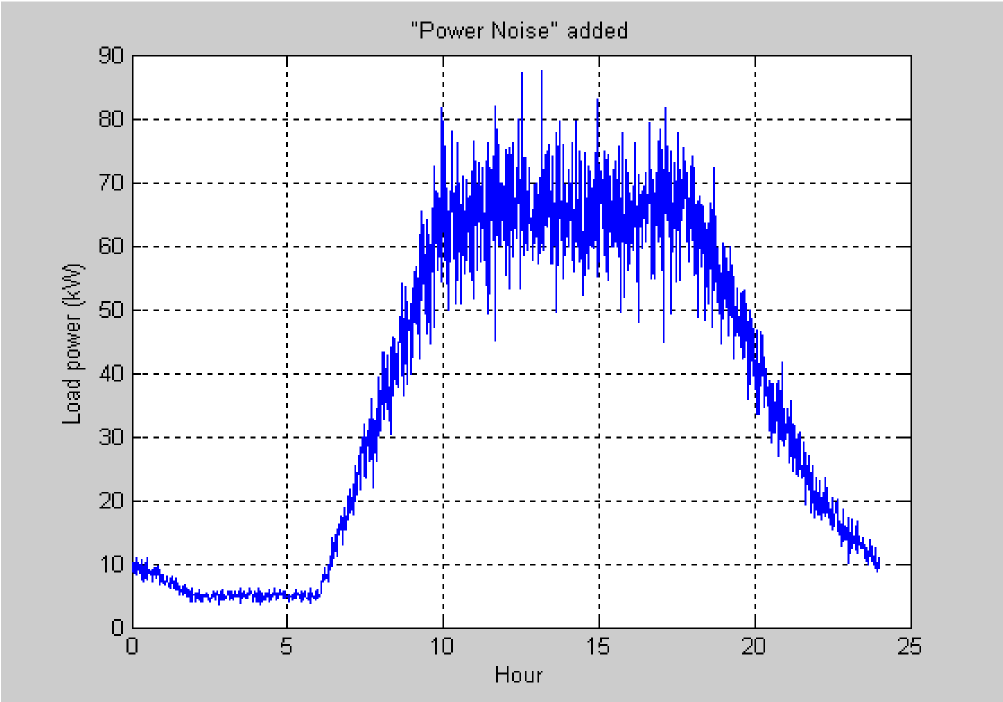


Figure 3.6-3 An example **with** power noise added to the base levels. The standard deviation *"L_sigma_H"* (in the example) is 10 % of present level without noise. The noise mean value *"L_My_H"* is zero.

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.

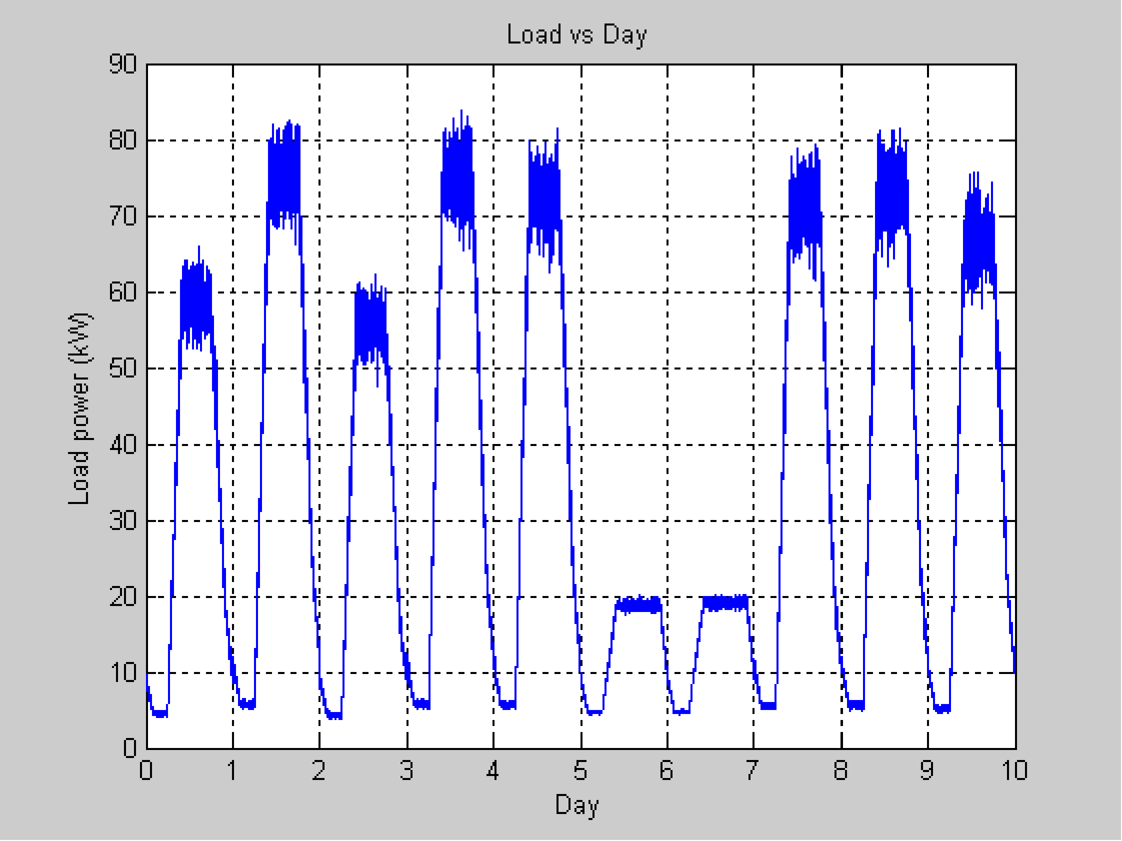


Figure 3.6-4 A simulation sequence corresponding to 5 working days followed by 2 days of weekend

3.6.2 Input parameters

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

Parameter name	**Purpose**
Sim_step_total Input via function argument from Main Program	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)
Sim_step_sec Input via function argument from Main Program	Time interval in seconds per simulation step (60 is a standard value)
a_limit	Number of days for modeling according category a, before change to category b.

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

Table 3.6-1 Input parameters for module “Load_make”

3.6.3 Examples

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

Parameter name	**Used values in the example**
Sim_step_total Input via function argument from Main Program	43200
Sim_step_sec Input via function argument from Main Program	60
a_limit	5
b_limit	2
A_prim_a	10 (kW)
B_prim_a	5 -“-
C_prim_a	65 -“-
D_prim_a	20 -“-
A_prim_b	10 -“-
B_prim_b	5 -“-
C_prim_b	20 -“-
D_prim_b	20 -“-
TP_1_a	2 (hour)
TP_2_a	6 -“-
TP_3_a	10 -“-
TP_4_a	18 -“-
TP_5_a	22 -“-
TP_1_b	2 (hour)
TP_2_b	6 -“-
TP_3_b	10 -“-
TP_4_b	18 -“-
TP_5_b	22 -“-
L_My_H_a	0.0
L_Sigma_H_a	0.04
L_My_L_a	1.0
L_Sigma_L_a	0.15
L_My_H_b	0.0
L_Sigma_H_b	0.02
L_My_L_b	1.0
L_Sigma_L_b	0.10
Load_power_file	‘Load_1’

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**.

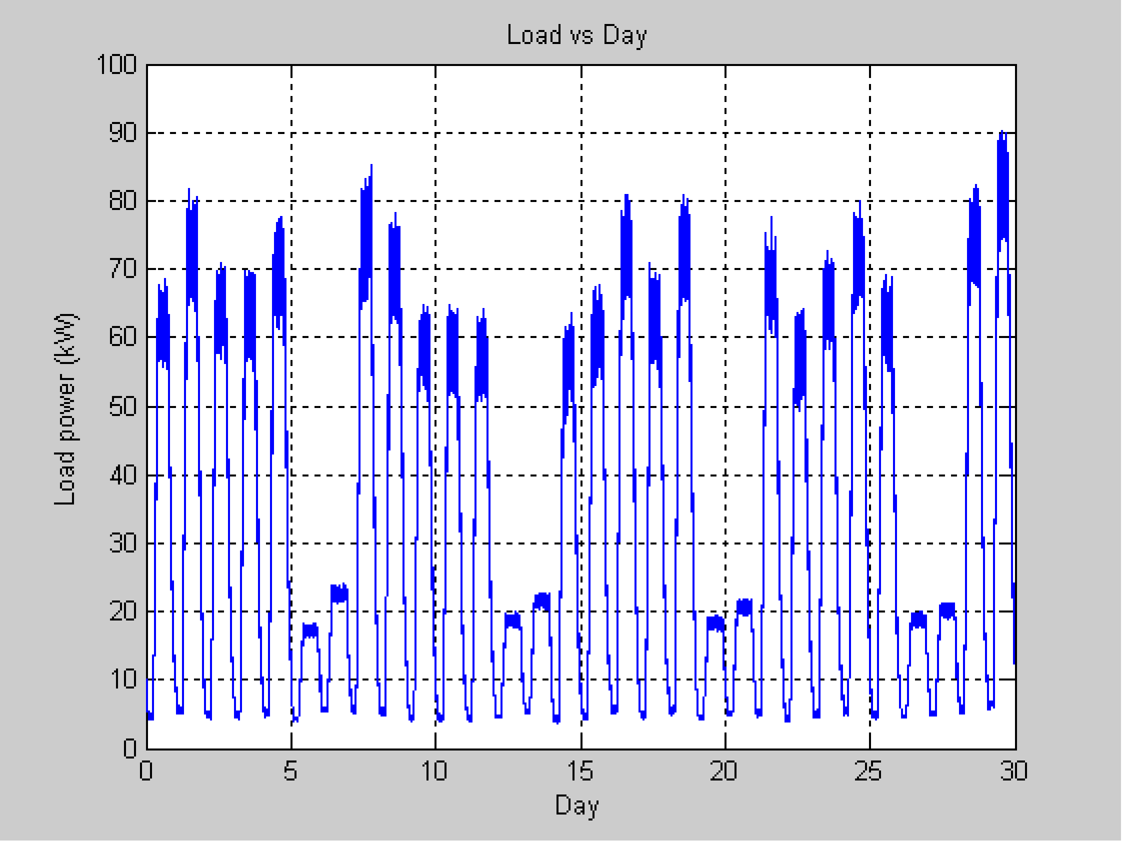


Figure 3.6-5 The loaded power for a simulation sequence of 30 days. Input parameters according to Table 3.6-2

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 gerator(s).

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

Parameter name	**Purpose**
P_wind_el_vector (Input via function argument from Main Program)	Vector with electric power generated by the wind generator(s) (for each single simulation step)
P_sun_el_vector (Input via function argument from Main Program)	Vector with electric power generated by the sun generator(s) (for each single simulation step)
P_load_vector (Input via function argument from Main Program)	Vector with electric loaded power (from the consumer grid) (for each single simulation step)

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 m^2
- 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**.

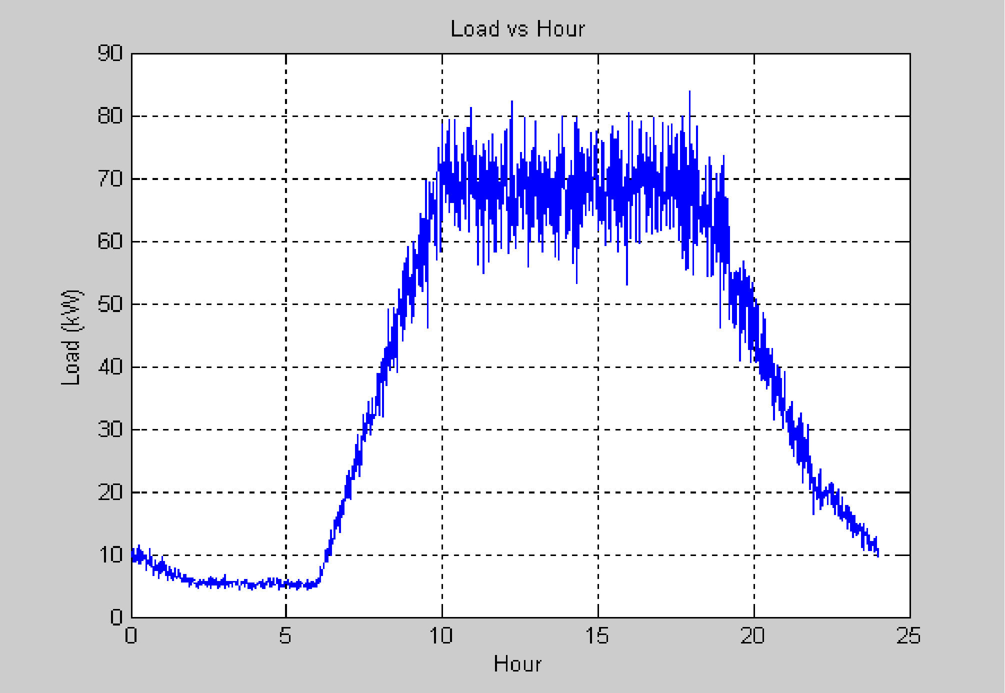


Figure 3.7-1 Loaded power. Example 1

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.

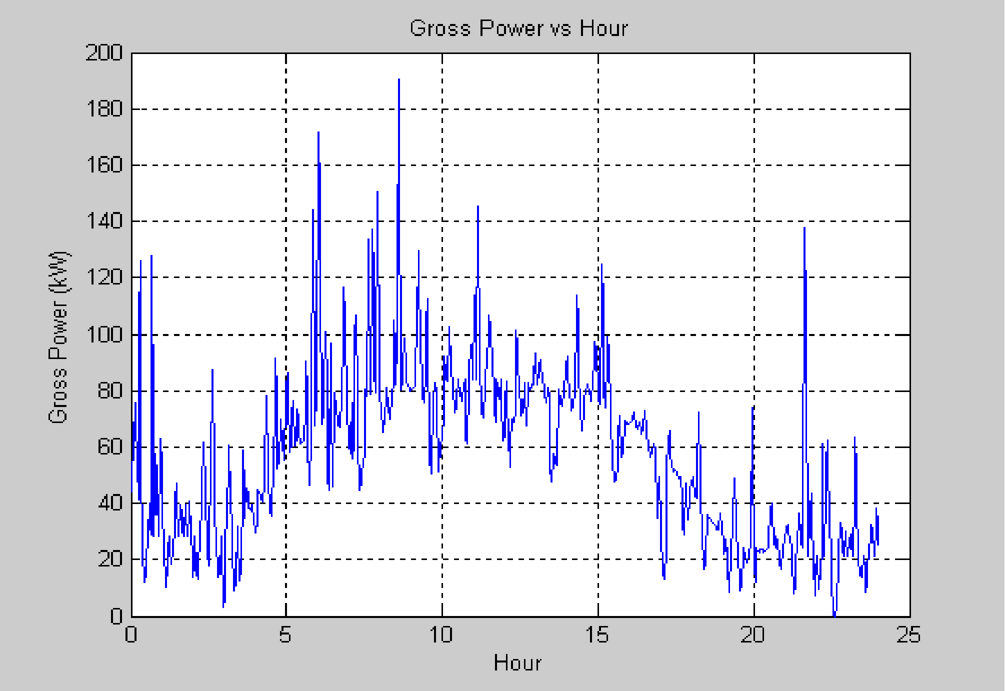


Figure 3.7-2 Generated gross power. Example 1

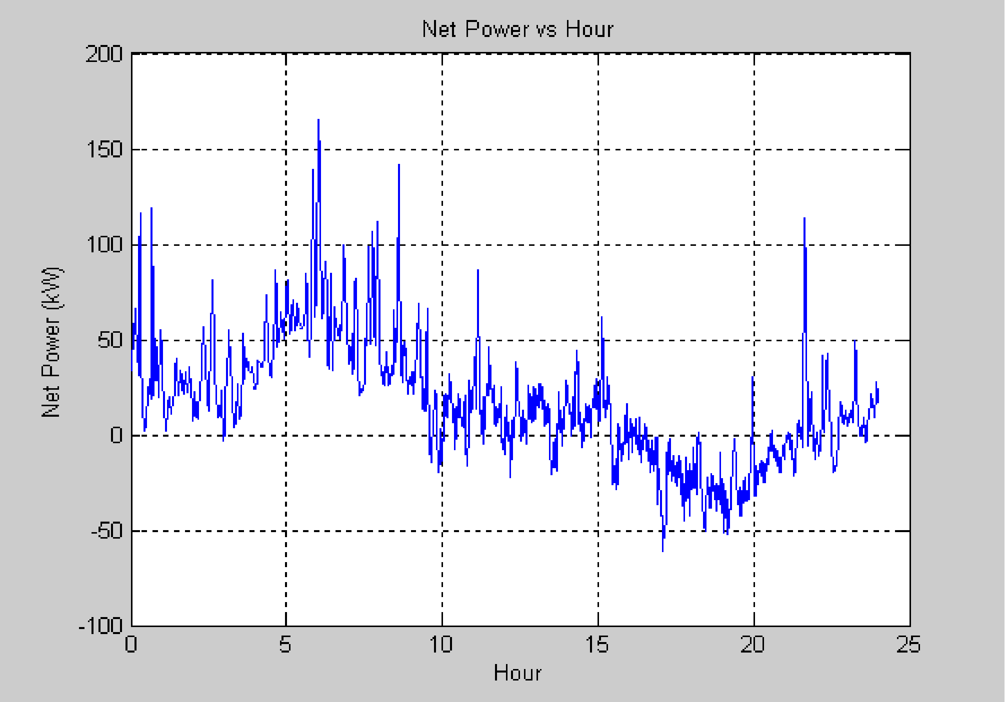


Figure 3.7-3 Generated net power. Example 1

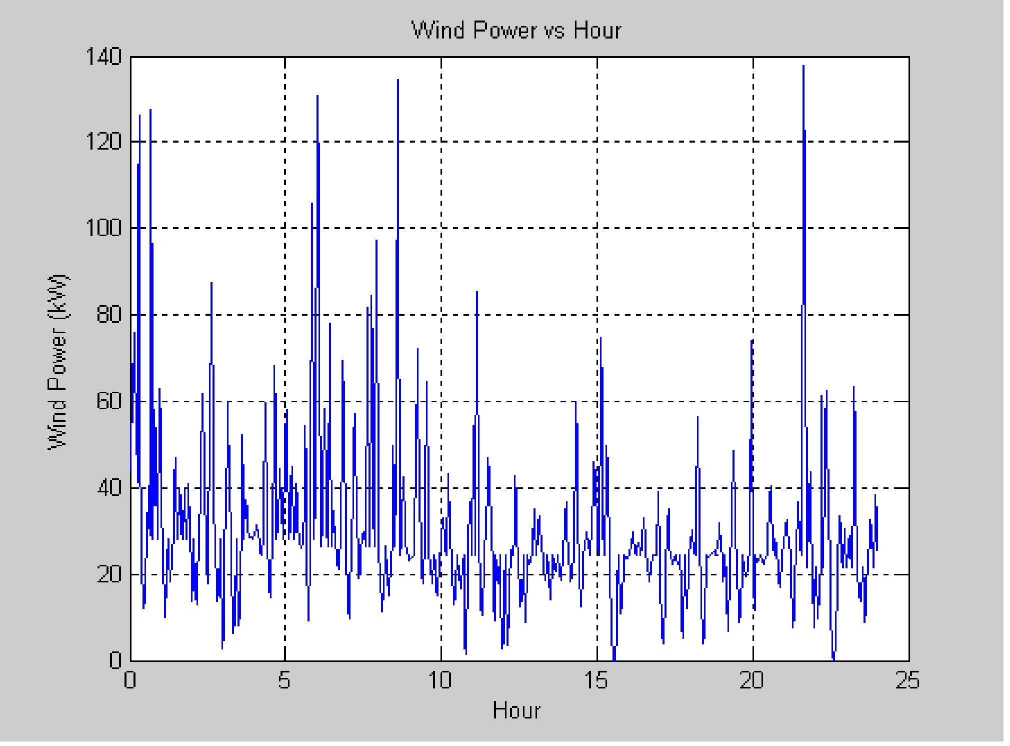


Figure 3.7-4 Generated Wind power. Example 1

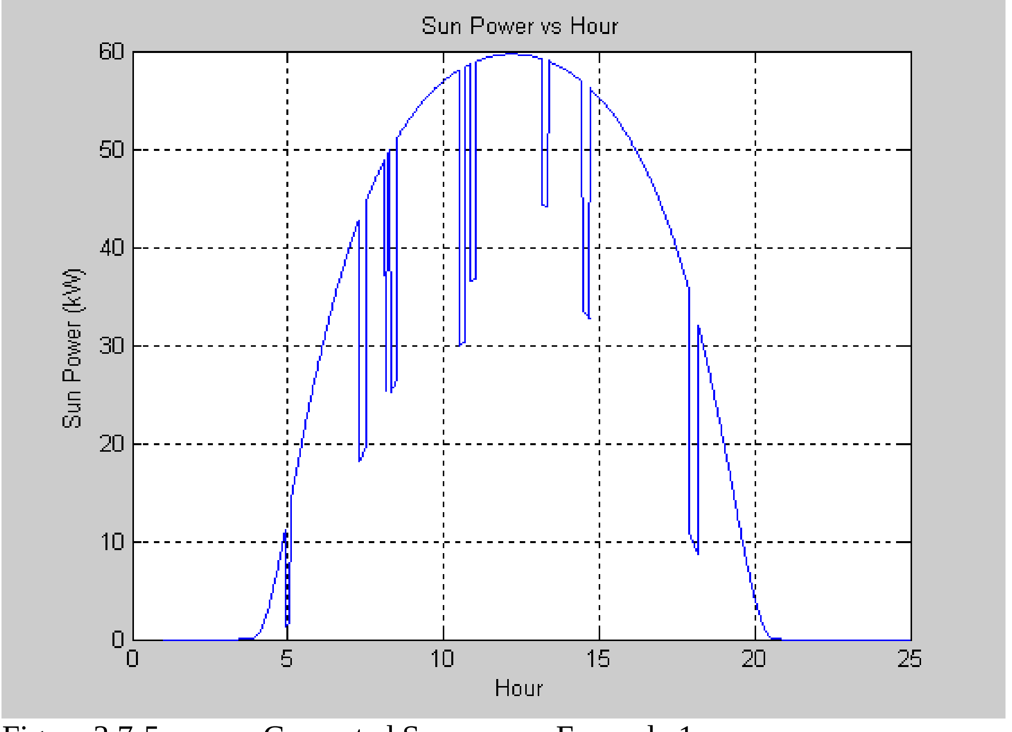


Figure 3.7-5 Generated Sun power. Example 1

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**.

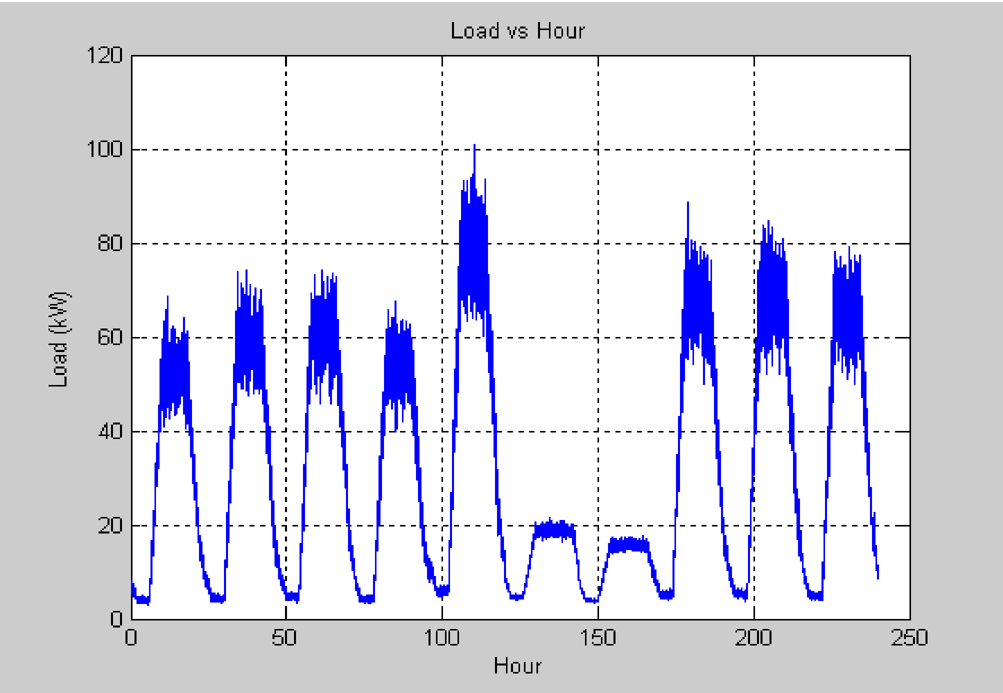


Figure 3.7-6 Loaded power. Example 2

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.

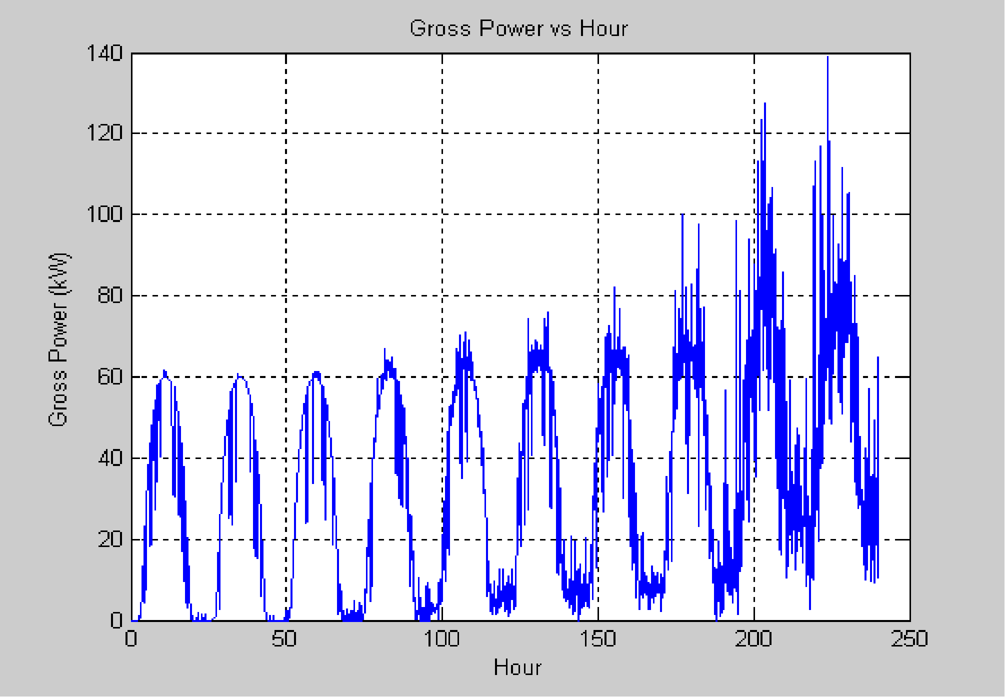


Figure 3.7-7 Generated gross power. Example 2

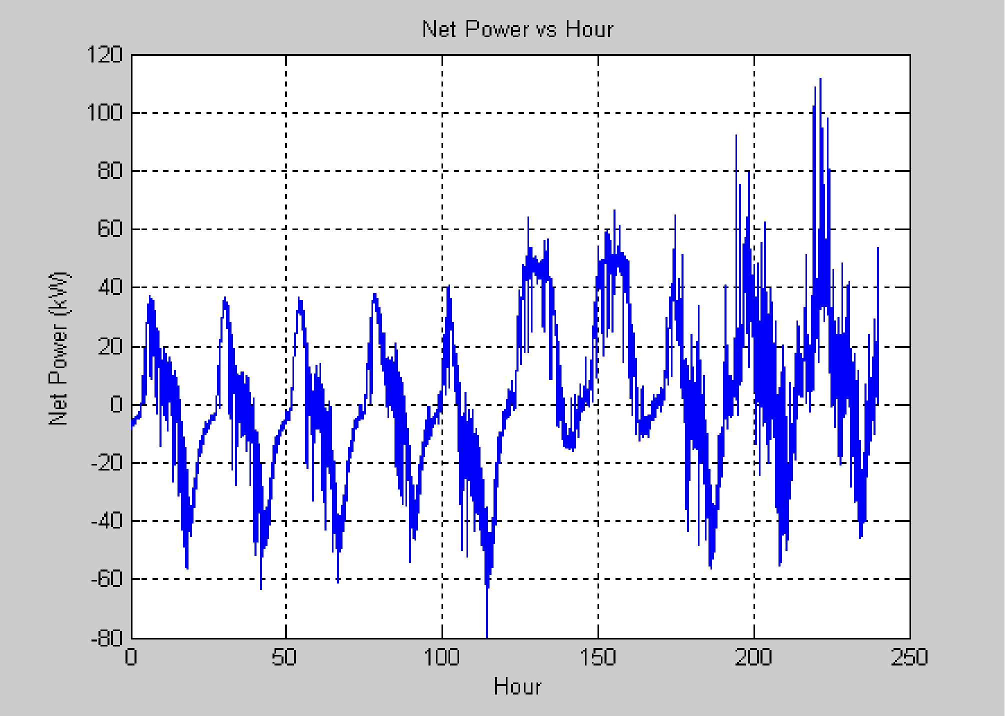


Figure 3.7-8 Generated net power. Example 2

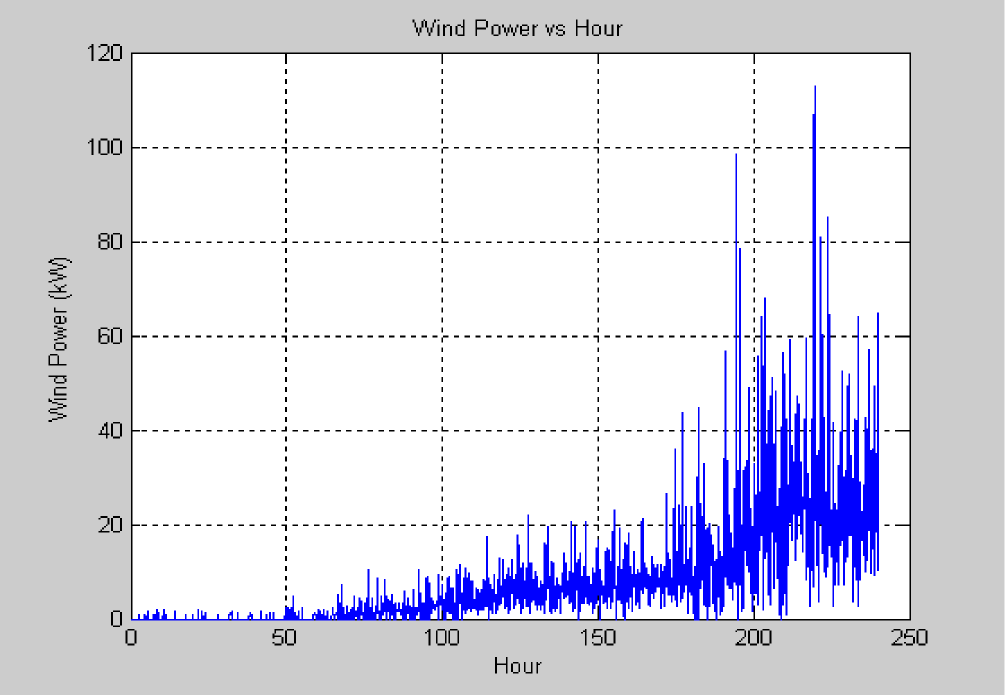


Figure 3.7-9 Generated Wind power. Example 2

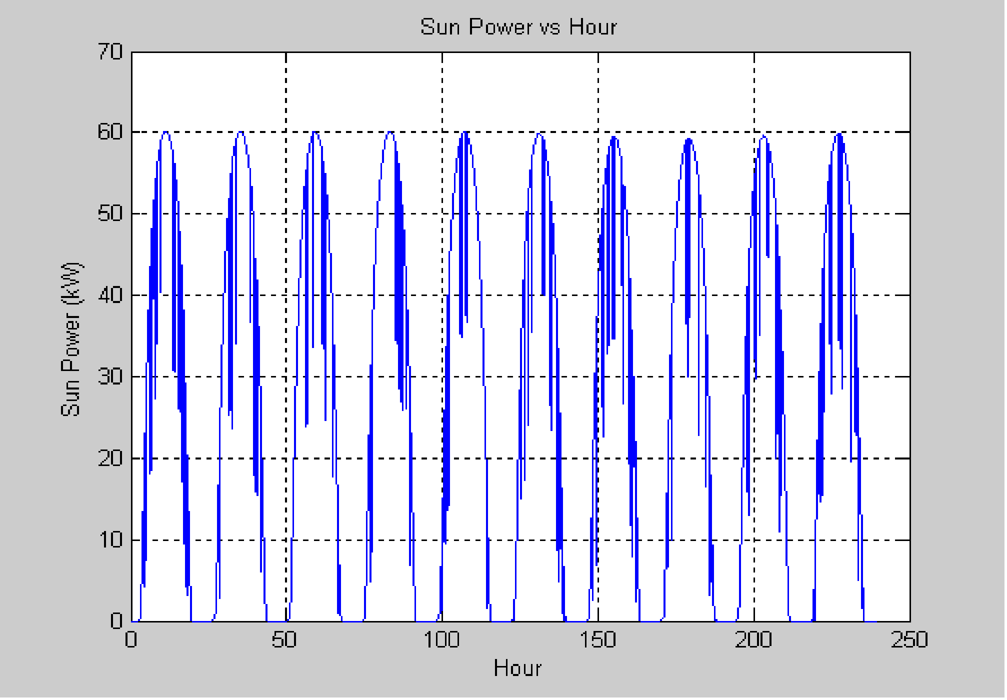


Figure 3.7-10 Generated Sun power. Example 2

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:

<u>Condition 1</u>:

a) Net power > *0* (see paragraph 3.7.1.2)

And

b) battery_charge(time_step) < *charge_level*_max

<u>Condition 2</u>:

a) Net power < *0* (see paragraph 3.7.1.2)

And

b) battery_charge(time_step) > *charge_level*_min

where

battery_charge(time_step):	current battery charge
*charge_level*_max:	maximum allowed charge level in the energy storage
*charge_level*_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:

$$Surplus\_energy = Net\_Power \times time\_step$$

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:

$$Deficiency\_energy = |Net\_Power| \times time\_step$$

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.

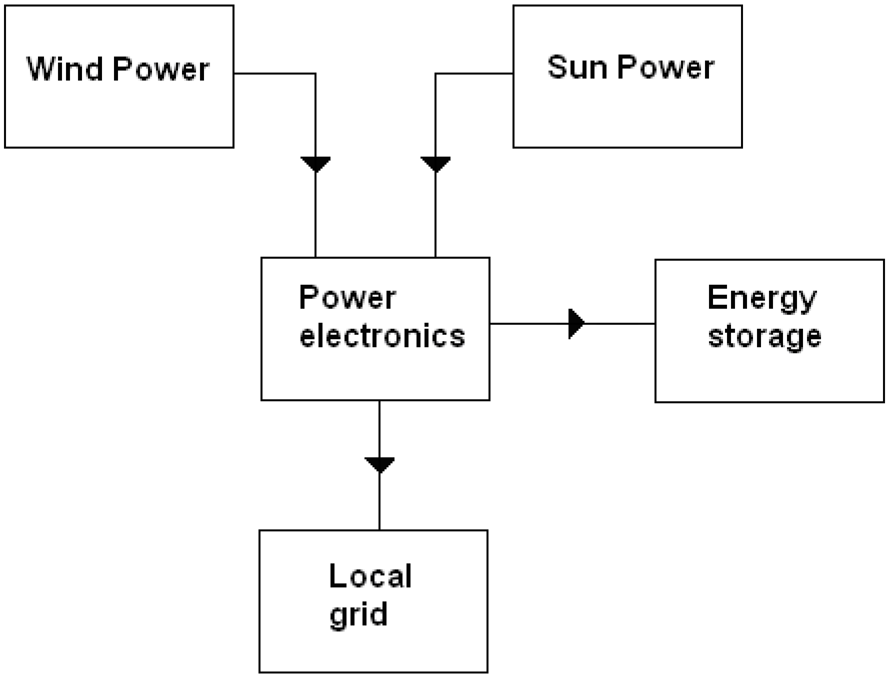


Figure 3.8-1 Energy flow for “*Condition 1*”.

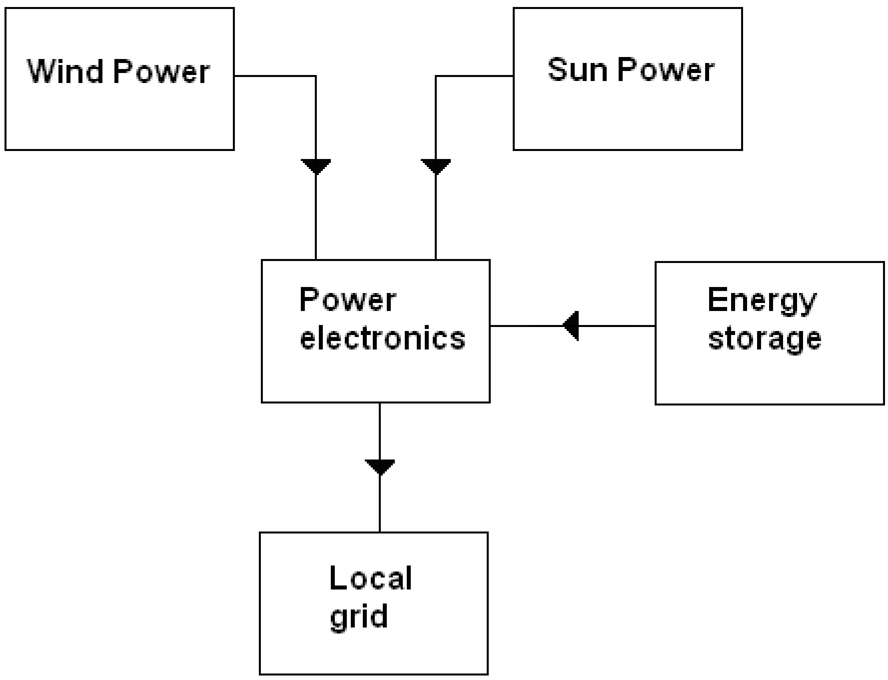


Figure 3.8-2 Energy flow for “*Condition 2*”.

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:

<u>Condition 3</u>:

Condition 1.a is fulfilled

Condition 1.b is **not** fulfilled

Then **export** of generated surplus energy to the distribution grid shall be realized.

<u>Condition 4</u>:

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 *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.

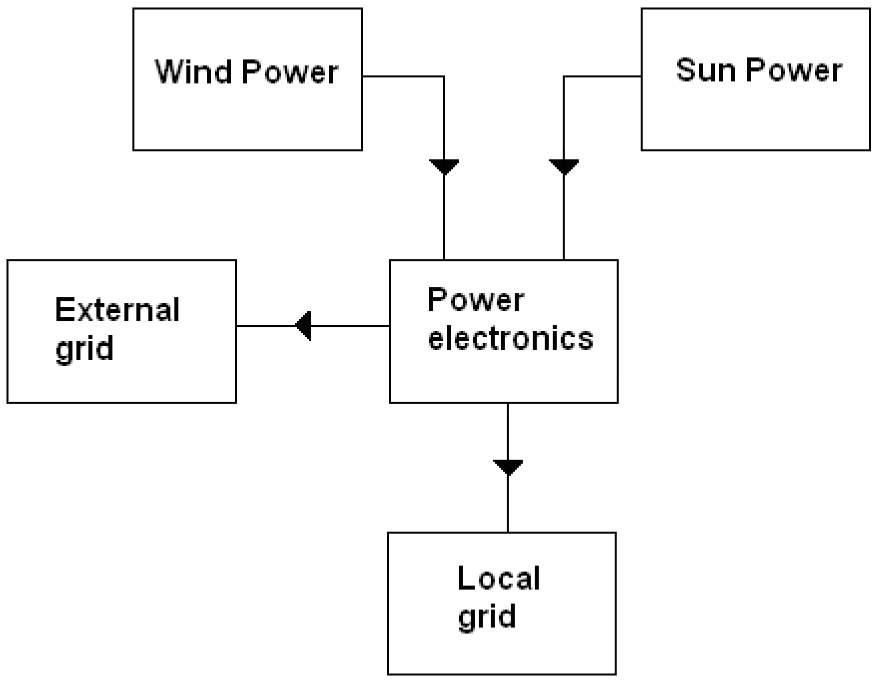


Figure 3.8-3 Energy flow for “*Condition 3* ”.

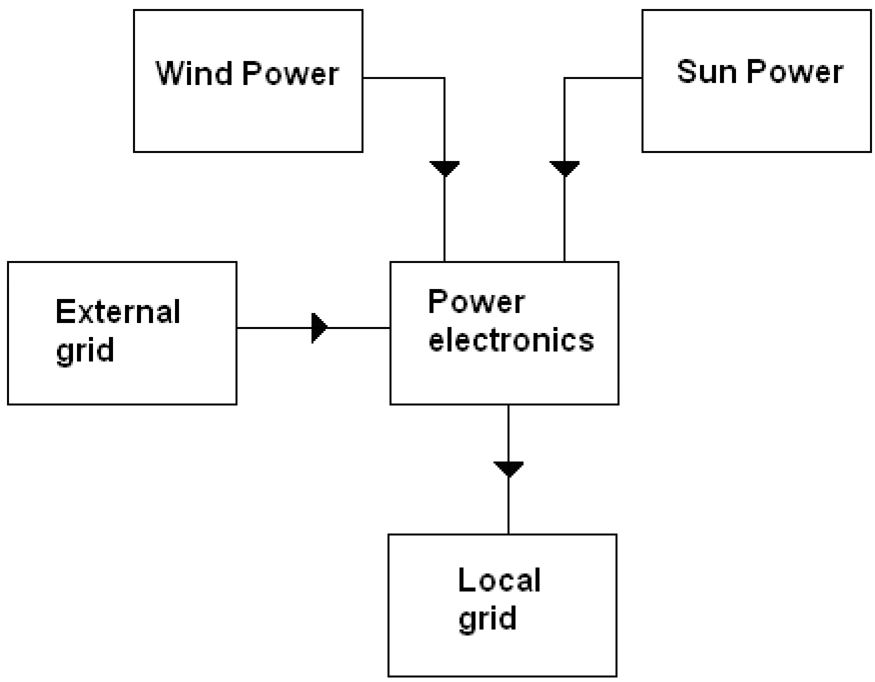


Figure 3.8-4 Energy flow for “*Condition 4”*.

3.8.2 Input parameters

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

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

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).

Parameter name	**Used value in the example**
P_buffer_vector (Input via function argument from Main Program)	See **Figure 3.8-5**.
Sim_step_sec (Input via function argument from Main Program)	60
charge_factor	0.8
load_factor	0.9
charge_level_init	800
charge_level_min	600
charge_level_max	1000
discharge_self	0.5
power_max_batt	100
power_max_distr	400

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**.

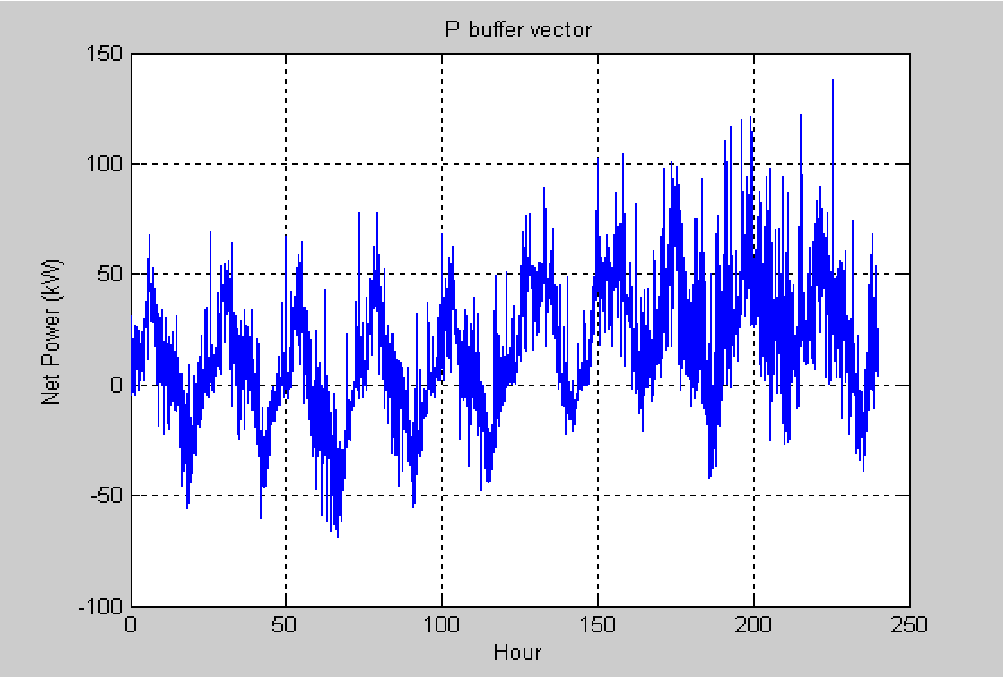


Figure 3.8-5 The Net Power vs Time (P_buffer_vector)

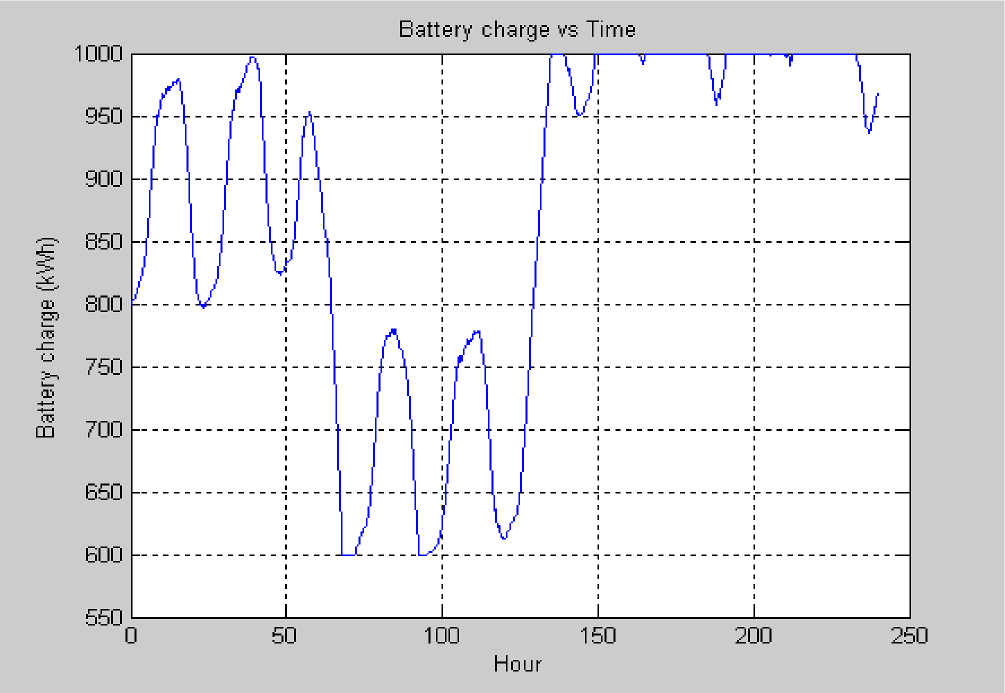


Figure 3.8-6 Battery charge vs Time

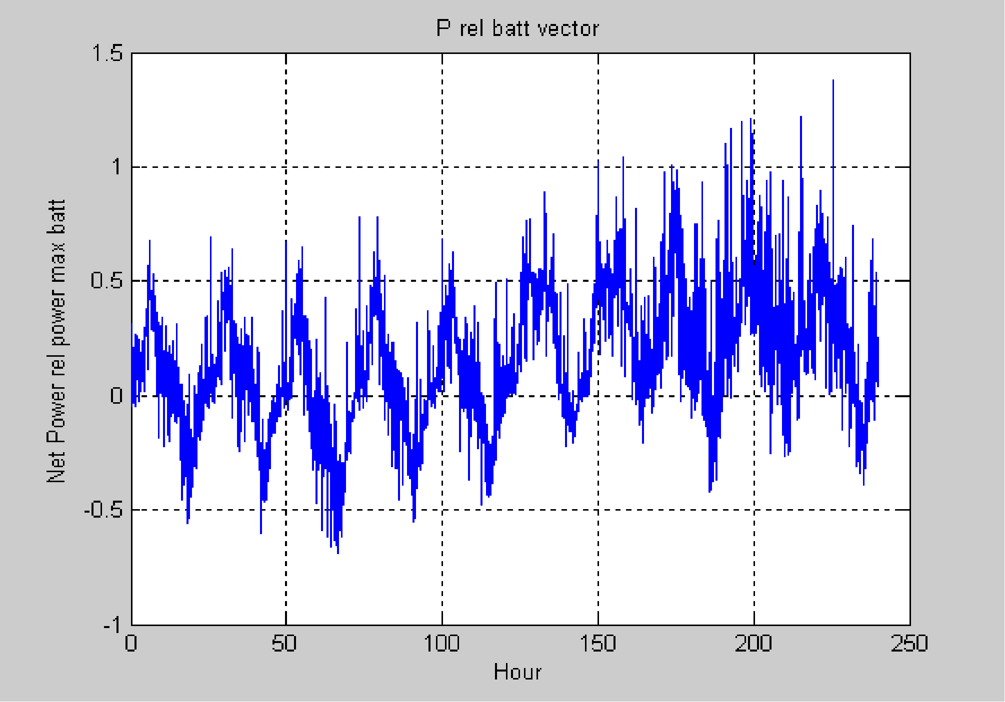


Figure 3.8-7 Net Power relative maximum storing / loading power vs Time

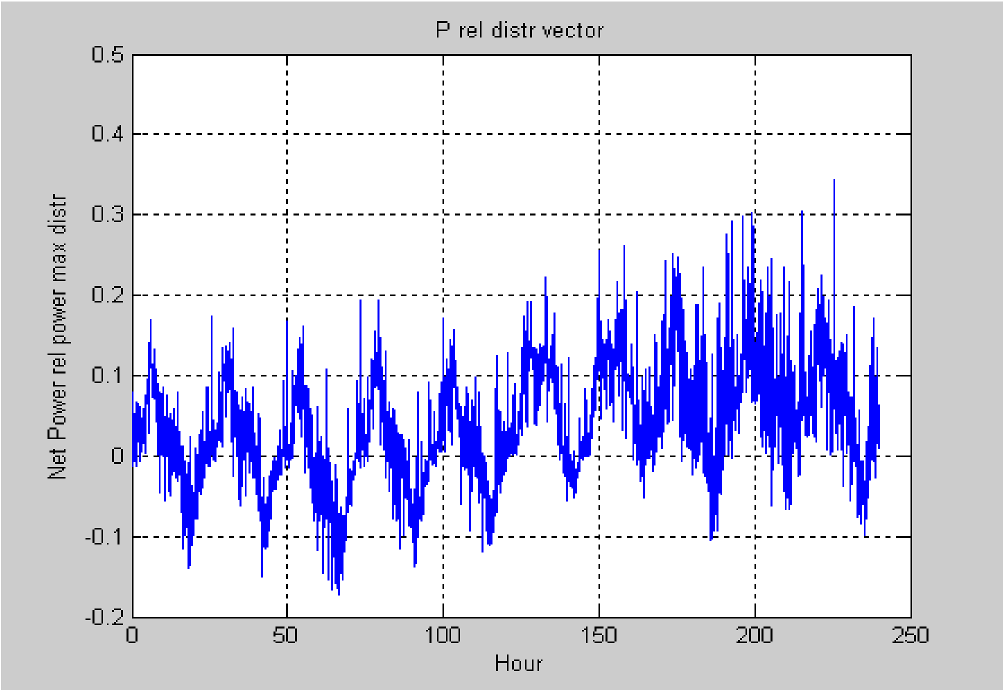


Figure 3.8-8 Net Power relative maximum export / import power vs Time

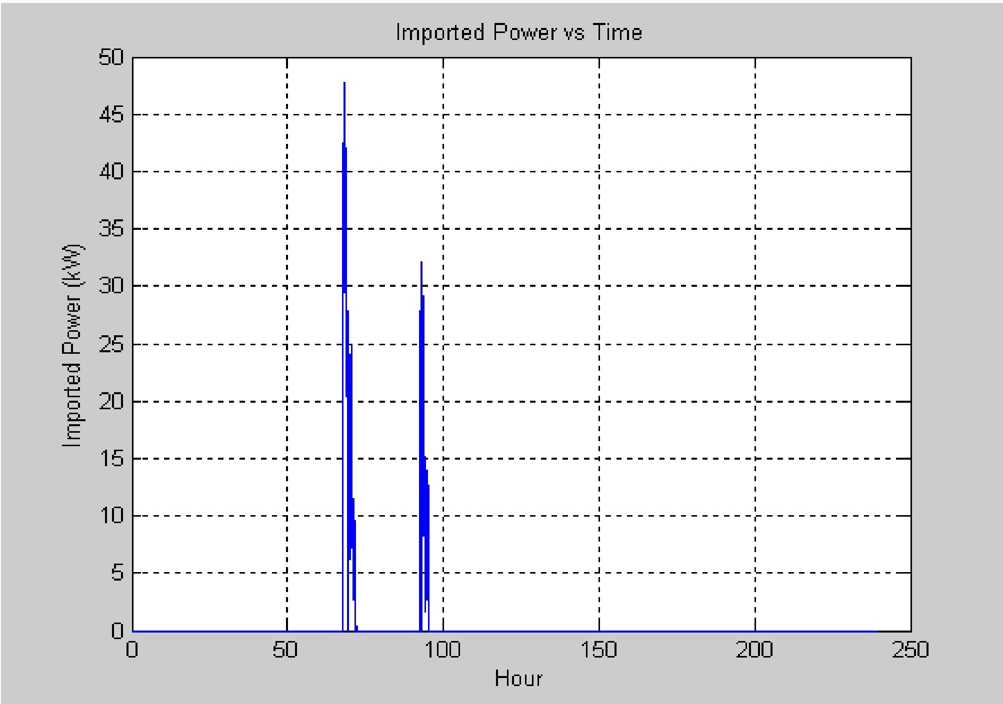


Figure 3.8-9 Imported Power vs Time

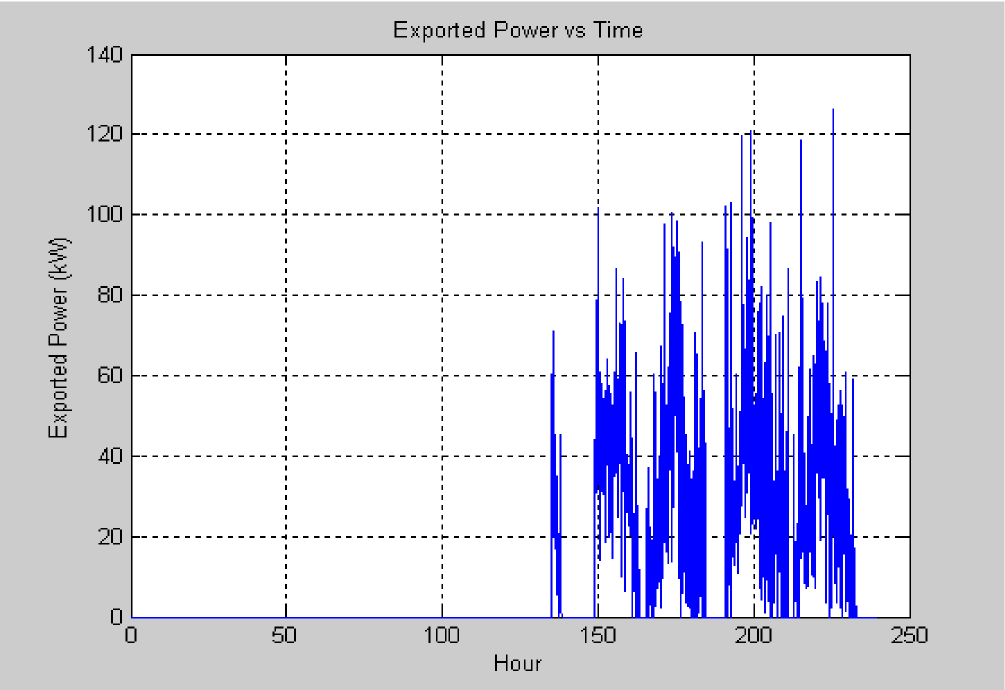


Figure 3.8-10 Exported Power vs Time

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_Wind*)
- Generated electric Sun Energy (*E_Sun*)
- Total generated (Wind + Sun) electric energy (*E_Gen*)
- Exported electric energy (*E_Exp*)
- Imported electric energy (*E_Imp*)
- Loaded (by the local grid) energy (*E_Load*)
- The difference between Exported and Imported electric energy (*D_Exp_Imp*)
- The quotient E_Wind / E_Gen (*Rel_Wind_Gen*)
- The quotient E_Sun / E_Gen (*Rel_Sun_Gen*)
- The quotient E_Gen / E_Load (*Rel_Gen_Load*)
- The quotient E_Exp / E_Gen (*Rel_Exp_Gen*)
- The quotient E_Imp / E_Load (*Rel_Imp_Load*)
- The quotient D_Exp_Imp / E_Gen (*Rel_DEI_Gen*)
- The quotient E_Battery / E_Load_day (*Rel_Battery_Load_day*). See comment below

Table 3.9-1 Parameters that are calculated

<u>Comment regarding "The quotient E_Battery / E_Load_day"</u>

E_Battery: maximum energy capacity of the battery system

E_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**.

