Simulation of a Wind Power Farm

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Content

1 INTRODUCTION

This document deals with simulation of an autonomous power system, where wind acts as power source. The wind speed and the load are generated stochastically. The autonomous system is equipped with an energy storage device. The system is connected to the utility grid to balance the power. Fig. 1 shows the main components in the autonomous system.

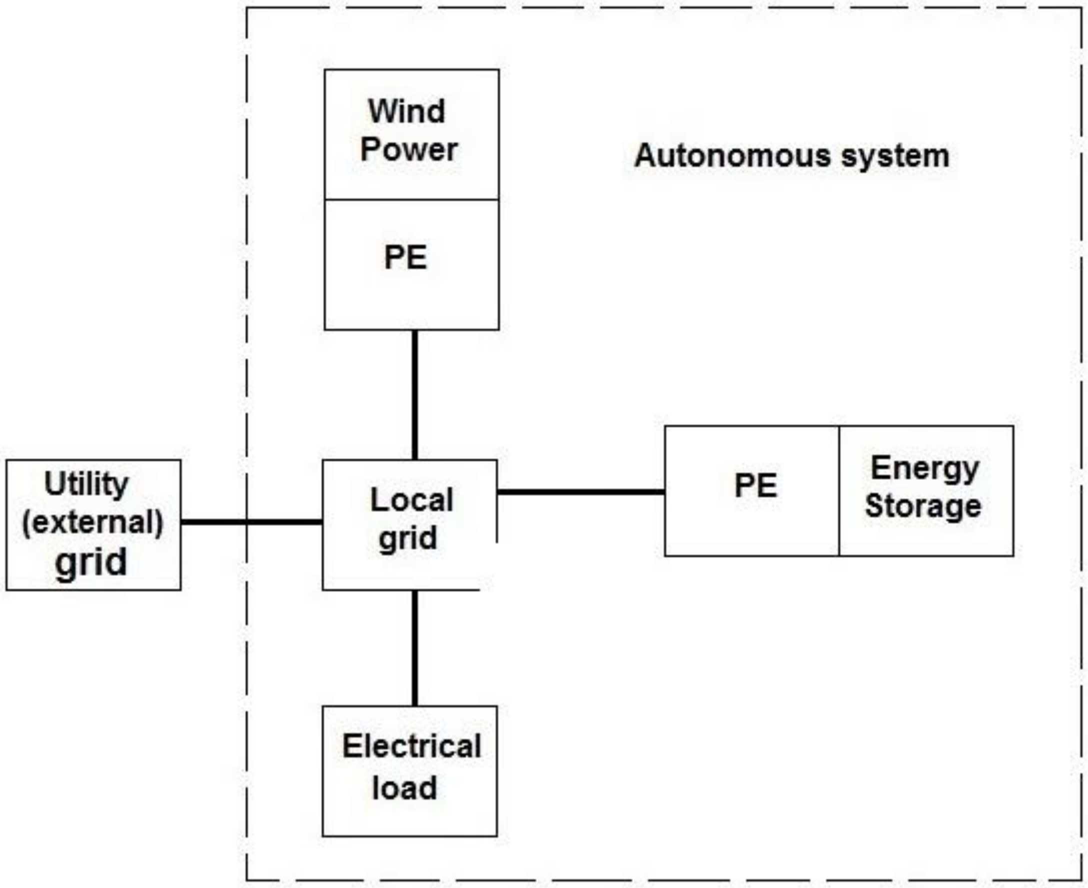

Fig. 1. The main components in the autonomous power system.

Subsystems in the power system according to Fig. 1:

Wind Power: Wind power plant.
Local grid: autonomous power grid.
Utility grid: power grid with facility to balance the power.
Energy storage: storage device with two purposes: 1) To store energy surplus. 2) To supply energy to the local grid to meet an energy deficit.
Electrical load: Active and reactive local electrical load.
PE: power electronics for electrical adaptation.

2 SIMULATION SYSTEM

2.1 Overview

The simulation system is built up of 9 modules according to Table I. The intention of the system is to enable a statistical basis for evaluation of a power system.

Table I. The modules in the simulation system.

System Modules	Function
Wind_make	Stochastic wind speed
Wind_turbine	Electrical wind power
Load_make	Stochastic load
Connect_gen_load	See section 2.5
Storage_distribution	See section 2.6
Power_evaluate	Simulation evaluation

The simulation flowchart is illustrated in Fig. 2. The loop is repeated "N" times. Evaluation of the simulation is presented in the form of statistical parameters.