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

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:

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

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.

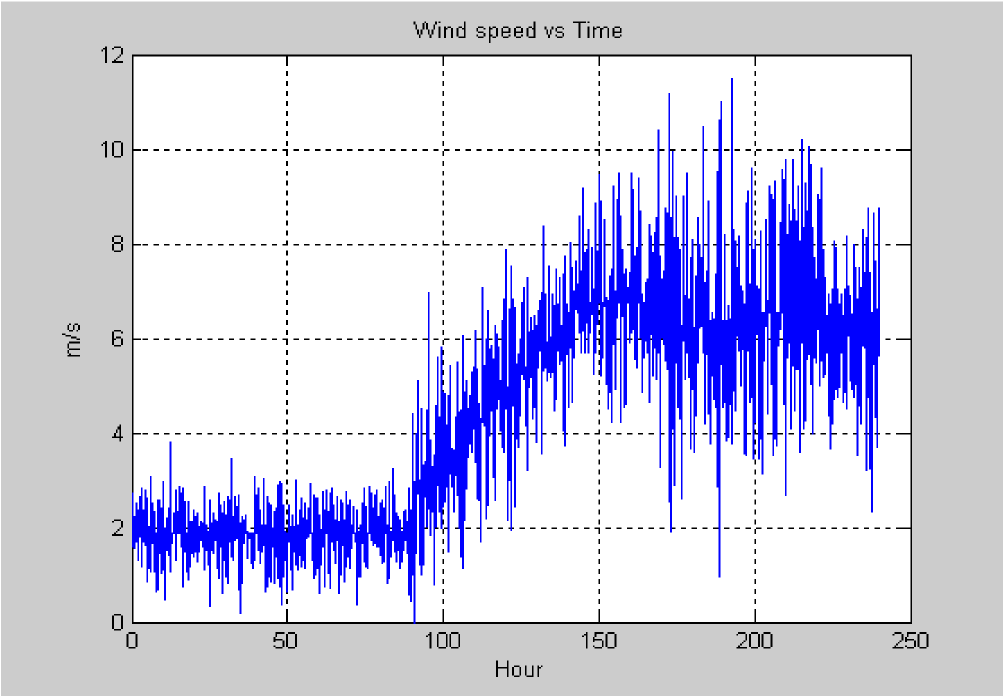


Figure 3.9-1 Wind speed vs Time

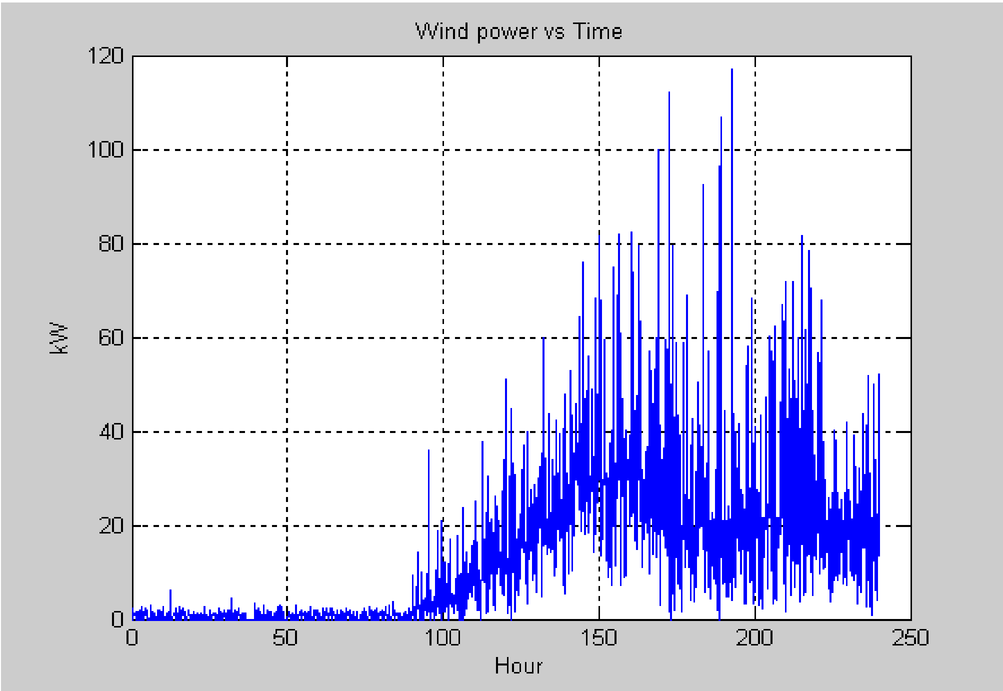


Figure 3.9-2 Wind power vs Time

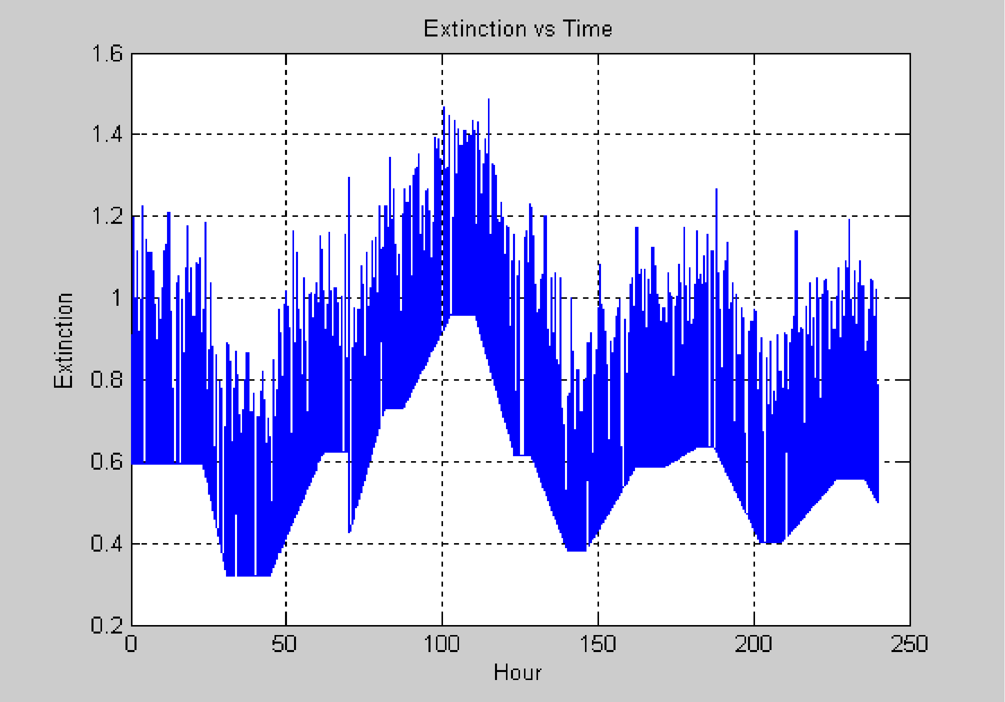


Figure 3.9-3 Extinction vs Time

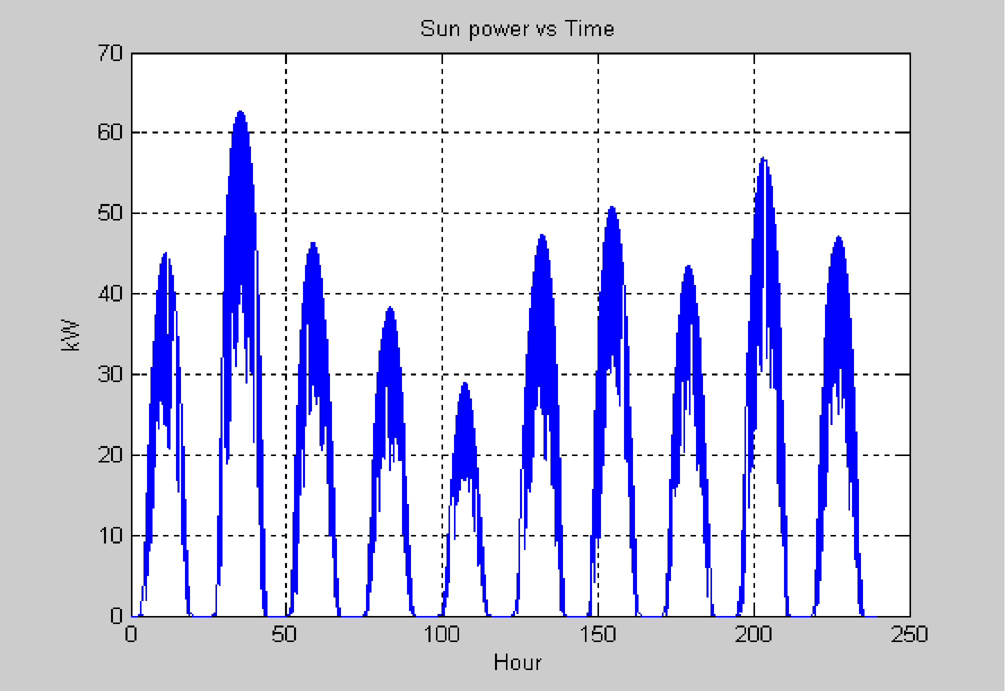


Figure 3.9-4 Sun power vs Time

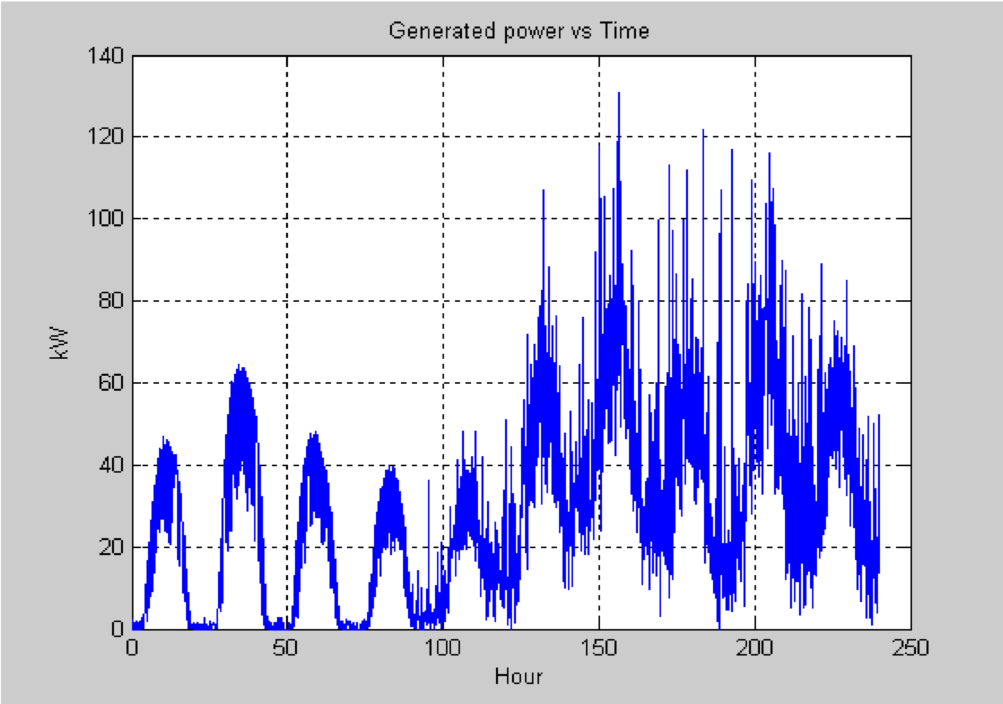


Figure 3.9-5 Gross power vs Time

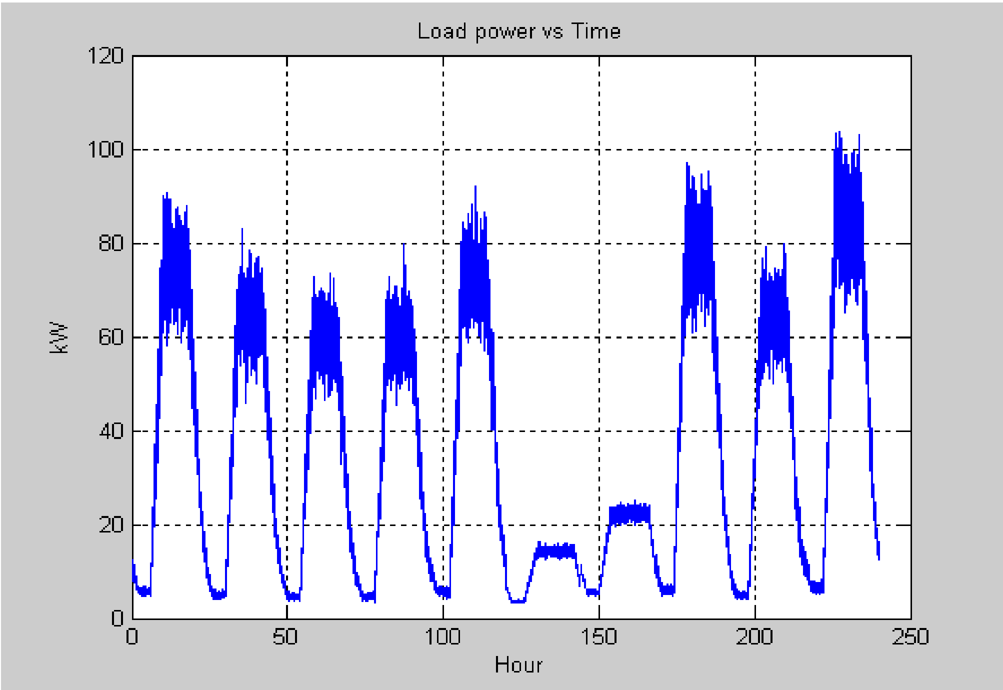


Figure 3.9-6 Load power vs Time

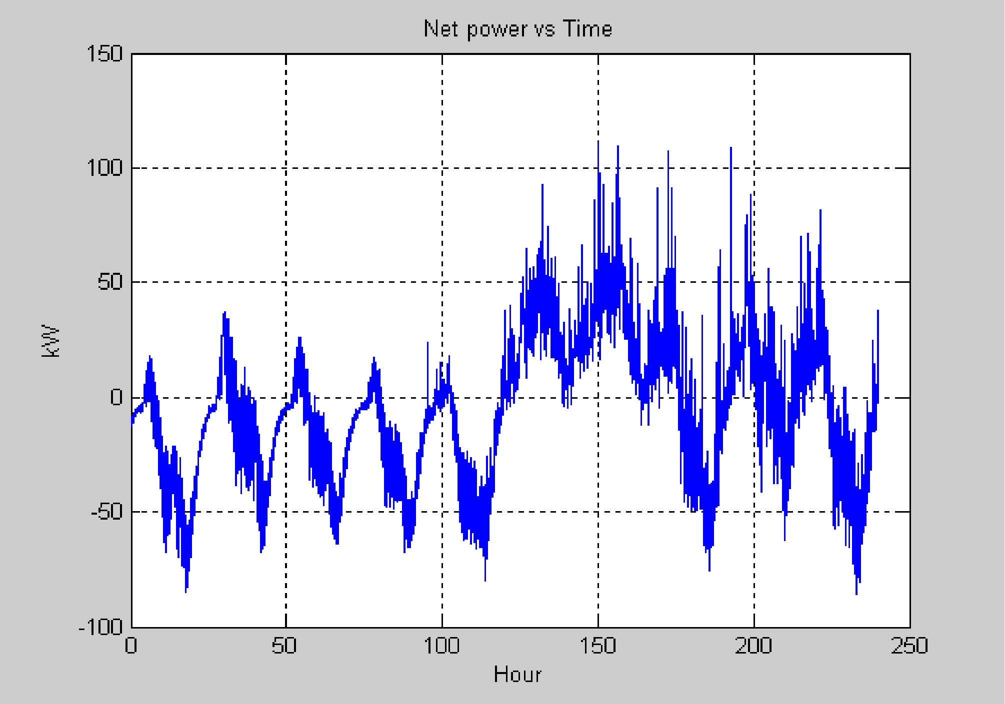


Figure 3.9-7 Net power vs Time

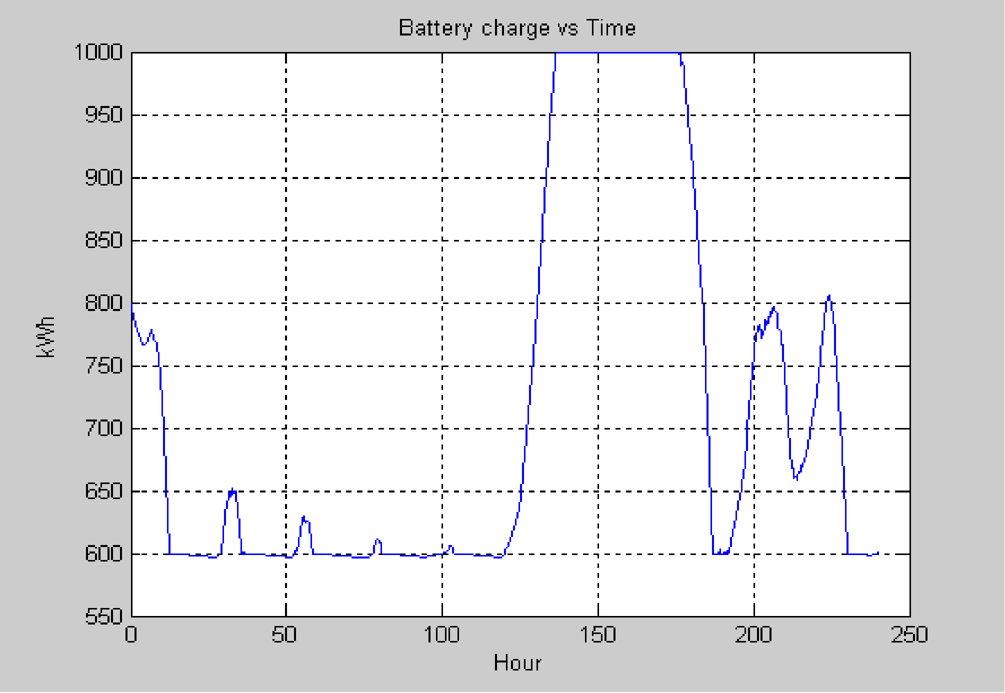


Figure 3.9-8 Battery charge vs Time

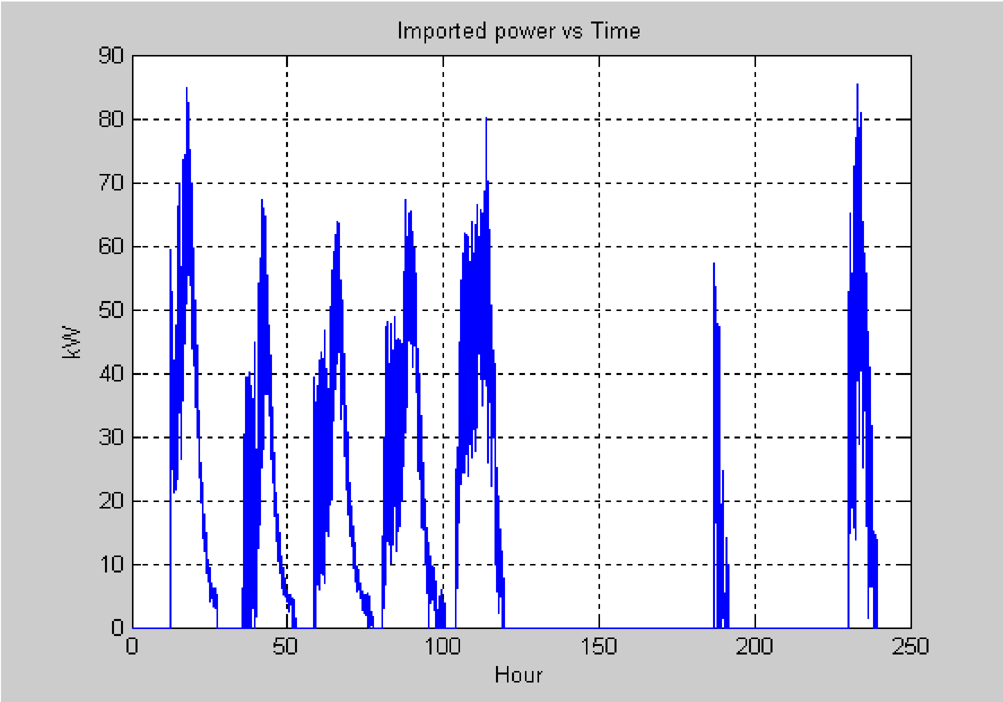


Figure 3.9-9 Imported power vs Time

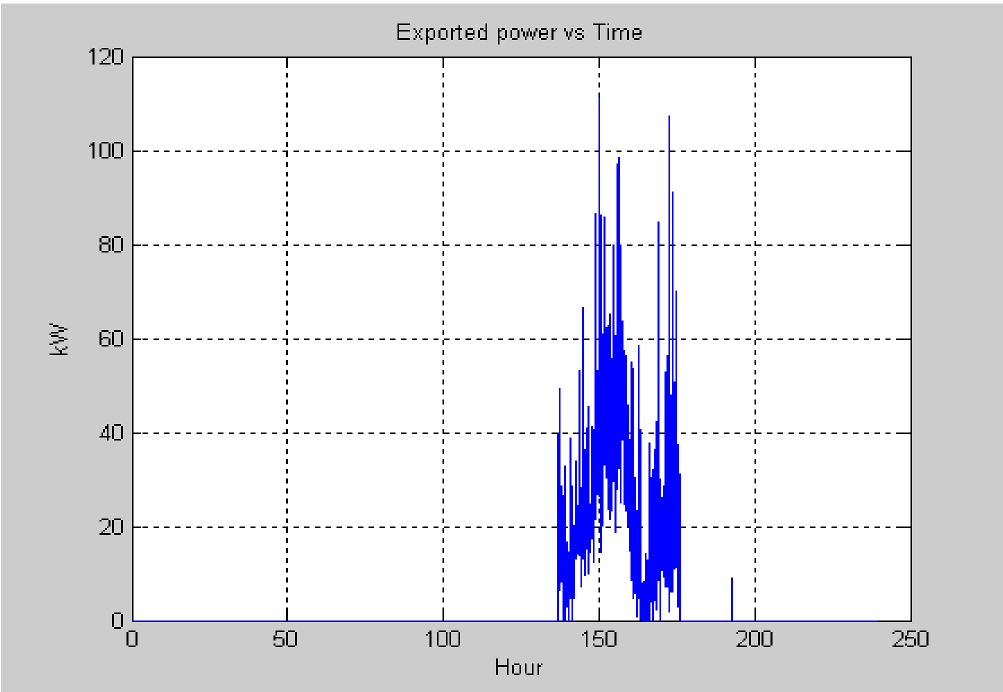


Figure 3.9-10 Exported power vs Time

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.

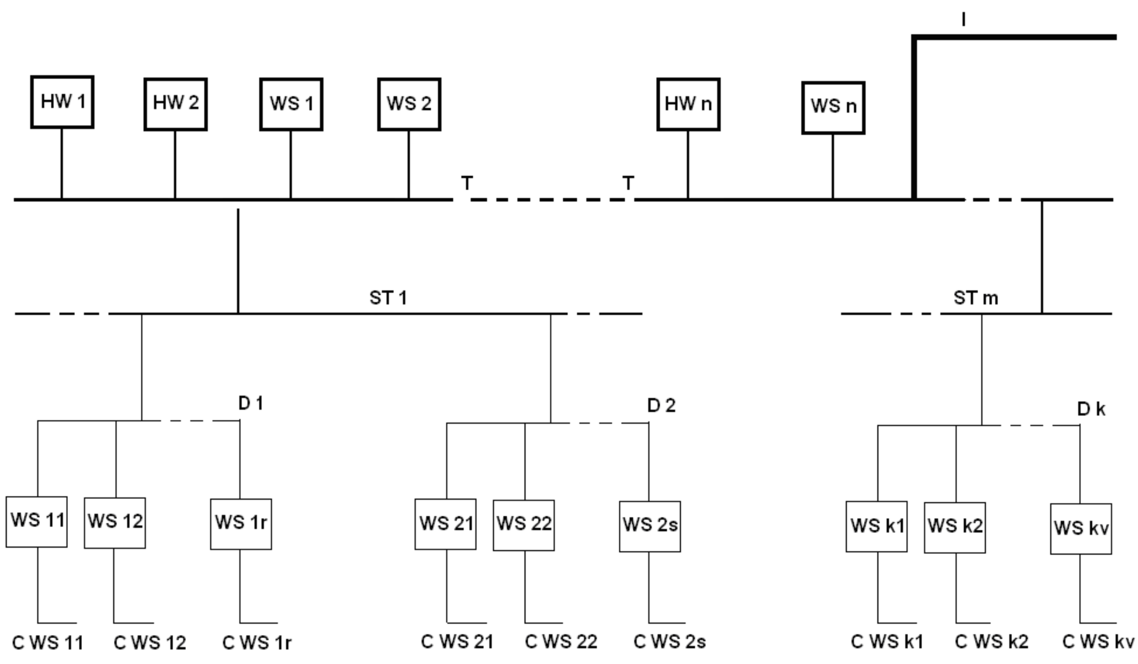


Figure 3.10-1 The base structure of the power system that could be analysed with a future simulation system that is completed with some features according the above list

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 a 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.

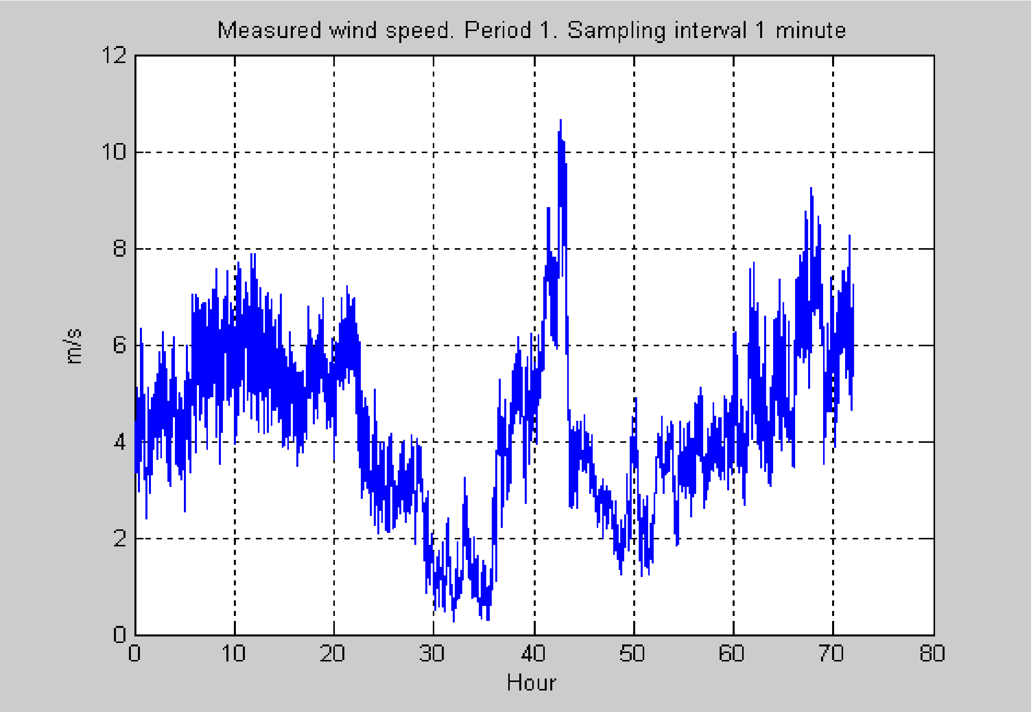


Figure 4.2-1 Measured wind speed. Period 1.
Mean value during a sampling period of 1 minute

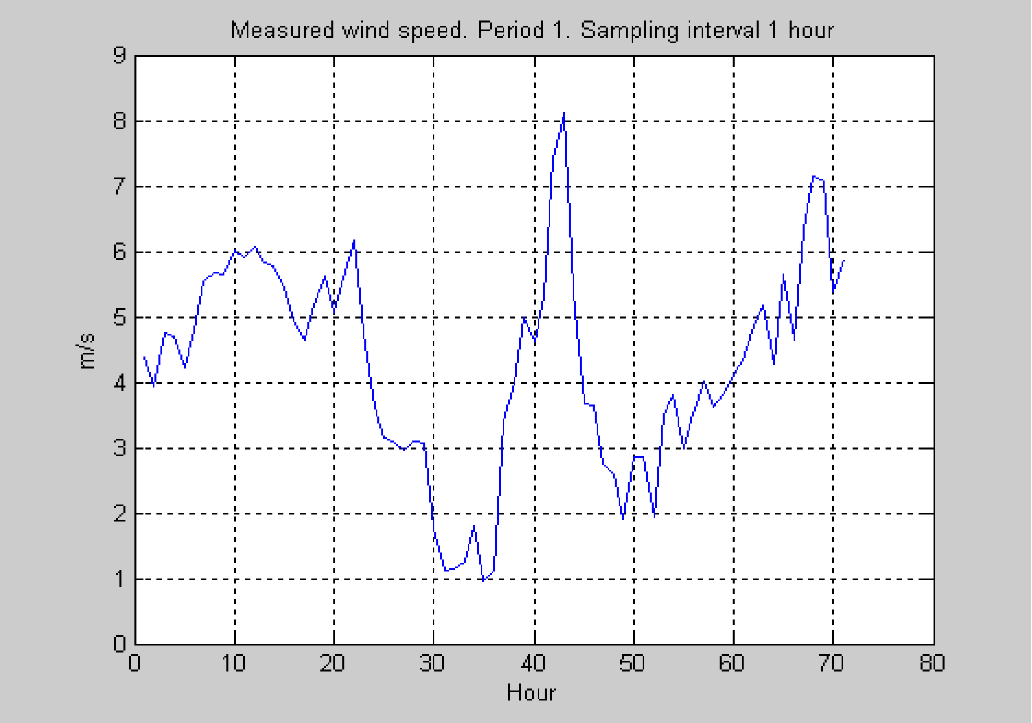


Figure 4.2-2 Measured wind speed. Period 1.
Mean value during a sampling period of 1 hour

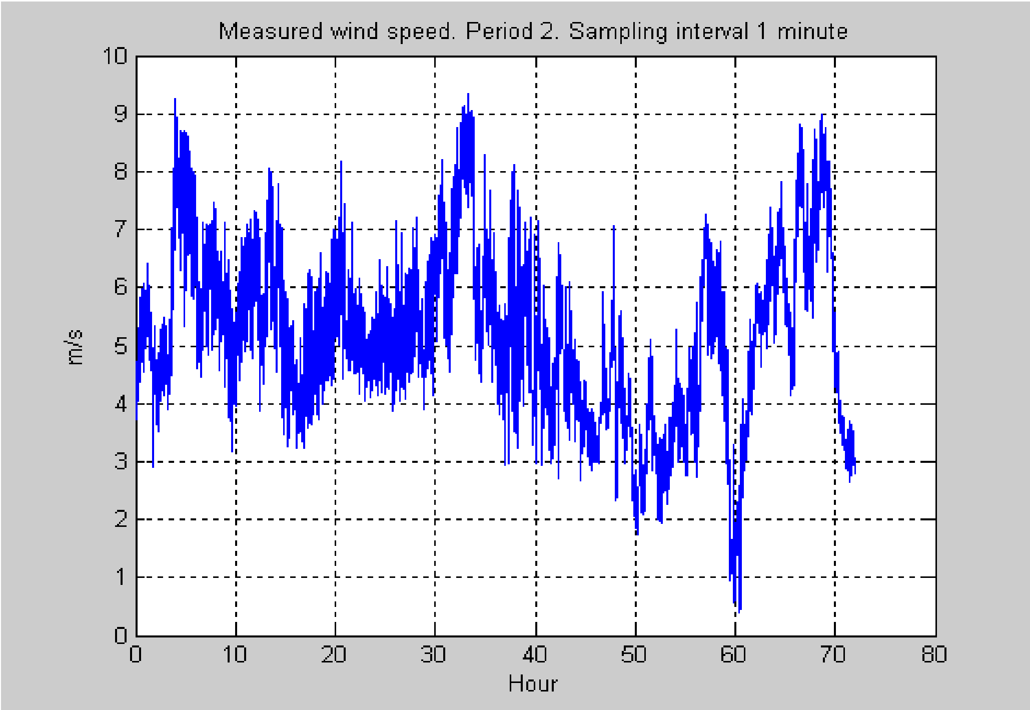


Figure 4.2-3 Measured wind speed. Period 2.
Mean value during a sampling period of 1 minute

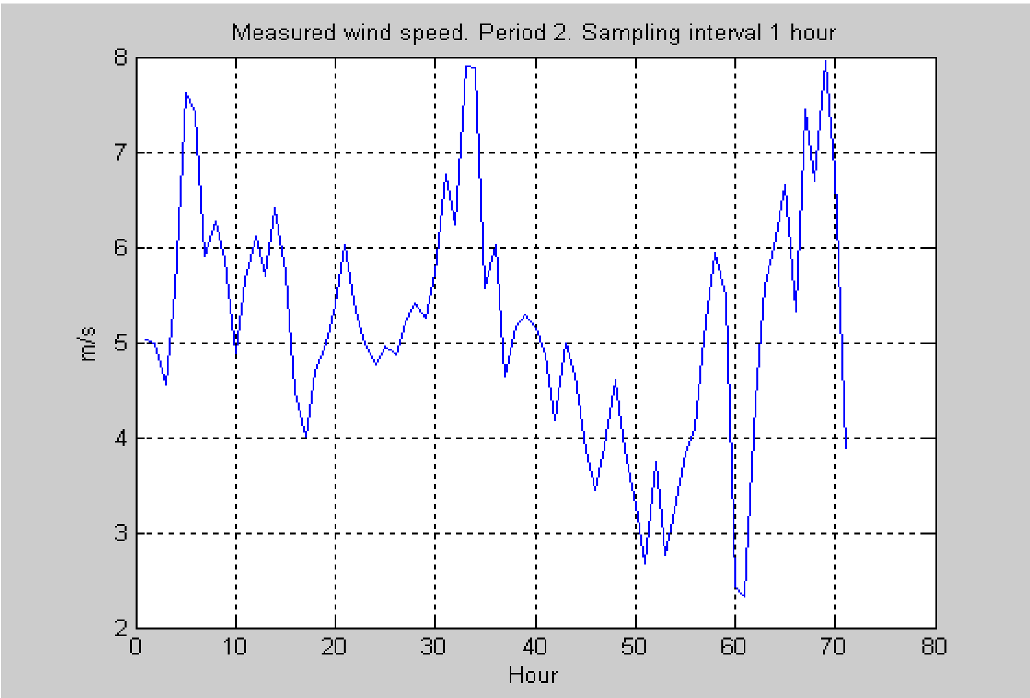


Figure 4.2-4 Measured wind speed. Period 2.
Mean value during a sampling period of 1 hour

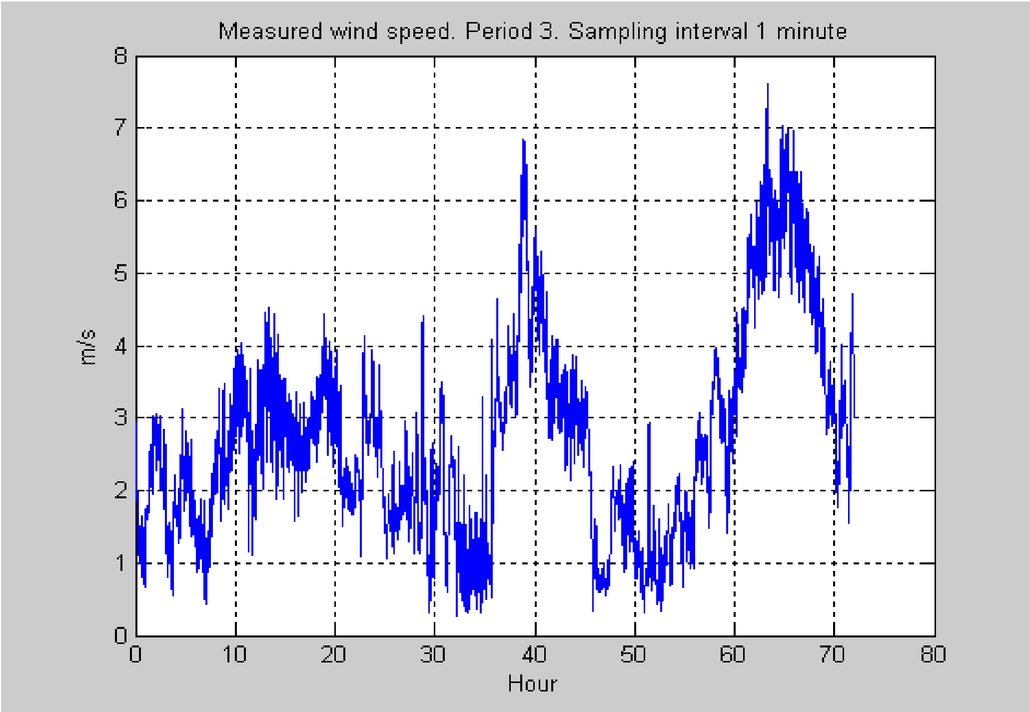


Figure 4.2-5 Measured wind speed. Period 3.
Mean value during a sampling period of 1 minute

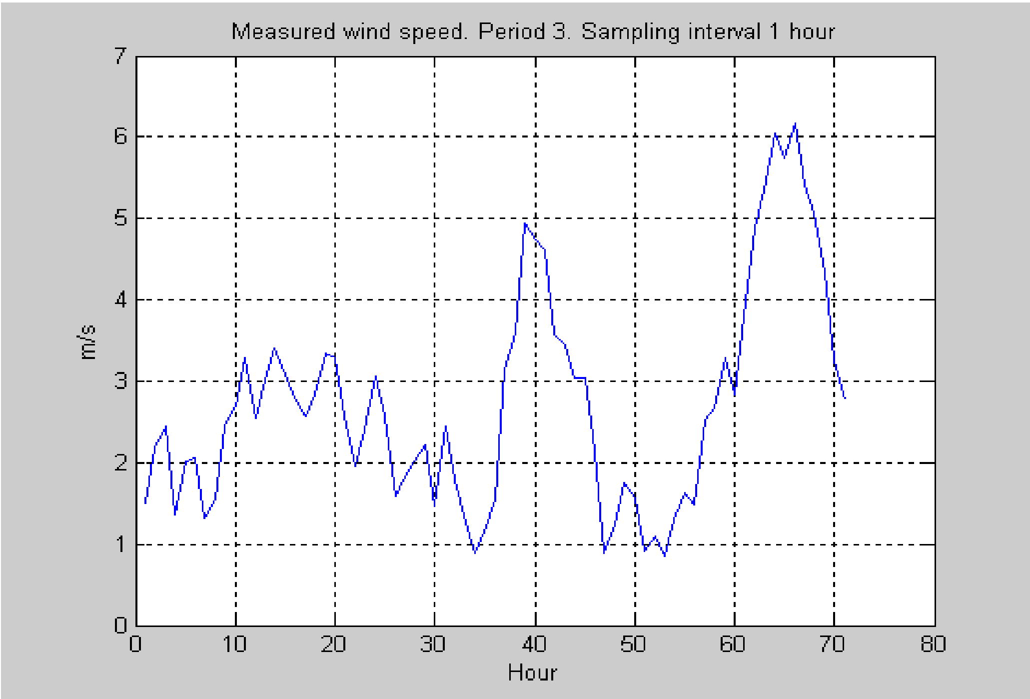


Figure 4.2-6 Measured wind speed. Period 3.
Mean value during a sampling period of 1 hour

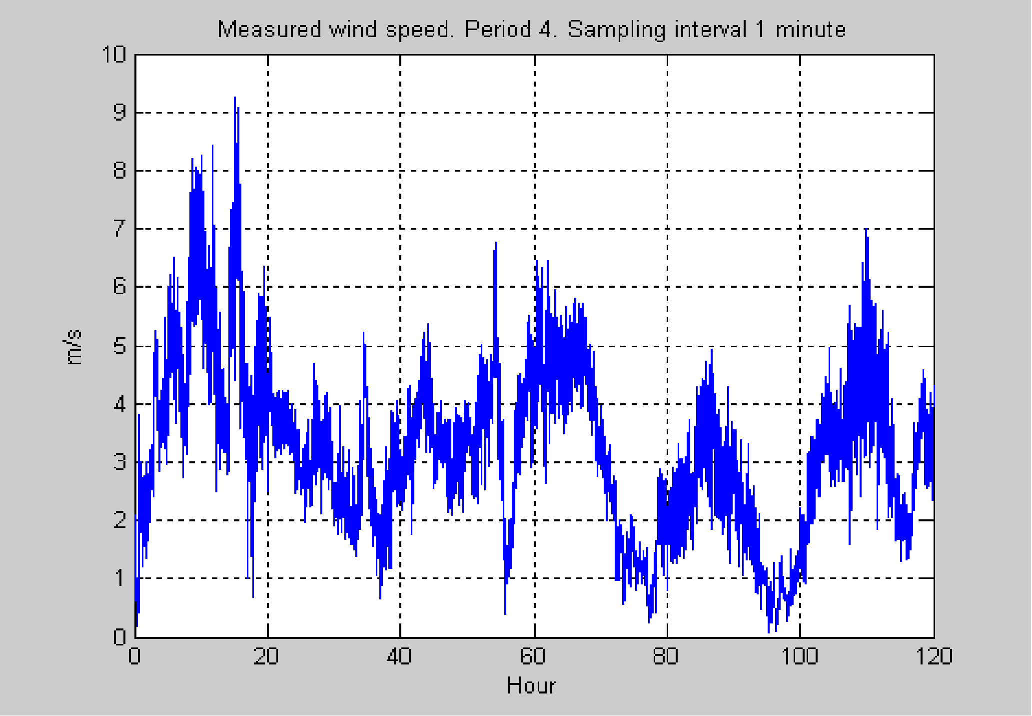


Figure 4.2-7 Measured wind speed. Period 4.
Mean value during a sampling period of 1 minute

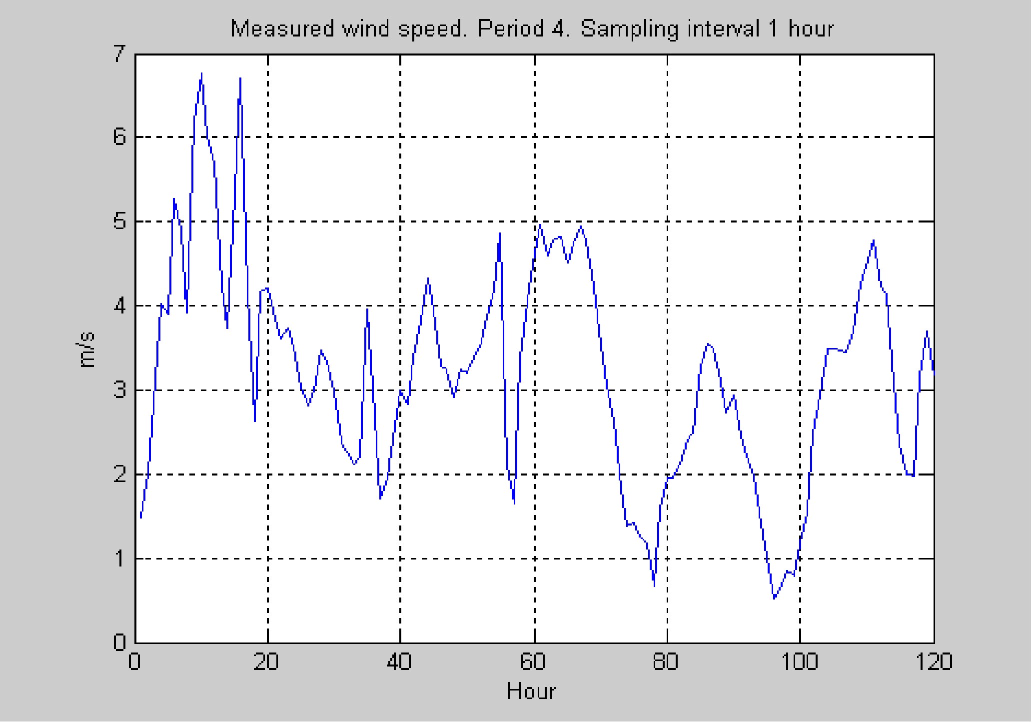


Figure 4.2-8 Measured wind speed. Period 4.
Mean value during a sampling period of 1 hour

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 Lewel_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**

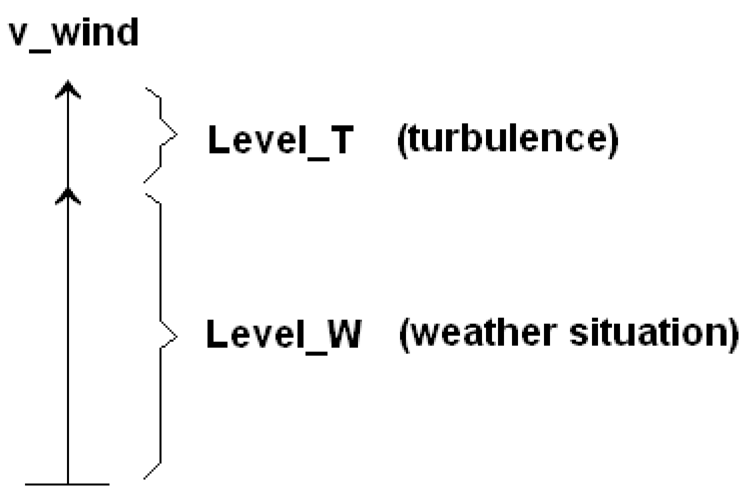


Figure 4.3-1 The wind speed is built up by two components, Level_W and Level_T

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 of a "specific" weather situation. See **Figure 4.3-2**.

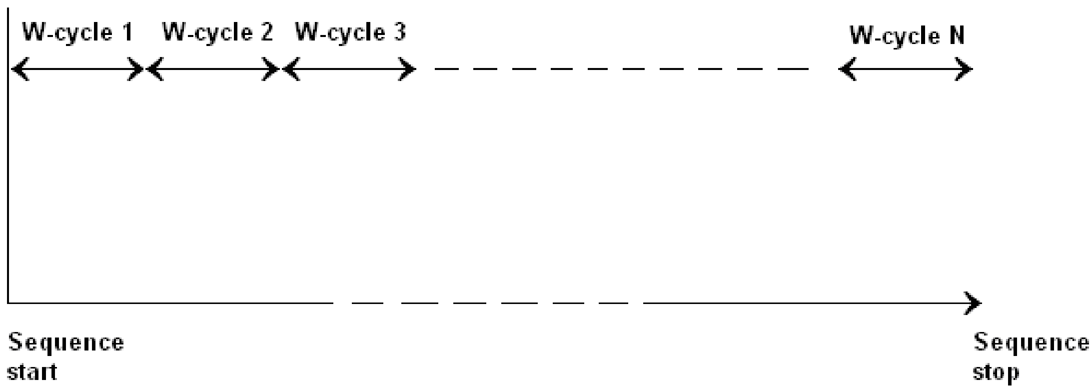


Figure 4.3-2 A total simulation sequence consists of a number (N) of W-cycles each of them representing a specific weather situation

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

Equation 4.3-1:

$$Level\_W = W(A, C)$$

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:

$$P(Level\_W \le S) \;=\; \int_0^S W(A,C)dS \;=$$

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

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 valuel 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.

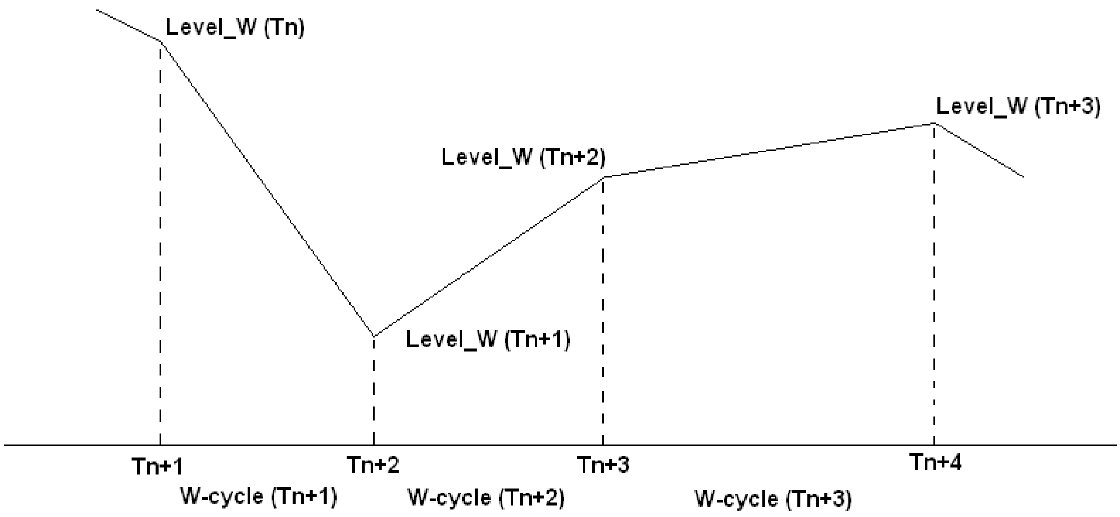


Figure 4.3-3 **Lewel_W is linearly assigned during the different W-cycle times**

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 stochasticly generated at time point Tn+1 and is then linearly distributed during the total W-cycle (Tn+1), Level_W (Tn+2) is stochasticly 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 stochasticly generated according to Equation 4.3-4.

Equation 4.3-4:

Sim_step_W_total = $N(\mu ,\sigma)$

Where:

N: a normal process
μ: an assigned mean value of simulation steps per W-cycle (*Sim_step_W_M*y)
σ: 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**.

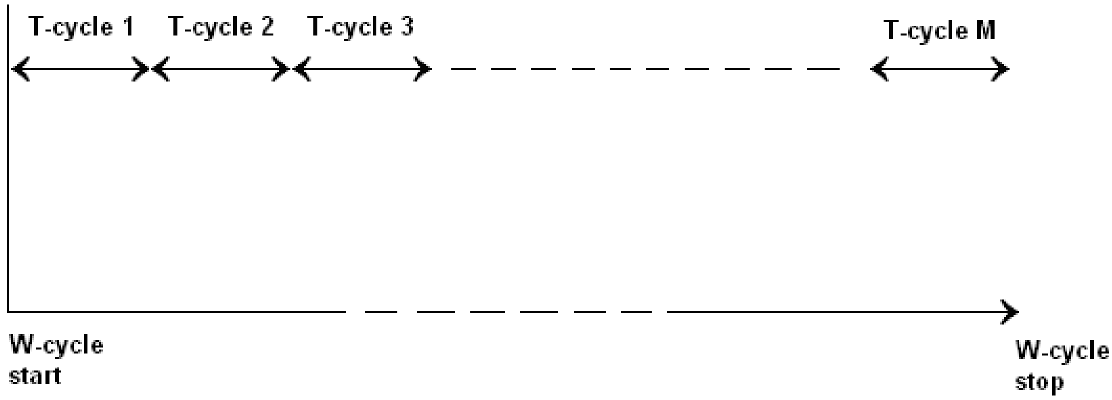


Figure 4.3-4 Every W-cycle is divided into a number (M) of T-cycles each of them representing a certain turbulence situation

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:

$Level\_T = N(\mu,\sigma)$

Where:
N: a normal process
μ: an assigned mean value of turbulence contribution per W-cycle (*Level_T_My*). *Level_T_My* is normaly assigned to zero, as the turbulence is proposed to fluctuate around the zero level.
σ: 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**.

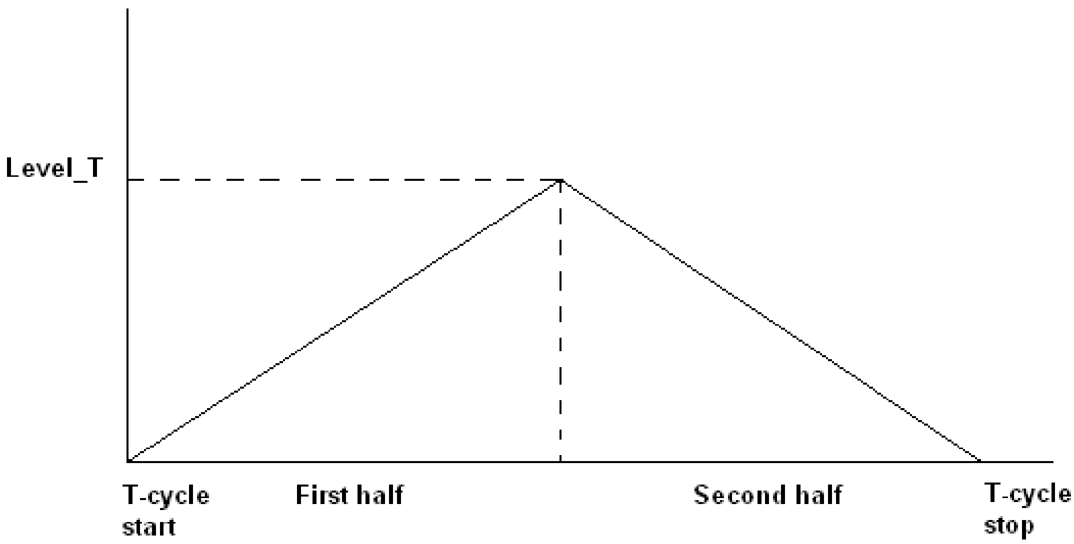


Figure 4.3-5 Distribution of Level_T during the T-cycle

The number of simulation steps for a single T-cycle, *Sim_step_T_total*, is stochasticly generated by a "Normal distribution" according to:

Equation 4.3-7:

$Sim\_step\_T\_total = N(\mu,\sigma)$

Where:

N: a normal process
μ: an assigned mean value of number of simulation steps per T-cycle (*Sim_step_T_My*)
σ: 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**.

Parameter name	Purpose
Sim_step_sec Input via function argument from Main Program	Time interval in seconds per simulation step (60 is a standard value)
Sim_step_total Input via function argument from Main Program	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)
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)

Level_T_Sigma_proc	Standard deviation of Level _T in percent of Level_W
v_wind_H	Upper limit of the wind speed
v_wind_L	Lower limit of the wind speed
Wind_speed_file	The name of a *Wind speed file* (string) to store the wind speed vector and the above parameters in this table

Table 4.3-1 Input parameters for module “Wind_make”

The parameters according to **Table 4.3-2** will be avaluated based on the measurements presented in paragraph 4.1 and 4.2.

Parameter name	**Purpose**
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)
Level_T_Sigma_proc	Standard deviation of Level _T in percent of Level_W

Table 4.3-2 Parameters that are evaluated based on the measurements in question

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:

$$Band(1) \quad = \quad \sum_{n} Wn(V)$$

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 vind rate *V*, time point *n*. $W_n(V)$ is for *Band(1)* defined as $W_n \; < \; k_1 \cdot W_{mean},$ $\quad k_1 = k_{min}$

W_{mean}: normalised mean energy of the process

k_{min}: defined parameter. <u>In this study k_{min} = 0.2</u>

Equation 4.3-9:

$$Band(n) \quad = \quad \sum_n W_n(V) \qquad\qquad n = 2, 3, \ldots\ldots, N\text{-}1$$

Where:

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

$W_n(V)$: normalised kinetic wind energy as a function of vind rate *V*, time point *n*. $W_n(V)$ is for *Band(n)* defined as $k_{n-1} \cdot W_{mean} \quad \leq \quad W_n(V) \quad < \quad k_n \cdot W_{mean}$, $k_n = k_{\min} + (n\text{-}1) \cdot k_{band}$, *n = 2, 3, ……, N-1*

N: number of bands. In this study *N* = 52

k_{band}: defined parameter. In this study $k_{band} = 0.2$

Equation 4.3-10:

$$Band(N) \quad = \quad \sum_n W_n(V)$$

Where:

Band(N): integrated normalized energy in highest band

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

4.3.3.2 Normalised Energy

A definition of what in this paper is named the *Normalised Energy* follows in Equation 4.3-11.

Equation 4.3-11:

$$W_{Normalised}(V) = \frac{W(V) \cdot \Delta V}{\int_{V\min}^{V\max} W(V)\, dV}$$

Where:

$W_{Normalised}(V)$:	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
ΔV:	a small wind rate region quite around *V*
Vmin:	minimum wind rate of the process
Vmax:	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:

$$W_N(b) = \frac{\int_{V_{Band}(b)}^{V_{Band}(b)+d_{Band}(b)} W(V)\, dV}{\int_{V\min}^{V\max} W(V)\, dV}$$

Where:

$W_N(b)$:	normalized (kinetic) energy per m^2 (perpendicular to the wind direction) in the energy band *b*
$V_{Band}(b)$:	a function that gives the lower wind rate limit for energy band *b*

$d_{Band}(b)$: 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:

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

Where:

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

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

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

Equation 4.3-14:

$$W_N(b) = \frac{\sum_{V(b)}^{V(b)+d(b)} V^3 \cdot g(V)}{\sum_{V_{\max}}^{V_{\min}} V^3 \cdot g(V)}$$

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 standarddeviation 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:

$$V\sigma \quad = \quad \sqrt{\frac{\sum_{k=1}^{N}\left(M(k) - V\mu\right)^2}{N-1}}$$

Where:

$V\sigma$: standarddeviation 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 (*Vmax and Vmin*) 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:

$$V\max \quad = \quad \max imum\{M(k)\},\ k = 1 \to N$$

Where:

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

Equation 4.3-18:

$$V\max \quad = \quad \min imum\{M(k)\},\ k = 1 \to N$$

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.

Measuring period (see paragraph 4.1)	Weather variation		Turbulence variation		Turbulence level
	Sim_step _W_My	Sim_step _W_Sigma	Sim_step _T_My	Sim_step _T_Sigma	Level_T _Sigma_proc
1	300	100	3	1	35
2	300	100	3	1	15
3	300	100	3	1	20
4	300	100	3	1	30

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

Measuring period (see paragraph 4.1)	Weibull parameters	
	A	C
1	4.80	3.12
2	5.80	3.60
3	3.30	2.40
4	3.80	2.50

Table 4.4-2 Resulting nominal model parameters after comparering 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.

<u>Comments regarding figures and tables</u>

<u>Figure 4.4-2 - Figure 4.4-5</u> 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.

<u>*Figure 4.4-6*</u> 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.

<u>*Figure 4.4-7*</u> 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.

<u>*Figure 4.4-8 and Figure 4.4-9*</u> 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 bee 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

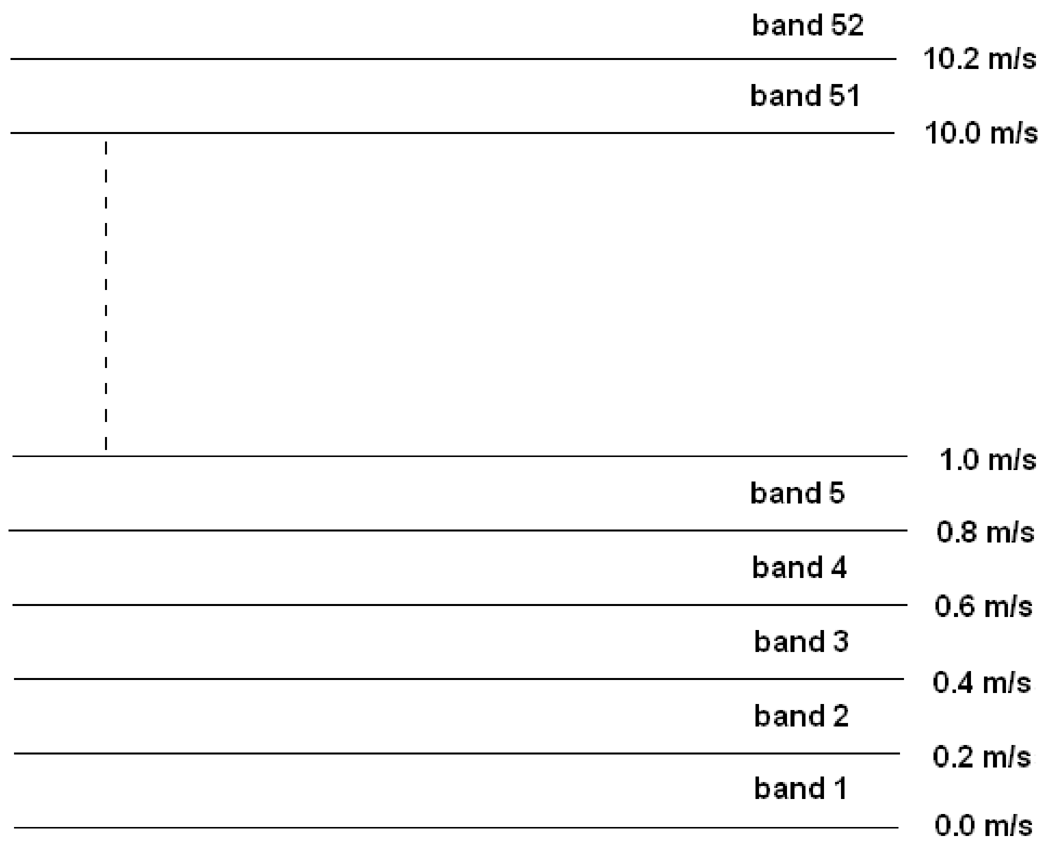


Figure 4.4-1 *"Wind rate Bands"* 1 to 52. The *Wind rate Bands* are defined according to Equation 4.4-1.

Equation 4.4-1:

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

Wind rate Band 52: $wind\ rate\ \geq\ 10.2\ m/s$

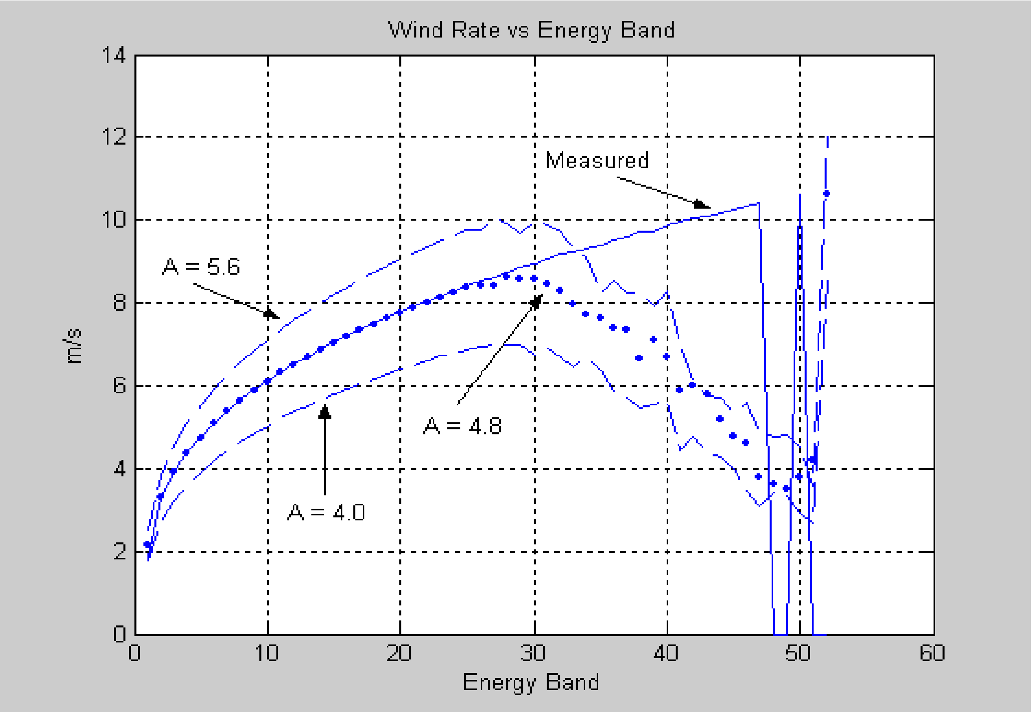


Figure 4.4-2 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

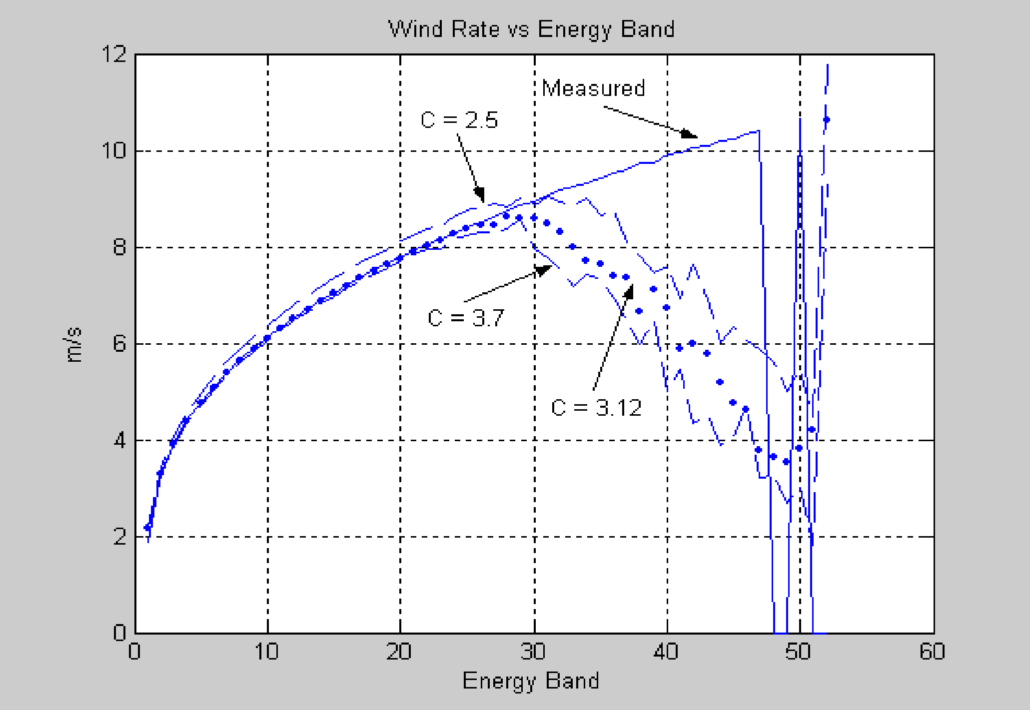


Figure 4.4-3 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

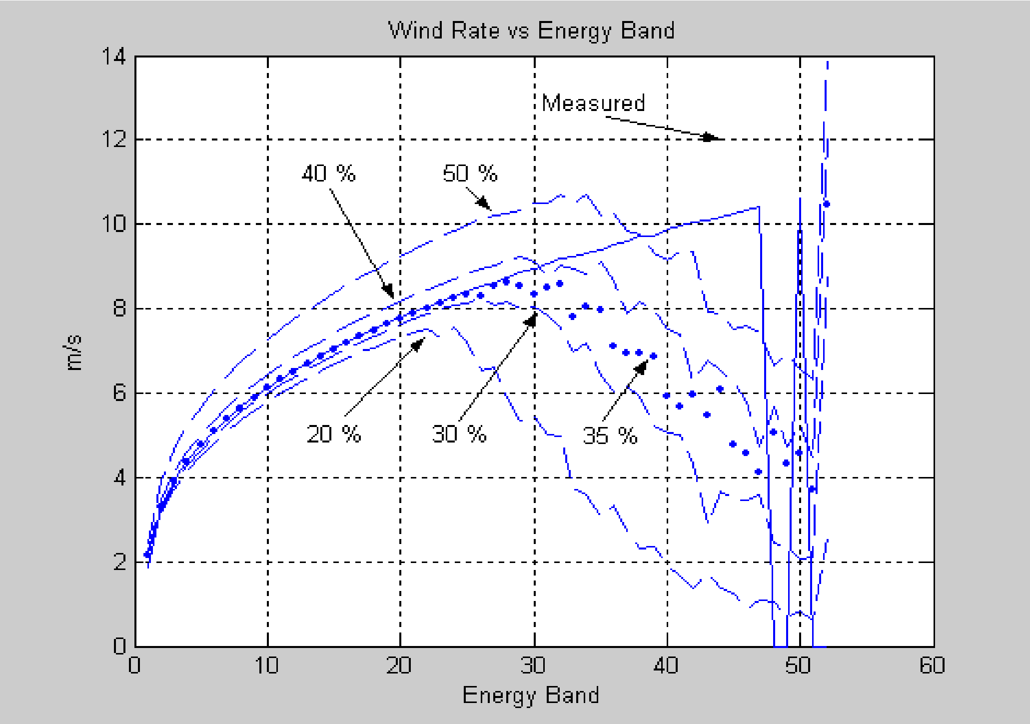


Figure 4.4-4 Wind rate vs Energy Band with altering Turbulence level. (C, A and Turbulence variation are fixed nominal)

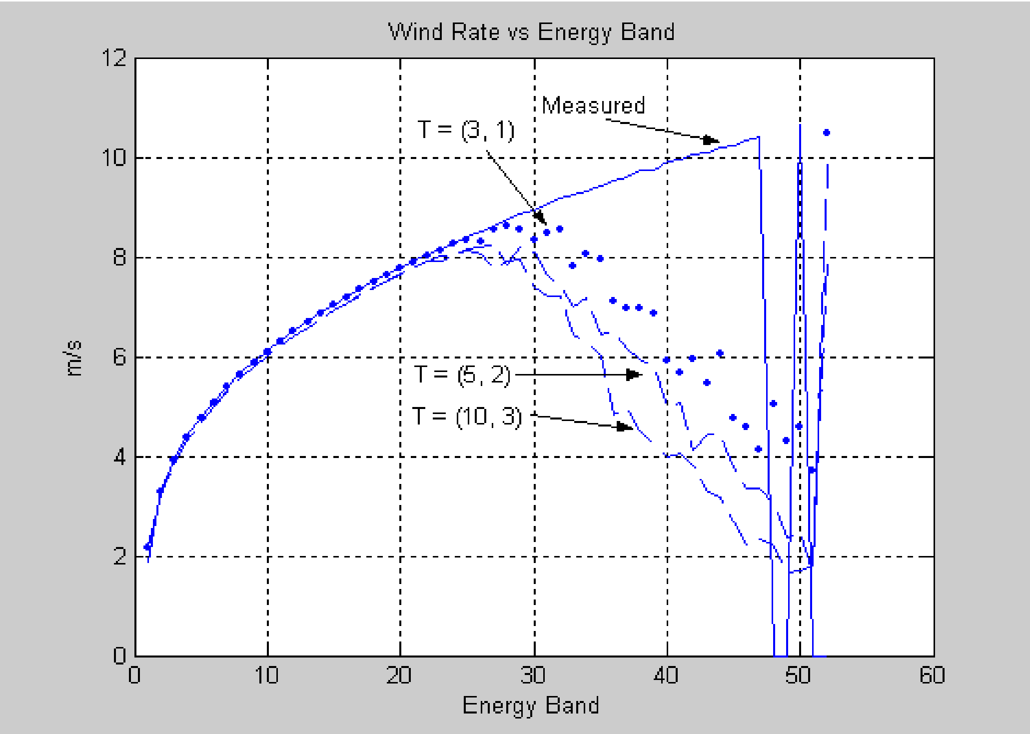


Figure 4.4-5 Wind rate vs Energy Band with altering Turbulence variation. (C, A and Turbulence are fixed nominal)

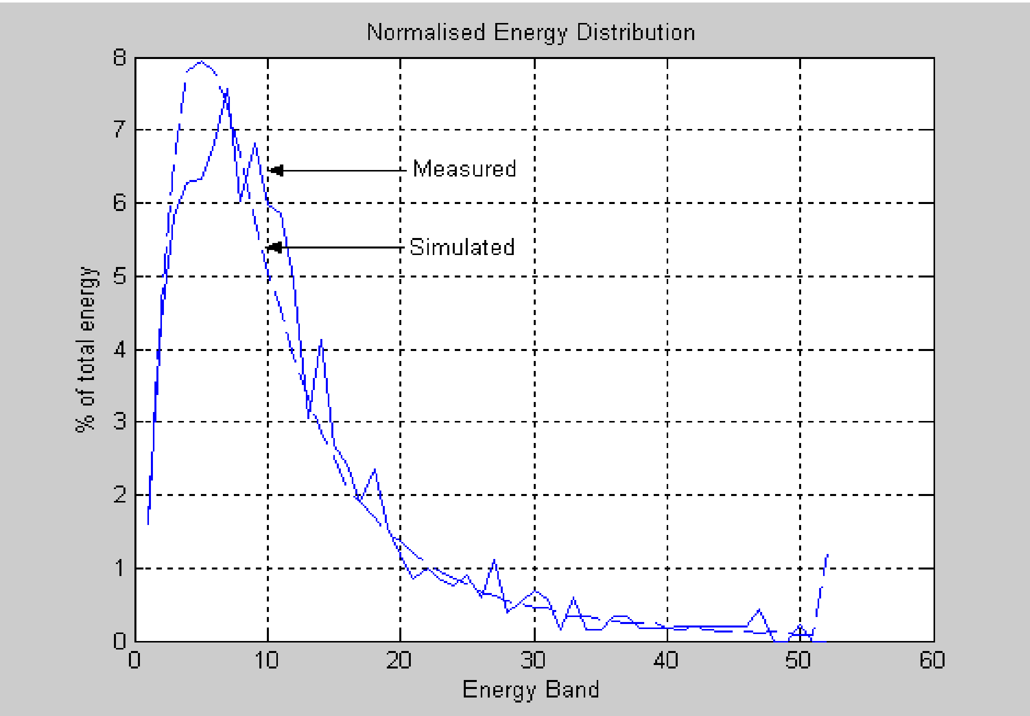


Figure 4.4-6 Normalised energy distribution vs energy band

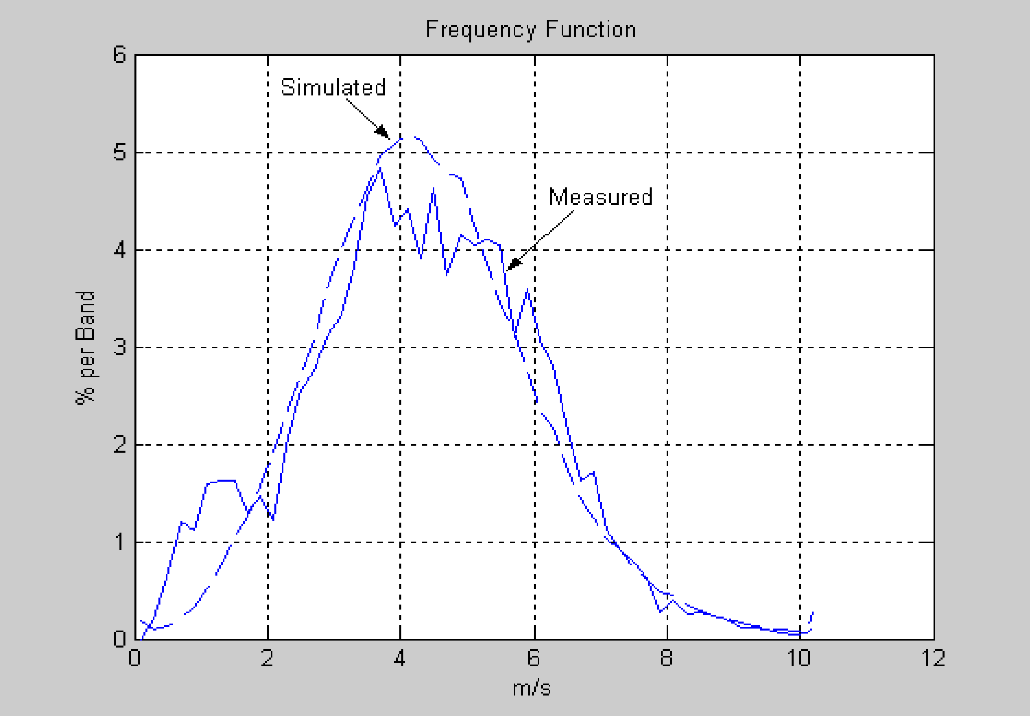


Figure 4.4-7 Frequency function vs wind rate band

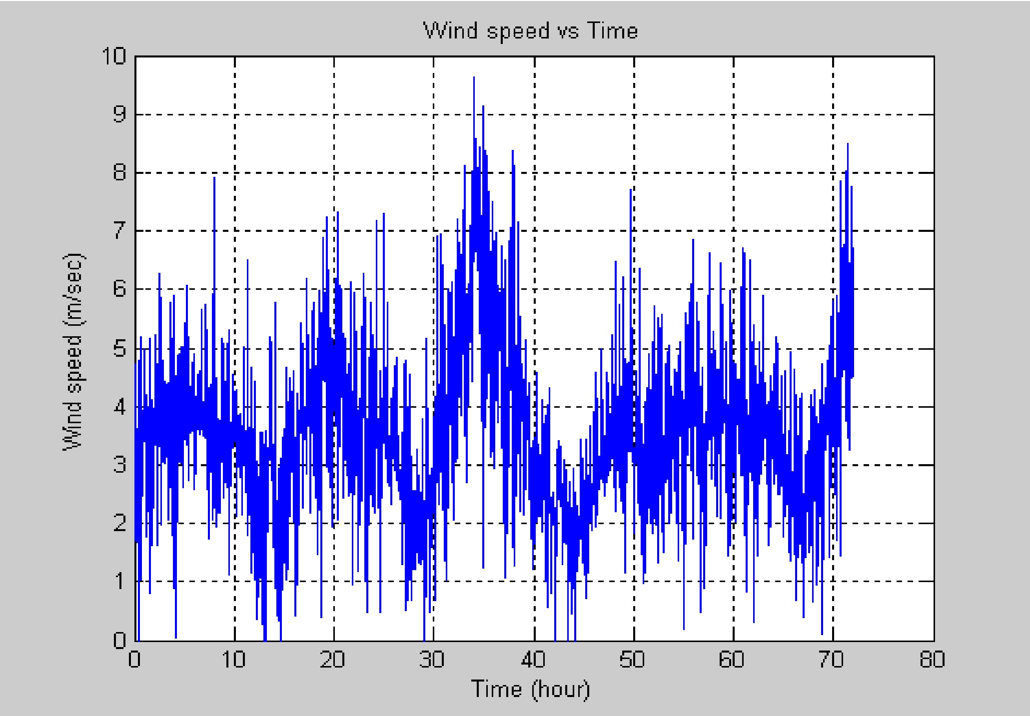


Figure 4.4-8 Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 1

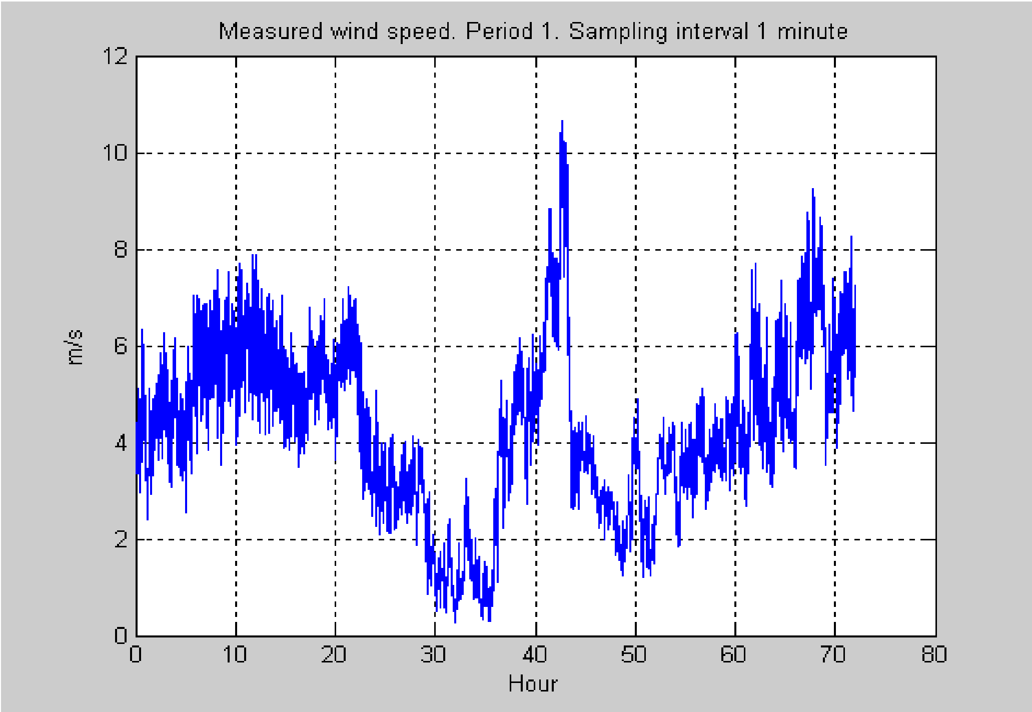


Figure 4.4-9 Measured wind speed. Period 1

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ \mathrm{Re}sult}{Measurement\ \mathrm{Re}sult}$
A (C, Turbulence and Turbulence variation nominal)	4.0	0.5785
	<u>4.8</u> (nominal)	**<u>1.0029</u>**
	5.6	1.6157
C (A, Turbulence and Turbulence variation nominal)	2.5	1.0934
	<u>3.12</u> (nominal)	**<u>1.0029</u>**
	3.7	0.9854
Turbulence (C, A and Turbulence variation nominal)	20 %	0.8523
	30 %	0.9254
	<u>35 %</u> (nominal)	**<u>1.0029</u>**
	40 %	1.1278
	50 %	1.7211
Turbulence variation (C, A and Turbulence nominal)	**<u>(3,1)</u>** (nominal)	**<u>1.0029</u>**
	(5,2)	0.9432
	(10,3)	0.9707

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

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
4.3	4.4	1.8	1.6	10.6	12.0	0.3	0.0

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)*) 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)*) 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.

Figure 4.4-19 and Figure 4.4-20 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

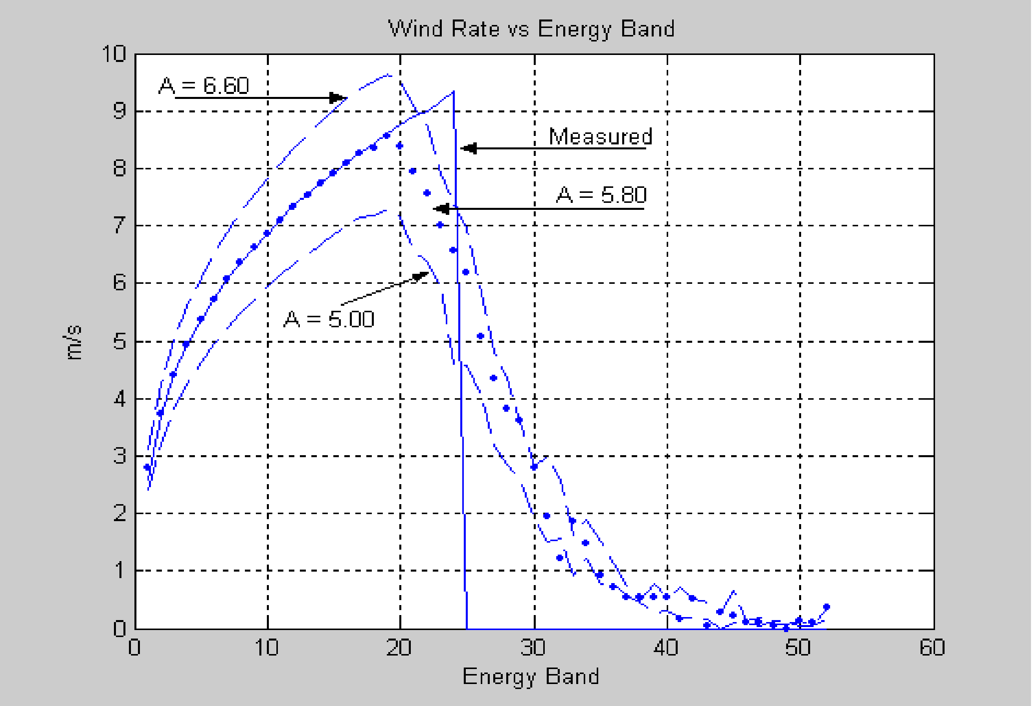


Figure 4.4-10 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

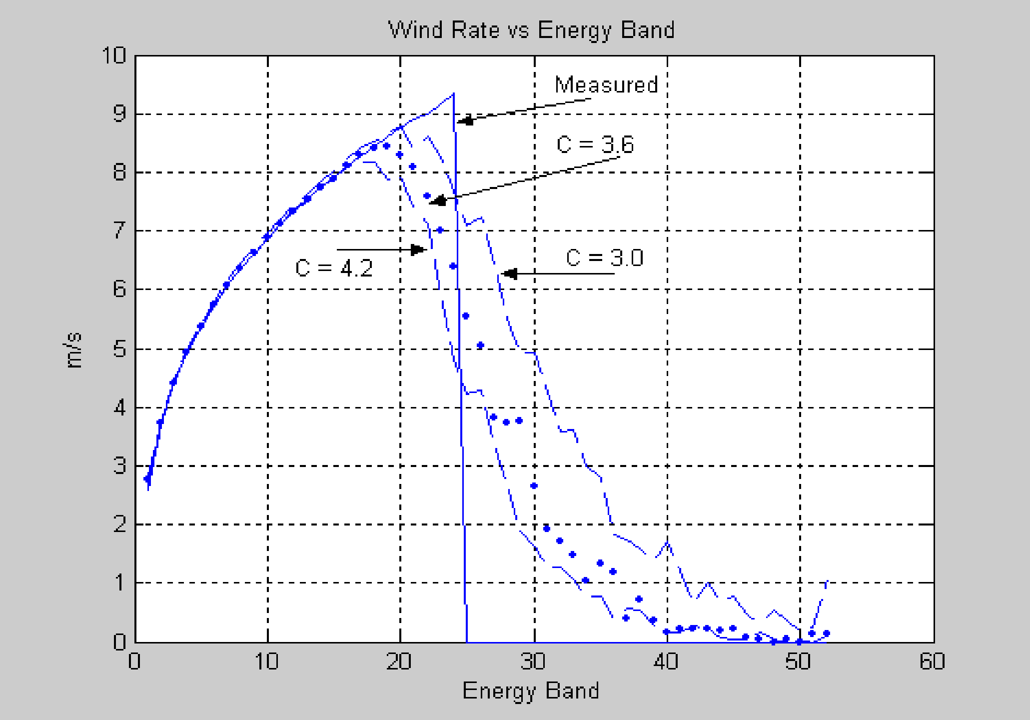


Figure 4.4-11 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

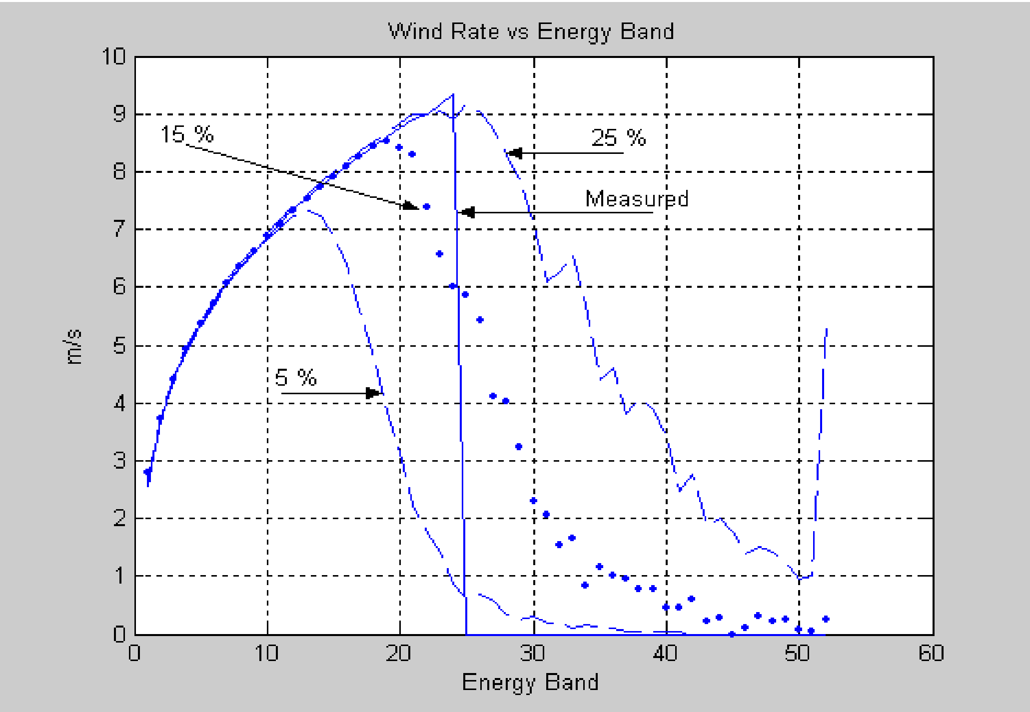


Figure 4.4-12 Wind rate vs Energy Band with altering Turbulence level. (A, C and Turbulence variation are fixed nominal)

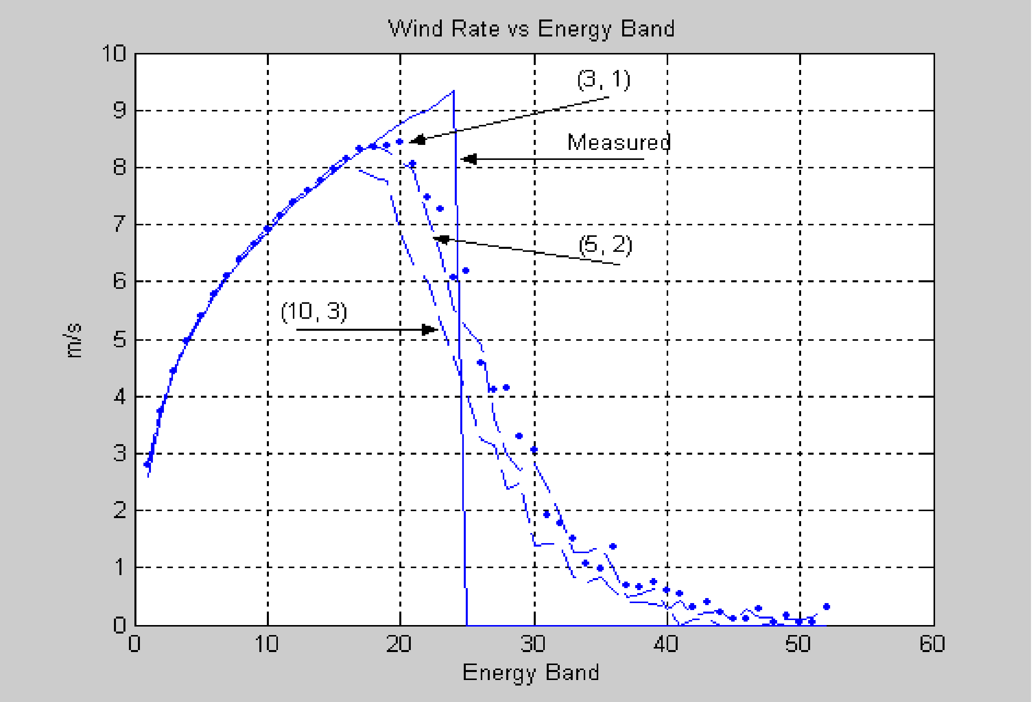


Figure 4.4-13 Wind rate vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

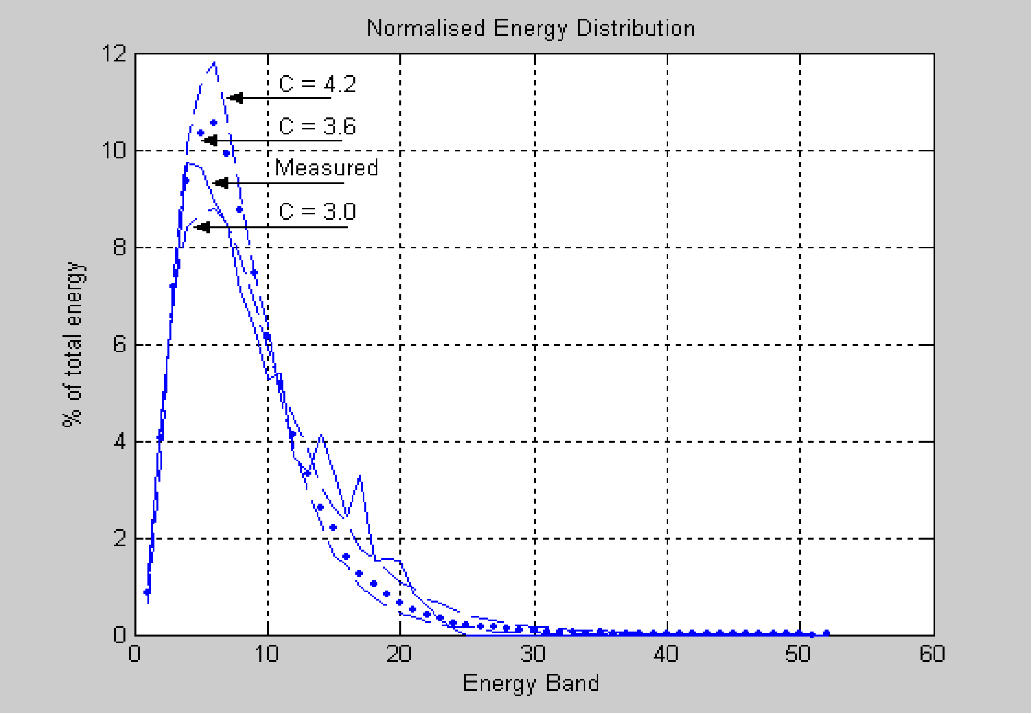


Figure 4.4-14 Normalised Energy Distribution vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

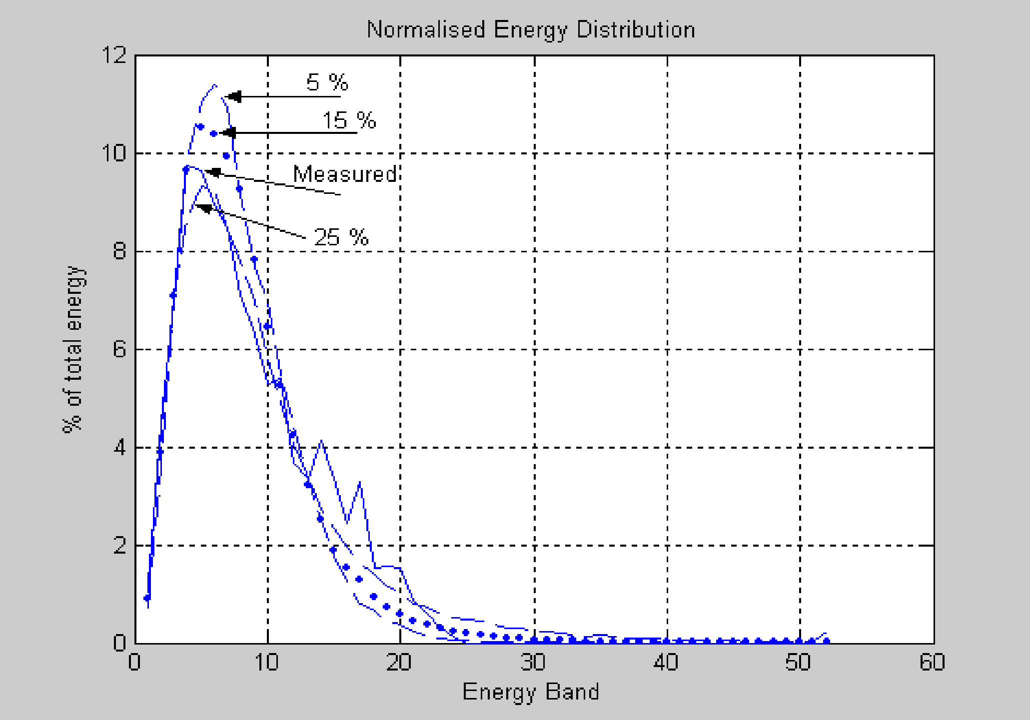


Figure 4.4-15 Normalised Energy Distribution vs Energy Band with altering Turbulence. (A, C and Turbulence variation are fixed nominal)

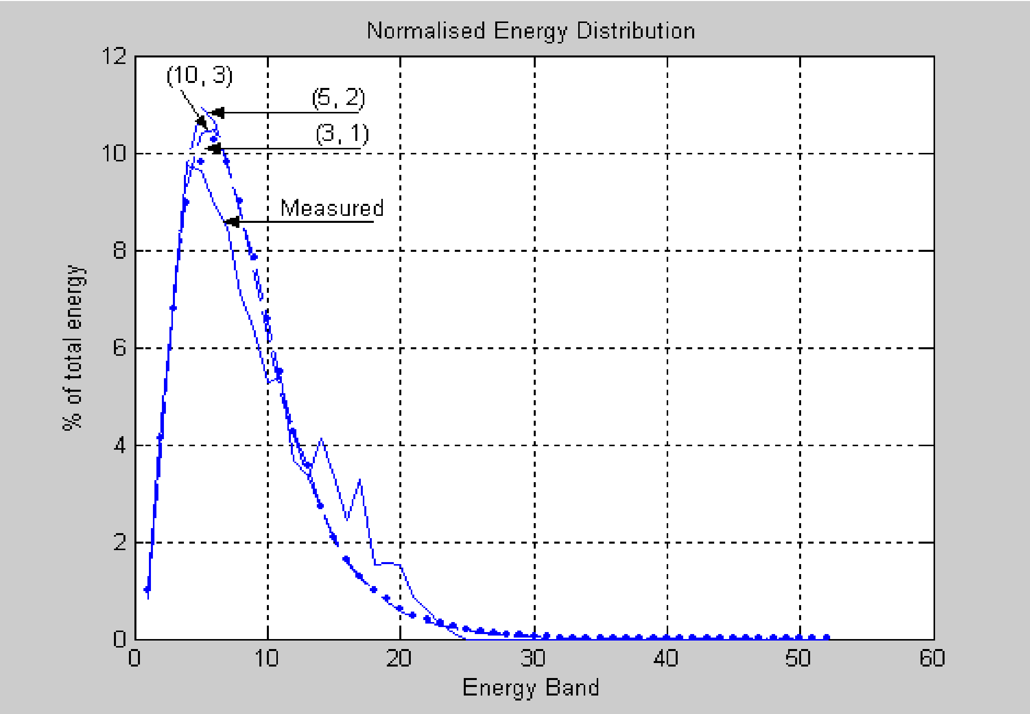


Figure 4.4-16 Normalised Energy Distribution vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

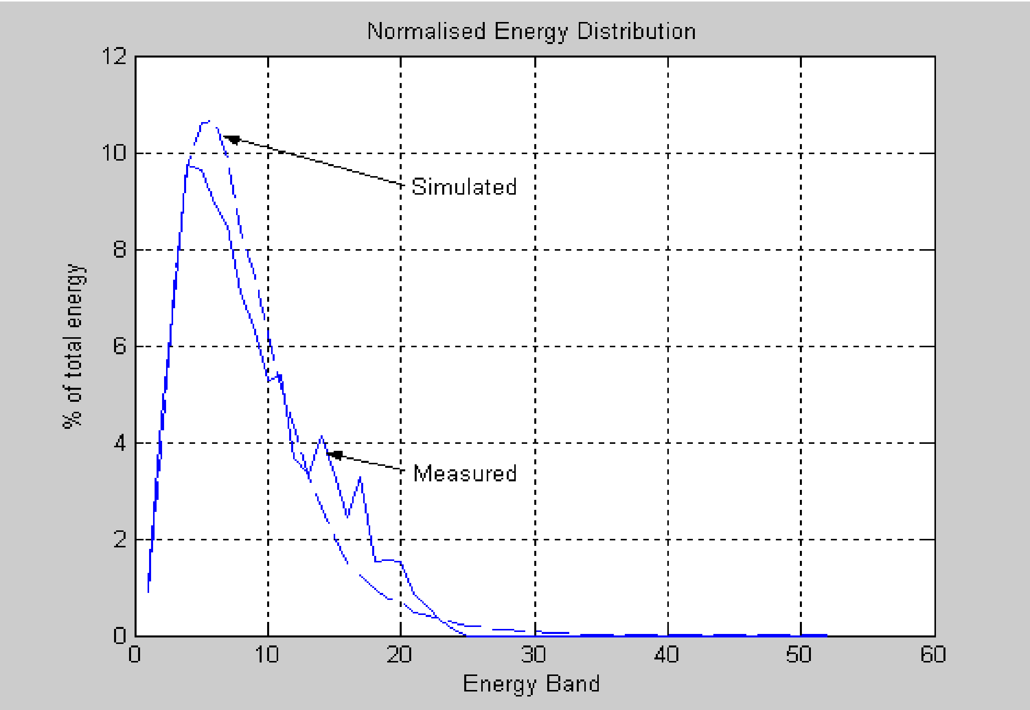


Figure 4.4-17 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

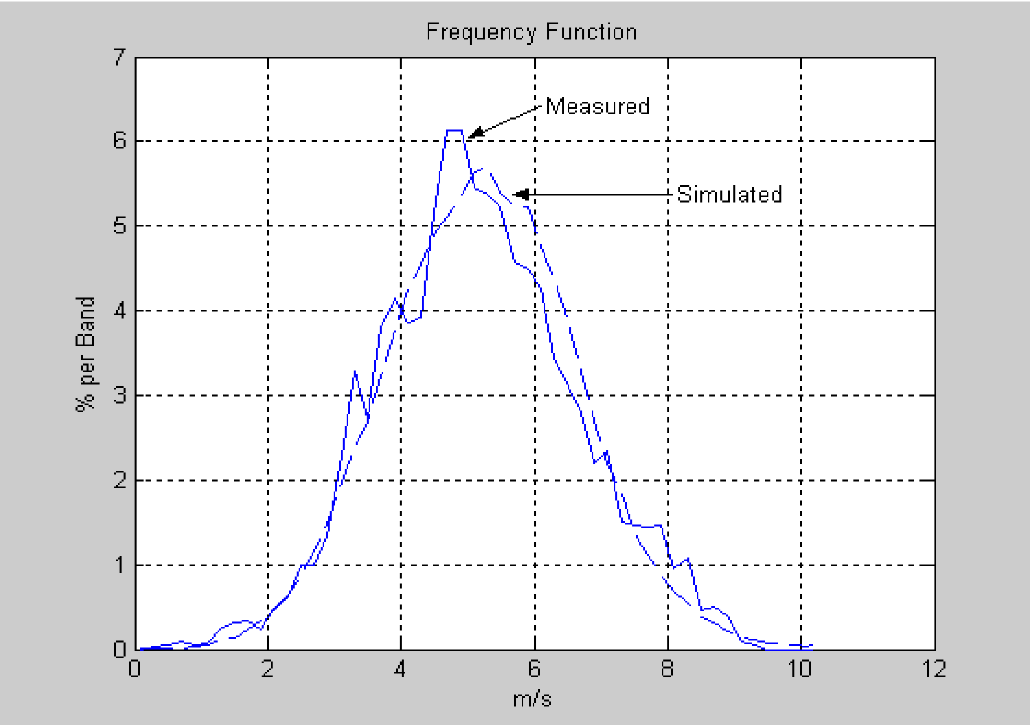


Figure 4.4-18 Frequency Function vs Wind Rate Band (see Figure 4.4-1). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

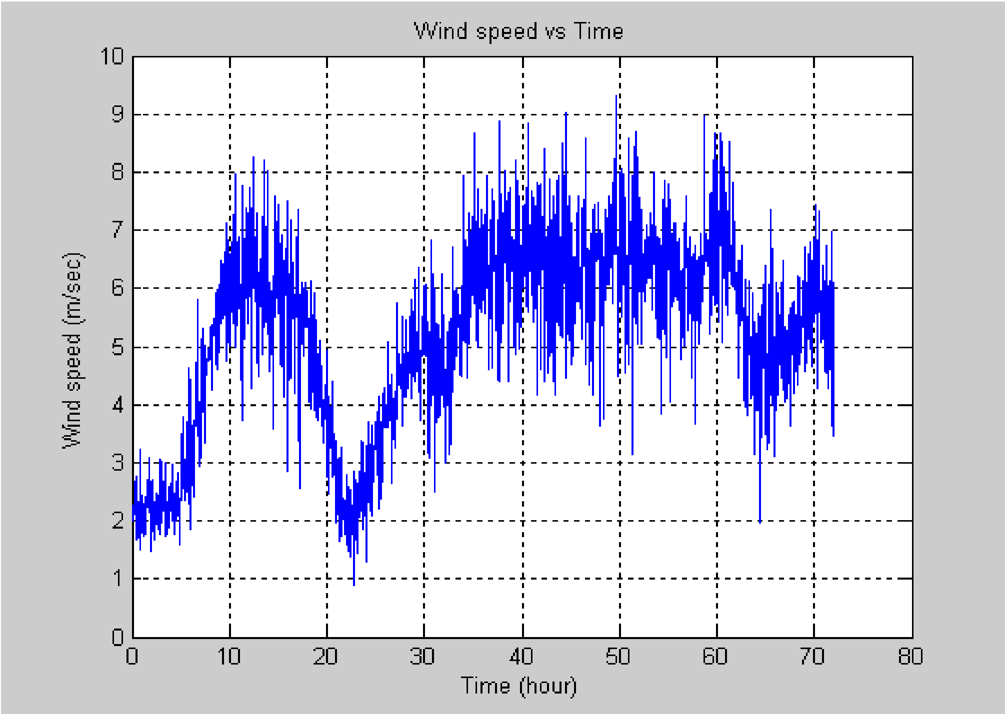


Figure 4.4-19 Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 2.