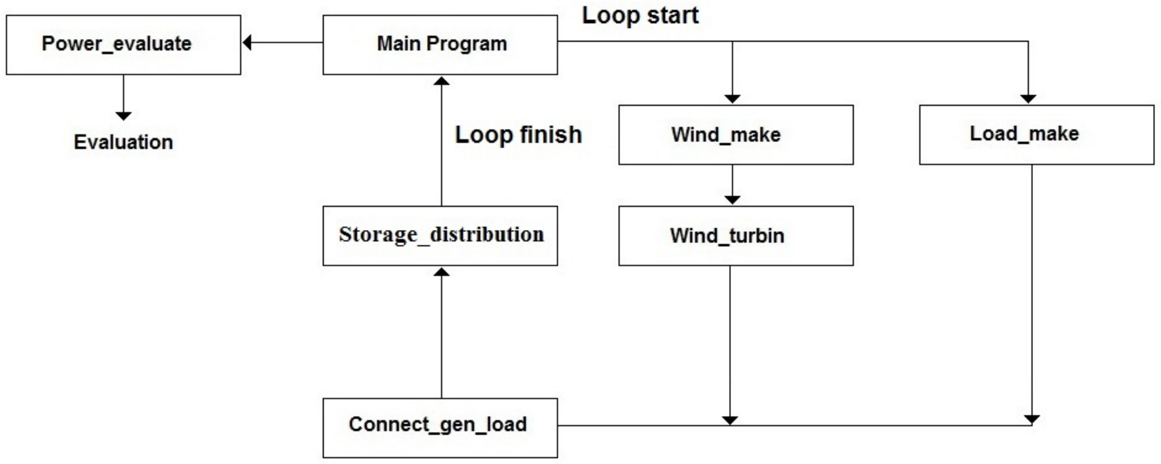

Fig. 2. Simulation flowchart. The loop repeated "N" times.

The modules are described in sections 2.2 to 2.7. These modules are also described in [1] that deals about an autonomous power system consisting of both wind power and solar power.

2.2 Module Wind_make

2.2.1 General description

The program module “Wind_make” generates stochastical wind speeds consisting of two components according to:

Equ. 1 $V = V_B + V_N$

Where: V: Total wind speed
V_B: Base component
V_N: Noise component

V_B is generated by a Weibull process
with the density function:

Equ. 2
$$W(A, C) = \frac{C}{A}\left(\frac{V_B}{A}\right)^{C-1} e^{-\left(\frac{V_B}{A}\right)^{C}}$$

Where: A,C: Weibull parameters

The base component is updated with equally spaced intervals during a simulation process. In order to get statistical confidence, this is done 10 times during a simulation process.

The component V_N is generated by using a factor C_W according to:

Equ. 3 $V_N = V_B \times C_W$

C_W is given by a Laplace distribution according to Equ. 4.

Equ. 4
$$p(x) = \frac{1}{2 \cdot \emptyset} \times \exp\left(- \frac{|x - \theta|}{\emptyset}\right)$$

The Laplace parameters have been chosen according to:

ø = 0.16
θ = 0

Updating of C_W is done each simulation step.

Fig. 3 illustrates the updating of V_B and V_N.

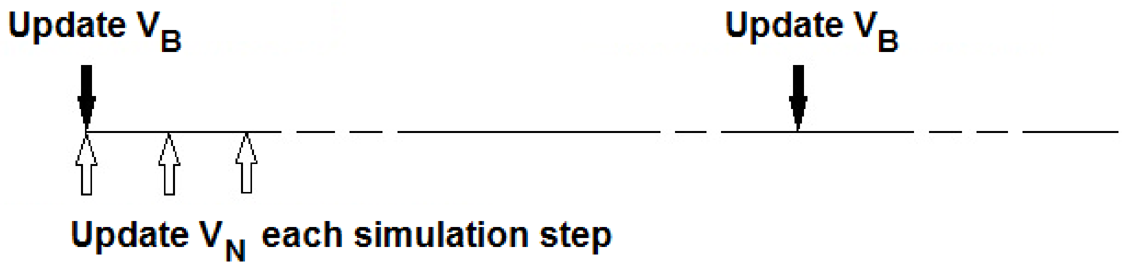

Fig. 3. The updating of V_B and V_N during a simulation process.