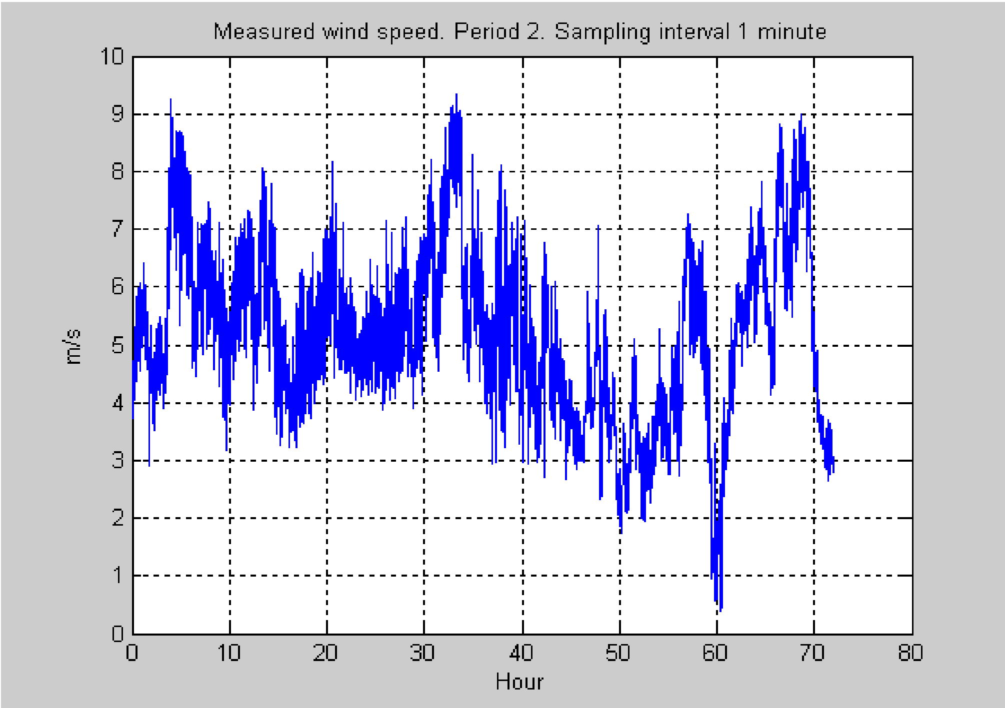


Figure 4.4-20 Measured wind speed. Period 2

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ \mathrm{Re}\,sult}{Measurement\ \mathrm{Re}\,sult}$
A (C, Turbulence and Turbulence variation nominal)	5.00	0.6468
	<u>5.80</u> (nominal)	**<u>1.0169</u>**
	6.60	1.5680
C (A, Turbulence and Turbulence variation nominal)	3.00	1.0764
	<u>3.60</u> (nominal)	**<u>1.0169</u>**
	4.20	1.0342
Turbulence (C, A and Turbulence variation nominal)	5 %	0.9863
	10 %	1.0219
	<u>15 %</u> (nominal)	**<u>1.0169</u>**
	20 %	1.0635
	25 %	1.0817
Turbulence variation (C, A and Turbulence nominal)	**<u>(3,1)</u>** (nominal)	**<u>1.0169</u>**
	(5,2)	1.0262
	(10,3)	1.0214

Table 4.4-5 Relative Mean Energy vs variation of some parameters

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
5.2	5.2	1.5	1.4	9.3	10.2	0.4	1.3

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 bee 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, standarddeviation: 1

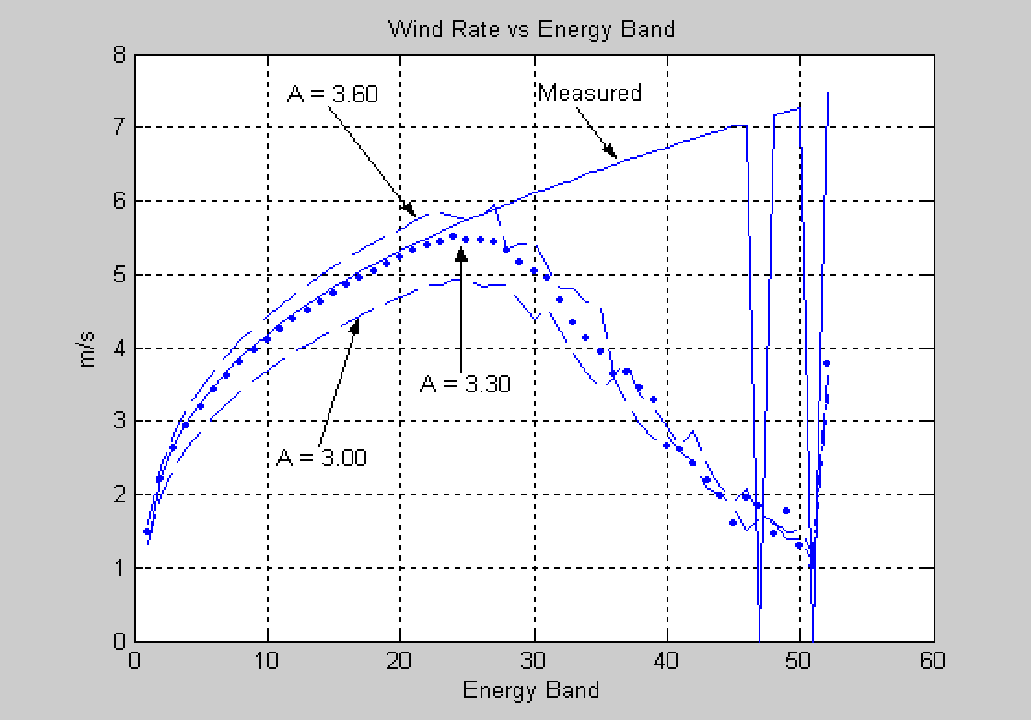


Figure 4.4-21 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

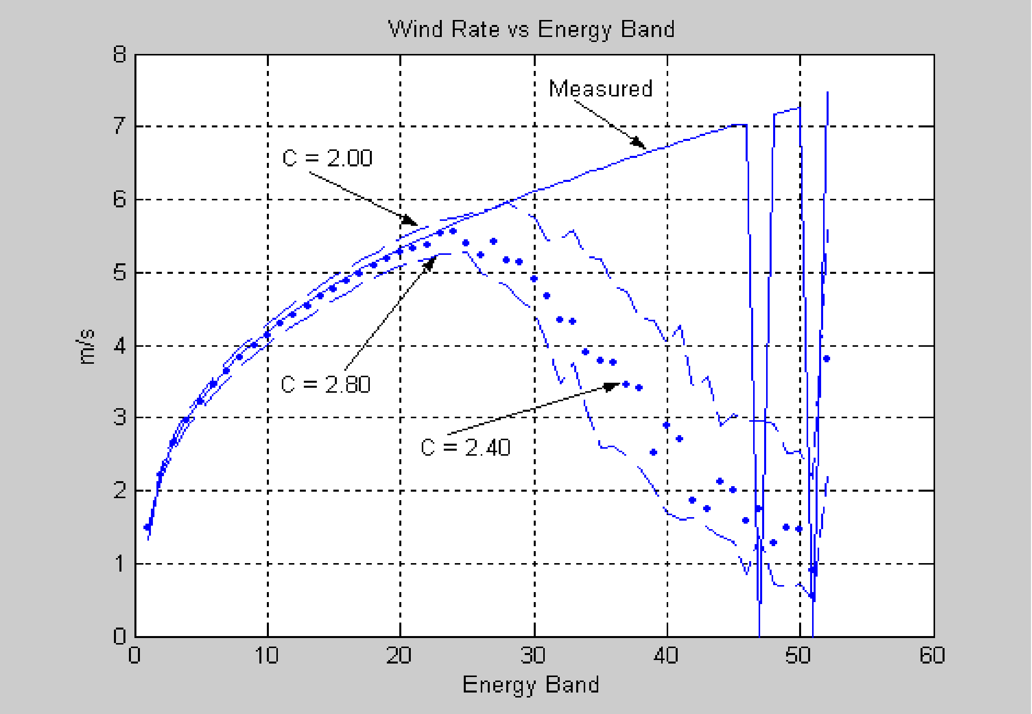


Figure 4.4-22 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

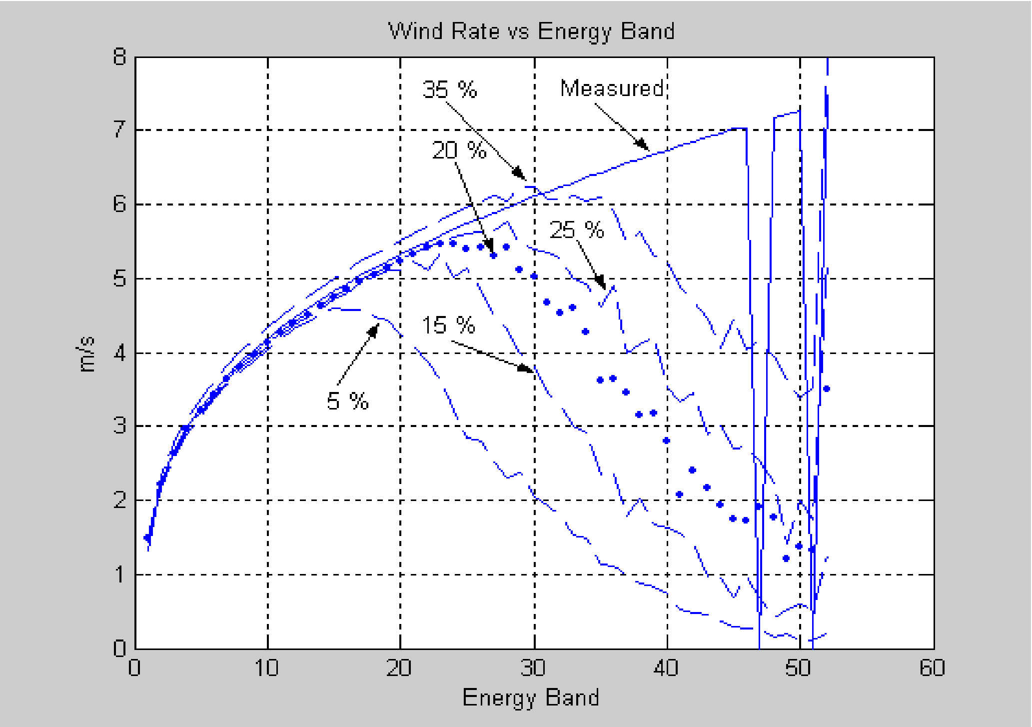


Figure 4.4-23 Wind rate vs Energy Band with altering Turbulence level. (A,C, and Turbulence variation are fixed nominal)

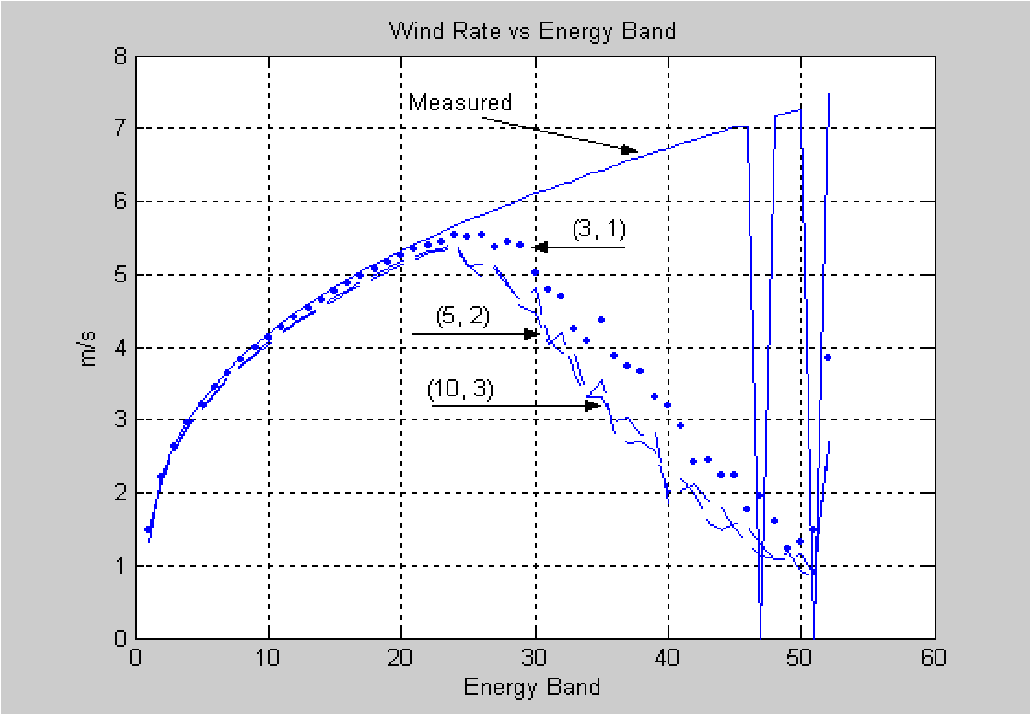


Figure 4.4-24 Wind rate vs Energy Band with altering Turbulence variation. (A, C and Turbulence are fixed nominal)

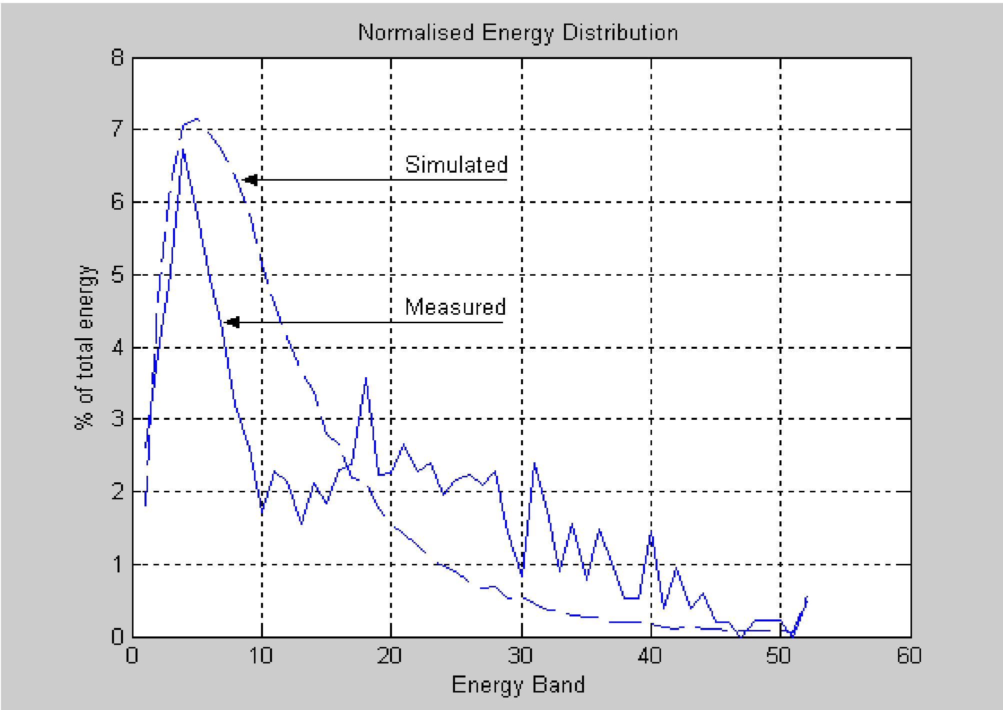


Figure 4.4-25 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

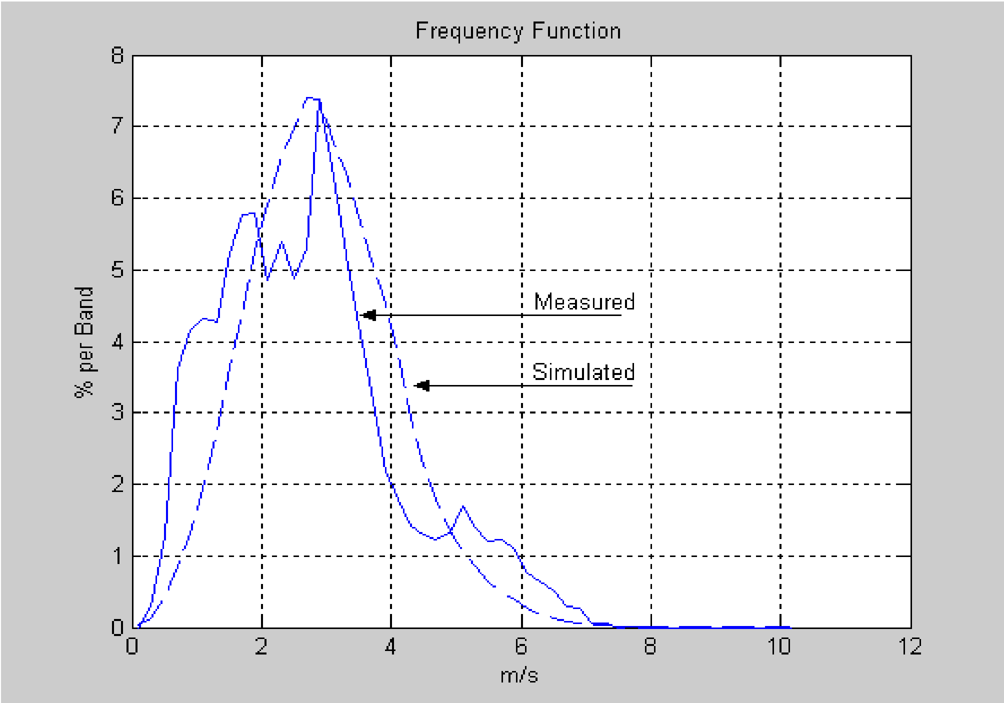


Figure 4.4-26 Frequency Function vs Wind Rate Band (see Figure 4.4-1). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

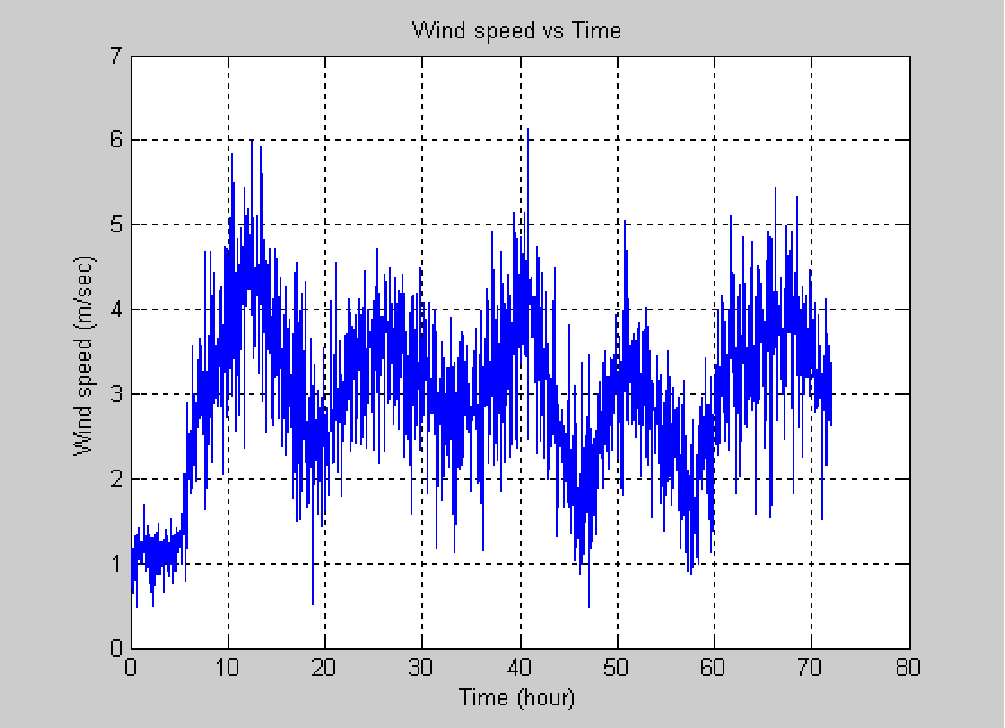


Figure 4.4-27 Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 3.

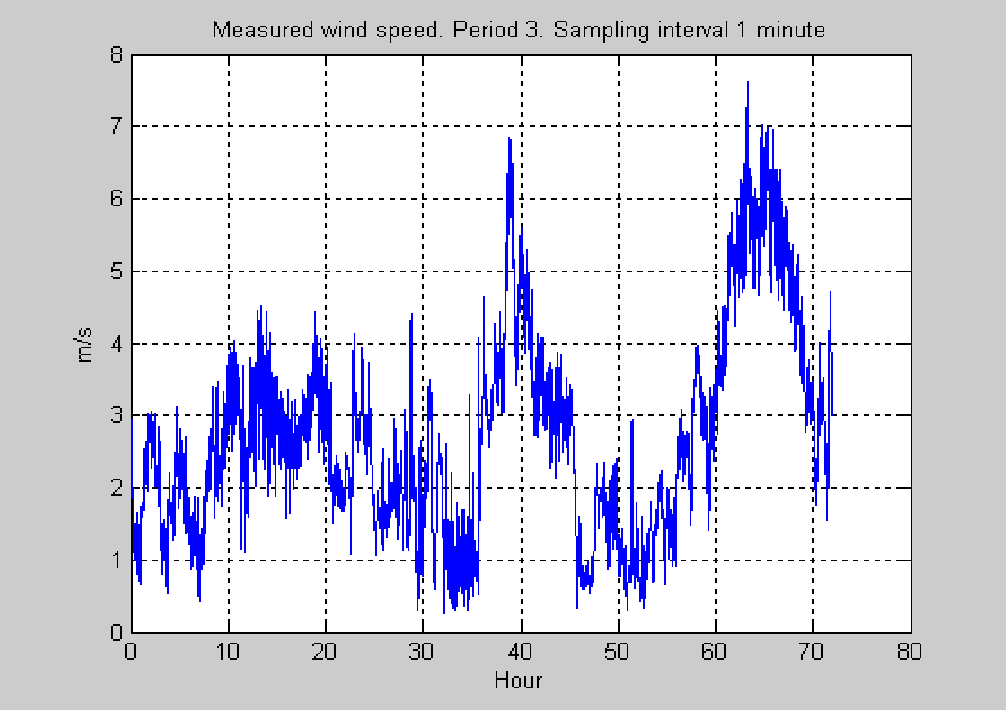


Figure 4.4-28 Measured wind speed. Period 3

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ Result}{Measurement\ Result}$
A (C, Turbulence and Turbulence variation nominal)	3.00	0.7123
	3.30 (nominal)	**0.9962**
	3.60	1.2358
C (A, Turbulence and Turbulence variation nominal)	2.00	1.1330
	2.40 (nominal)	**0.9962**
	2.80	0.9099
Turbulence (C, A and Turbulence variation nominal)	5 %	0.9398
	15 %	0.9674
	20 % (nominal)	**0.9962**
	25 %	1.0033
	35 %	1.1718
Turbulence variation (C, A and Turbulence nominal)	(3,1) (nominal)	**0.9962**
	(5,2)	0.9341
	(10,3)	0.9607

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

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
2.7	2.9	1.4	1.1	7.6	7.3	0.3	0.2

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.

<u>Comments regarding figures and tables</u>:

<u>*Figure 4.4-29 - Figure 4.4-33*</u> 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.

<u>*Figure 4.4-34 - Figure 4.4-35*</u> 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.

<u>*Figure 4.4-36*</u> 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.

<u>*Figure 4.4-37 - Figure 4.4-38*</u> 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 bee noted, simulation with the nominal parameters results in good adaption 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 adaption between simulation results and measurement result.

*) mean value: 3, standarddeviation: 1

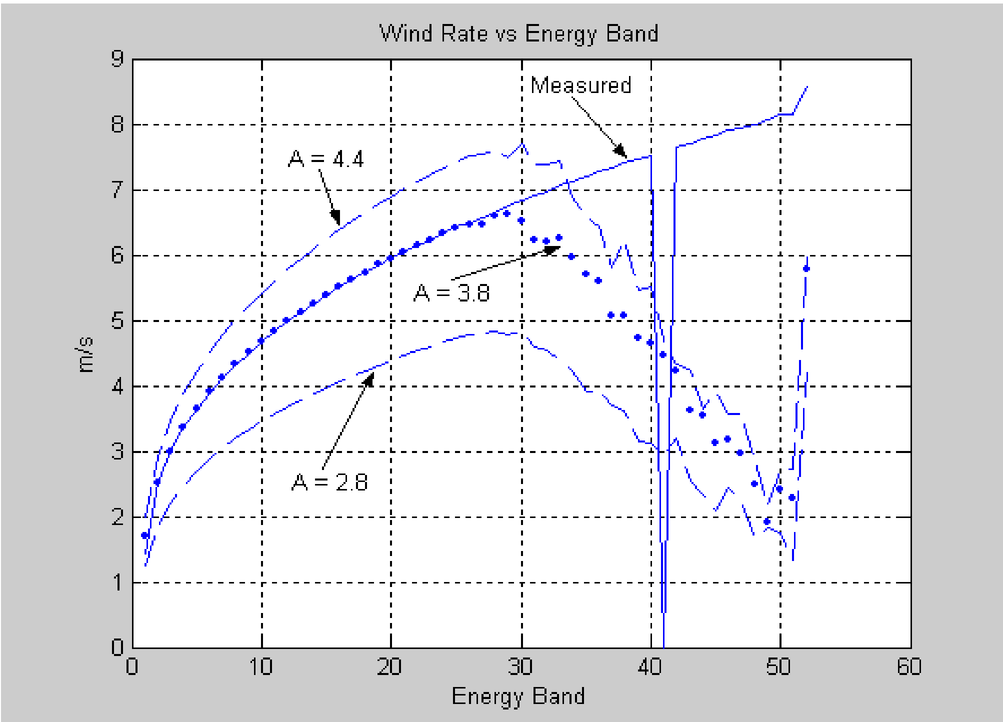


Figure 4.4-29 Wind rate vs Energy Band with altering A-parameter. (C, Turbulence and Turbulence variation are fixed nominal)

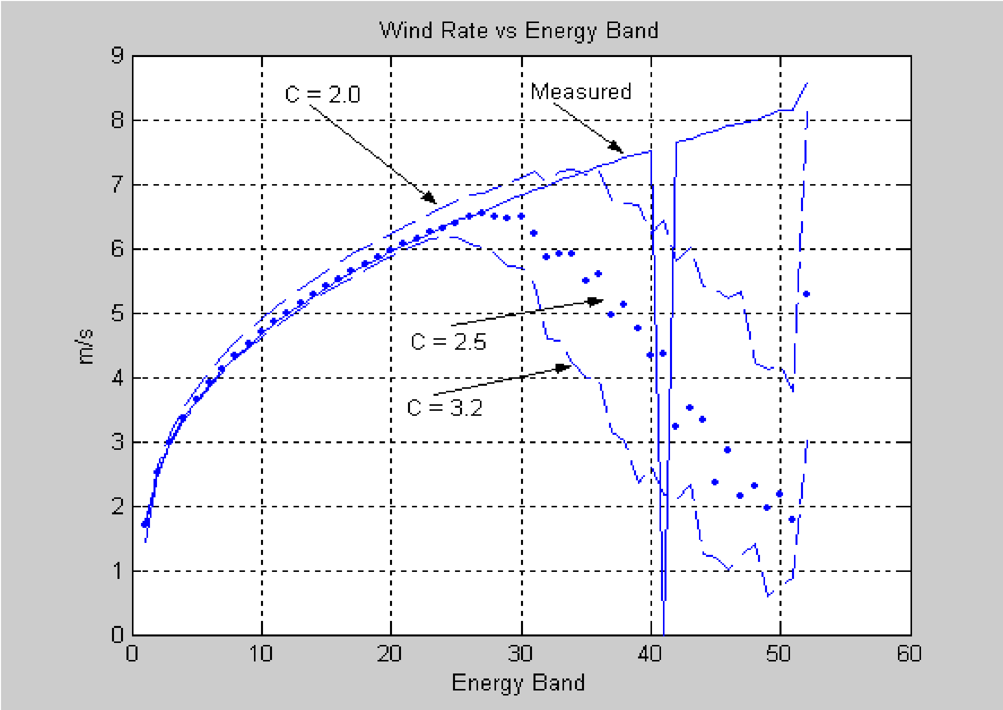


Figure 4.4-30 Wind rate vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

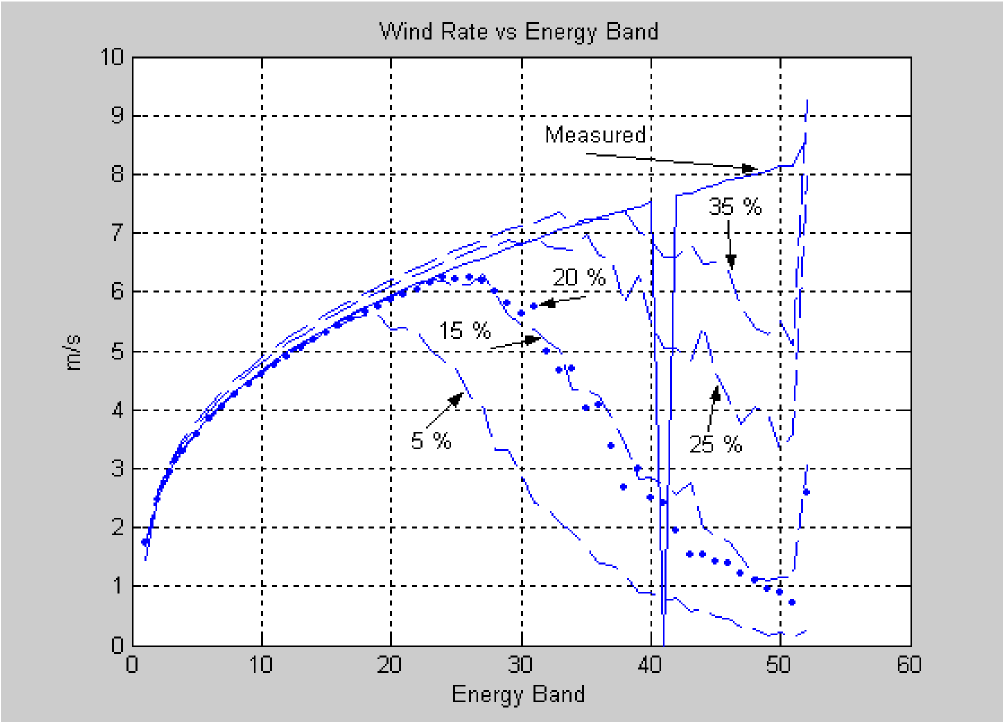


Figure 4.4-31 Wind rate vs Energy Band with altering Turbulence. (A, C, and Turbulence variation are fixed nominal)

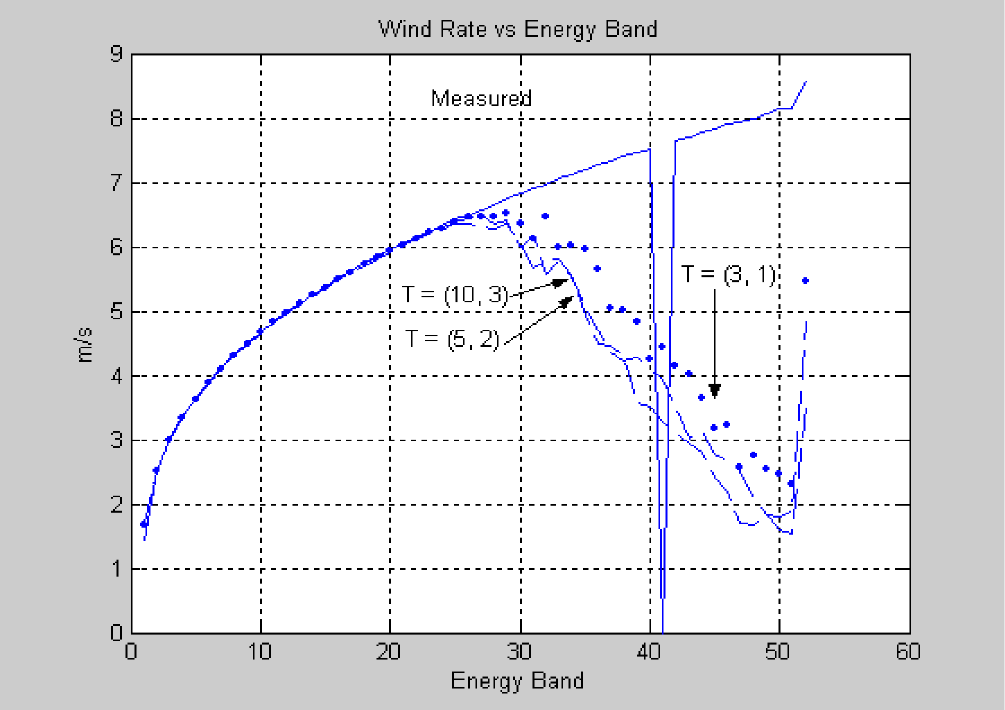


Figure 4.4-32 Wind rate vs Energy Band with altering Turbulence variation. (A, C, Turbulence are fixed nominal)

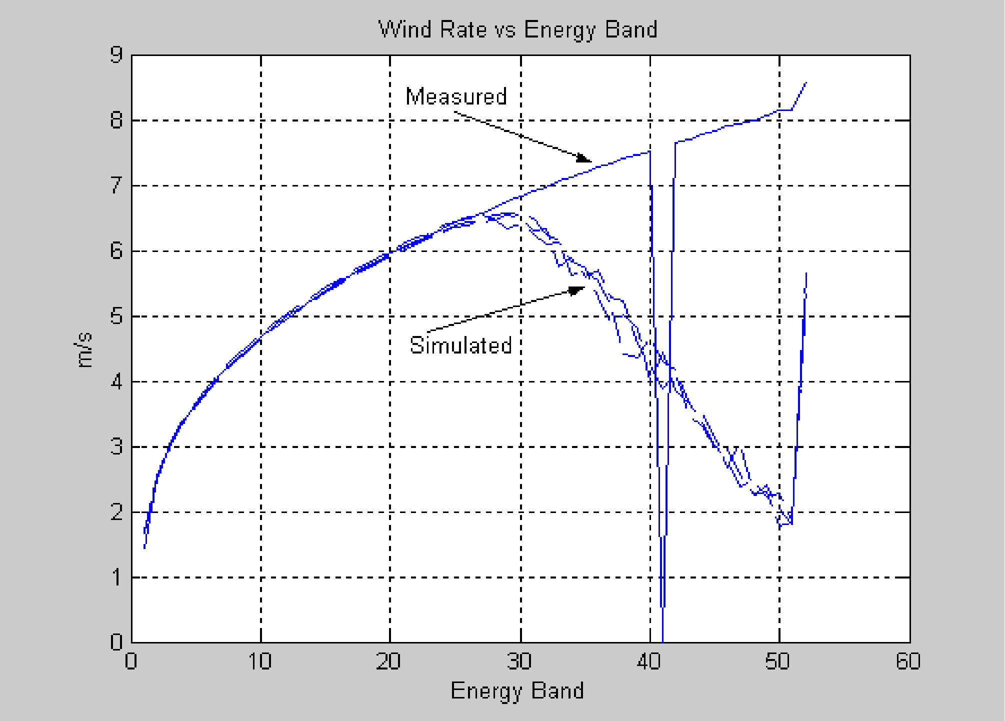


Figure 4.4-33 Wind rate vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation). 3 separated simulation sequences are compared

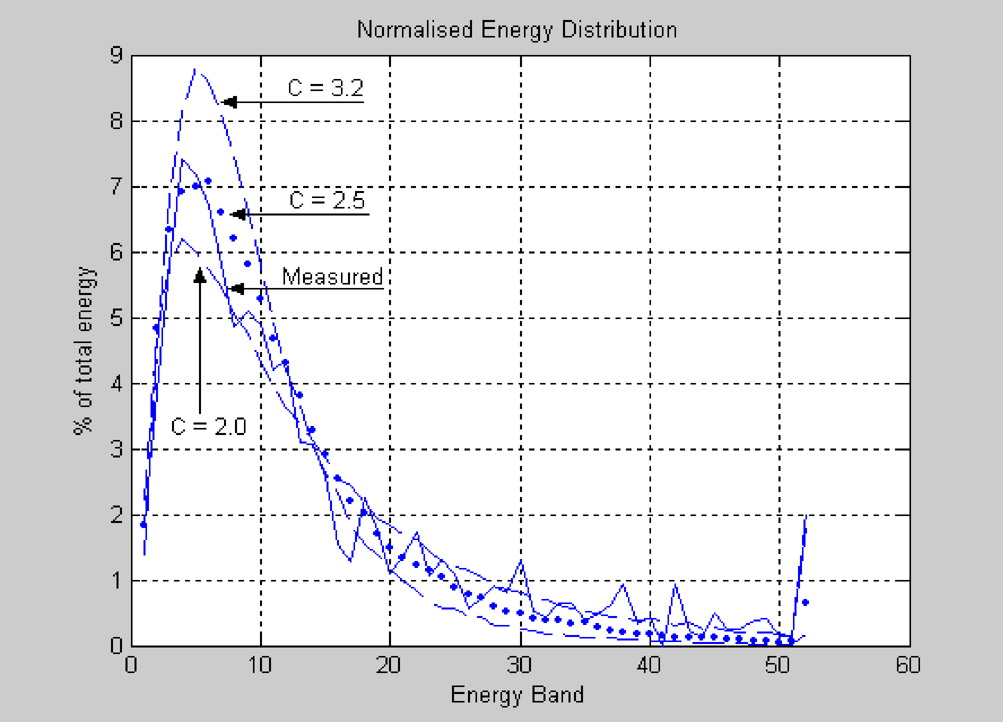


Figure 4.4-34 Normalised Energy Distribution vs Energy Band with altering C-parameter. (A, Turbulence and Turbulence variation are fixed nominal)

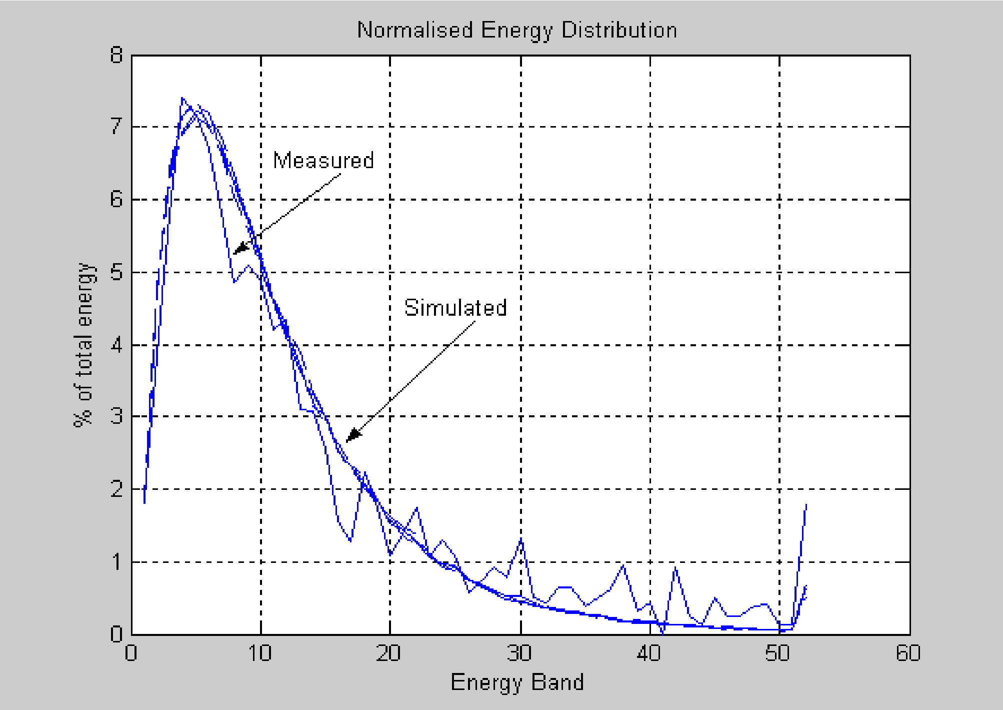


Figure 4.4-35 Normalised Energy Distribution vs Energy Band. (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation). 3 separated simulation sequences are compared

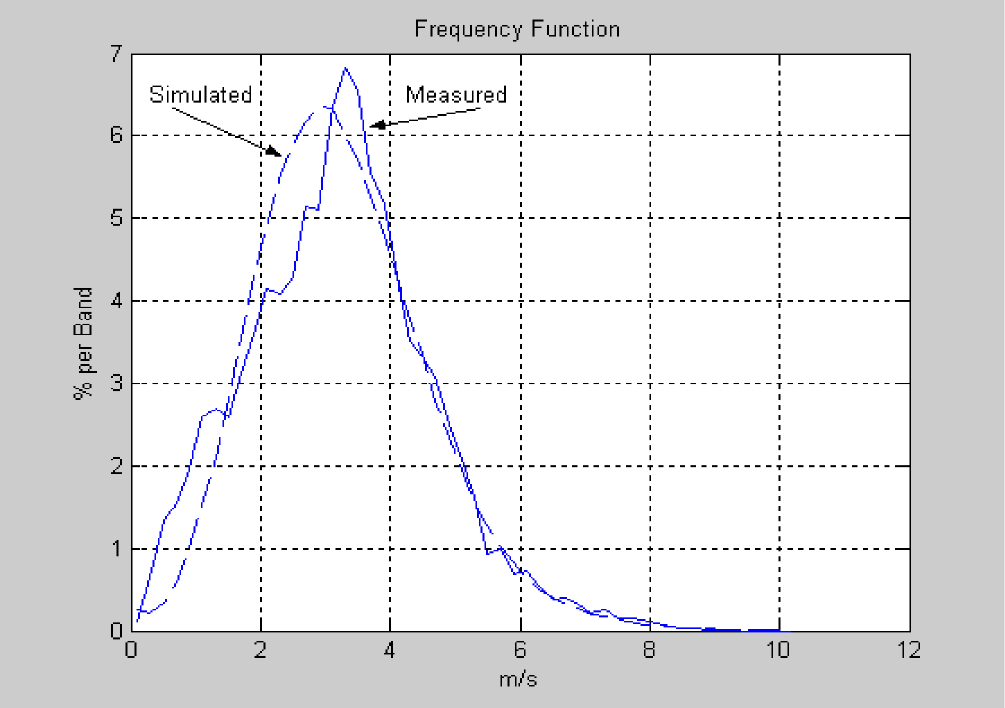


Figure 4.4-36 Frequency Function vs Wind Rate Band (see Figure 4.4-1). (A, C, Turbulence and Turbulence variation are fixed nominal in the simulation)

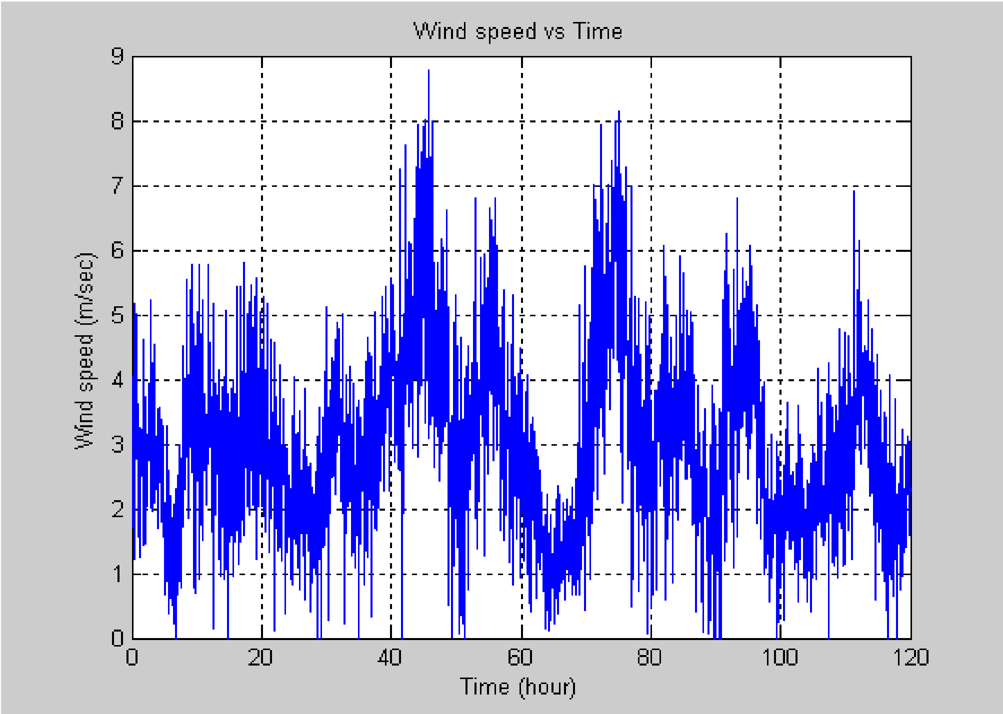


Figure 4.4-37 Simulated wind speed with nominal model parameters according to Table 4.4-1 and Table 4.4-2. Period 4.

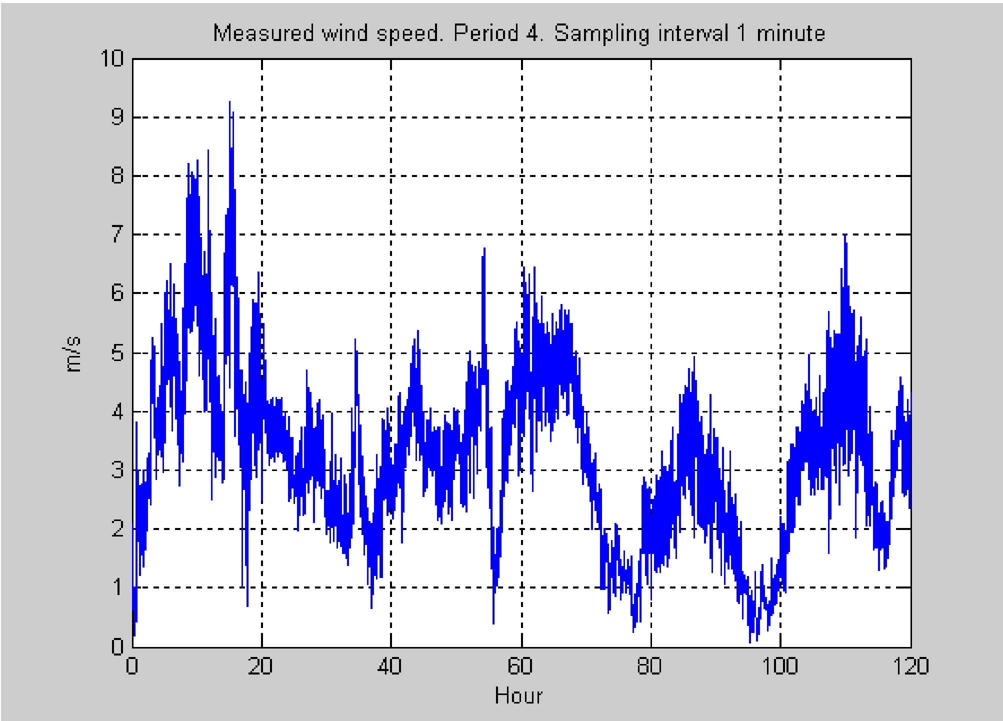


Figure 4.4-38 Measured wind speed. Period 4

Parameter	**Parameter Value**	**Relative Mean Energy:** $\frac{Simulated\ \mathrm{Re}\,sult}{Measurement\ \mathrm{Re}\,sult}$
A (C, Turbulence and Turbulence variation nominal)	2.80	0.4111
	3.80 (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	4.40	1.5980
C (A, Turbulence and Turbulence variation nominal)	2.00	1.1971
	2.50 (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	3.20	0.9766
Turbulence (C, A and Turbulence variation nominal)	5 %	0.9875
	15 %	1.0149
	20 % (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	25 %	1.1075
	35 %	1.1687
Turbulence variation (C, A and Turbulence nominal)	(3,1) (nominal)	**<u>1.0328</u>** (1.0359, 1.0587)
	(5,2)	1.0310
	(10,3)	1.0101

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

Mean (m/s)		Standarddev. (m/s)		Maximum (m/s)		Minimum (m/s)	
Meas.	Sim.	Meas.	Sim.	Meas.	Sim.	Meas.	Sim.
3.2	3.4 (3.4, 3.4)	1.4	1.2 (1.2, 1.2)	9.2	8.6 (8.5, 8.7)	0.1	0.1 (0.2, 0.1)

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 recommened:

- *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 bee canseled 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 bee canseled if point b) is realized.

b) The graphs that give the correlation between the 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 bee canseled 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

Model parameter	Estimation method
Sim_step_W_My	Visual comparison between the measurement and simulation regarding the period of time
Sim_step_W_Sigma	-“-
Sim_step_T_My	-“-
Sim_step_T_Sigma	-“-
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 teorethical 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:

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

Equation 5.1-2:

$$S = S_0 \cdot \tau$$

Equation 5.1-3:

$$M = \frac{h}{h_0}$$

Equation 5.1-4:

$$S_M = S \cdot \cos\beta + Sdiff$$

Where:

τ: the atmospheric transmission (0 – 1)

Ext: the extinction coefficient (in the wave length region of silicon photovoltaic solarcells)

M : 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: the atmospheric depth

h_0: the atmospheric depth for $\alpha = \frac{\pi}{2}$

α: the Sun's altitude above the horizon

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

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

Sdiff: 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: effective irradiance (W/m^2) against a measuring surface (solar panel)

β: the angle between the surface normal of the measuring surface (solar panel) and the direction to Sun

Cos β 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

Ω_Z : the normal angle of the measuring surface relative to zenith

Ω_S : the normal angle of the measuring surface relative to south

θ : the Sun's azimuth

α: the Sun's altitude above the horizon

α and θ are calculated according to paragraph 3.4 (Module *"Sun_intensity"*).

See **Figure 5.1-1** for some illustration of the above parameters.

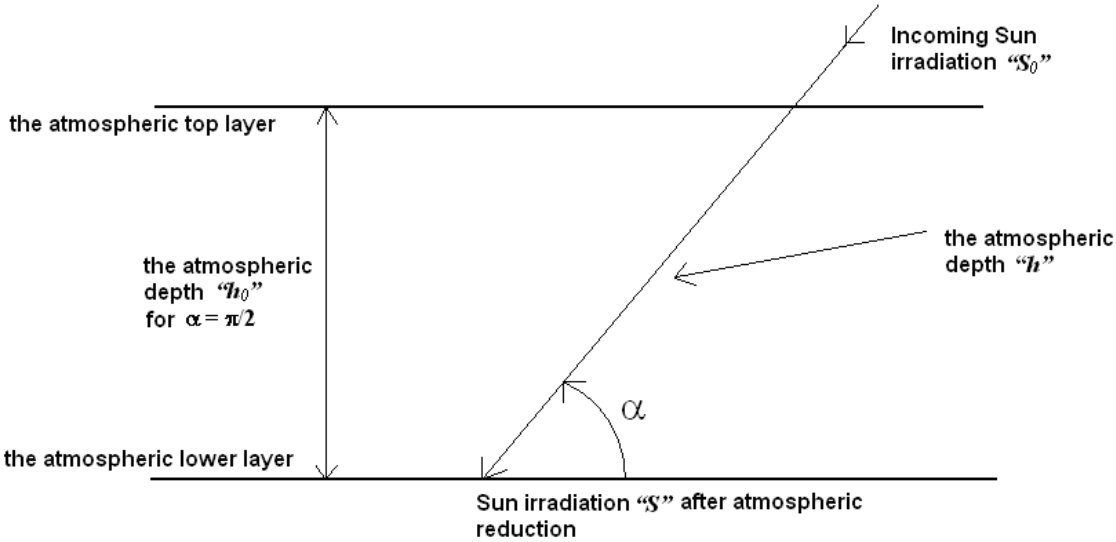


Figure 5.1-1 The radiation is reduced as an effect of the atmospheric influence

From **Figure 5.1-1** it could be established the following relation between M and α::

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
- Huminiy

- 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.

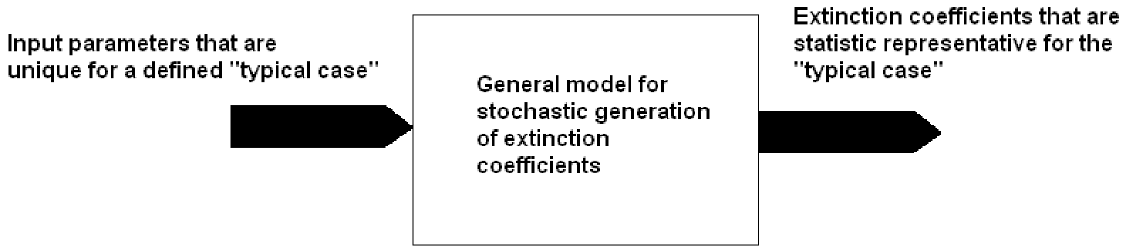


Figure 5.1-2 The principle of the stochastic model for generation of extinction coefficients

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

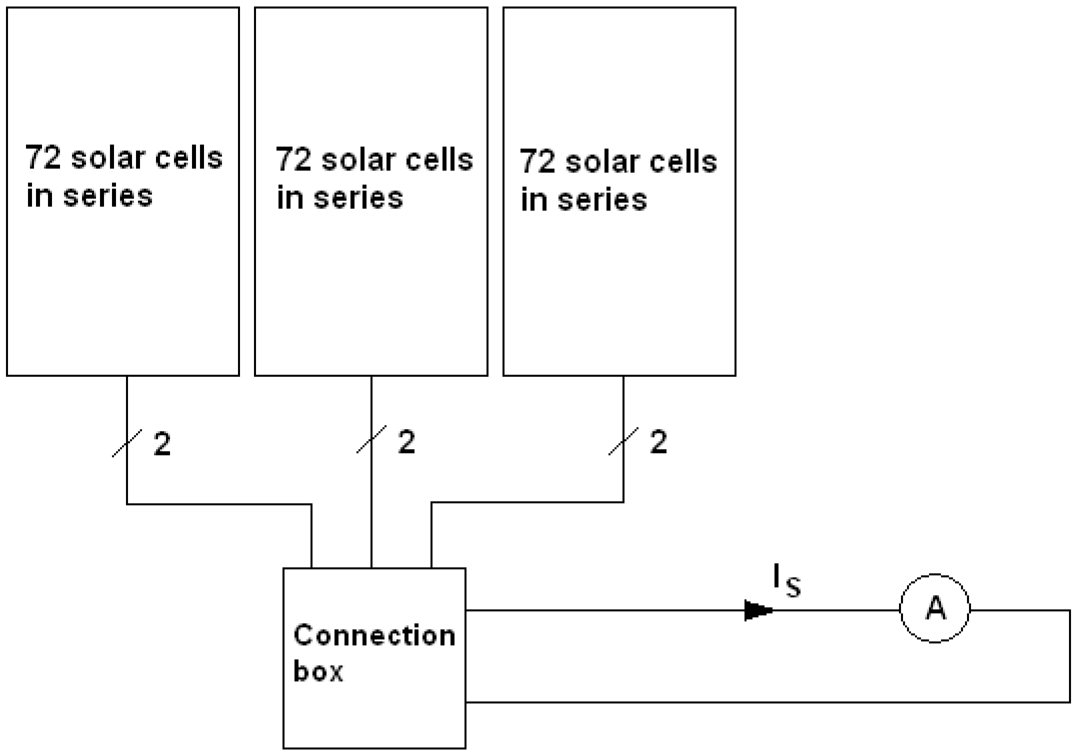


Figure 5.3-1 The principle for the measurement arrangement. The connection box connects the three solar cells panels in series. This results in 216 series connected solar cells

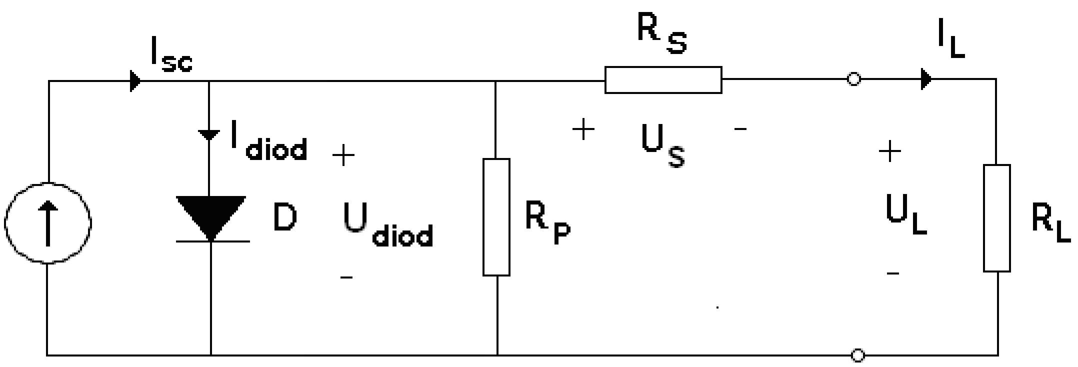


Figure 5.3-2 The equivalent circuit of a solar cell

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 mΩ) 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:

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

I.e.

$I_{SC} = I_S$ (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

$$S_M = S \cdot \cos\beta + Sdiff$$

This gives:

Equation 5.3-3:

$$I_S = G \cdot S_0 \cdot \exp(-Ext \cdot M) \cdot \cos\beta + G \cdot Sdiff = I_M \cdot \exp(-Ext \cdot M) \cdot \cos\beta + Idiff$$

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:

$$Ext = \frac{-\ln \dfrac{I_S - Idiff}{I_M \cdot \cos\beta}}{M}$$

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**.

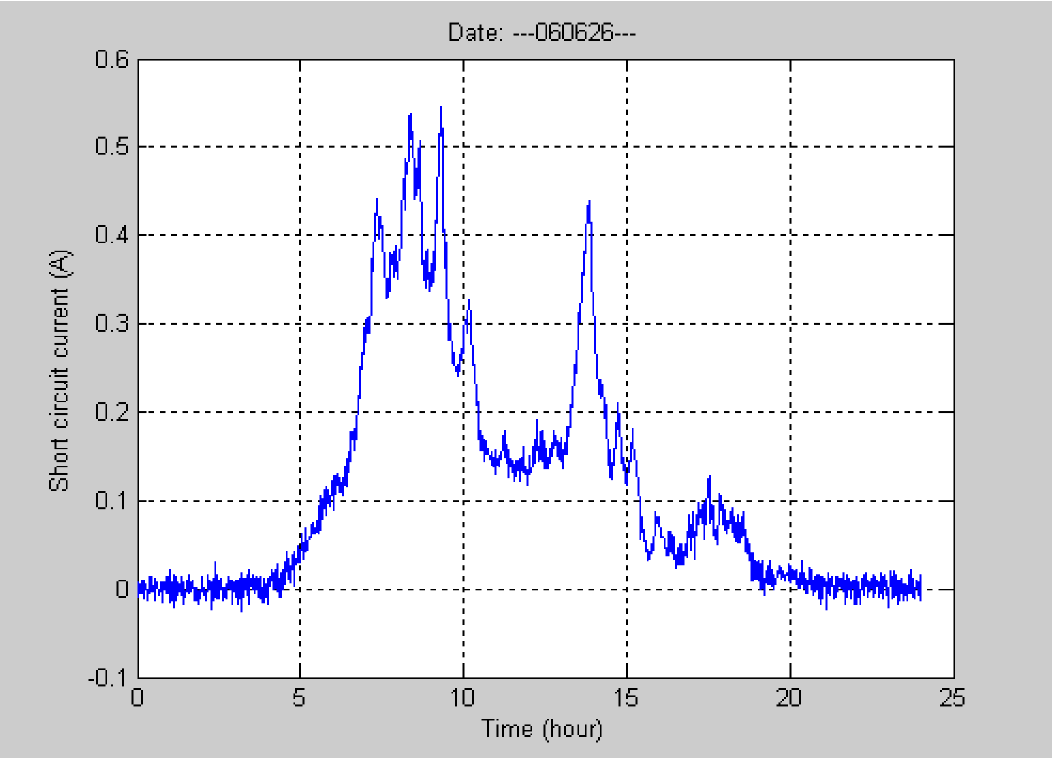


Figure 5.4-1 Short circuit current 060626

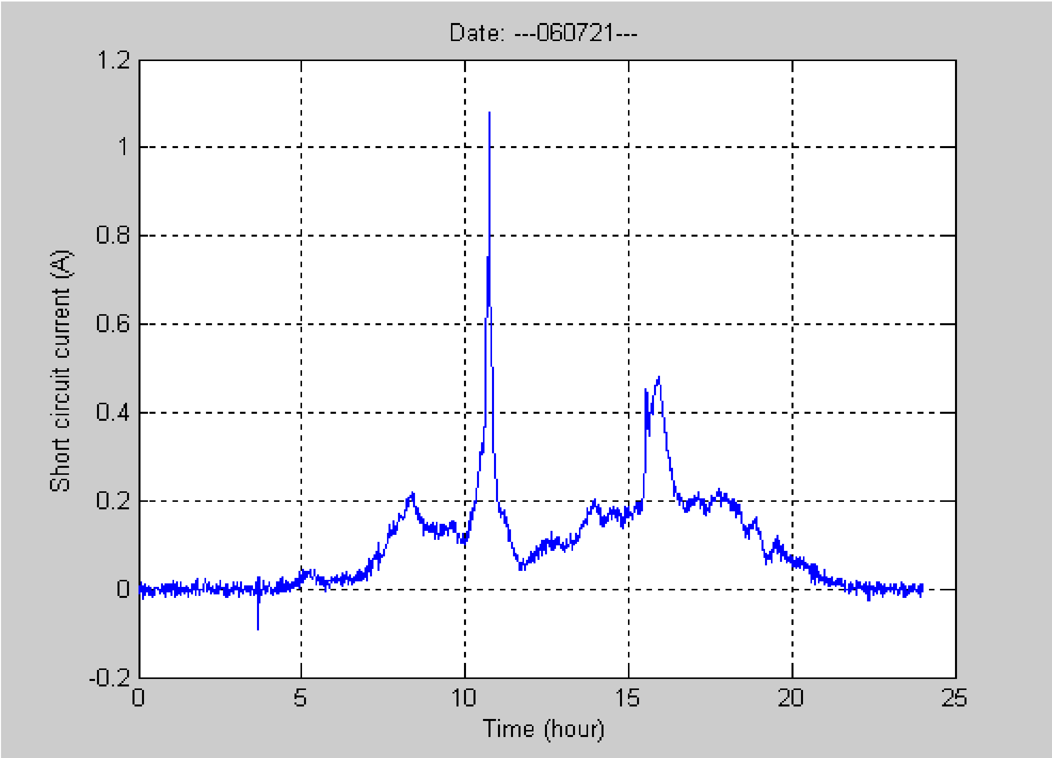


Figure 5.4-2 Short circuit current 060721

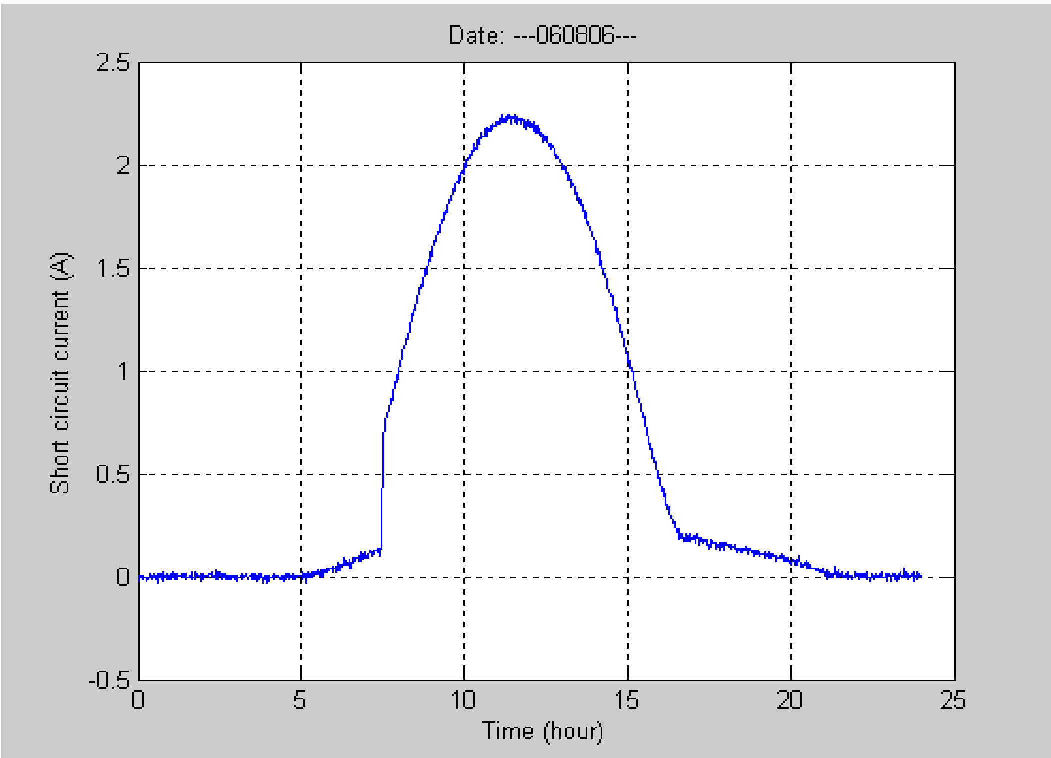


Figure 5.4-3 **Short circuit current 060806**

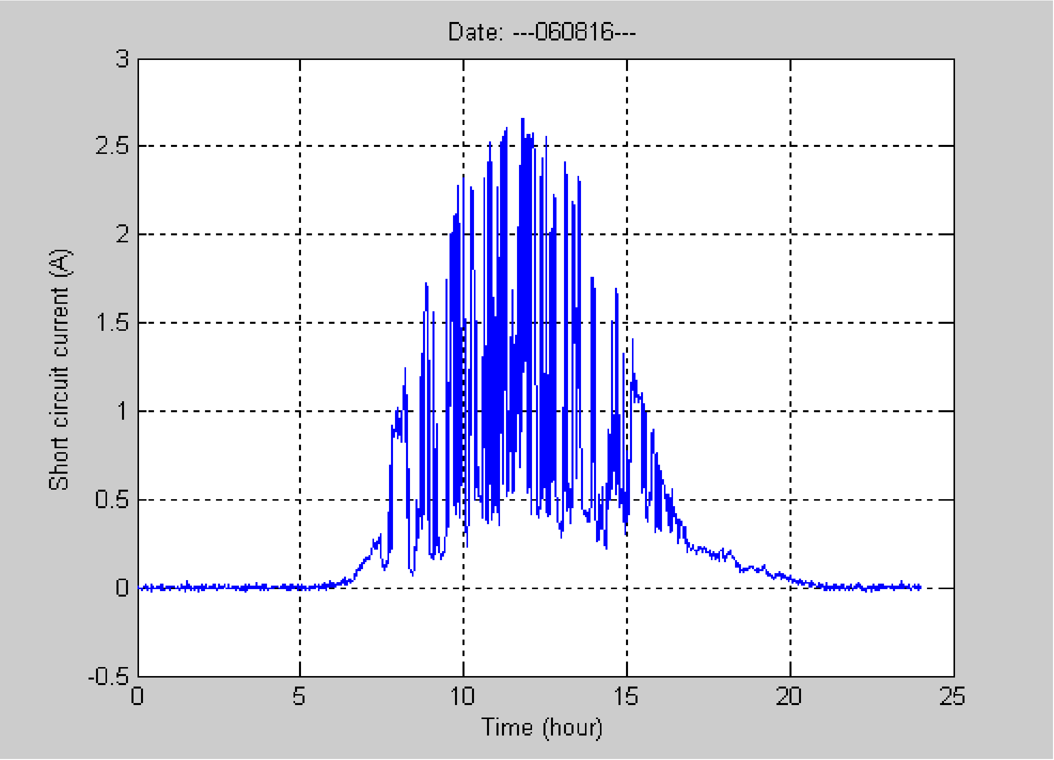


Figure 5.4-4 Short circuit current 060816

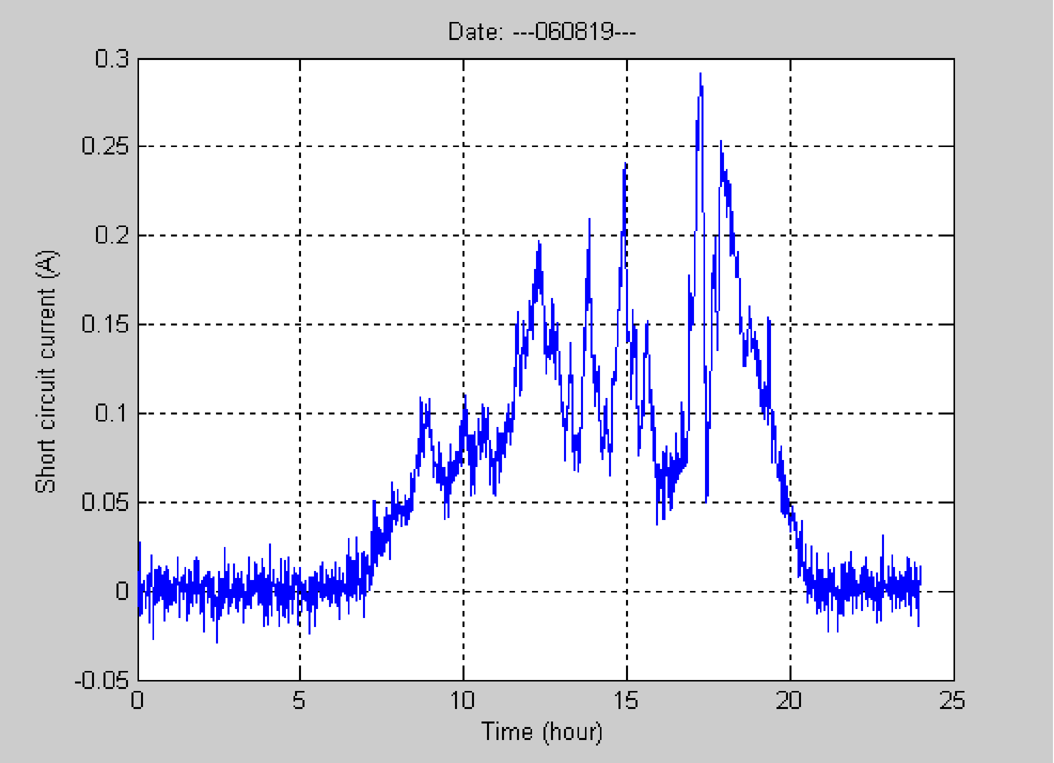


Figure 5.4-5 Short circuit current 060819

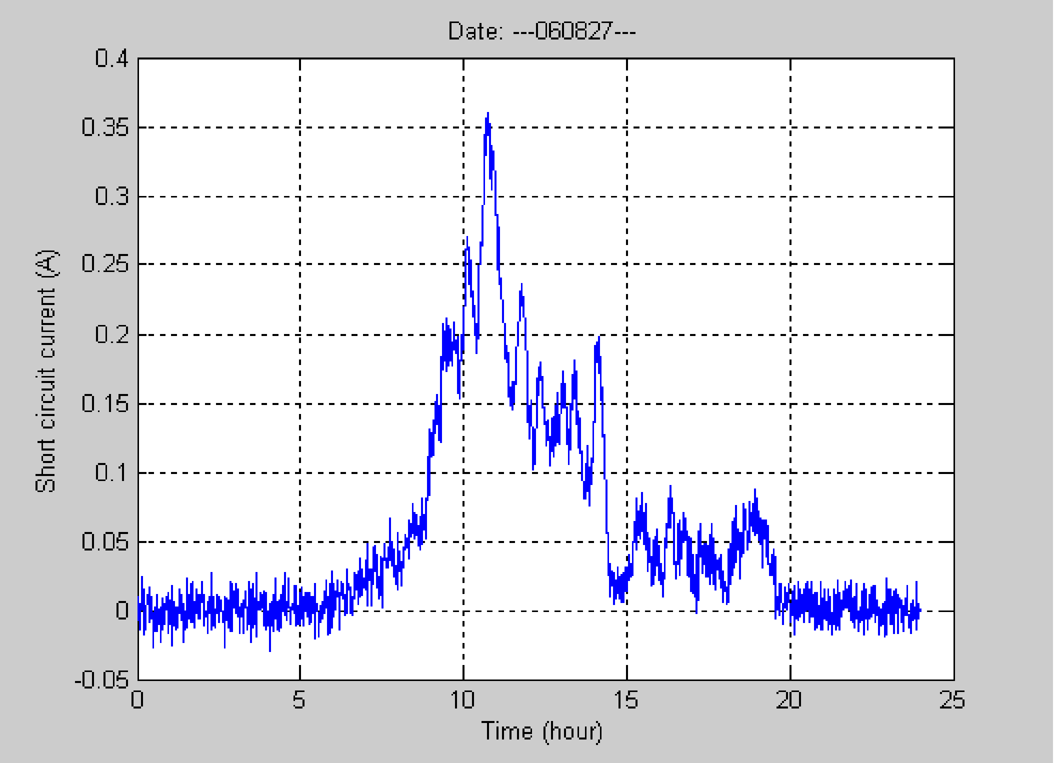


Figure 5.4-6 Short circuit current 060827

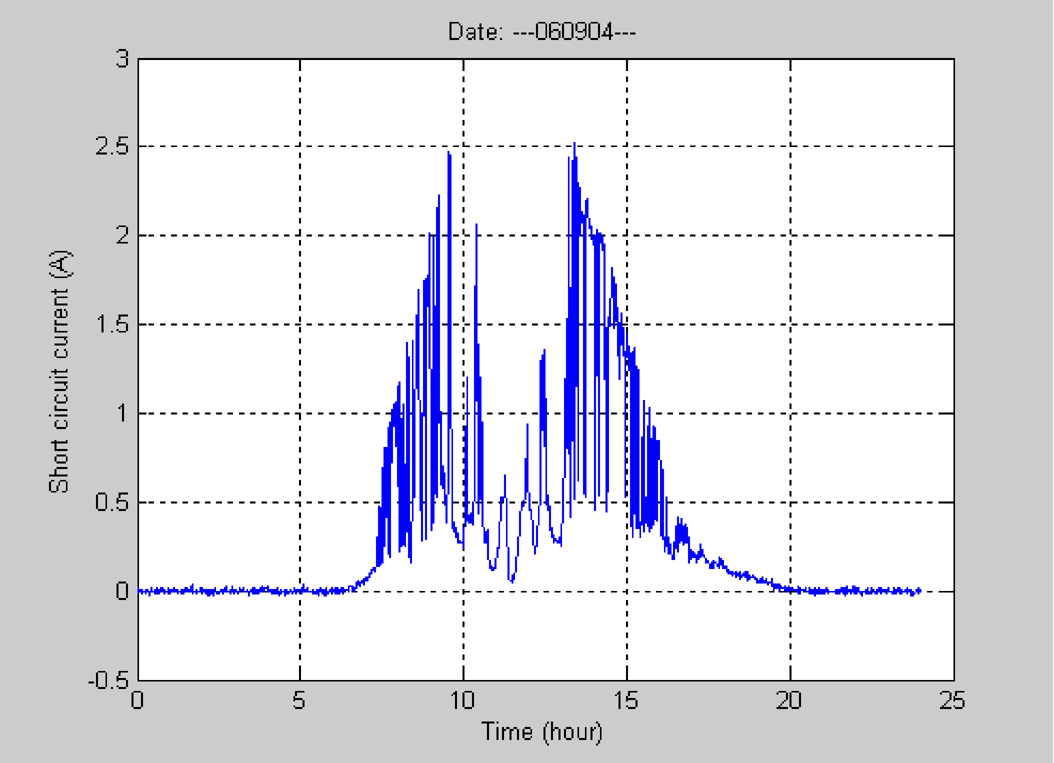


Figure 5.4-7 Short circuit current 060904

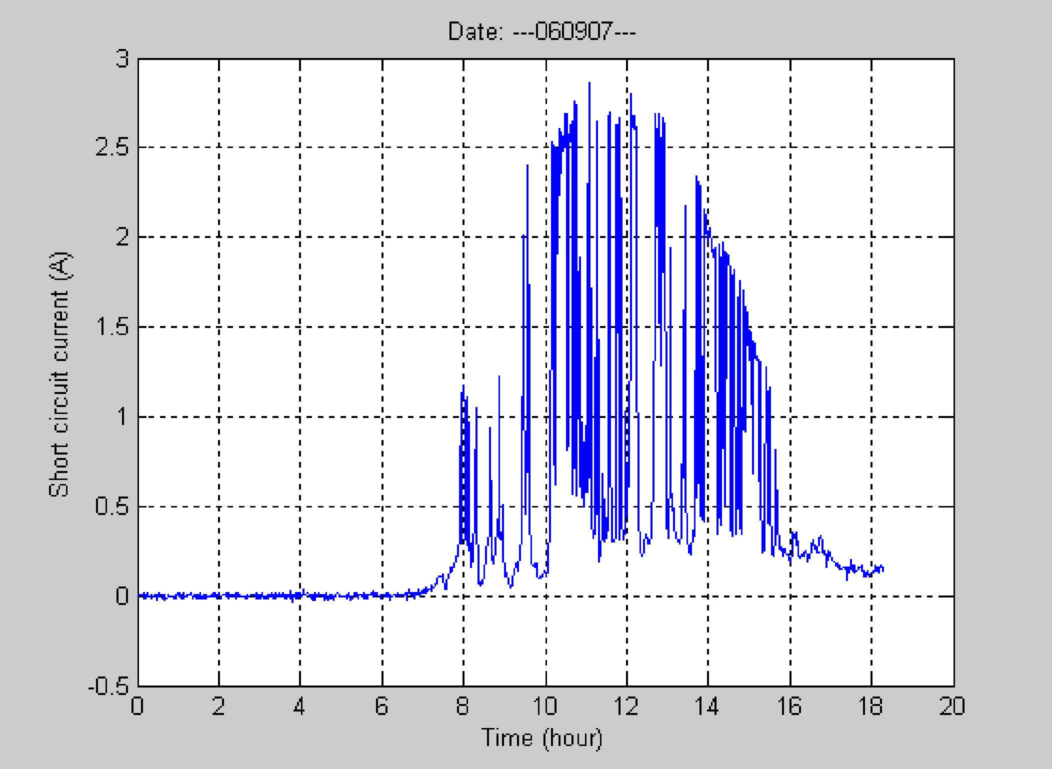


Figure 5.4-8 Short circuit current 060907

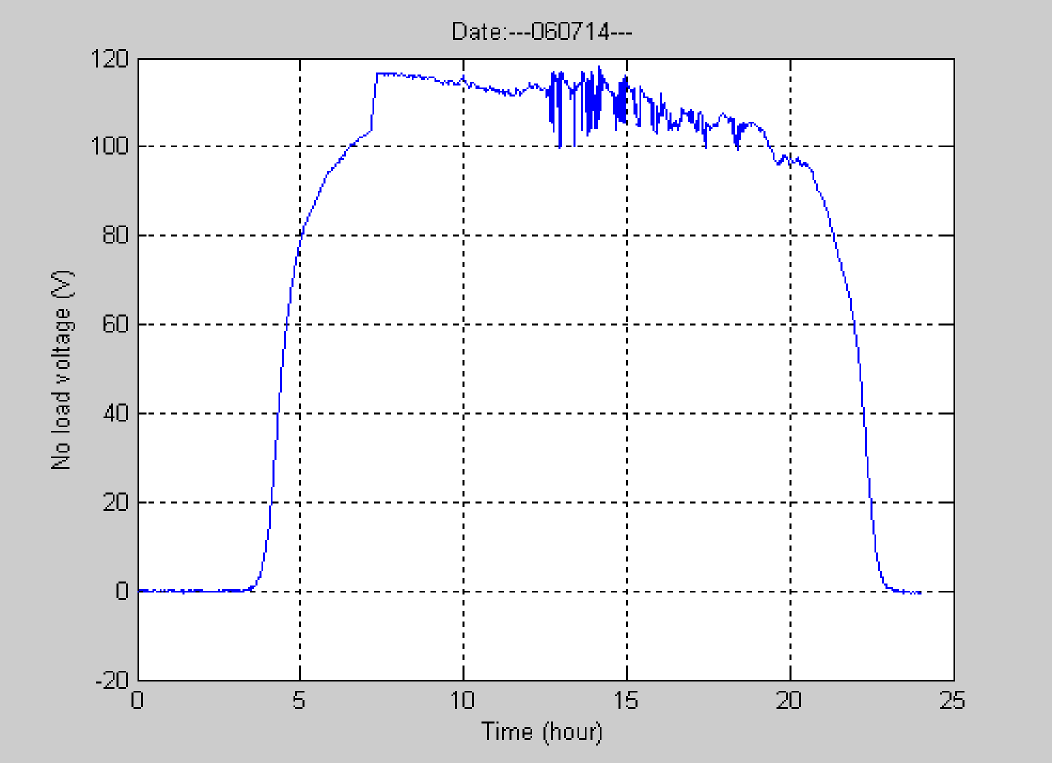


Figure 5.4-9 No load voltage 060714

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 enougt 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 answeres about these questions.

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

Idiff: 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 mesurements, 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”.

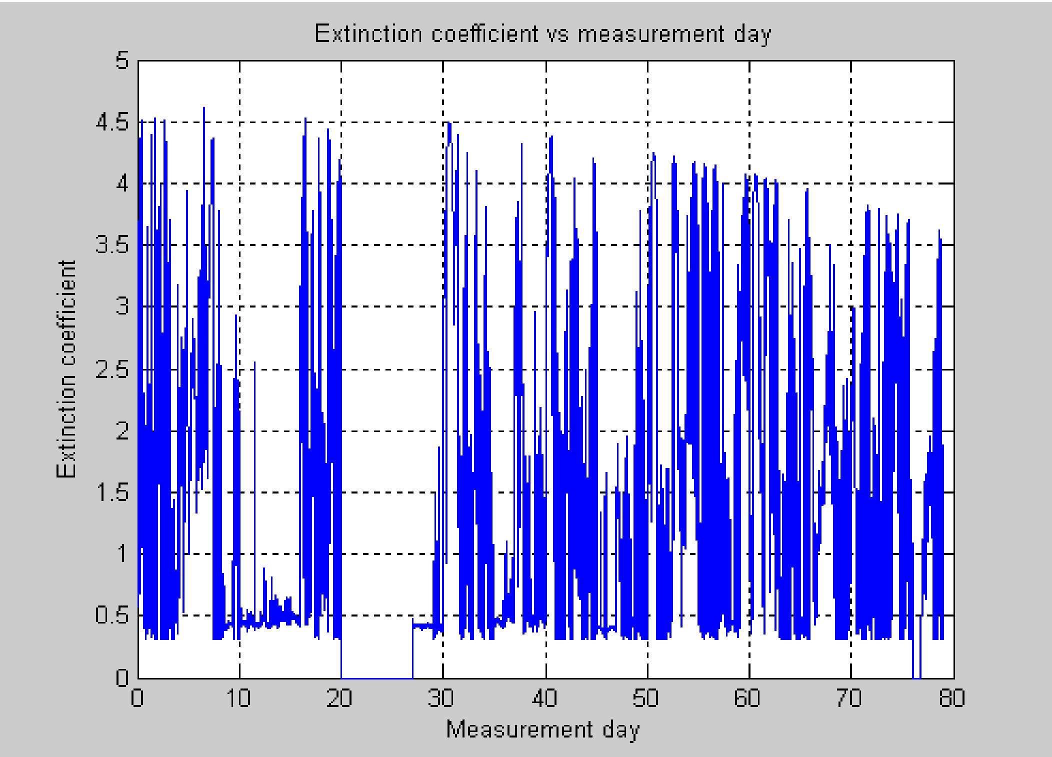


Figure 5.5-1 Profile of the extinction coefficient, based on the mesurements, during the period from 21/6 to 7/9 2006.

Measuring day (number)	Date	Cloudiness (mean value)	Mean value of extinction coefficient 9 am to 15 pm	Standard deviation of extinction coefficient 9 am to 15 pm
1	2006-06-21	5 – 6/8	1.82	1.12
2	-22	5 – 6/8	1.58	1.18
3	-23	5 – 6/8	2.03	1.09
4	-24	3 – 4/8	0.94	0.70
5	-25	5 – 6/8	1.98	0.62
6	-26	5 – 6/8	2.08	0.50
7	-27	7 – 8/8	2.42	0.49
8	-28	5 – 6/8	1.96	1.56
9	-29	1 – 2/8	0.65	0.56
10	-30	3 – 4/8	0.99	0.79
11	-07-01	0 – 1/8	0.44	0.04
12	-02	0 – 1/8	0.46	0.17
13	-03	0 – 1/8	0.46	0.05
14	-04	0 – 1/8	0.48	0.05
15	-05	0 – 1/8	0.50	0.04
16	-06	0 – 1/8	0.48	0.02
17	-07	7 – 8/8	2.27	1.54
18	-08	5 – 6/8	1.96	1.15
19	-09	5 – 6/8	1.72	1.00
20	-10	5 – 6/8	1.84	1.06
28	-18	0 – 1/8	0.42	0.01
29	-19	0 – 1/8	0.42	0.01
30	-20	0 – 1/8	0.41	0.12
31	-21	7 – 8/8	3.85	0.75
32	-22	7 – 8/8	2.42	1.42
33	-23	5 – 6/8	1.60	1.10
34	-24	5 – 6/8	1.99	1.22
35	-25	5 – 6/8	1.49	0.96
36	-26	0 – 1/8	0.44	0.02
37	-27	0 – 1/8	0.53	0.08
		Mean value:	1.35	0.65

Table 5.5-1 Mean values and standard deviations of extinction koefficients 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

$\mu tot = -0.8863$ and $\sigma tot = 0.9652$

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

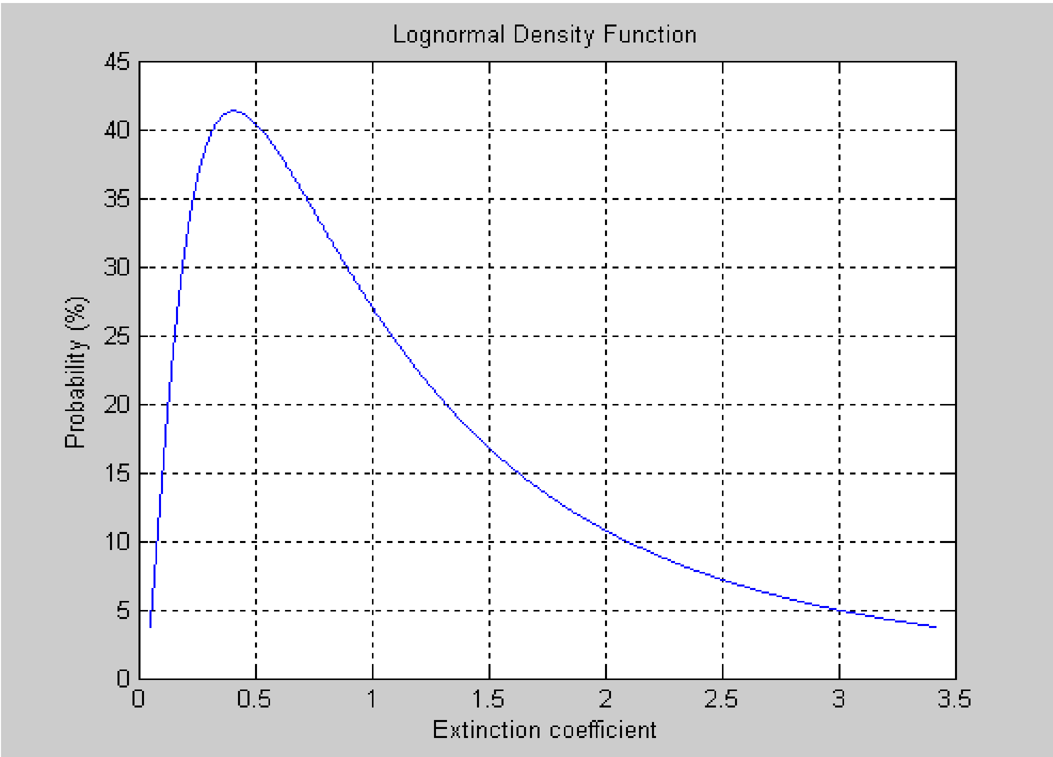


Figure 5.5-2 The extinction coefficient density function with $\mu tot = -0.8863$ and $\sigma tot = 0.9652$

Measuring day (number)	Date	Cloudiness (mean value)	Mean value of nat log for extinction coefficient 9 am to 15 pm **μ**	Standard deviation of nat log for extinction coefficient 9 am to 15 pm **σ**
1	2006-06-21	5 – 6/8	0.0602	1.0661
2	-22	5 – 6/8	-0.5869	1.6811
3	-23	5 – 6/8	-0.1390	2.2193
4	-24	3 – 4/8	-1.0329	1.4186
5	-25	5 – 6/8	0.4247	0.4587
6	-26	5 – 6/8	0.5209	0.3211
7	-27	7 – 8/8	0.7211	0.2264
8	-28	5 – 6/8	-0.8158	2.5341
9	-29	1 – 2/8	-2.0478	1.4178
10	-30	3 – 4/8	-1.8986	2.8009
11	-07-01	0 – 1/8	-2.0920	0.2162
12	-02	0 – 1/8	-2.0284	0.3451
13	-03	0 – 1/8	-1.9814	0.2419
14	-04	0 – 1/8	-1.8449	0.2668
15	-05	0 – 1/8	-1.6916	0.2056
16	-06	0 – 1/8	-1.7998	0.1313
17	-07	7 – 8/8	0.1217	1.2163
18	-08	5 – 6/8	0.0141	1.3137
19	-09	5 – 6/8	0.0854	0.7732
20	-10	5 – 6/8	-0.1951	1.7054
28	-18	0 – 1/8	-2.2442	0.0905
29	-19	0 – 1/8	-2.2309	0.0792
30	-20	0 – 1/8	-2.5169	0.8713
31	-21	7 – 8/8	1.2291	0.2951
32	-22	7 – 8/8	0.2460	1.3772
33	-23	5 – 6/8	-0.3687	1.5807
34	-24	5 – 6/8	-0.1083	1.5530
35	-25	5 – 6/8	-0.7527	2.1293
36	-26	0 – 1/8	-2.0537	0.1183
37	-27	0 – 1/8	-1.5838	0.3016
		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 dached-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 (corresponding to the Sun in zenith)

S: 1000 W/m^2

S_0: 1367 W/m^2

The dached-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**.

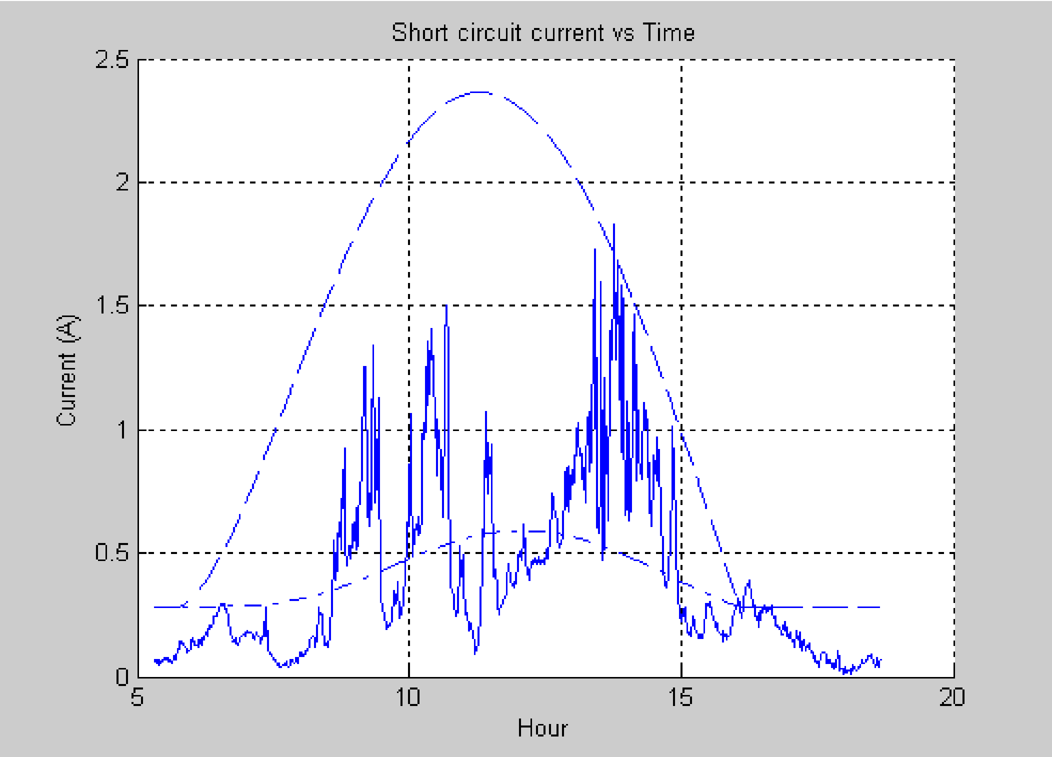


Figure 5.5-3 Measured and calculated short circuit current 060621
____: measured, _ _: 0.3126, _ . _: 1.8242

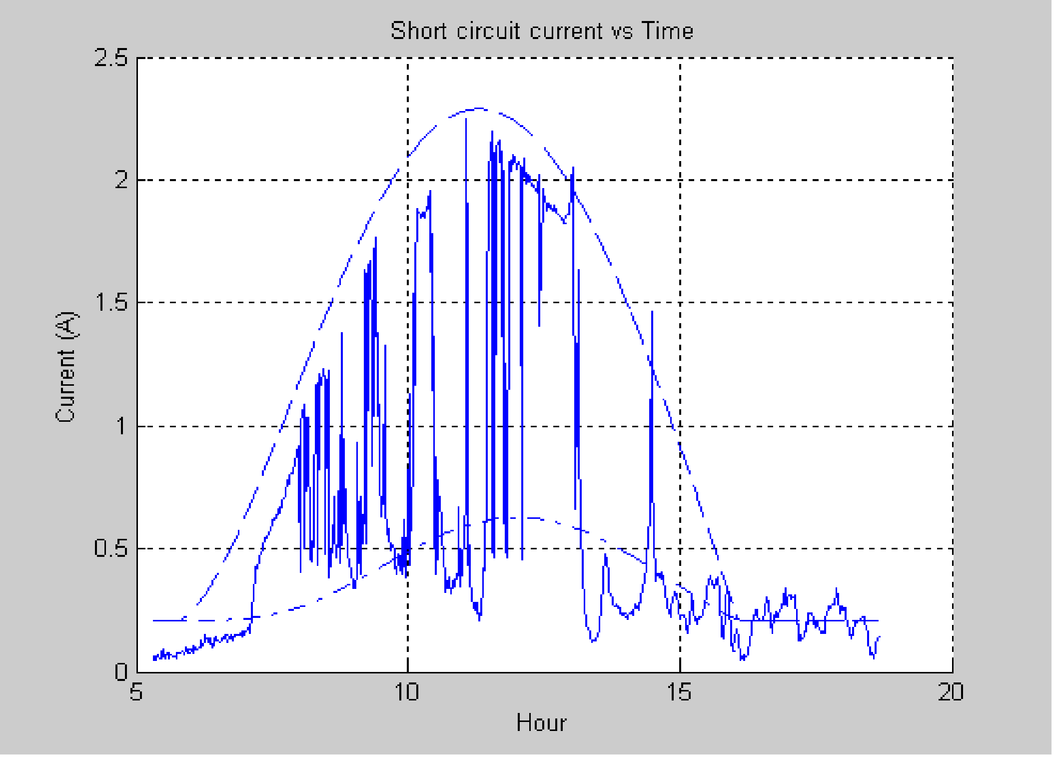


Figure 5.5-4 Measured and calculated short circuit current 060622
____: measured, _ _: 0.3126, _ . _: 1.5760

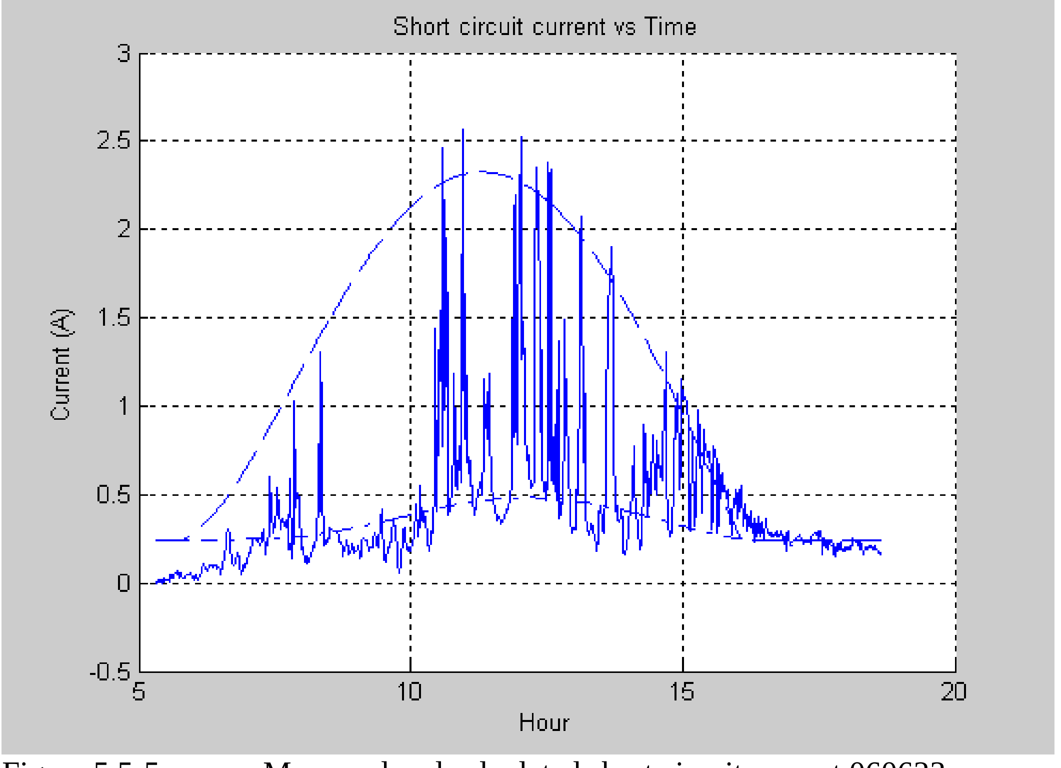


Figure 5.5-5 Measured and calculated short circuit current 060623
____: measured, _ _: 0.3126, _ . _: 2.0317

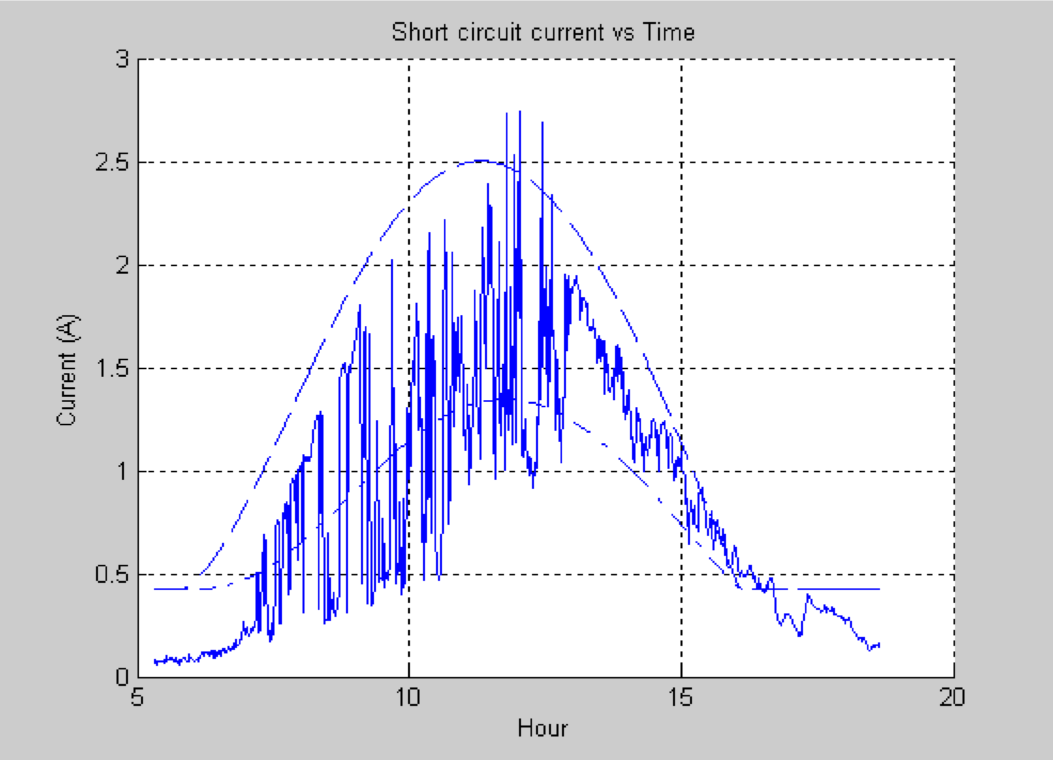


Figure 5.5-6 Measured and calculated short circuit current 060624
____: measured, _ _: 0.3126, _ . _: 0.9449

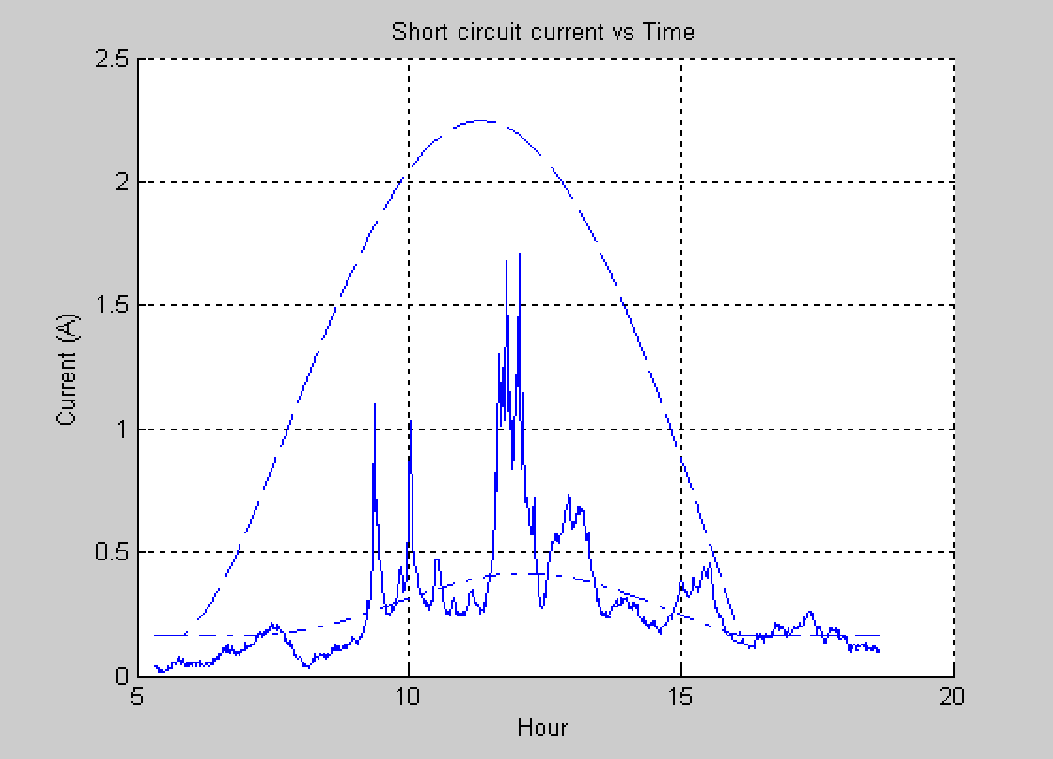


Figure 5.5-7 Measured and calculated short circuit current 060625
____: measured, _ _: 0.3126, _ . _: 1.9826