A detailed description of the statistical princip for wind generation is given in [2].

The module has a special function, in order to predict the wind speeds, to an optional hight over the ground.

This is based on the so called “Power Law” according to:

Equ. 5. $$V2 = V1 \times \left(\frac{H2}{H1}\right)^{\alpha}$$

Where:

V1: Measured wind speed
V2: New predicted wind speed
H1: Hight over the ground when the wind speed was measured
H2: Hight over the ground corresponding to wind speed V2
α : The ground surface friction coefficient

The module presupposes H1 = 18.5 m.

The coefficient α has been determined on many occasions around the world. Estimated mean values are given in e.g. [4]. See Table II.

Table II. Estimated mean values for coefficient α.

Terrain type	**α**
Lake, ocean, smooth hard ground	0.10
Foot high grass on ground	0.15
Tall crops, hedges, shrubs	0.20
Wooded country with trees	0.25
Small town with some trees and shrubs	0.30
City with tall buildings	0.40

2.2.2 Example

Fig. 4 shows an example of stochastically generated wind profile with Weibull parameter A = 6.2 and C = 1.9. Hight over the ground 18.5 m.

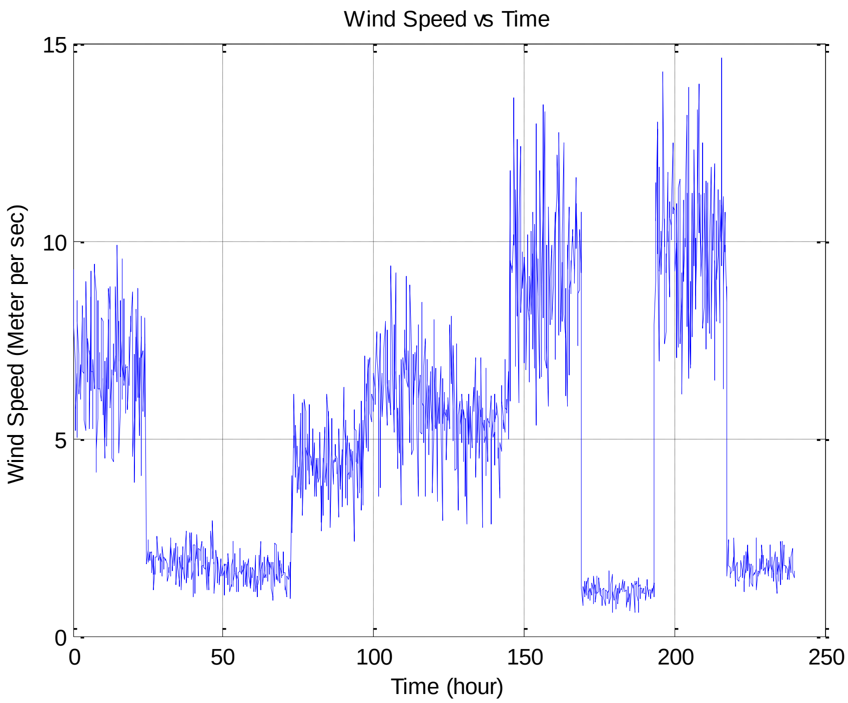

Fig. 4. Stochastically y generated wind speed with Weibull parameter A = 6.2 and C = 1.9. Hight over the ground 18.5m.

2.2.3 Input/Output parameters

Input parameters to the module:

- Weibull parameters A and C
- Hight over the ground

Output parameters from the module:

- Stochastical wind speeds to module “Wind_turbine”.

2.3 Module Wind_turbine

2.3.1 General description

The program module “Wind_turbine” simulates the function of a wind farm consisting of one or more wind turbines. The active generated power is calculated according to:

Equ. 6 $$Pw = \frac{Cp \times \rho \times A \times V^3 \times Pfw \times Nt}{2}$$

Where:

Pw: Generated active wind power (W)
$C_p(\lambda)$: Power coefficient
ρ: Air density (kg/m^3)
A: Rotor sweeping area (m^2)
V: Wind speed (m/s)
Pfw: Wind power turbine efficiency excluding Cp
Nt: Number of wind power turbines in the farm
The air density (ρ) is calculated according to:

Equ. 7 $$\rho = \frac{1.293}{1+0.00367 \times Tair} \times \frac{Pair}{1013}$$

Where:

Tair: Air temperature (°C)
Pair: Air pressure (mbar)

The rotor sweeping area (A) is calculated according to:

Equ. 8 $$A = \boldsymbol{\pi} \times \frac{D^2}{4}$$

Where: D: Rotor diameter

Power coefficient $C_p(\lambda)$ is in the module calculated according to:

Equ. 9 $$C_p(\lambda) = a0 + a1\lambda + a2\lambda^2 + a3\lambda^3 + a4\lambda^4 + a5\lambda^5$$

Where:

λ: Tip speed ratio
a0 = 1.142515
a1 = - 1.253909
a2 = 4.78158×10^{-1}
a3 = $- 7.554 \times 10^{-2}$
a4 = 5.426×10^{-3}
a5 = $- 1.4623 \times 10^{-4}$

Paremeters a0 – a5 are results from a polynomial adaption to measurements on Chalmers wind power turbine at Hönö outside Göteborg. Fig. 5 shows a comparison between measurements and polynomial adaptation.

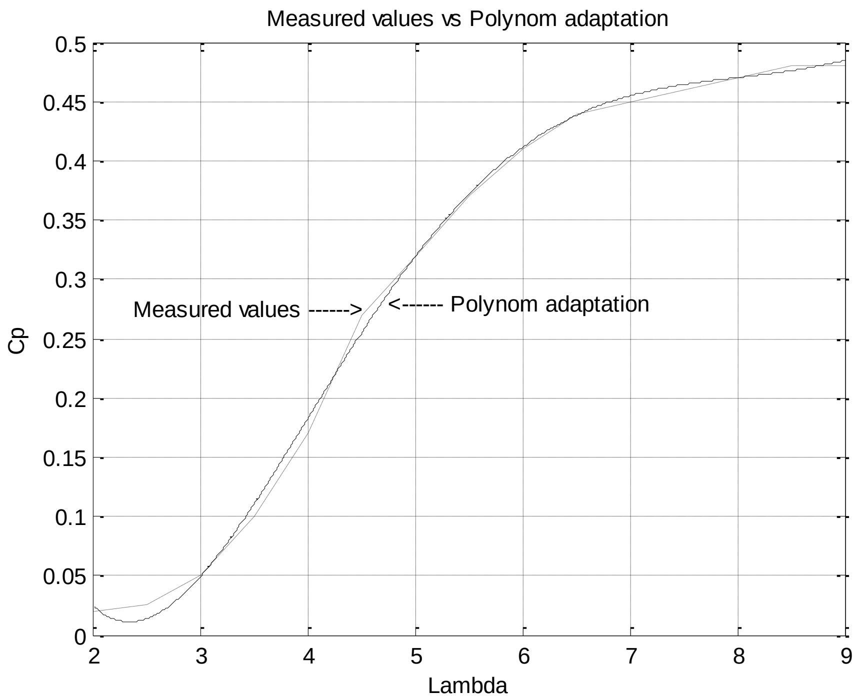

Fig. 5. Comparison between measurements and polonomial adaptation regarding coefficient Cp and parameter λ.

The tip speed ratio (λ) is calculated according to:

Equ. 10 $\lambda = Vt / V$

Where:

Vt: Wind turbine blade tip speed (m/s)
V: Wind speed (m/s)

The turbine rotor rotation speed is calculated according to:

Equ. 11 $$V_{rotor} = \frac{Vt}{\pi \times D} \times 60$$

Where: V_{rotor}: Turbine rotor rotation speed of the

The rotation speed is regulated to get the optimal value of tip speed ratio for the current wind speed. See Equ. 10. This value is unique for the wind turbine in question and means that $C_p(\lambda)$ is optimized. See Equ. 9 and thereby that Pw optimized. See Equ. 6.

If the wind speed exceeds a certain defined maximum level the turbine(s) is (are) stopped, resulting in no output power. If the wind speed is lower than a certain defined minimum level the turbine(s) does (do) not produce any output power.

The rotation speed of a wind turbine is limited by centrifugal forces and in this model limited by an 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.
Fig. 6 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 Fig. 7. This will on the other hand decrease the Cp-value (following the relation according to Fig. 5) as is shown in Fig. 8.

Fig. 9 gives the electrical output power as a function of wind speed. The electrical output power could be limited by an input parameter. The figure gives two examples. The rough part represents the case with a power limit of 35 kW. The thin part represents the power without any limit.