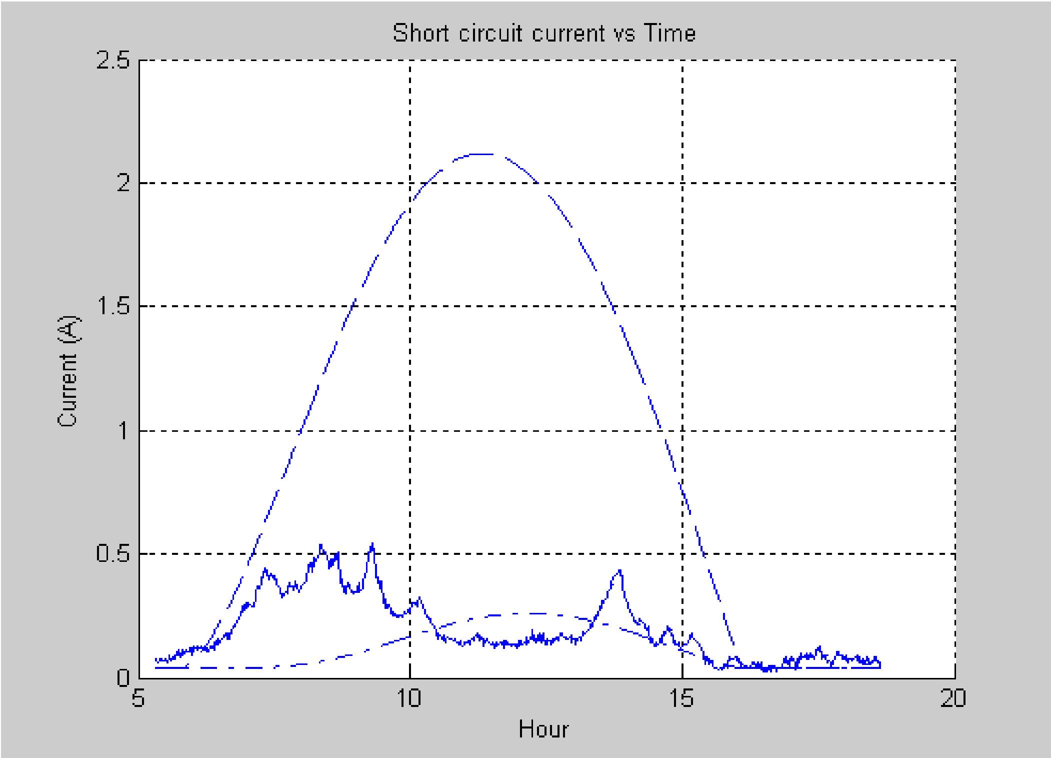


Figure 5.5-8 Measured and calculated short circuit current 060626

_____: measured, _ _: 0.3126, _ . _: 2.0771

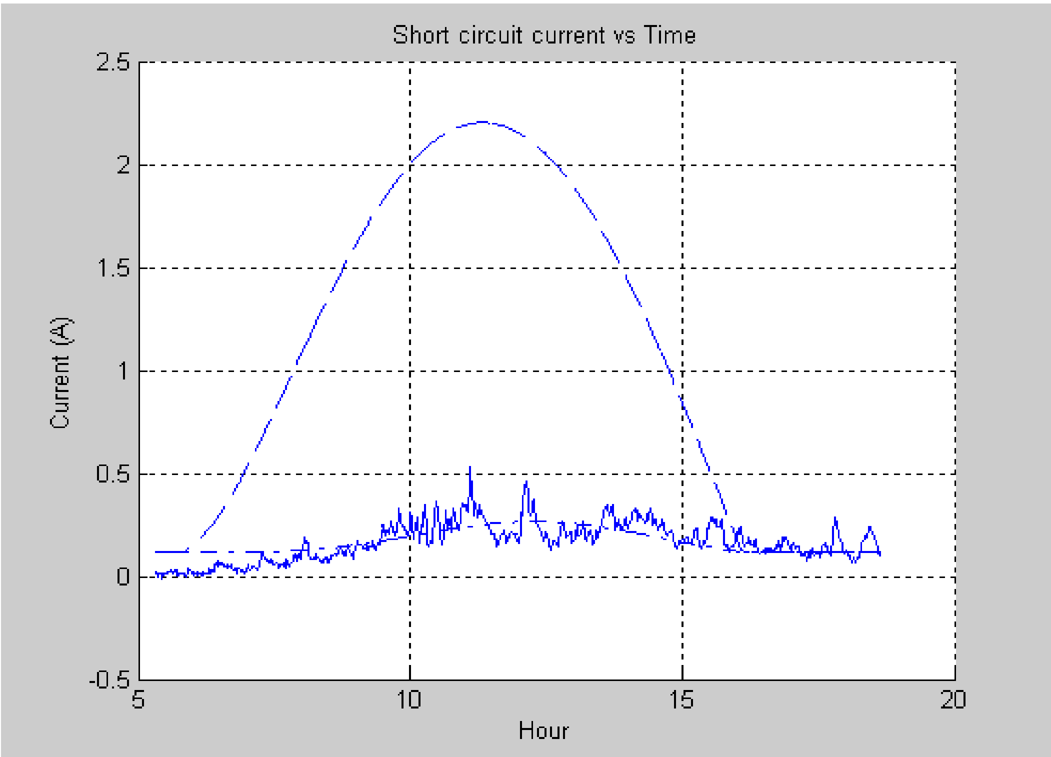


Figure 5.5-9 Measured and calculated short circuit current 060627

_____: measured, _ _: 0.3126, _ . _: 2.4233

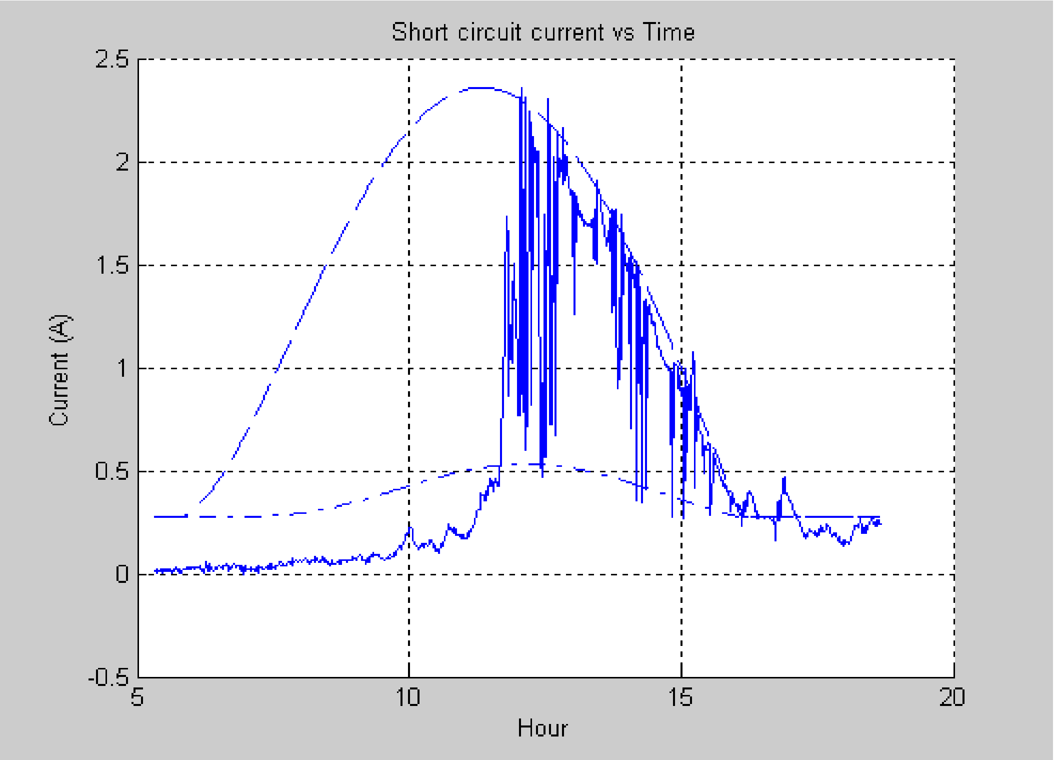


Figure 5.5-10 Measured and calculated short circuit current 060628
____: measured, _ _: 0.3126, _ . _: 1.9638

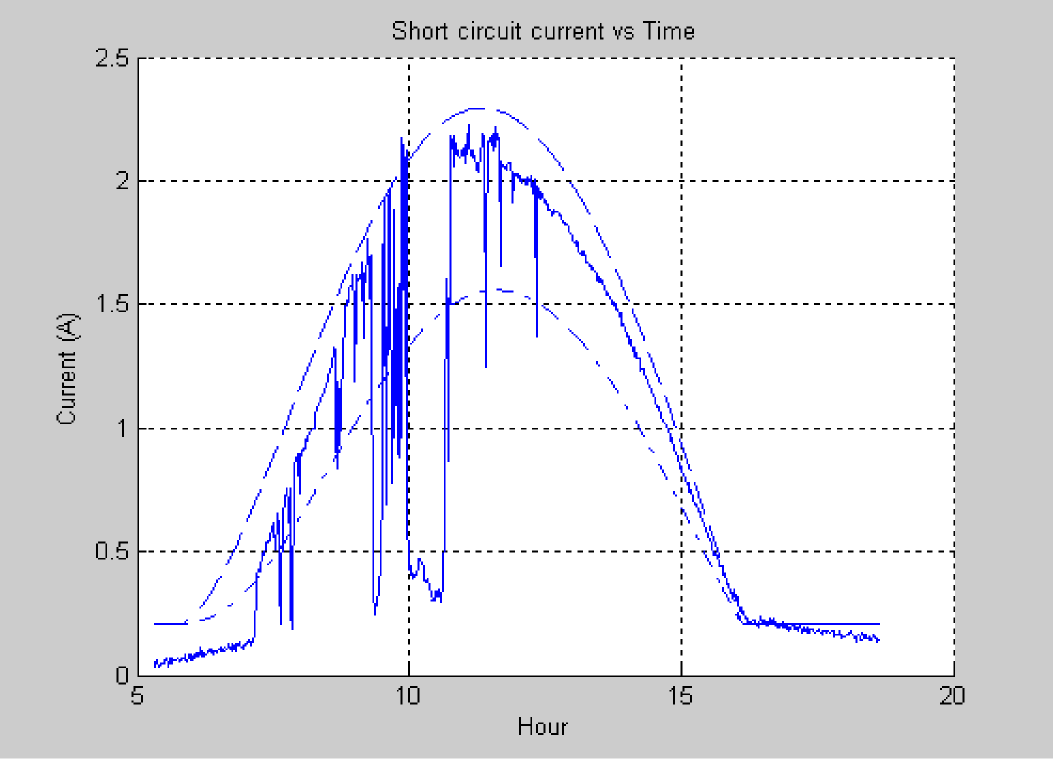


Figure 5.5-11 Measured and calculated short circuit current 060629
____: measured, _ _: 0.3126, _ . _: 0.6486

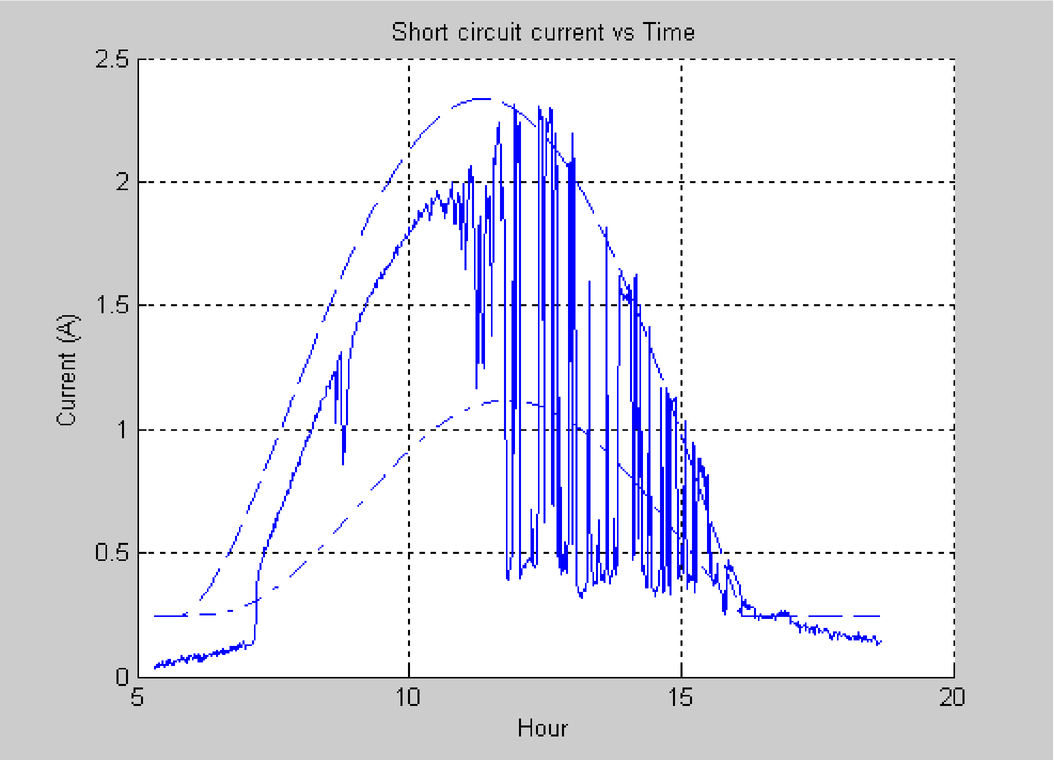


Figure 5.5-12 Measured and calculated short circuit current 060630
_____: measured, _ _: 0.3126, _ . _: 0.9933

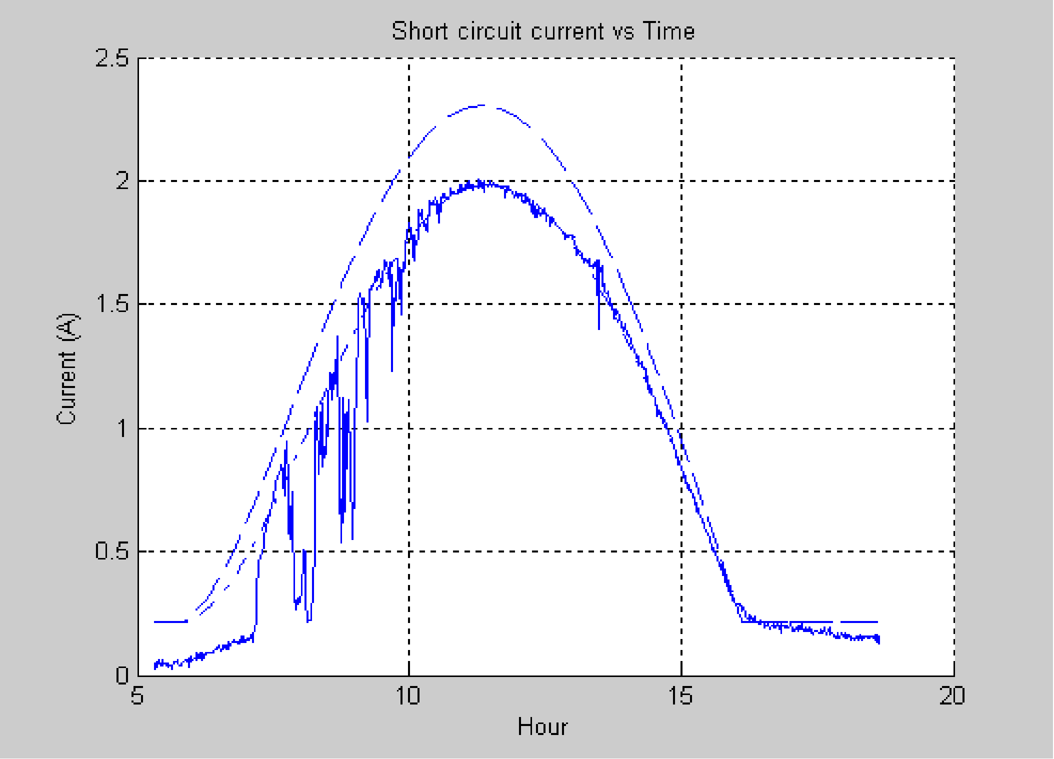


Figure 5.5-13 Measured and calculated short circuit current 060701
_____: measured, _ _: 0.3126, _ . _: 0.4393

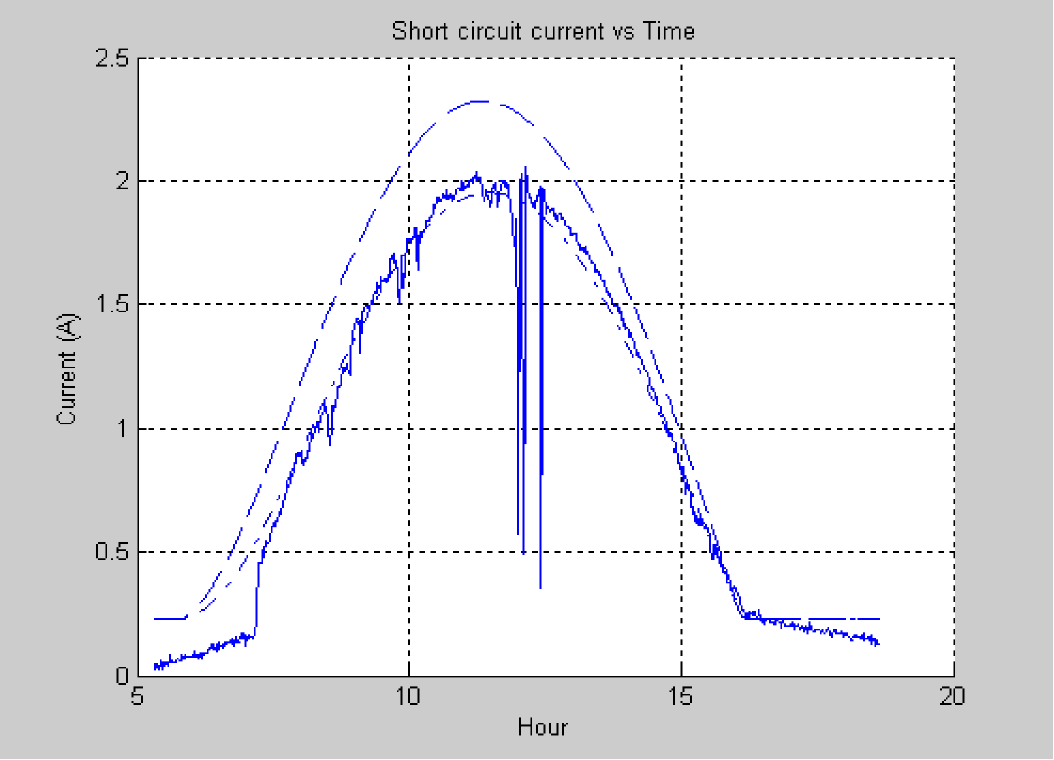


Figure 5.5-14 Measured and calculated short circuit current 060702
____: measured, _ _: 0.3126, _ . _: 0.4615

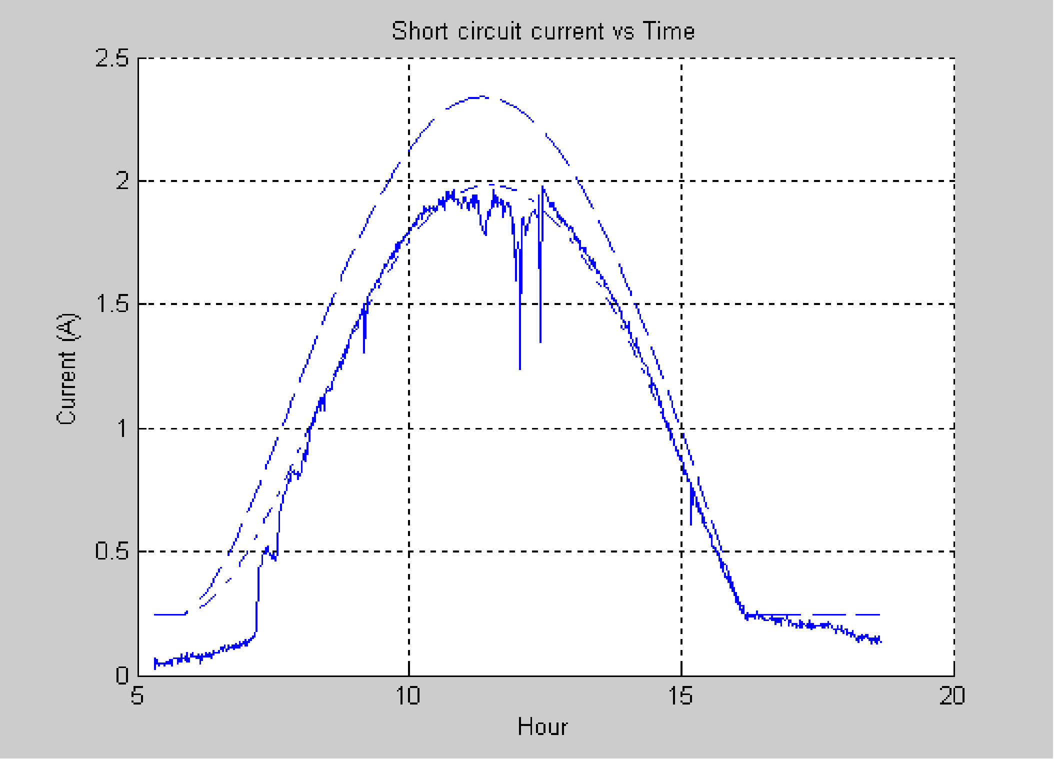


Figure 5.5-15 Measured and calculated short circuit current 060703
____: measured, _ _: 0.3126, _ . _: 0.4553

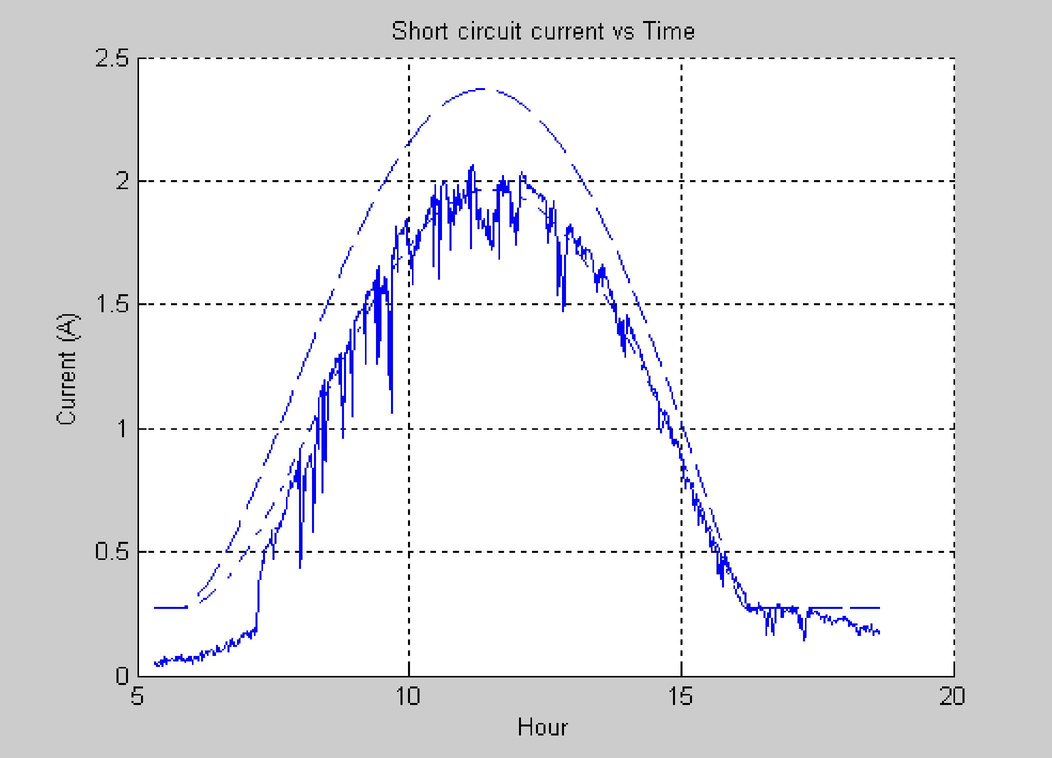


Figure 5.5-16 Measured and calculated short circuit current 060704
____: measured, _ _: 0.3126, _ . _: 0.4769

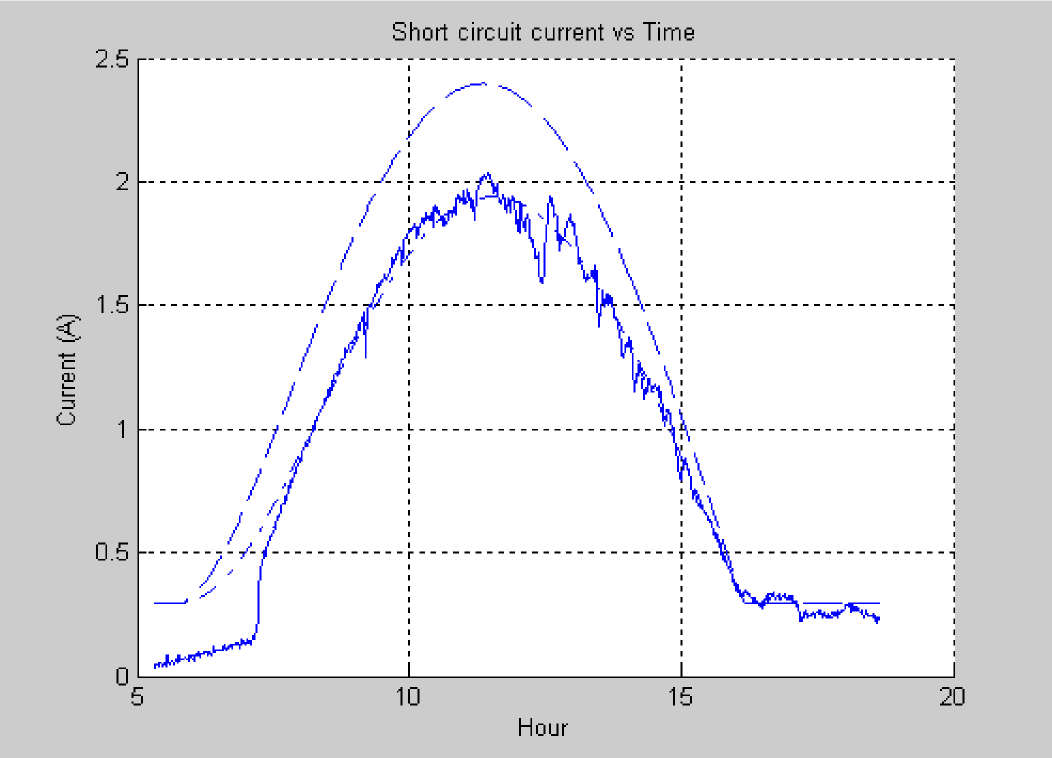


Figure 5.5-17 Measured and calculated short circuit current 060705
____: measured, _ _: 0.3126, _ . _: 0.5008

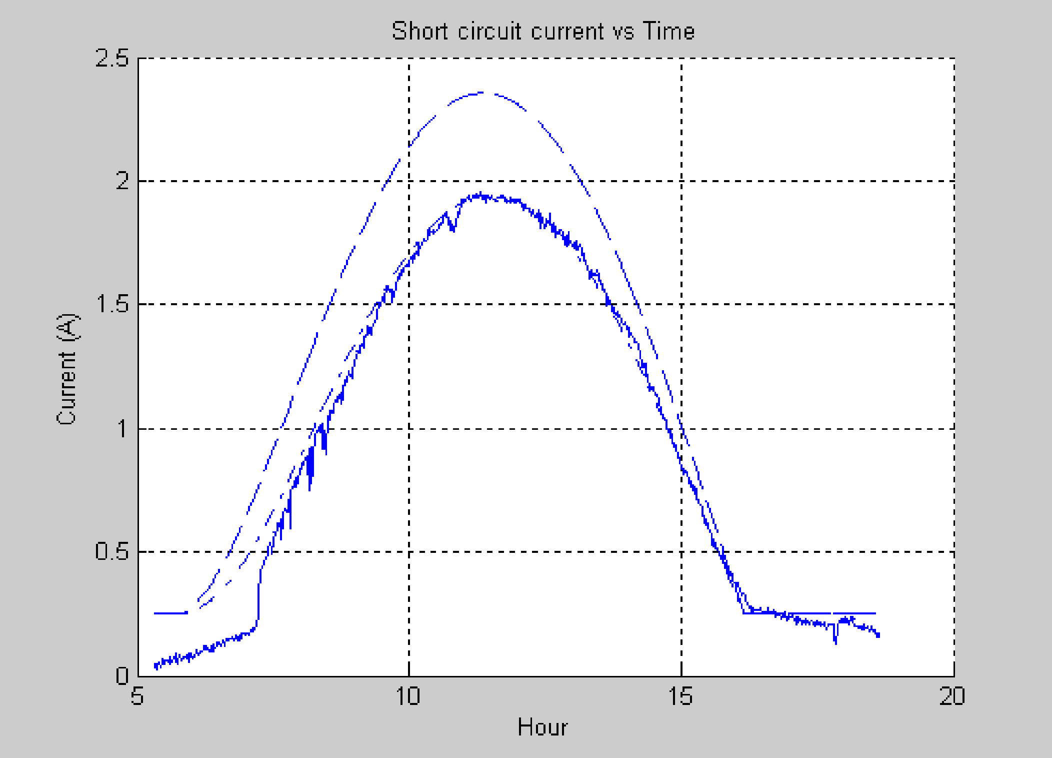


Figure 5.5-18 Measured and calculated short circuit current 060706
____: measured, _ _: 0.3126, _ . _: 0.4792

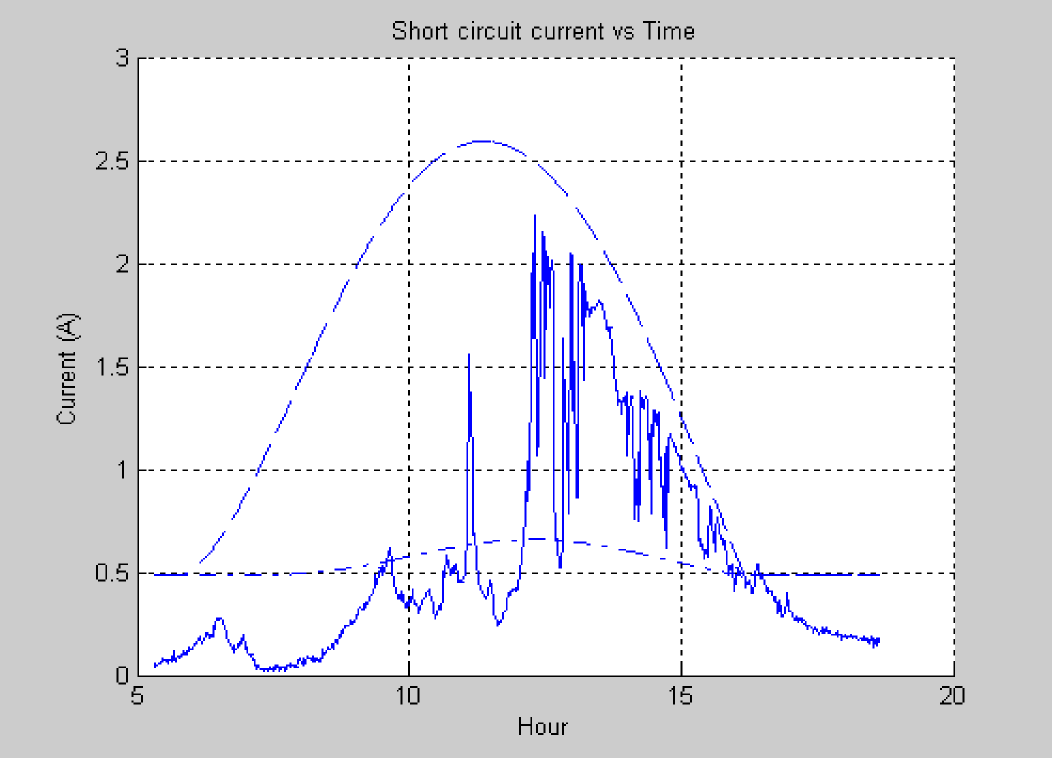


Figure 5.5-19 Measured and calculated short circuit current 060707
____: measured, _ _: 0.3126, _ . _: 2.2706

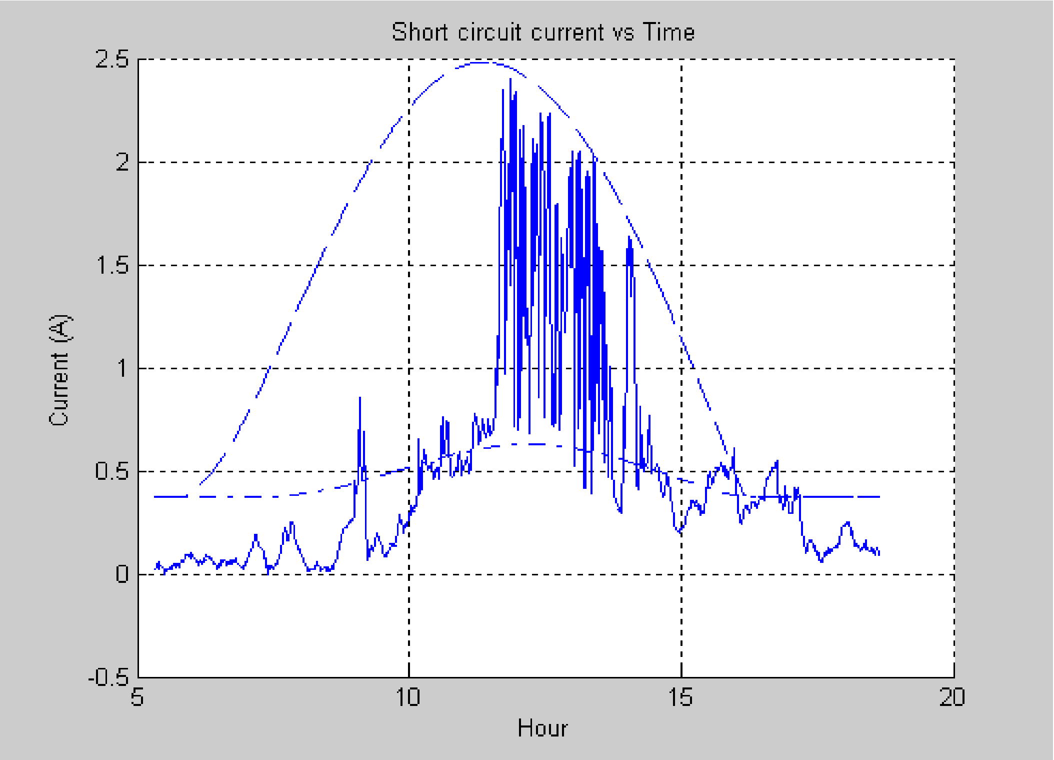


Figure 5.5-20 Measured and calculated short circuit current 060708
____: measured, _ _: 0.3126, _ . _: 1.9575

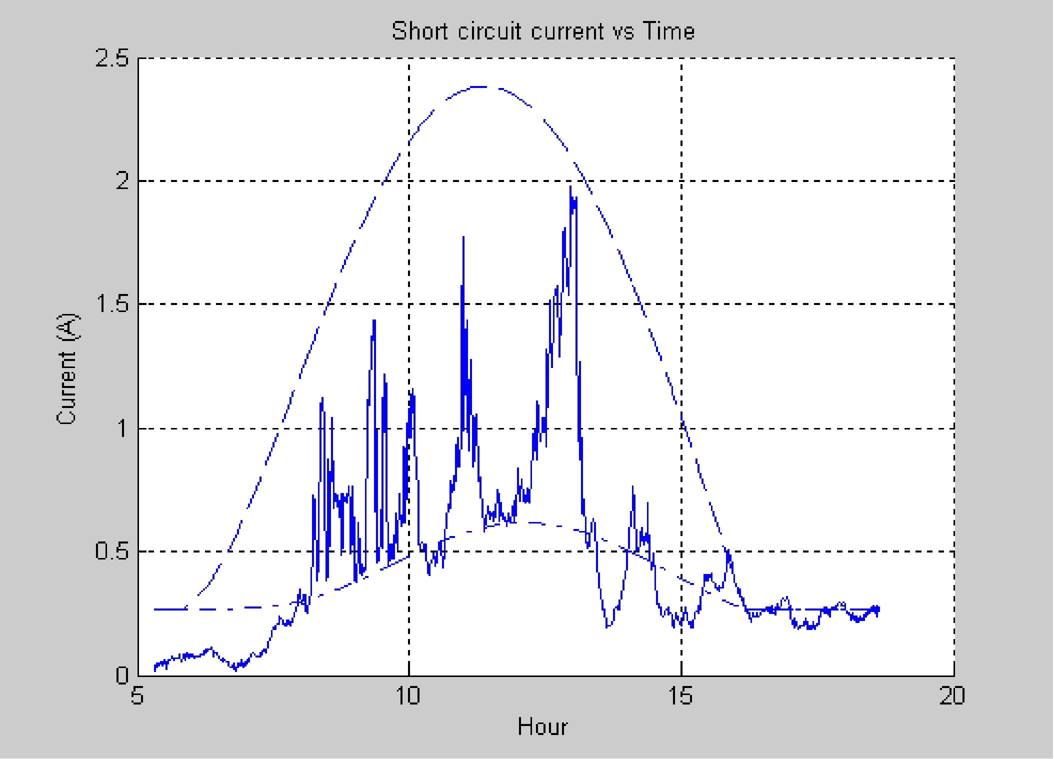


Figure 5.5-21 Measured and calculated short circuit current 060709
____: measured, _ _: 0.3126, _ . _: 1.7162

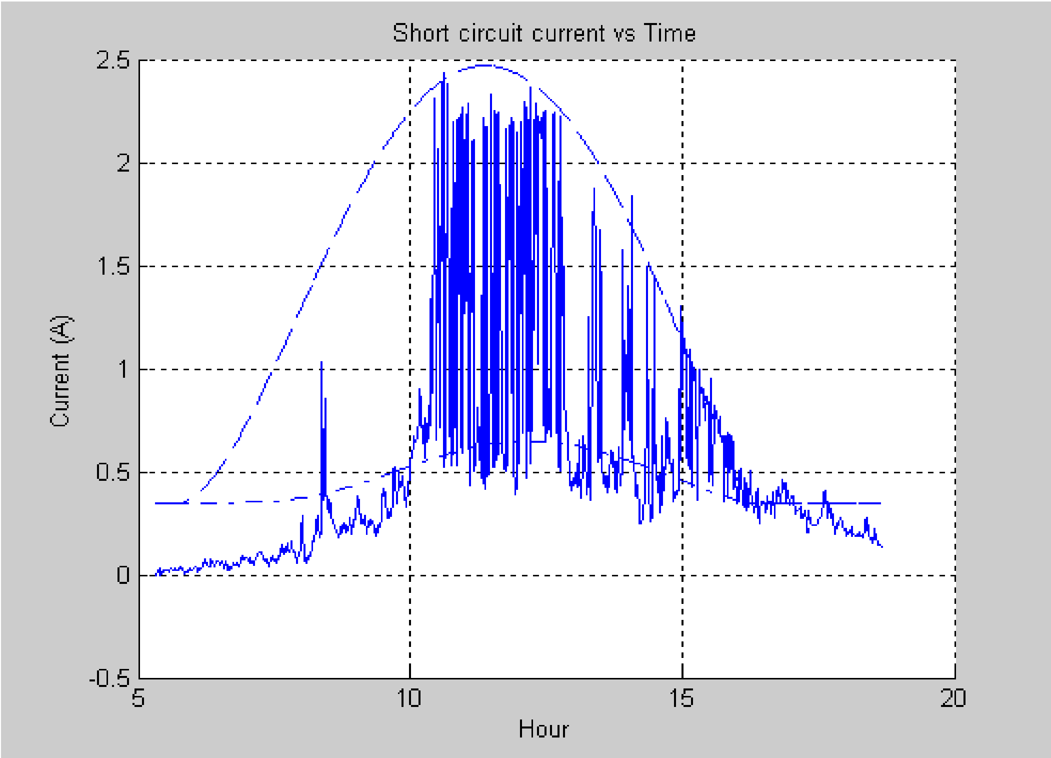


Figure 5.5-22 Measured and calculated short circuit current 060710
_____: measured, _ _: 0.3126, _ . _: 1.8421

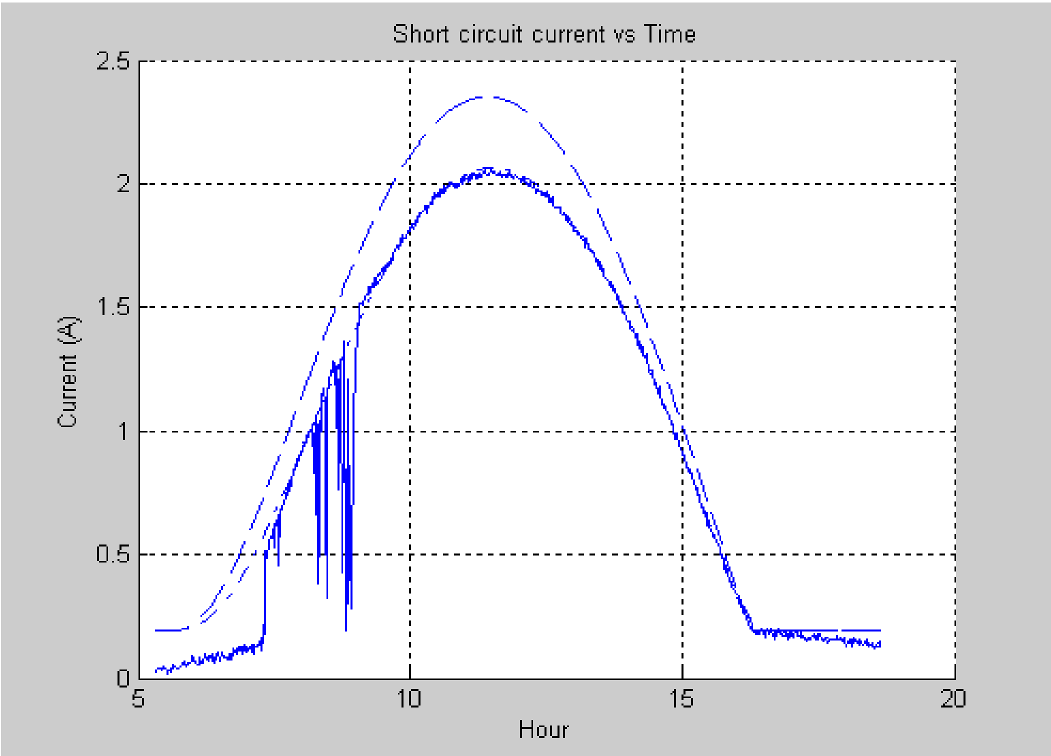


Figure 5.5-23 Measured and calculated short circuit current 060718
_____: measured, _ _: 0.3126, _ . _: 0.4189

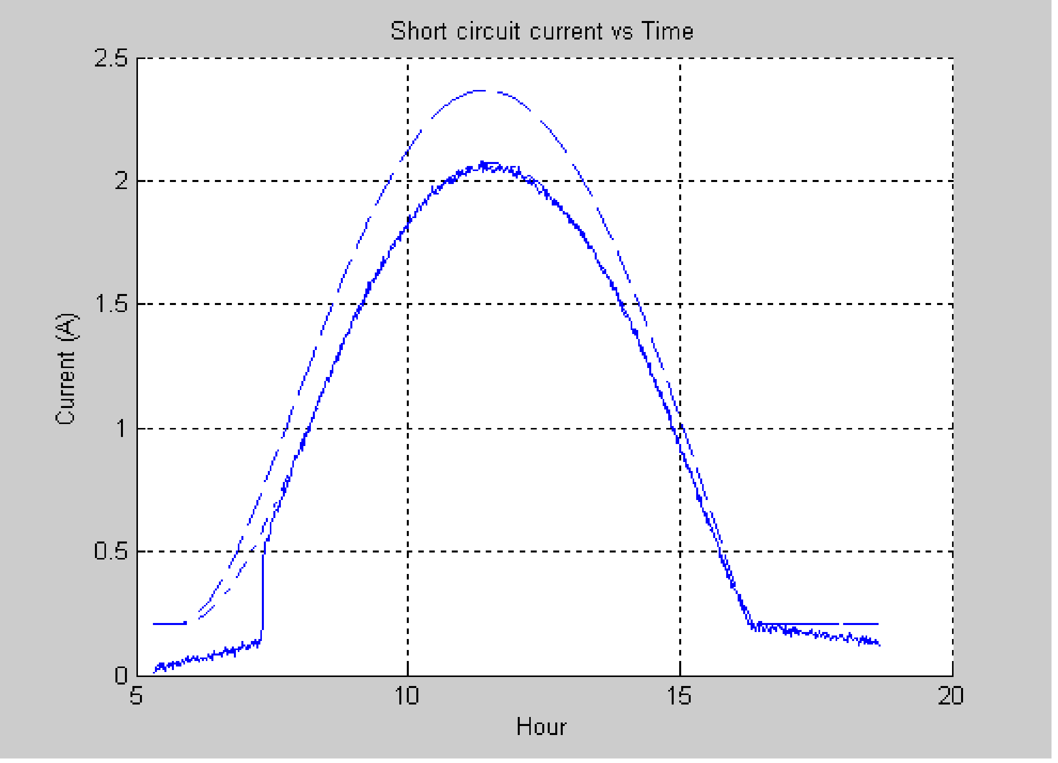


Figure 5.5-24 Measured and calculated short circuit current 060719
____: measured, _ _: 0.3126, _ . _: 0.4203

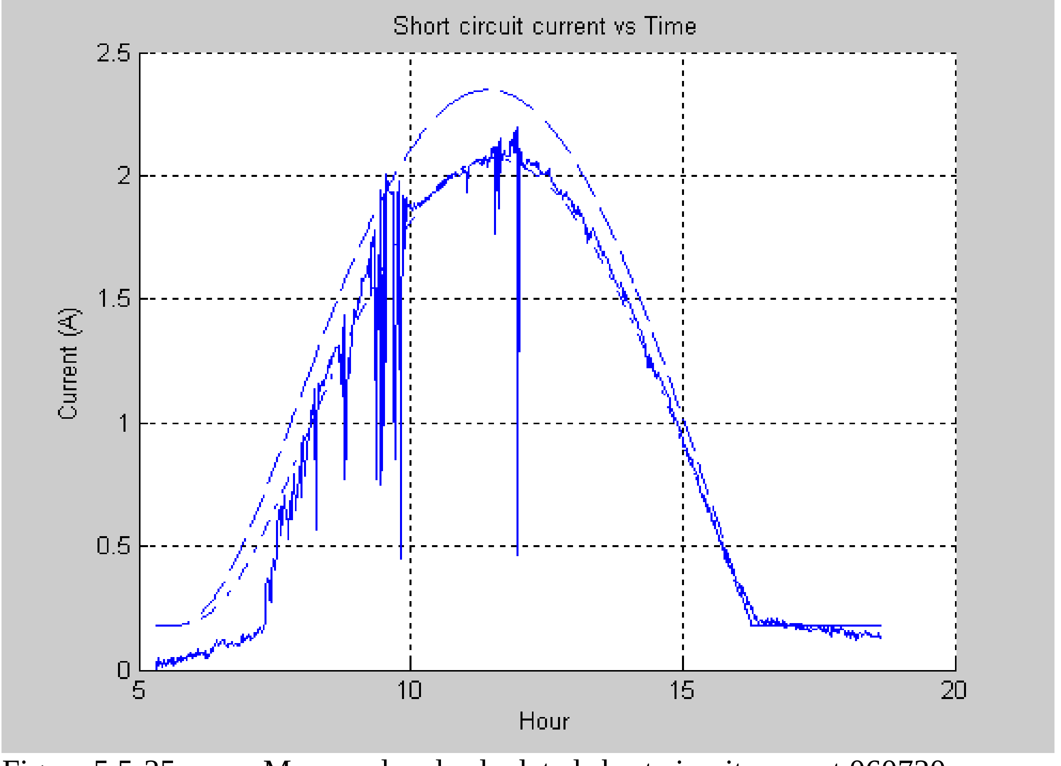


Figure 5.5-25 Measured and calculated short circuit current 060720
____: measured, _ _: 0.3126, _ . _: 0.4144

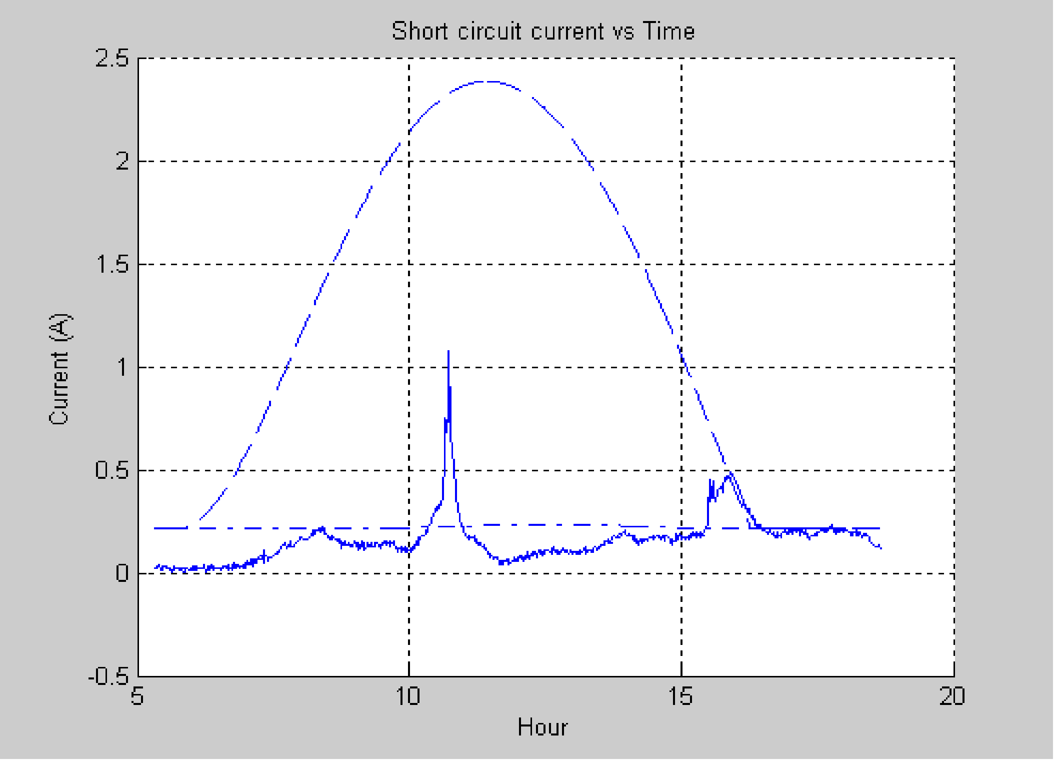


Figure 5.5-26 Measured and calculated short circuit current 060721
____: measured, _ _: 0.3126, _ . _: 3.8493

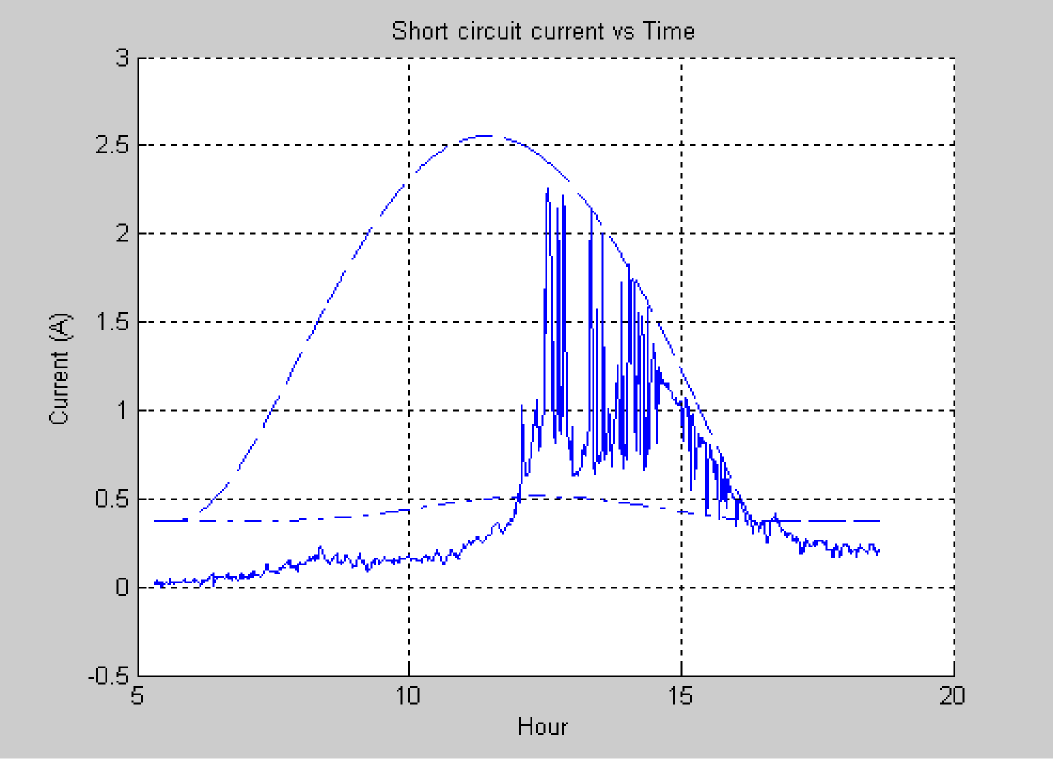


Figure 5.5-27 Measured and calculated short circuit current 060722
____: measured, _ _: 0.3126, _ . _: 2.4203

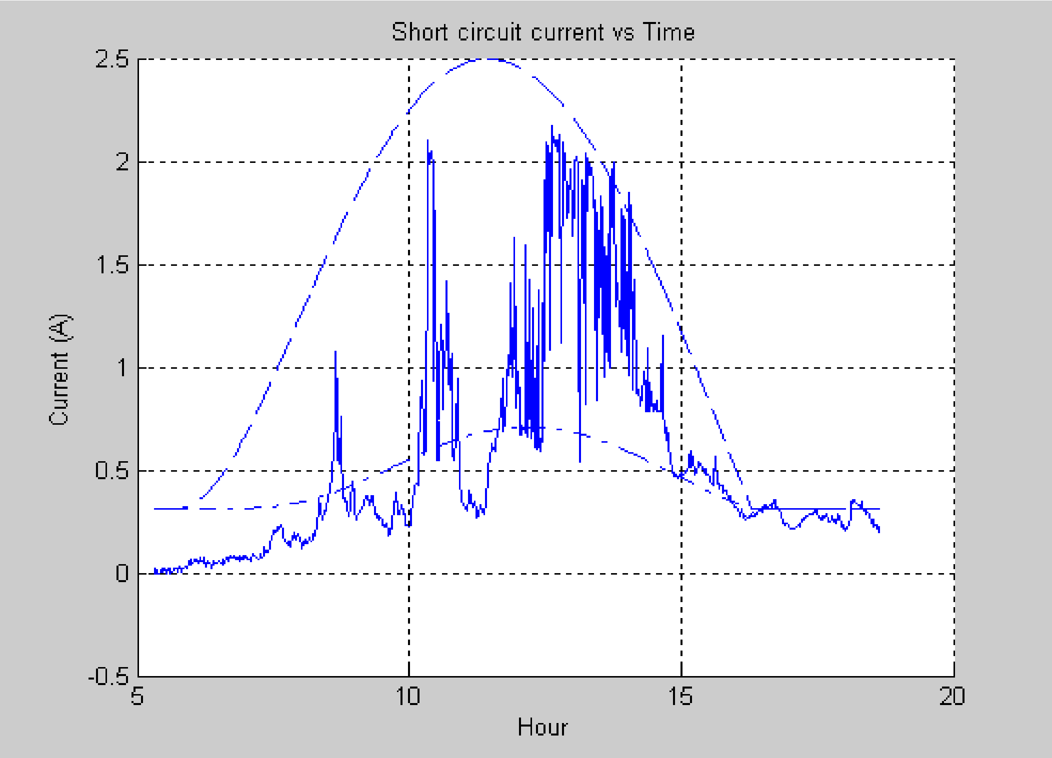


Figure 5.5-28 Measured and calculated short circuit current 060723
____: measured, _ _: 0.3126, _ . _: 1.6010

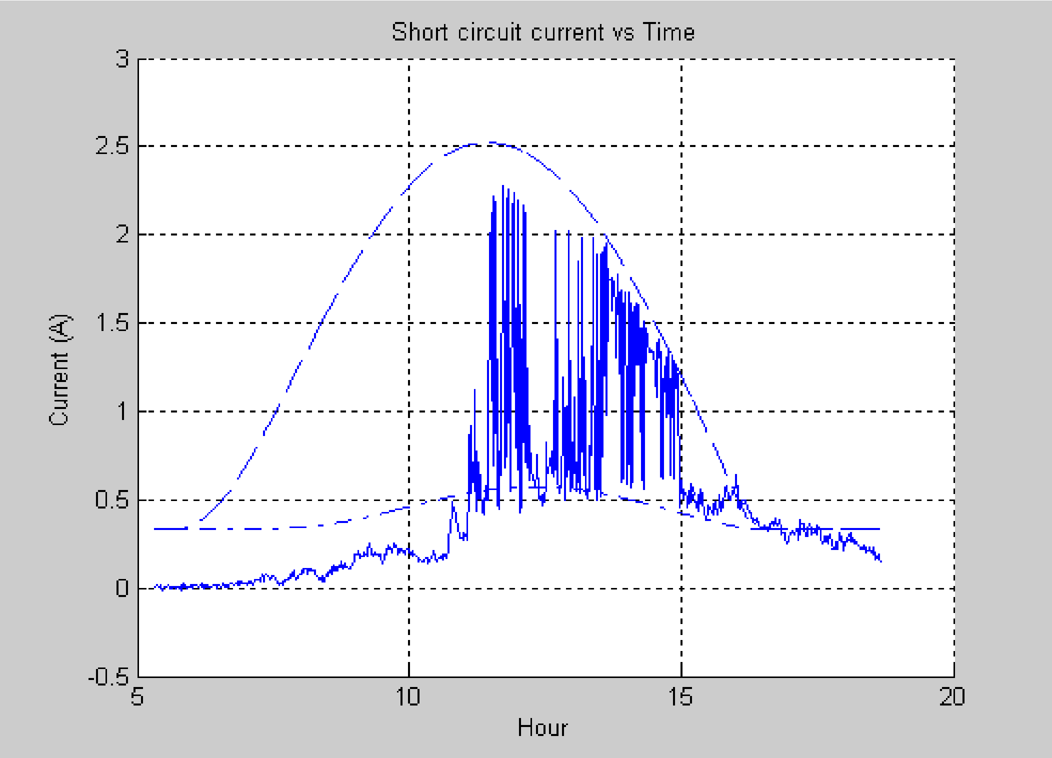


Figure 5.5-29 Measured and calculated short circuit current 060724
____: measured, _ _: 0.3126, _ . _: 1.9856

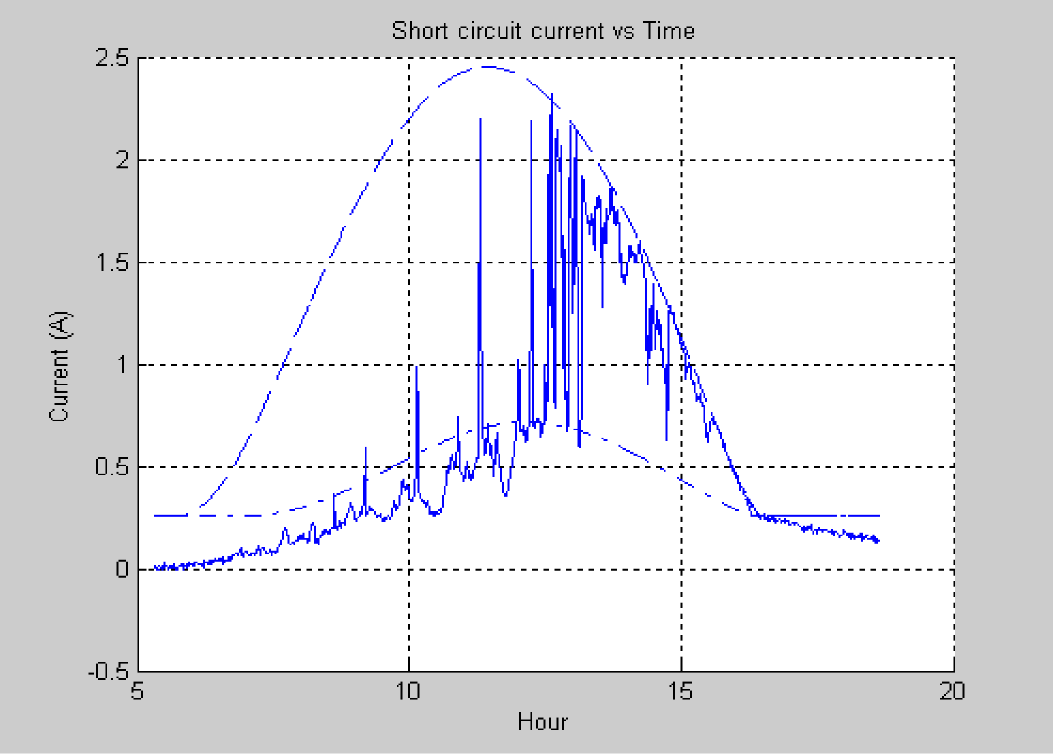


Figure 5.5-30 Measured and calculated short circuit current 060725
____: measured, _ _: 0.3126, _ . _: 1.4888

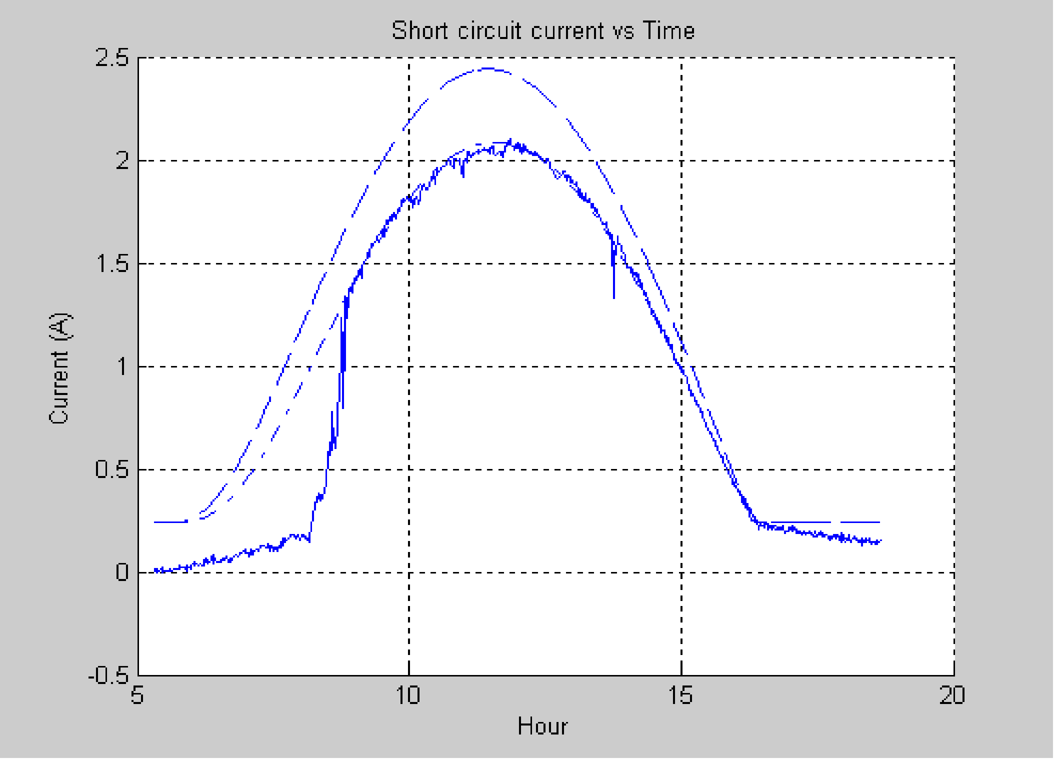


Figure 5.5-31 Measured and calculated short circuit current 060726
____: measured, _ _: 0.3126, _ . _: 0.4417

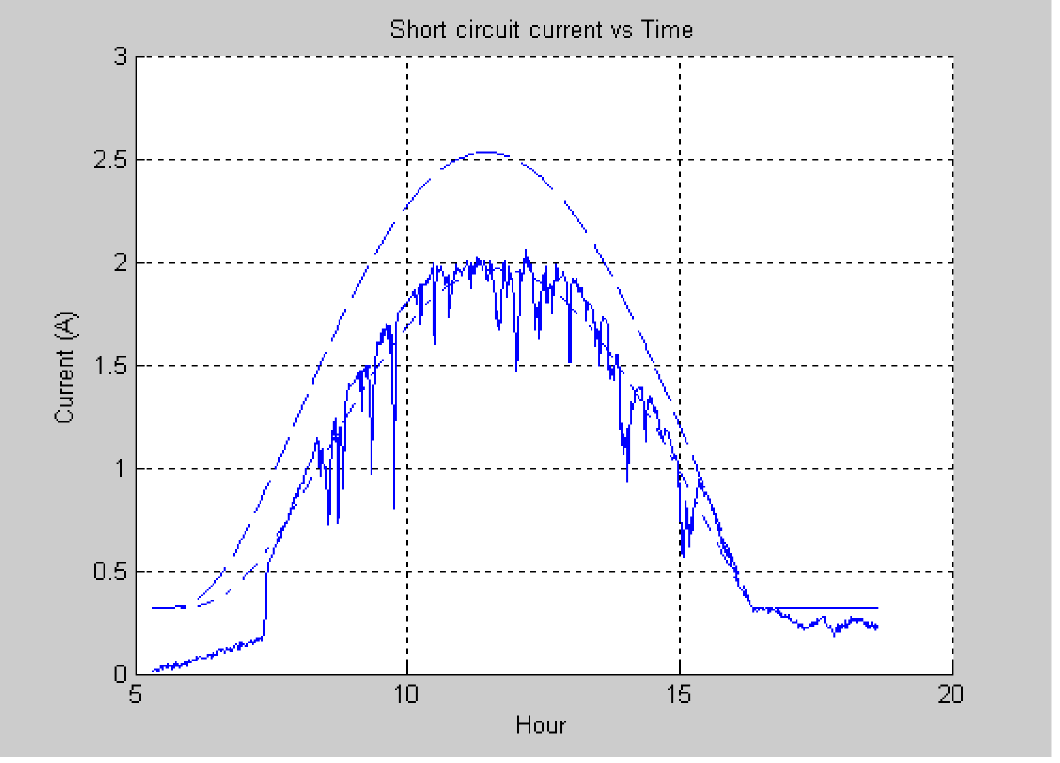


Figure 5.5-32 Measured and calculated short circuit current 060727
____: measured, _ _: 0.3126, _ . _: 0.5288

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 coeffient (low atmospheric transmission) results in a low short circuit current. A low extinction coefficient (high atmospheric transmission) results in a high short circuit current.

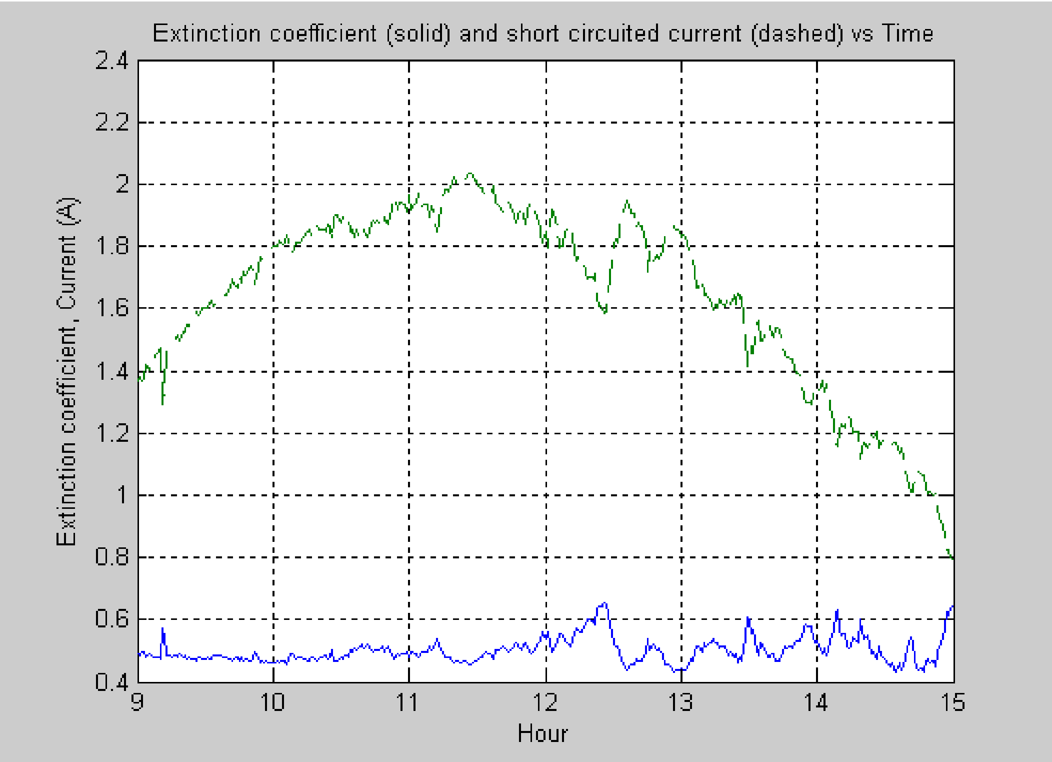


Figure 5.5-33 Extinction coefficient (lower curve) and short circuited current (upper curve) vs Time. 060705

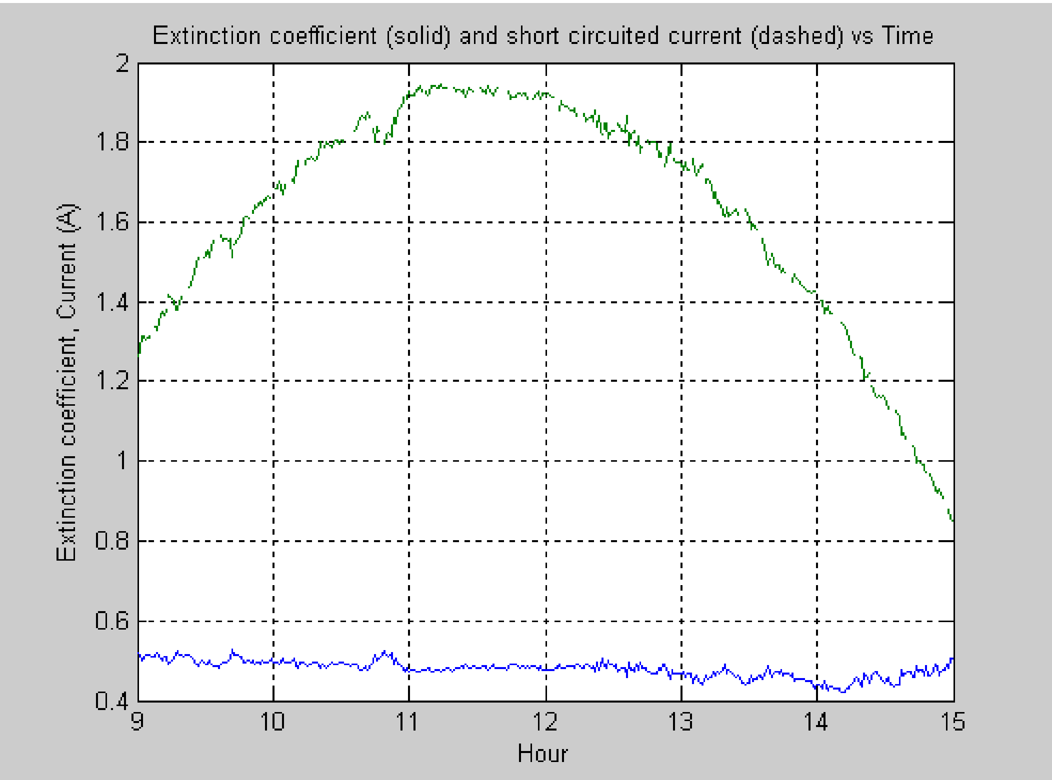


Figure 5.5-34 Extinction coefficient (lower curve) and short circuited current (upper curve) vs Time. 060706

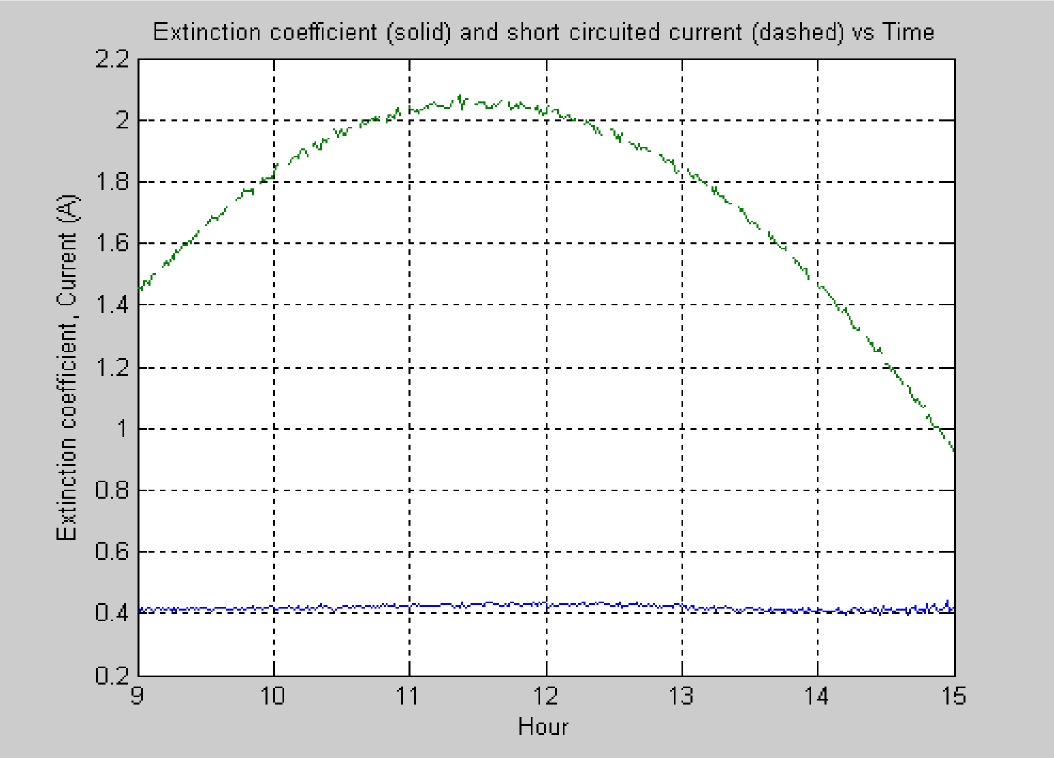


Figure 5.5-35 Extinction coefficient (lower curve) and short circuited current (upper curve) vs Time. 060719

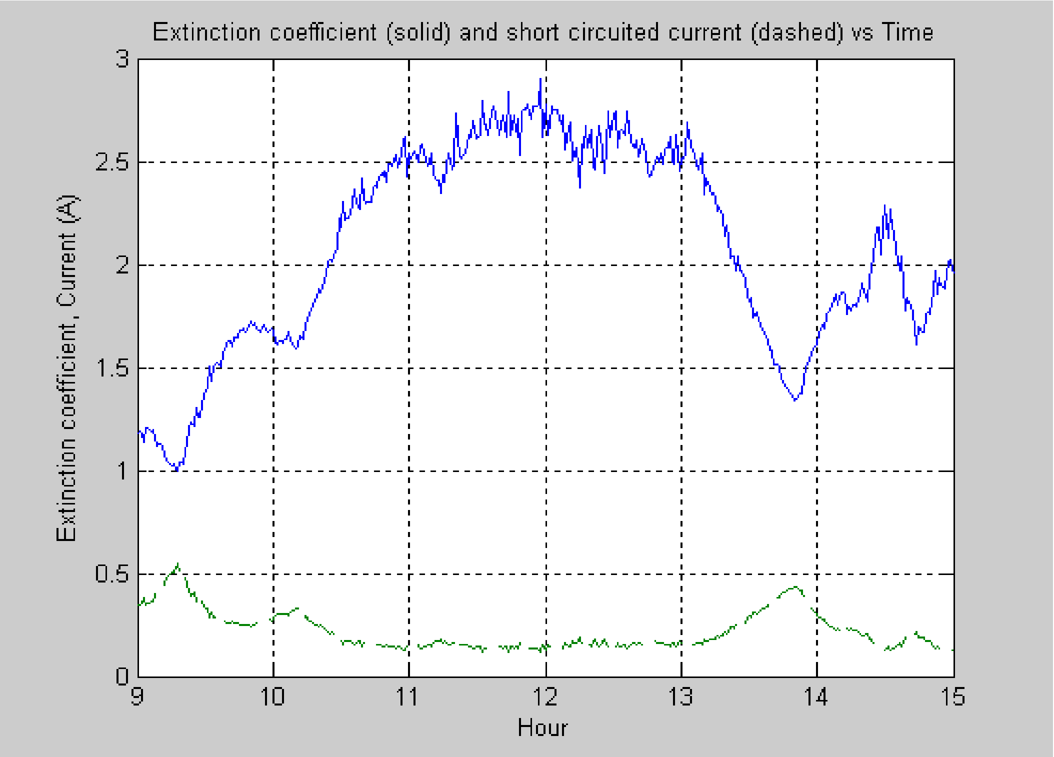


Figure 5.5-36 Extinction coefficient (upper curve) and short circuited current (lower curve) vs Time. 060626

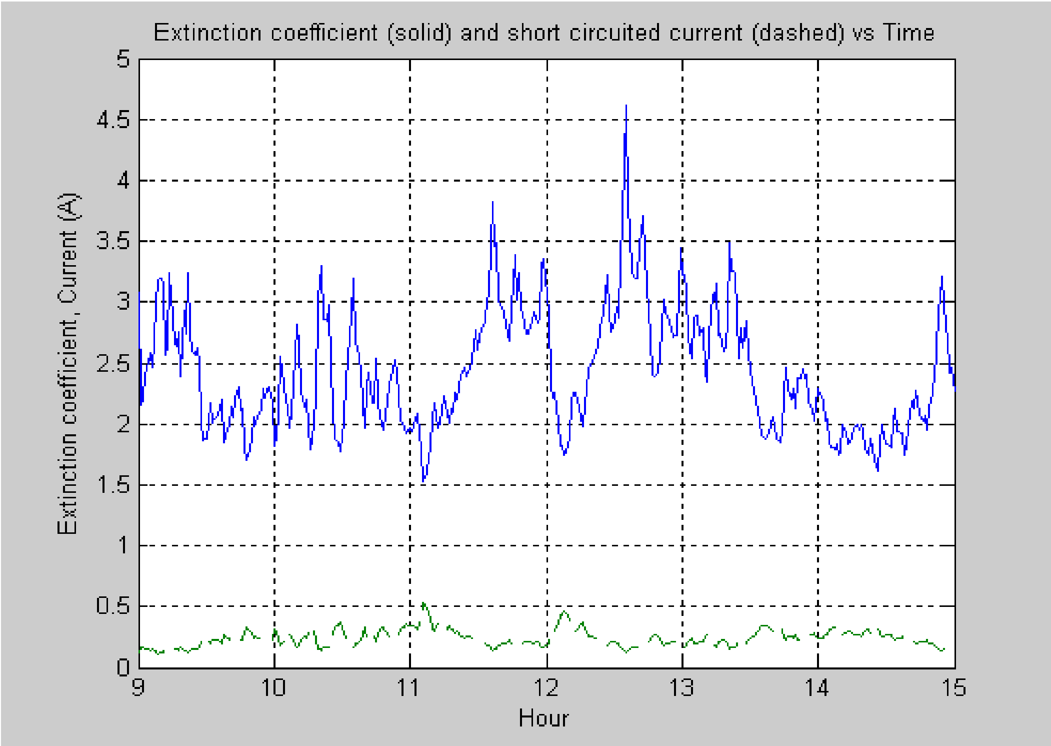


Figure 5.5-37 Extinction coefficient (upper curve) and short circuited current (lower curve) vs Time. 060627

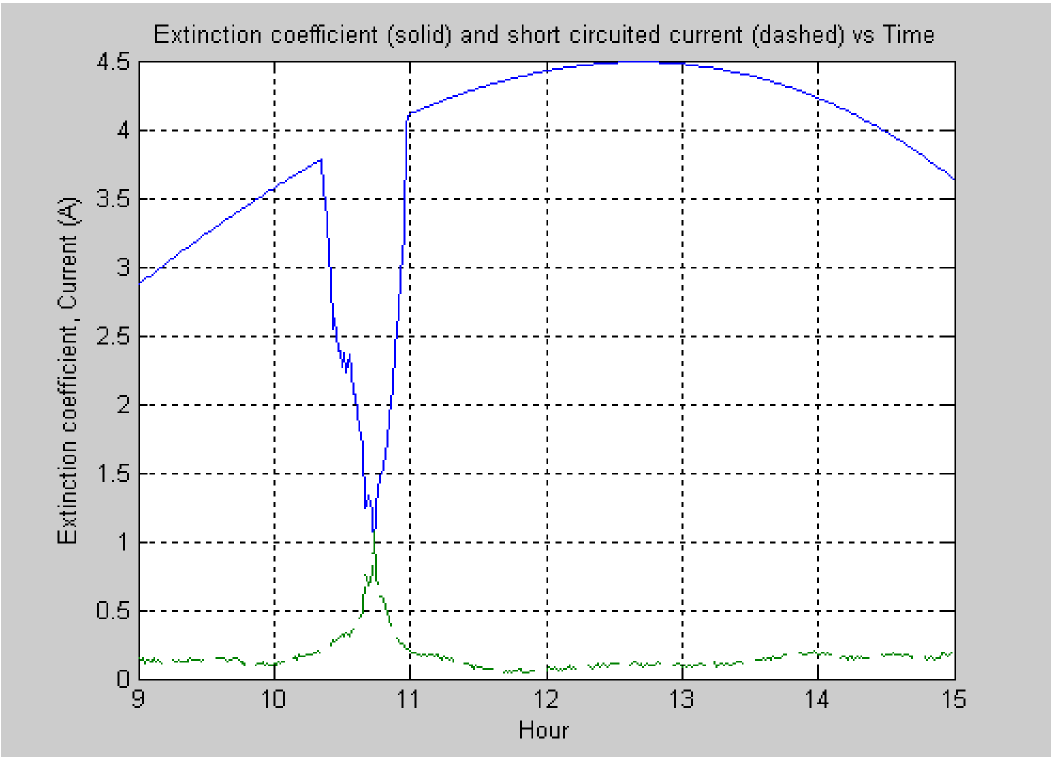


Figure 5.5-38 Extinction coefficient (upper curve) and short circuited current (lower curve) vs Time. 060721

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 campagne 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

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

Table 6.1-1 Name and power consumption for the companies that where involved during the measurement campage in question

Figure 6.1-1 illustrates the total power consumption for the company area during the measurement interval in question.

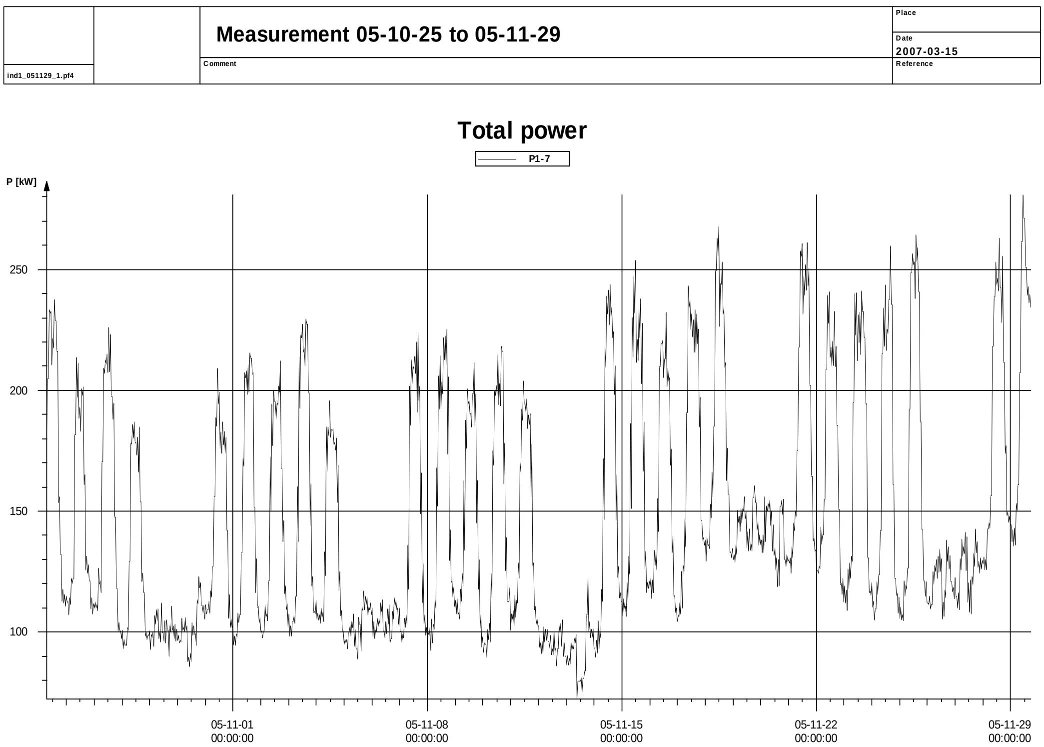


Figure 6.1-1 The power consumption for the studied company area during the measurement interval in question

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, Suterday 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.

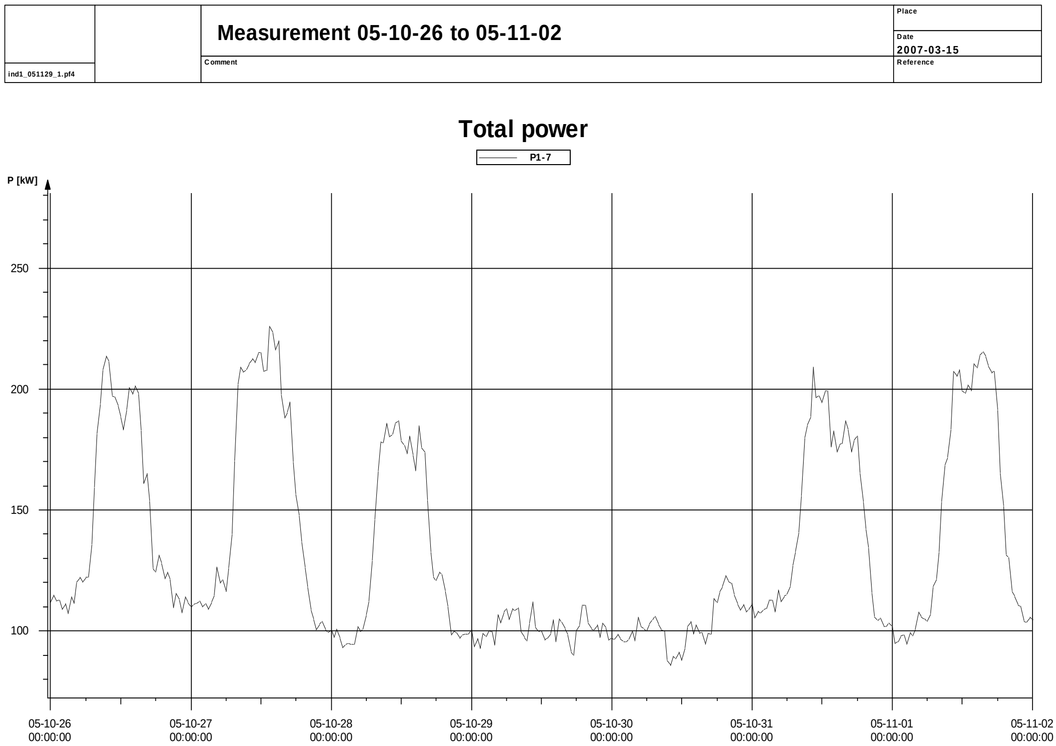


Figure 6.1-2 The power consumption for the studied company area during a sample period of seven days

Figure 6.1-3 illustrates the total power consumtion 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”*).

Comparering **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 ponts, 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

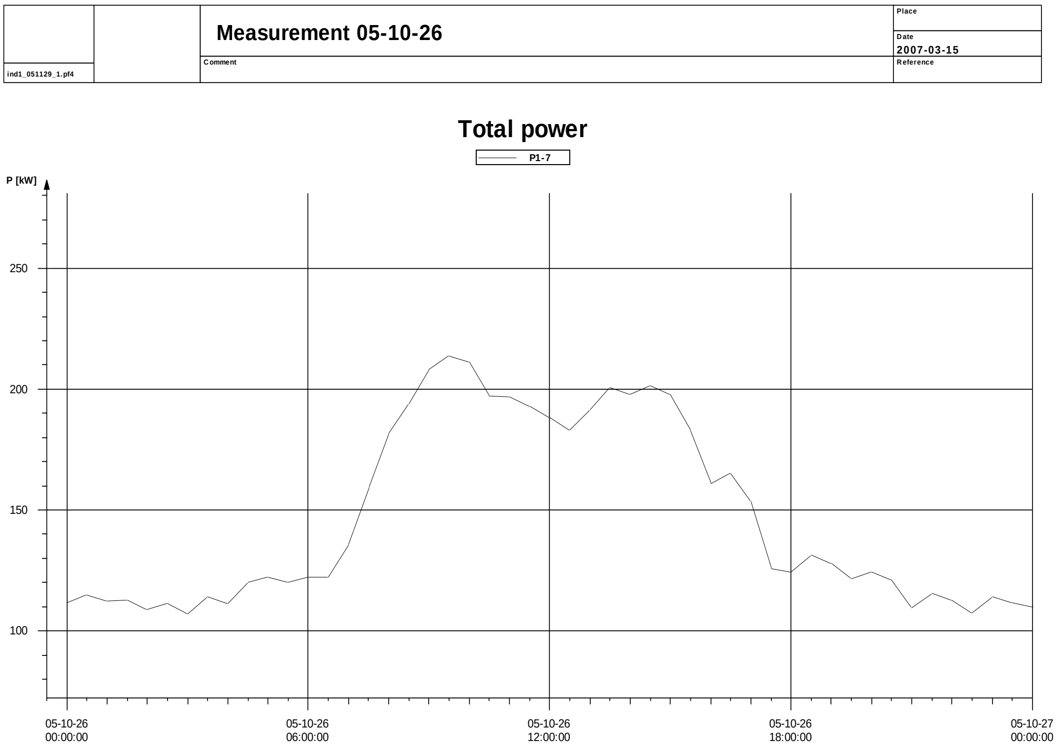


Figure 6.1-3 The power consumption for the studied company area during a sample period of 24 hours (26/10, 00.00 – 27/10, 00.00)

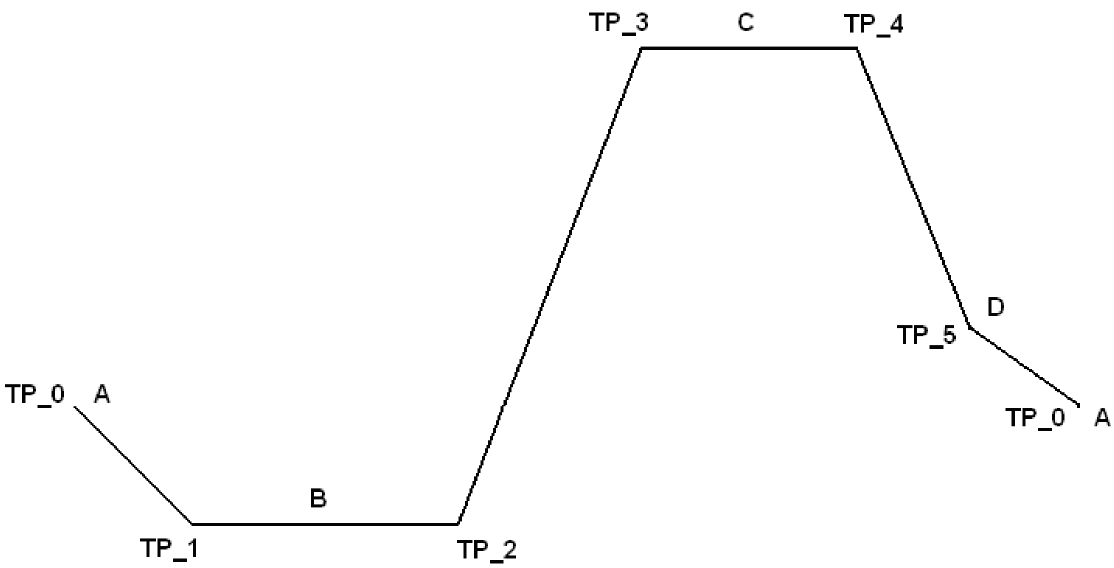


Figure 6.1-4 An illustration of the base power shifts between the different time points during a 24 hours cycle

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.

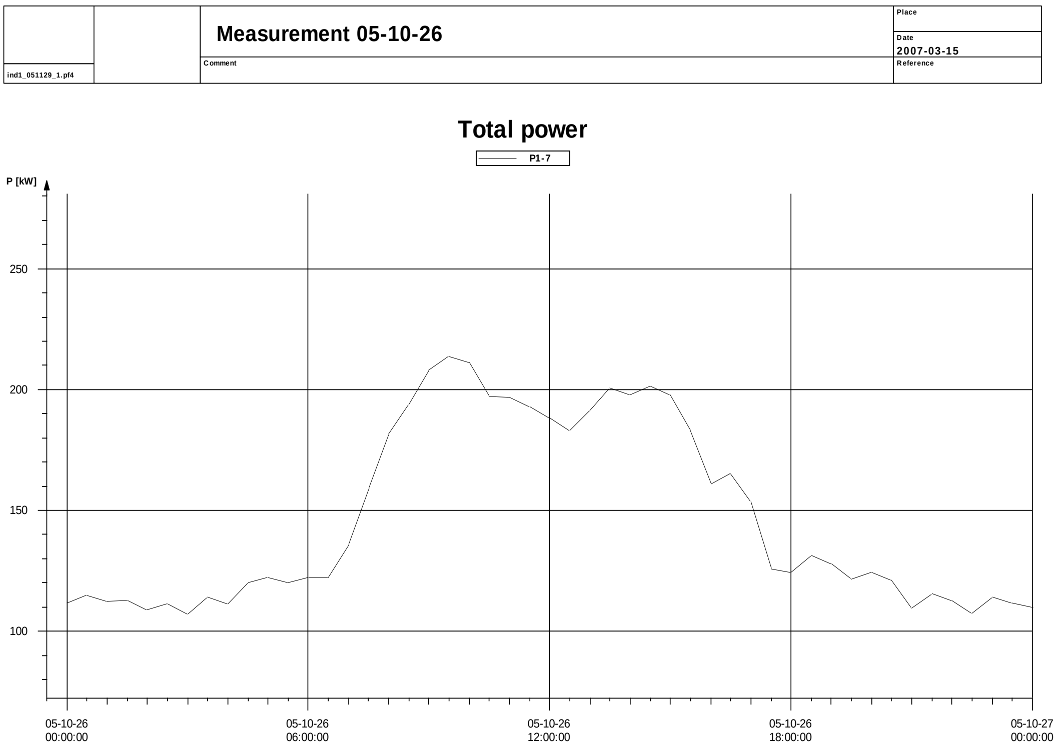


Figure 6.2-1 Power consumption 26/10, 00.00 – 27/10, 00.00. Working day

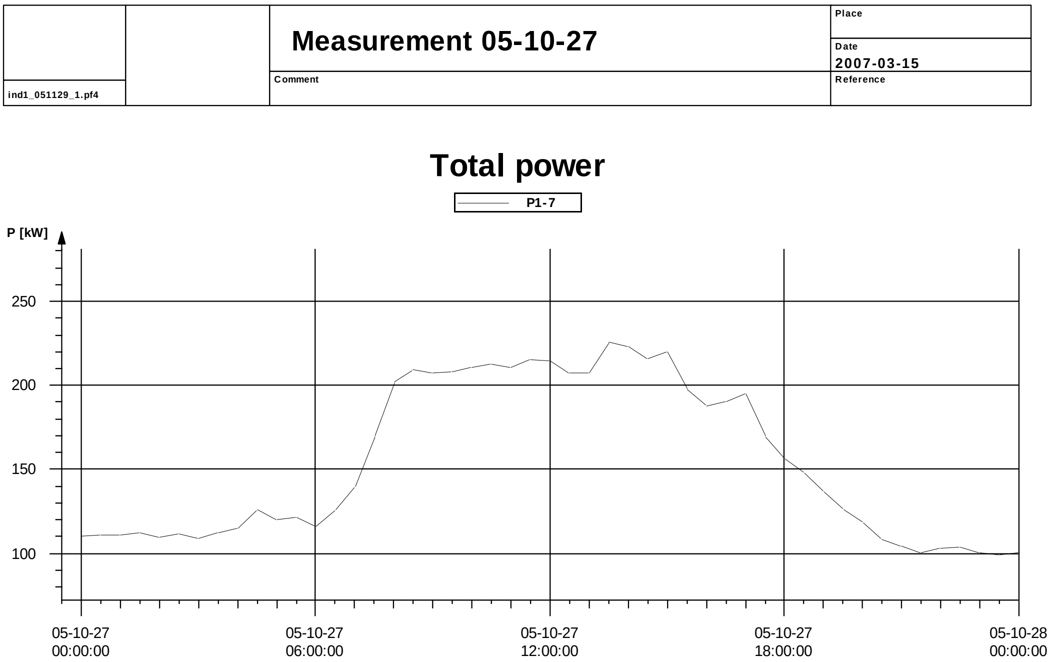


Figure 6.2-2 Power consumption 27/10, 00.00 – 28/10, 00.00. Working day

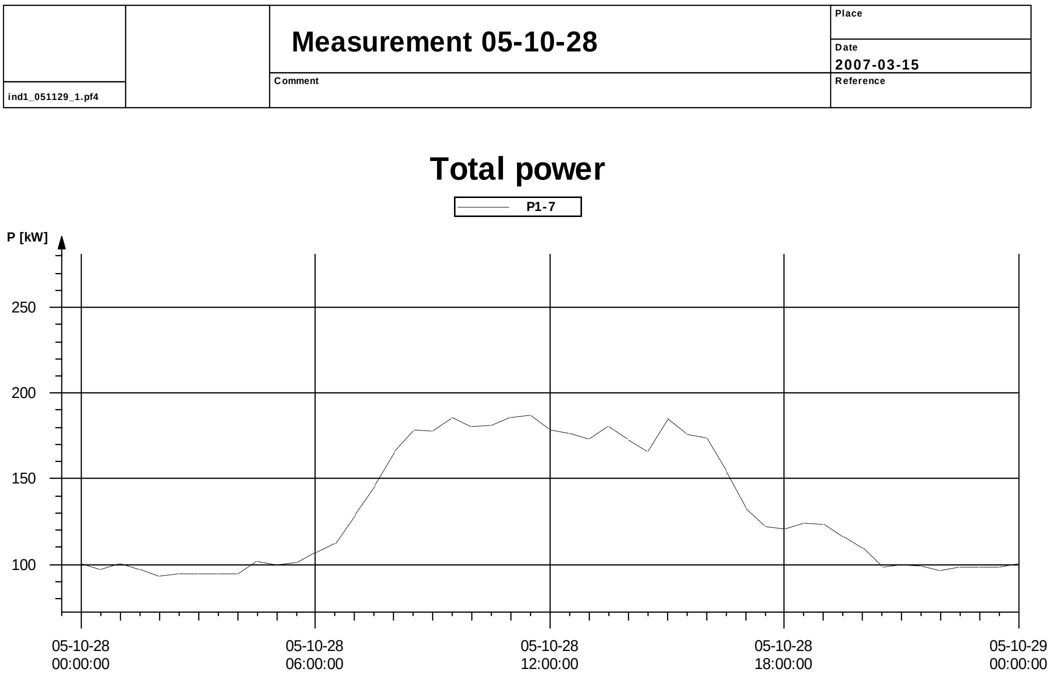


Figure 6.2-3 Power consumption 28/10, 00.00 – 29/10, 00.00. Working day

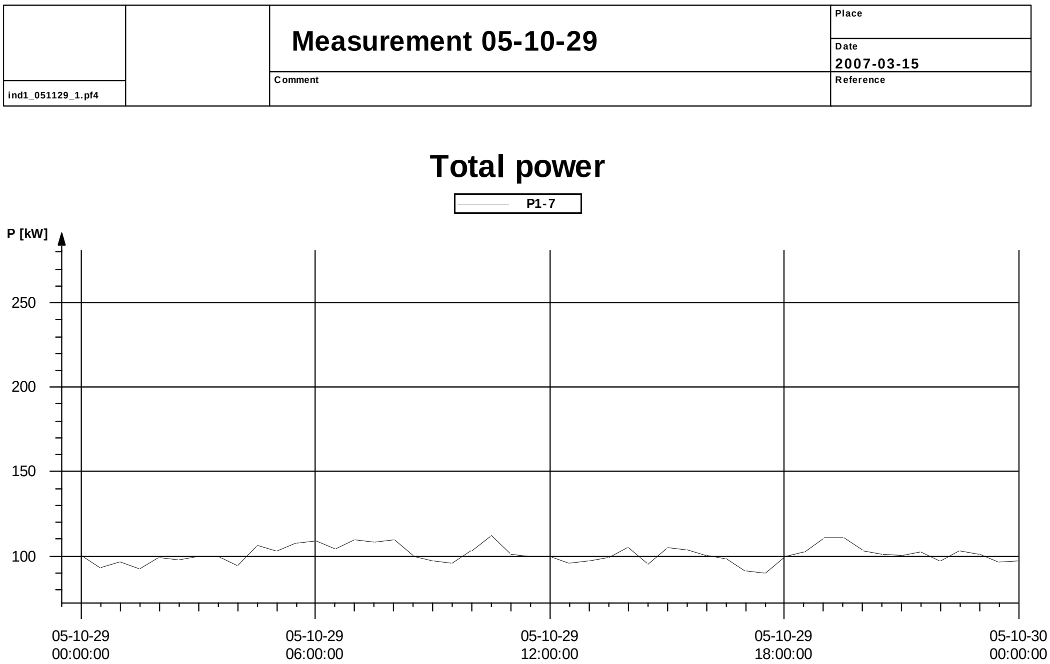


Figure 6.2-4 Power consumption 29/10, 00.00 – 30/10, 00.00. Weekend day

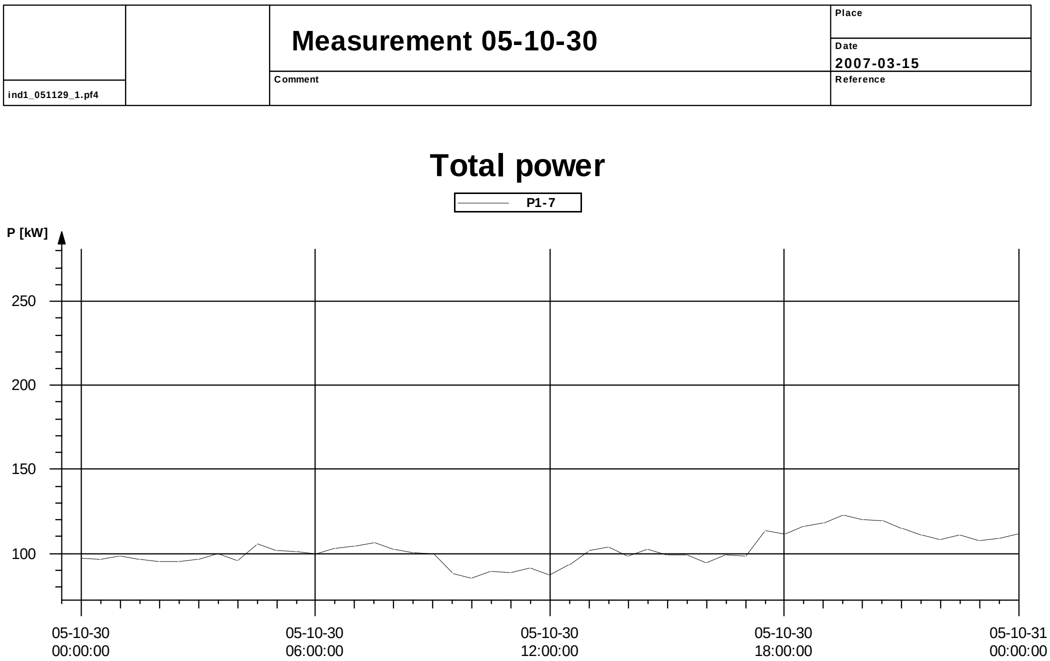


Figure 6.2-5 Power consumption 30/10, 00.00 – 31/10, 00.00. Weekend day

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**.

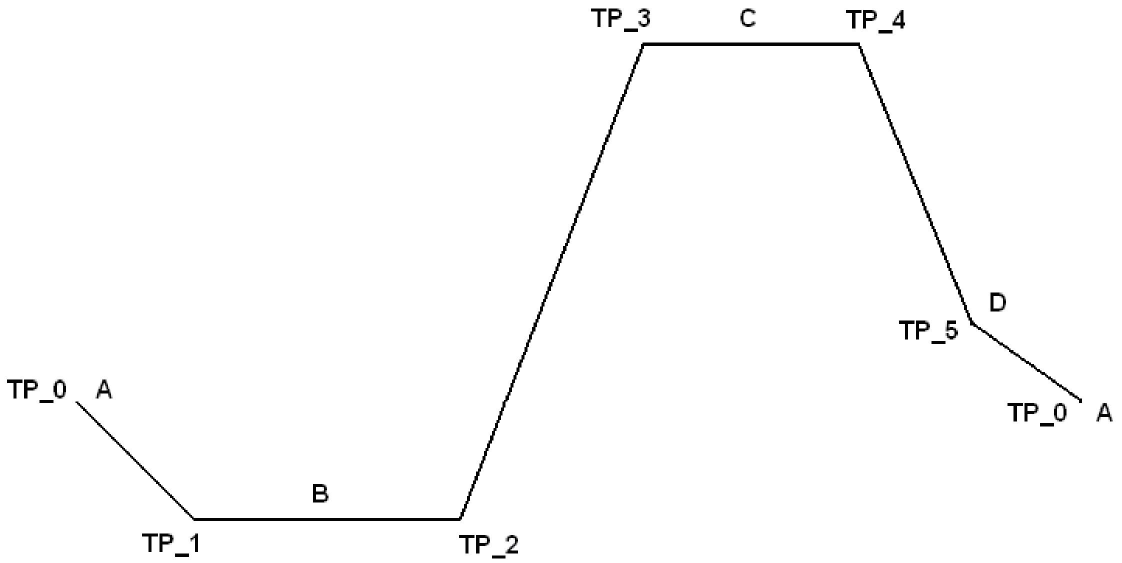


Figure 6.3-1 An illustration of the base power shifts between the different time points during a 24 hours cycle

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 $A = A\_prim \cdot Load\_factor$

Equation 6.3-2 $B = B\_prim \cdot Load\_factor$

Equation 6.3-3 $C = C\_prim \cdot Load\_factor$

Equation 6.3-4 $D = D\_prim \cdot Load\_factor$

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).

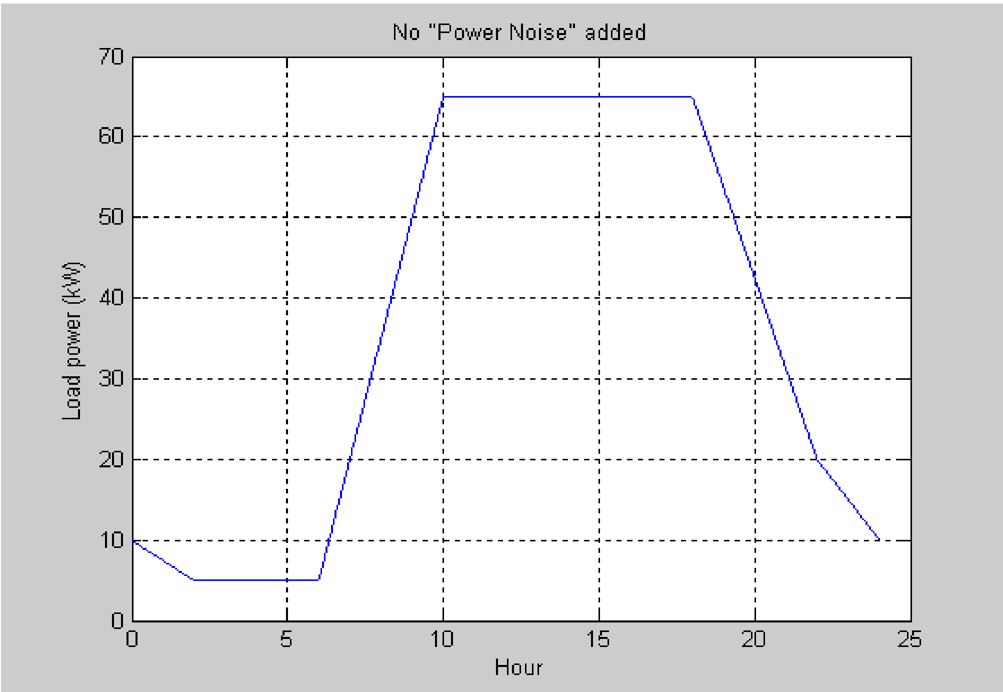


Figure 6.3-2 An example with **no** high frequency noise added to the base levels.

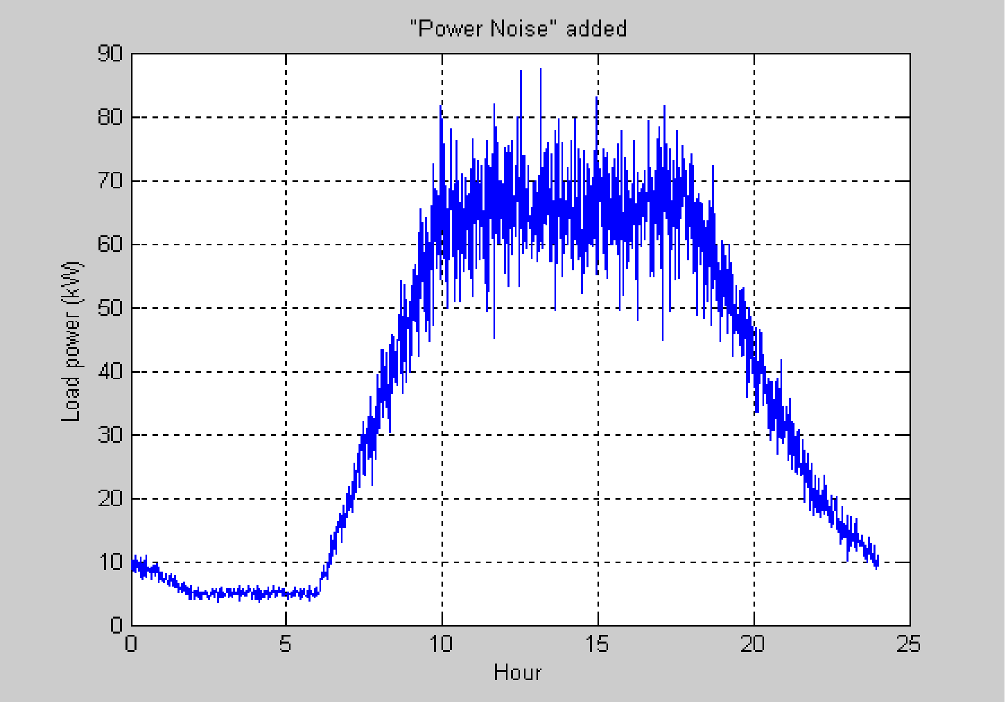


Figure 6.3-3 An example **with** high frequency noise added to the base levels. The standard deviation *"L_sigma_H"* (in this example) is 10 % of present base level. The noise mean value *"L_My_H"* is zero.

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_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_limit". This sequence, category a to category b ans 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.

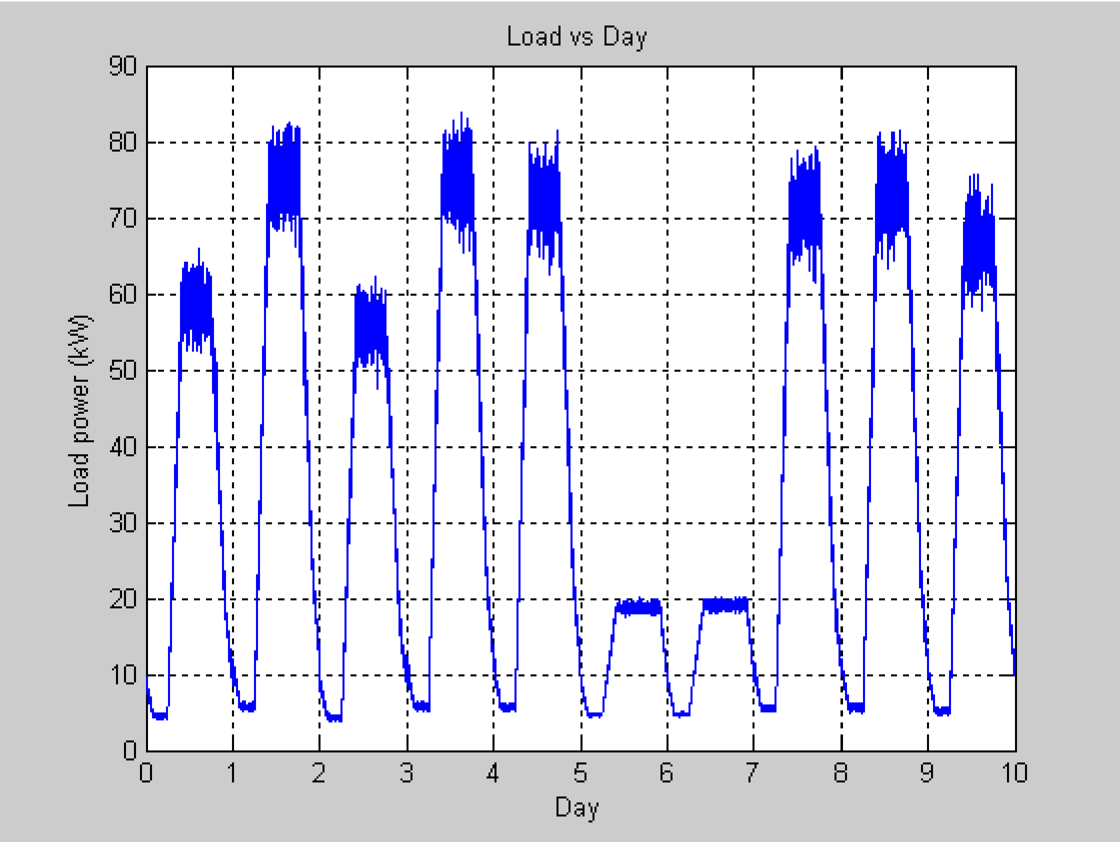


Figure 6.3-4 A simulation sequence corresponding to 5 working days followed by 2 days of weekend

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 raws 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 $\overline{\overline{M}}^{W}$ and $\overline{\overline{M}}^{WE}$ are defined in Equation 6.3-5 and Equation 6.3-6.

The mean values of the columns in each matrix results in vectors $\overline{P^{W}}$ and $\overline{P^{WE}}$ 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**.

Equation 6.3-5:

$$
\overline{\overline{M^W}} = \left[\begin{array}{ccc:cc}
M^W{}_{1,1} & M^W{}_{1,2} & M^W{}_{1,n} & M^W{}_{1,n+1} & M^W{}_{1,48} \\
M^W{}_{2,1} & M^W{}_{2,2} & M^W{}_{2,n} & M^W{}_{2,n+1} & M^W{}_{2,48} \\
 & & & & \\
M^W{}_{m,1} & M^W{}_{m,2} & M^W{}_{m,n} & M^W{}_{m,n+1} & M^W{}_{m,48} \\
\hdashline
M^W{}_{m+1,1} & M^W{}_{m+1,2} & M^W{}_{m+1,n} & M^W{}_{m+1,n+1} & M^W{}_{m+1,48} \\
 & & & & \\
M^W{}_{24,1} & M^W{}_{24,2} & M^W{}_{24,n} & M^W{}_{24,n+1} & M^W{}_{24,48}
\end{array}\right]
$$

The measure samples for the working days are organised in a matrix $\overline{\overline{M^W}}$ with 24rows(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 6.3-6:

$$
\overline{\overline{M^{WE}}} = \left[\begin{array}{ccc|cc}
M^{WE}{}_{1,1} & M^{WE}{}_{1,2} & M^{WE}{}_{1,n} & M^{WE}{}_{1,n+1} & M^{WE}{}_{1,48} \\
M^{WE}{}_{2,1} & M^{WE}{}_{2,2} & M^{WE}{}_{2,n} & M^{WE}{}_{2,n+1} & M^{WE}{}_{2,48} \\
 & & & & \\
M^{WE}{}_{m,1} & M^{WE}{}_{m,2} & M^{WE}{}_{m,n} & M^{WE}{}_{m,n+1} & M^{WE}{}_{m,48} \\
\hline
M^{WE}{}_{m+1,1} & M^{WE}{}_{m+1,2} & M^{WE}{}_{m+1,n} & M^{WE}{}_{m+1,n+1} & M^{WE}{}_{m+1,48} \\
 & & & & \\
M^{WE}{}_{10,1} & M^{WE}{}_{10,2} & M^{WE}{}_{10,n} & M^{WE}{}_{10,n+1} & M^{WE}{}_{10,48}
\end{array}\right]
$$

The measure samples for the weekend days are organised in a matrix $\overline{\overline{M^{WE}}}$ 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:

$$\overline{P^W} = \begin{bmatrix} P_1^W & P_2^W & P_3^W & & P_n^W & \vdots & P_{n+1}^W & & P_{49}^W \end{bmatrix}$$

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

Equation 6.3-12:

$$\overline{P^{WE}} = \left[P_1^{WE} \quad P_2^{WE} \quad P_3^{WE} \qquad \qquad P_n^{WE} \; \vdots \; P_{n+1}^{WE} \qquad \qquad P_{49}^{WE} \right]$$

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

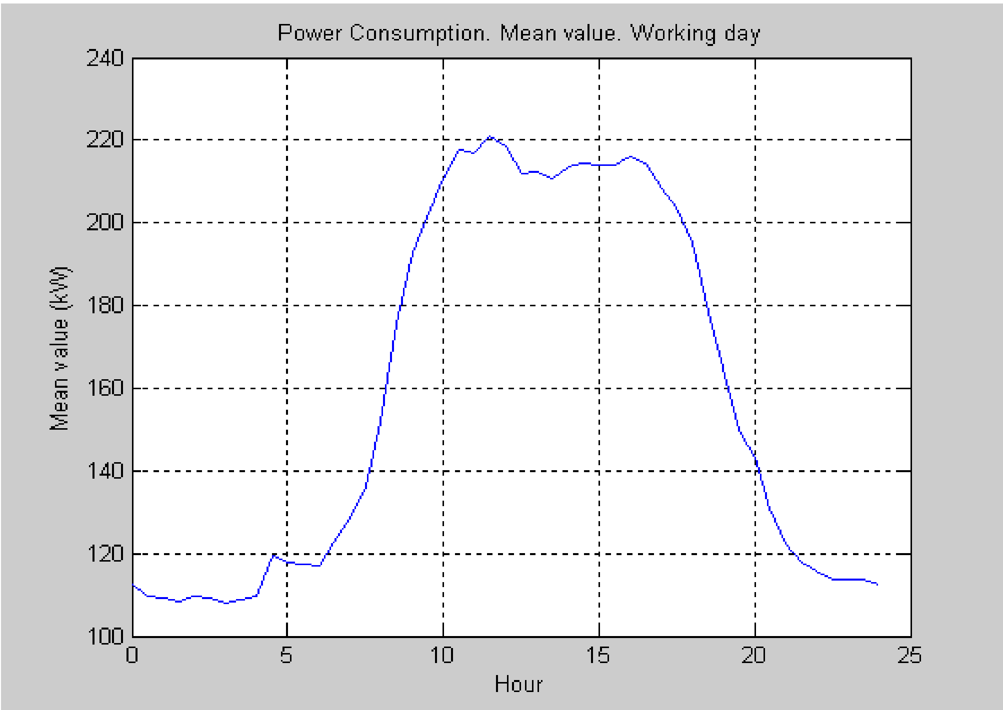


Figure 6.3-5 The power consumption mean value profile for a working day

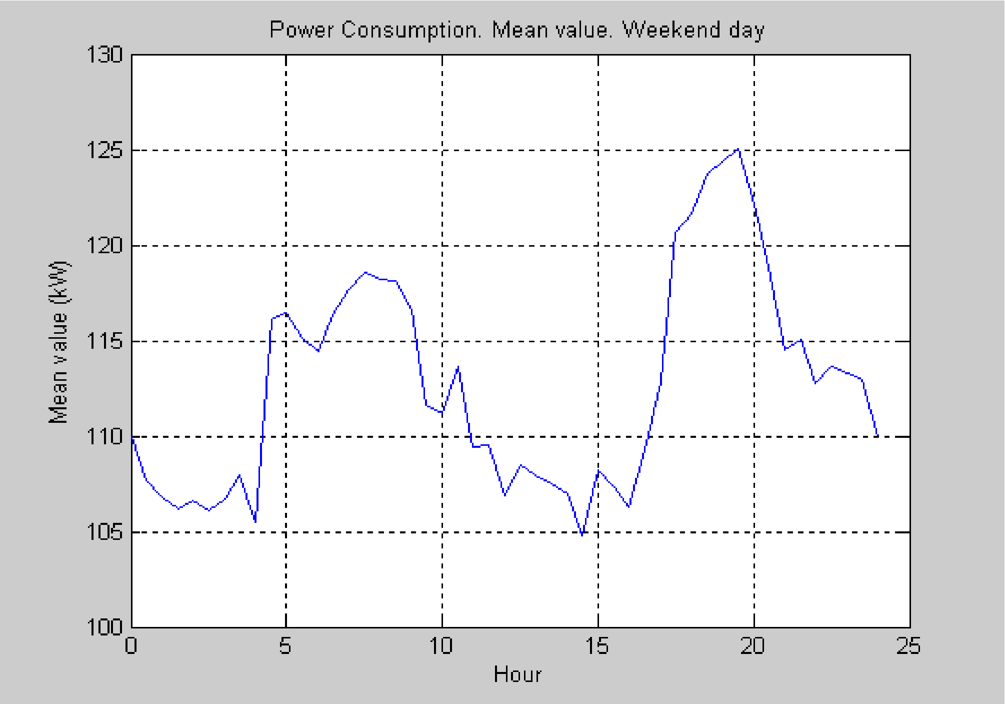


Figure 6.3-6 The power consumption mean value profile for a weekend day

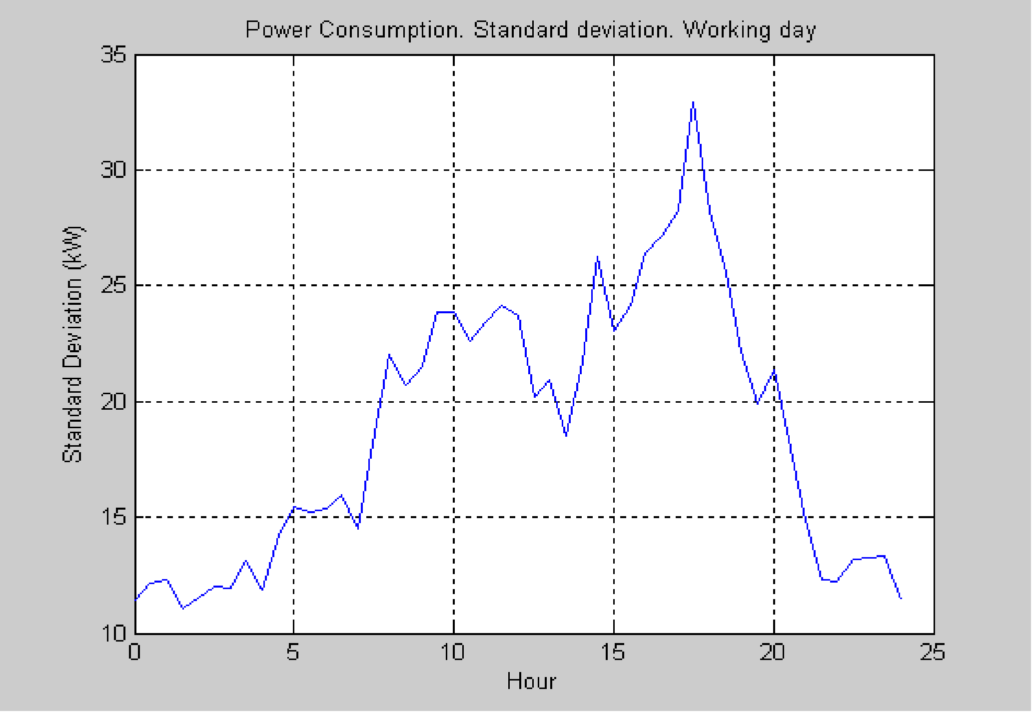


Figure 6.3-7 The power consumption standard deviation profile for a working day

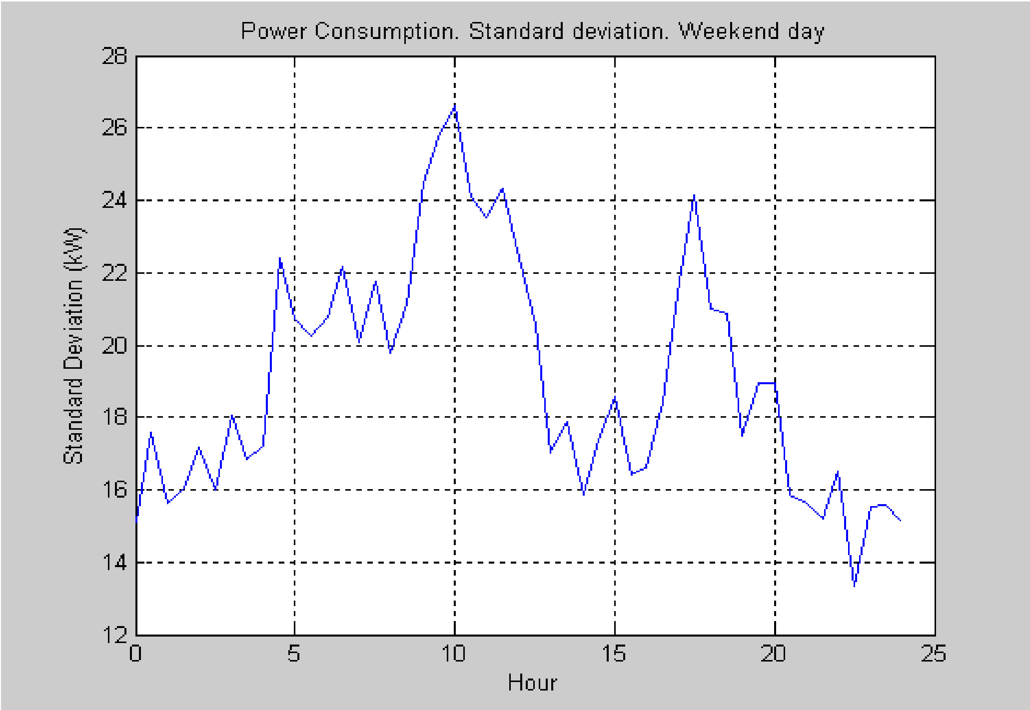


Figure 6.3-8 The power consumption standard deviation profile for a weekend day

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:

$$C\_prim = \mu P_{34}$$

Where:

μP_{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_n^W : element *n* in power vector $\overline{P^W}$ (Equation 6.3-11)

pos_TP_3, *pos_TP_4*: the vector positions (n-values) corresponding to the time points TP_3 respectively TP_4 in vector $\overline{P^W}$

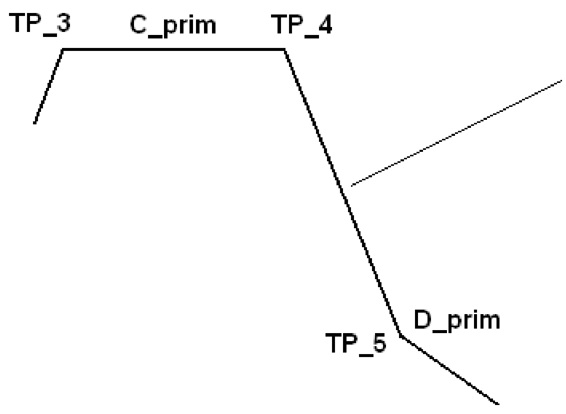
Equation 6.3-15:

$$D\_prim = 2 \cdot \mu P_{45} - C\_prim$$

Where:

μP_{45}: power mean value in the time region TP_4 to TP_5 (Equation 6.3-16)

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



$$\mu_C^D = \frac{C\_prim + D\_prim}{2}$$

μ_C^D : *The mean value of* C_prim *and* D_prim

μ_C^D *is assumed to the same value as* μP_{45}

where μP_{45} *is the measured power mean value in the time region* TP_4 *to* TP_5

consequently:

$$\frac{C\_prim + D\_prim}{2} = \mu P_{45}$$

or :

$$D\_prim = 2 \cdot \mu P_{45} - C\_prim$$

Figure 6.3-9 The principle of Equation 6.3-15

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 $\overline{P^W}$ (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 $\overline{P^W}$

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 $\overline{P^W}$ (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

μP_{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

μP_{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:

$$B\_prim\_2 = 2 \cdot \mu P_{01} - A\_prim\_2$$

Where:

B_prim_2: a second calculated value of B_prim

μP_{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:

$$B\_prim\_3 = \mu P_{12}$$

Where:

B_prim_3: a third calculated value of B_prim

μP_{12}: the power mean value in the time region TP_1 to TP_2 (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 $\overline{P^W}$ (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 $\overline{P^W}$

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).

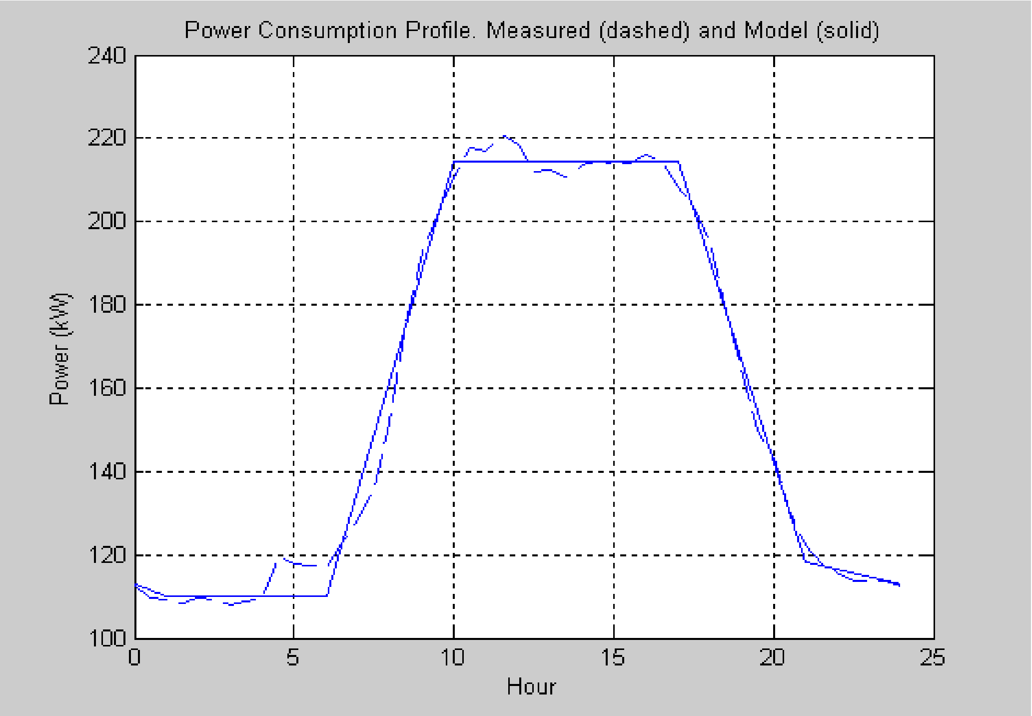


Figure 6.3-10 Measured power consumption profile (dashed) together with the model profile (solid) if TP_1 to TP_5 according to paragraph 6.3.4.1.1 and A_prim, B_prim, C_prim and D_prim according to the values above are used

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:

$$L\_Sigma\_L = \frac{\sigma(\overline{E^W})}{\mu(\overline{E^W})}$$

Where:

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

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

$\overline{E^W}$: vector where the elements are defined according to Equation 6.3-32

Equation 6.3-30:

$$\sigma(\overline{E^W}) = \sqrt{\frac{\sum_{m=1}^{24}\left(E_m^W - \mu(\overline{E^W})\right)^2}{23}}$$

Equation 6.3-31:

$$\mu(\overline{E^W}) = \frac{\sum_{m=1}^{24} E_m^W}{24}$$

Equation 6.3-32:

$$E_m^W = \sum_{n=1}^{48} M_{m,n}^W \qquad m = 1 \text{ to } 24$$

Where:

$M_{m,n}^W$: elements in matrix $\overline{\overline{M^W}}$ (Equation 6.3-5)

According to Equation 6.3-29, *L_Sigma_L* will be the relative standard deviation of the daily energy consumption.

Equation 6.3-29 results in:

L_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:

$$L\_Sigma\_H = \mu(\overline{C^W})$$

Where:

$\mu(\overline{C^W})$: the mean value of vector $\overline{C^W}$ according to Equation 6.3-35. The elements C_m^W in vector $\overline{C^W}$ are defined according to Equation 6.3-36 and Equation 6.3-37. This vector contains the relative standarddeviation (the standard deviation relative to the mean value) of the power in the time interval TP_3 to TP_4 for each working day (1 to 24). Consequently L_Sigma_H is a measure of the mean value of the relative standarddeviation for the power consumption.

Equation 6.3-35:

$$\mu(\overline{C^W}) = \frac{\sum_{m=1}^{24} C_m^W}{24}$$

Equation 6.3-36:

$$C_m^W = \frac{\sqrt{\dfrac{\sum_{n=pos\_TP\_3}^{pos\_TP\_4}\left(M_{m,n}^W - M^W\mu(m,3\_4)\right)^2}{pos\_TP\_4 - pos\_TP\_3 - 1}}}{M^W\mu(m,3\_4)} \qquad m = 1 \text{ to } 24$$

Where:

$M_{m,n}^W$: element I matrix $\overline{\overline{M^W}}$ (Equation 6.3-5)

$M^W\mu(m,3\_4)$: see Equation 6.3-37

Equation 6.3-37:

$$M^W\mu(m,3\_4) = \frac{\sum_{n=pos\_TP\_3}^{pos\_TP\_4} M_{m,n}^W}{pos\_TP\_4 - pos\_TP\_3}$$

Where:

Pos_TP_3, *Pos_TP_4*: the time positions (n-values) corresponding to the time points TP_3 respectively TP_4 in matrix $\overline{\overline{M^W}}$

Equation 6.3-34 results in:

L_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 $\overline{P^W}$ shall be replaced by the power vector $\overline{P^{WE}}$, the following changes must be done regarding some equations according to:

<u>Equation</u>	<u>Changes</u>
Equation 6.3-14	$P_n^W \Rightarrow P_n^{WE}$
Equation 6.3-16	-“-
Equation 6.3-17	$P_{49}^W \Rightarrow P_{49}^{WE}$
Equation 6.3-19	$P_n^W \Rightarrow P_n^{WE}$
Equation 6.3-22	-“-
Equation 6.3-24	-“-
Equation 6.3-26	-“-

The calculations result in:

A_prim:	110.14 kW
B_prim:	107.73 kW
C_prim:	113.96 kW
D_prim:	113.75 kW

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_prim, B_prim, C_prim and D_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).

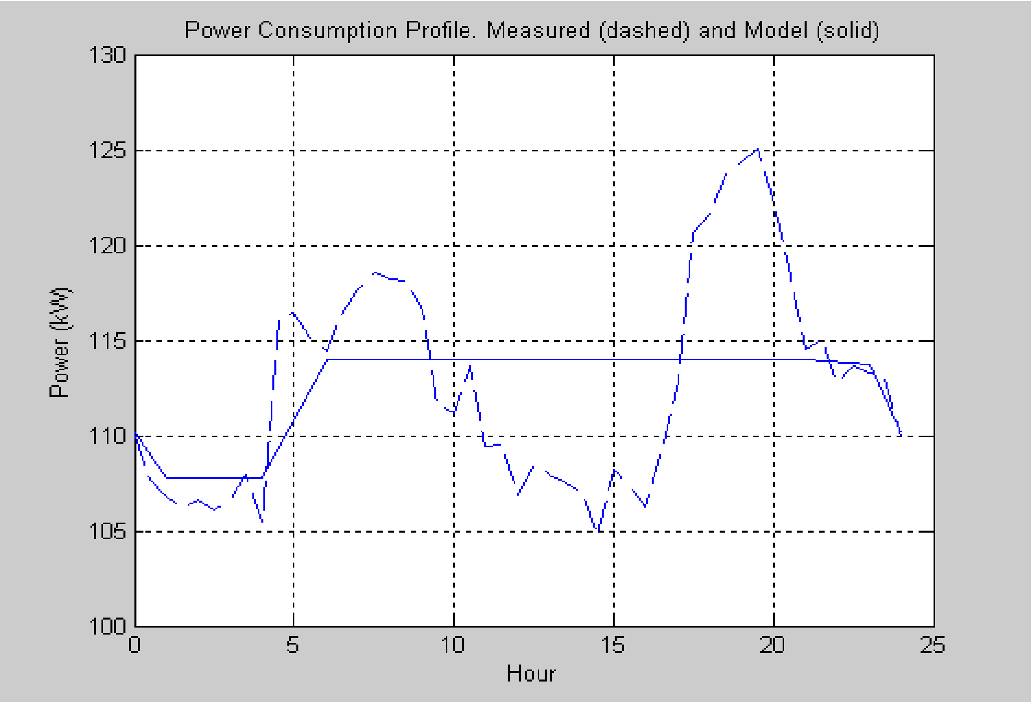


Figure 6.3-11 Measured power consumption profile (dashed) together with the model profile (solid) if TP_1 to TP_5 according to paragraph 6.3.4.2.1 and A_prim, B_prim, C_prim and D_prim according to the values above are used.

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 bee done regarding the equations:

Equation	Changes
Equation 6.3-29	$\overline{E^{W}} \Rightarrow \overline{E^{WE}}$
Equation 6.3-30	$\overline{E^{W}} \Rightarrow \overline{E^{WE}}$, $E_m^{W} \Rightarrow E_m^{WE}$
Equation 6.3-31	-“- -“-
Equation 6.3-32	$E_m^{W} \Rightarrow E_m^{WE}$, $M_{m,n}^{W} \Rightarrow M_{m,n}^{WE}$

The calculations results 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:

Equation	Changes
Equation 6.3-34	$\overline{C^{W}} \Rightarrow \overline{C^{WE}}$
Equation 6.3-35	$\overline{C^{W}} \Rightarrow \overline{C^{WE}}$, $C_m^W \Rightarrow C_m^{WE}$
Equation 6.3-36	$C_m^W \Rightarrow C_m^{WE}$, $M_{m,n}^W \Rightarrow M_{m,n}^{WE}$, $M^W\mu(m,3\_4) \Rightarrow M^{WE}\mu(m,3\_4)$
Equation 6.3-37	$M^W\mu(m,3\_4) \Rightarrow M^{WE}\mu(m,3\_4)$, $M_{m,n}^W \Rightarrow M_{m,n}^{WE}$

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.

Model Parameter	**Working day**	**Weekend day**
TP_1	1	1
TP_2	6	4
TP_3	10	6
TP_4	17	21
TP_5	21	23
A_prim	112.76 kW	110.14 kW
B_prim	109.92 kW	107.73 kW
C_prim	214.30 kW	113.96 kW
D_prim	118.20 kW	113.75 kW
L_My_L	1	1
L_Sigma_L	0.0957	0.1632
L_My_H	0	0
L_Sigma_H	0.0458	0.0755

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).

Figure	Day *)	Number of days	L_Sigma_L **)	L_Sigma_H **)	Comment
Figure 6.4-1	W	1	0	0	No noise
Figure 6.4-2	W	1	0	M	“High frequency noise” included
Figure 6.4-3	W	3	M	M	“High- and low frequency noise” included
Figure 6.4-4	WE	1	0	0	No noise
Figure 6.4-5	WE	1	0	M	“High frequency noise” included
Figure 6.4-6	WE	3	M	M	“High- and low frequency noise” included
Figure 6.4-7	W WE	10	M	M	“High- and low frequency noise” included
Figure 6.4-8	W WE	34	M	M	“High- and low frequency noise” included

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

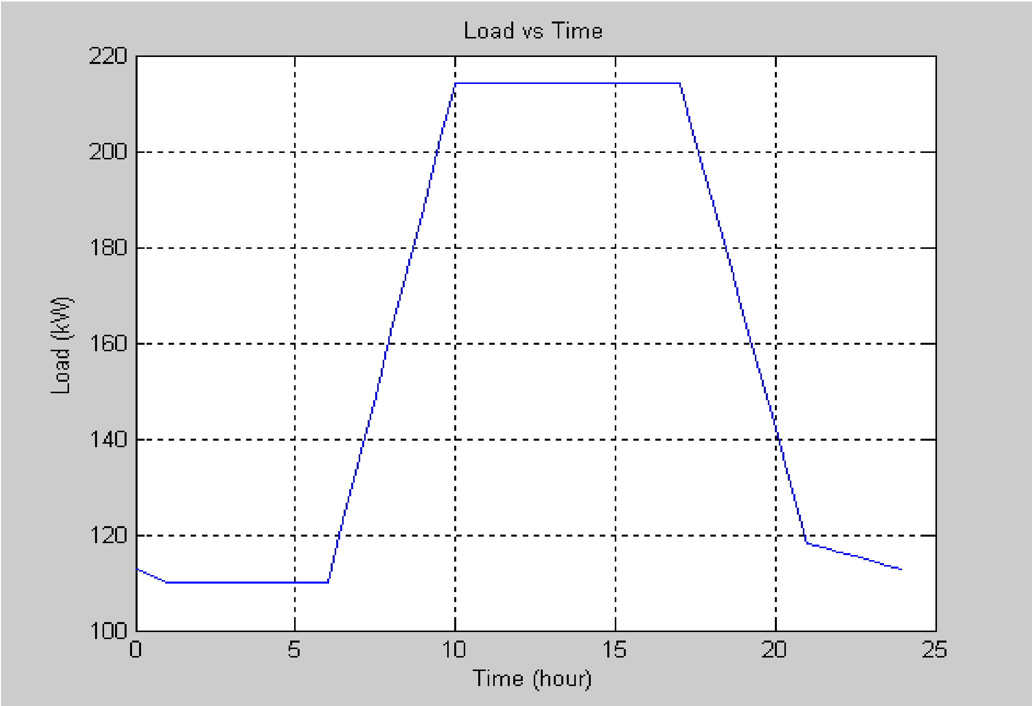


Figure 6.4-1 Simulated power profil. 1 working day. No noise

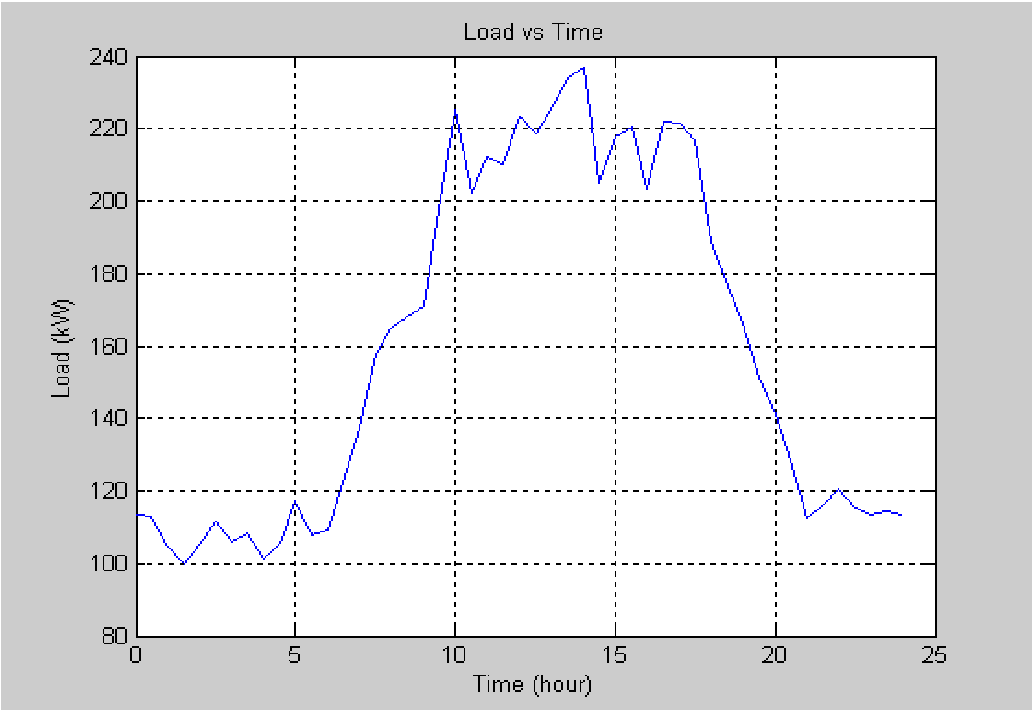


Figure 6.4-2 Simulated power profil. 1 working day. High frequency noise

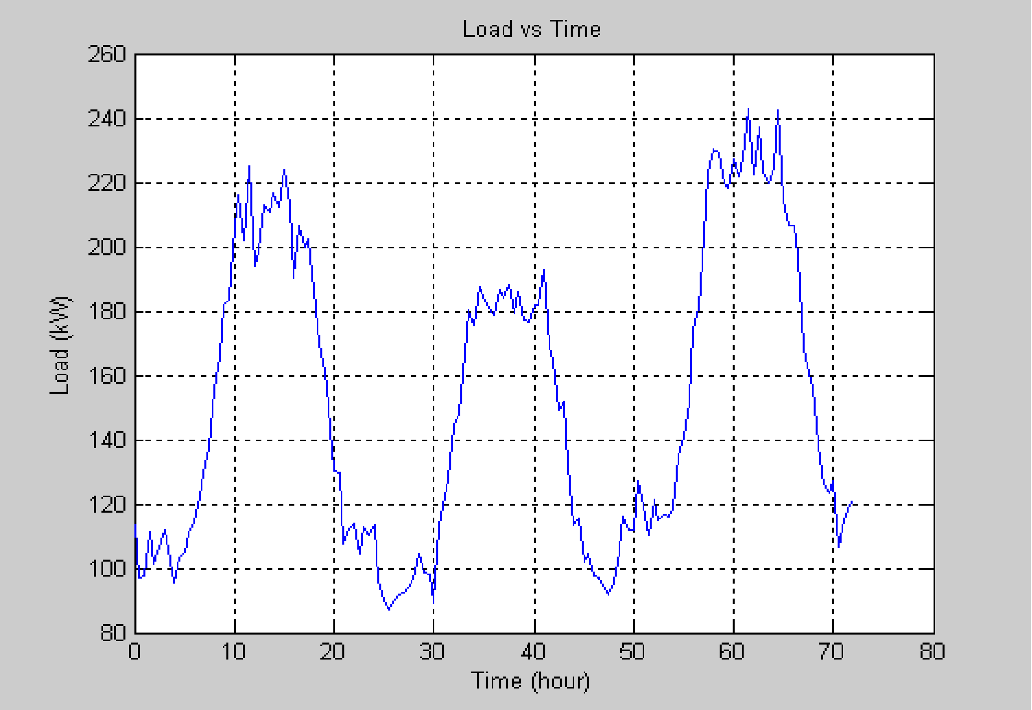


Figure 6.4-3 Simulated power profile. 3 working days. High- and low frequency noise

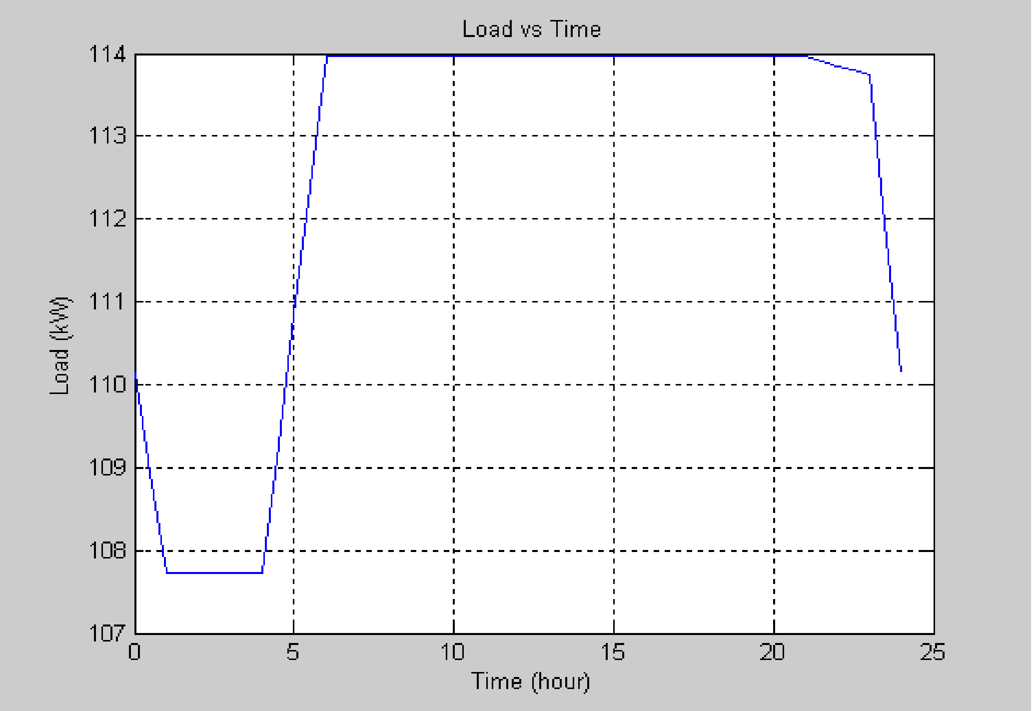


Figure 6.4-4 Simulated power profile.1 weekend day. No noise

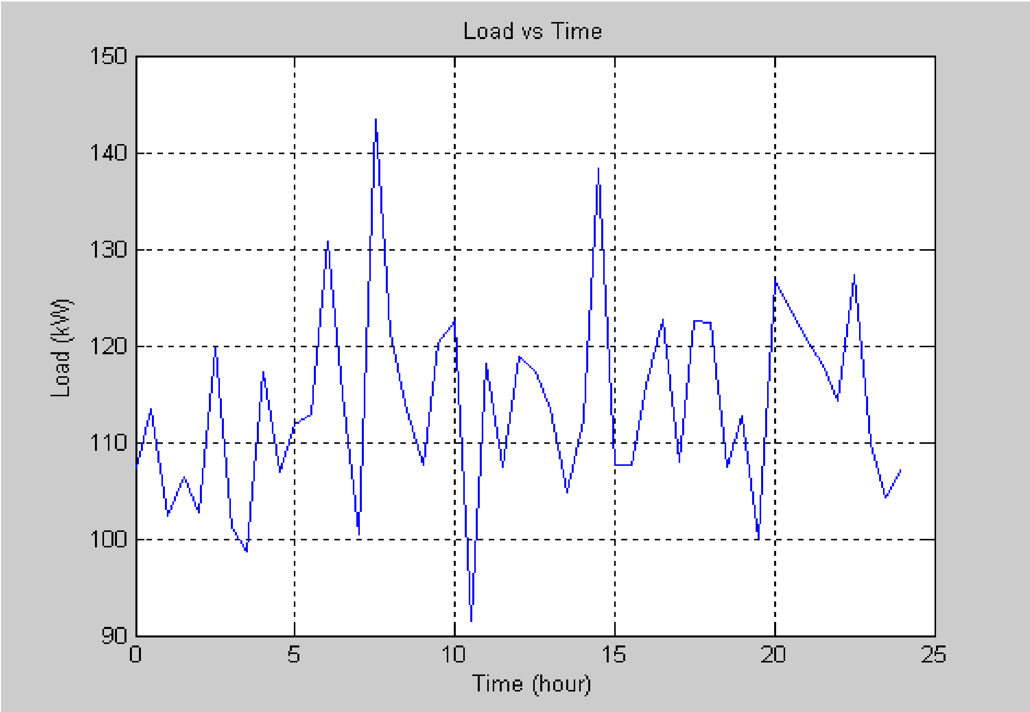


Figure 6.4-5 Simulated power profile.1 weekend day. High frequency noise

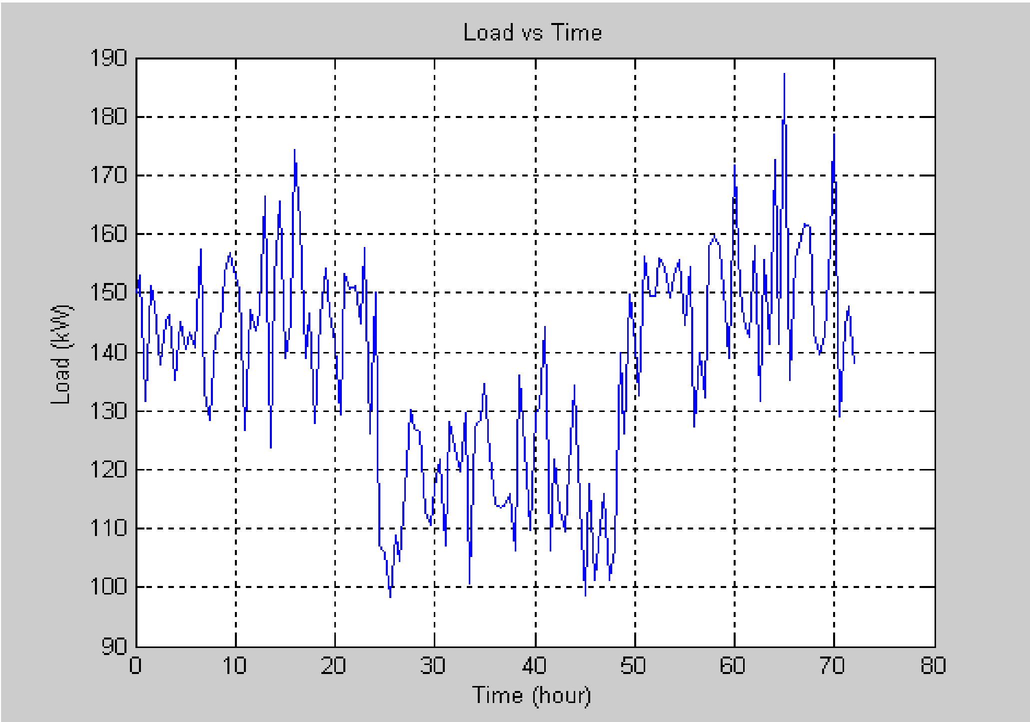


Figure 6.4-6 Simulated power profile.3 weekend days. High- and low frequency noise

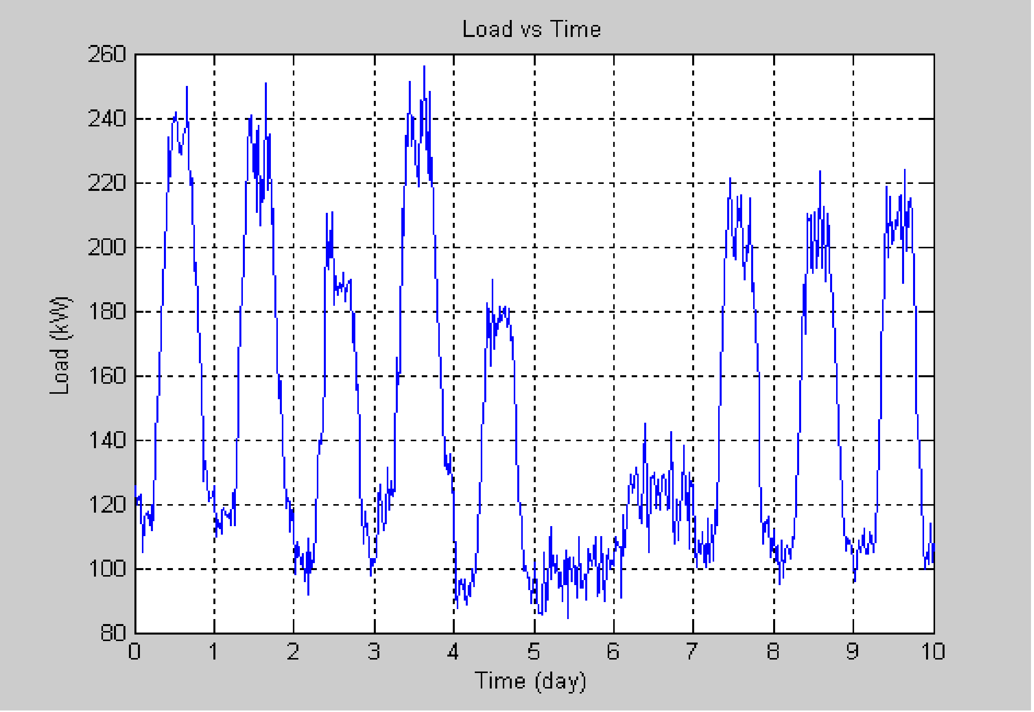


Figure 6.4-7 Simulated power profile.10 days with a week consisting of 5 working days and 2 weekend days. High- and low frequency noise

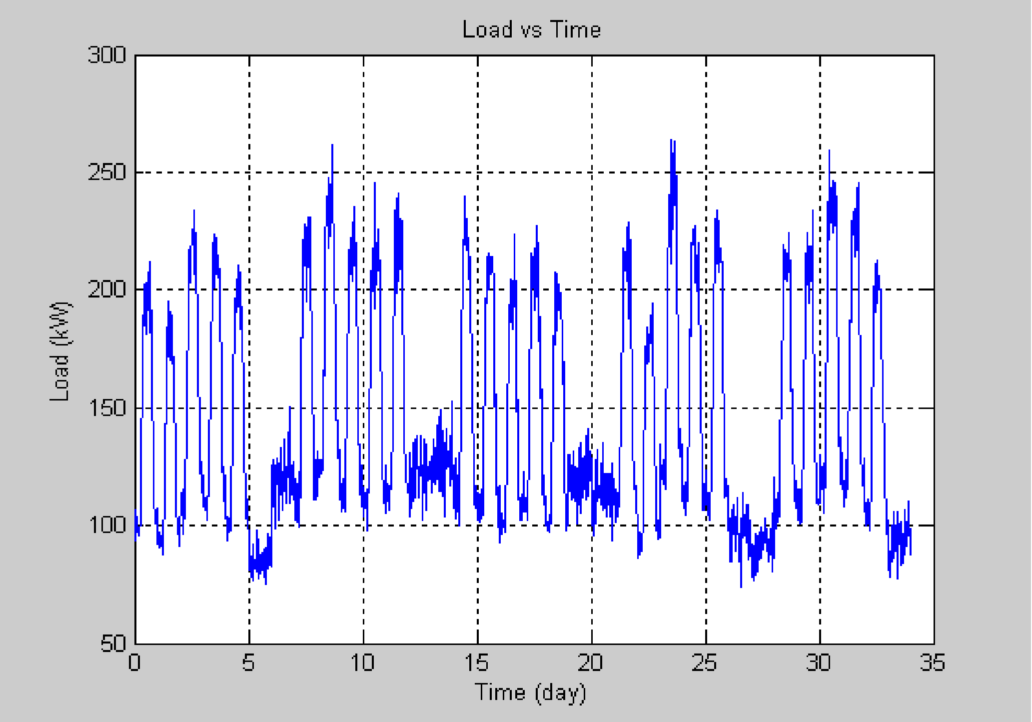


Figure 6.4-8 Simulated power profile.34 days with a week consisting of 5 working days and 2 weekend days. High- and low frequency noise

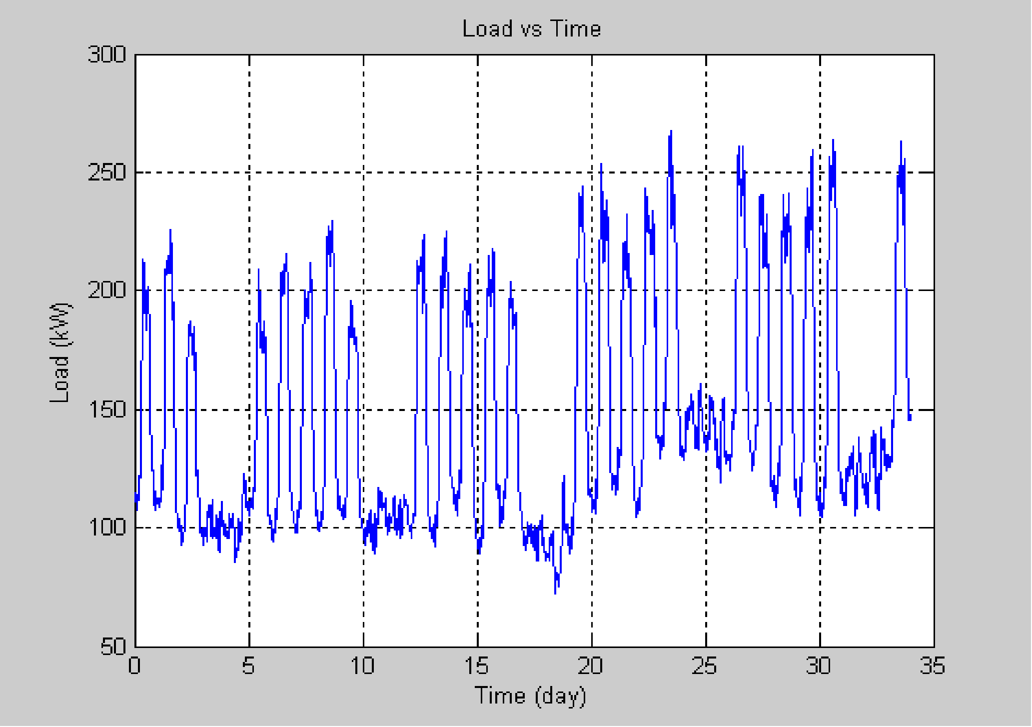


Figure 6.4-9 Measured power profile. 34 days of the measuring period have been analysed. The weeks consisted of 5 working days and 2 weekend days.

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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