Other input parameters that have been used in the current examples is:

λ_{ref} = 9.0

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

Component efficiency η = 0.85.

Where η is defined according to

Equ. 12 $$P_E = P_W \times \eta$$

Where:

P_E: Electrical power.
P_W: Wind power according Equ. 6.

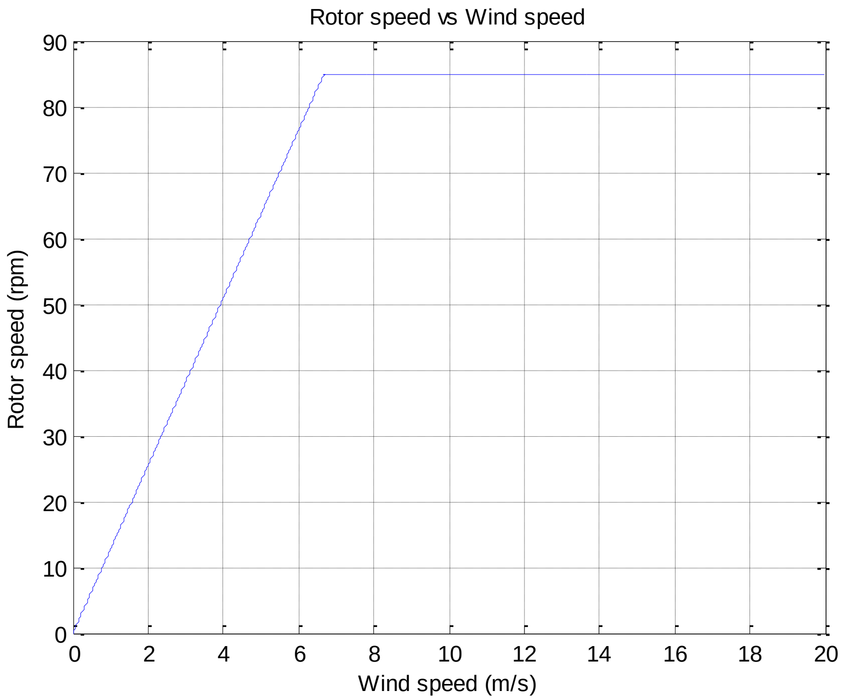

Fig. 6. The rotor speed is limited. In this example at 85 rpm.

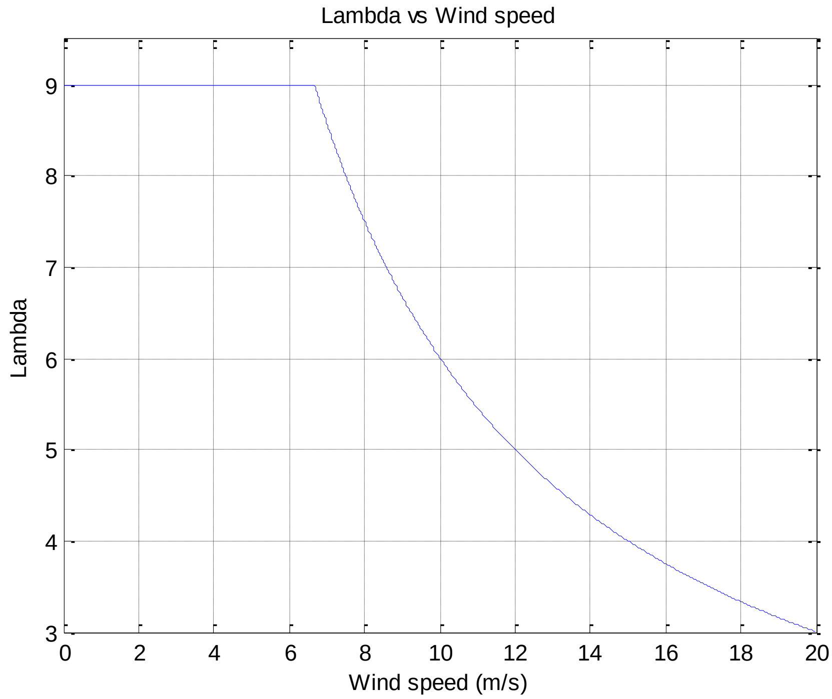

Fig. 7. λ as a function of wind speed with a rotor speed limit of 85 rpm. As the rotor speed is limited the λ - value will decrease for rotor speeds that exceeds the limit.

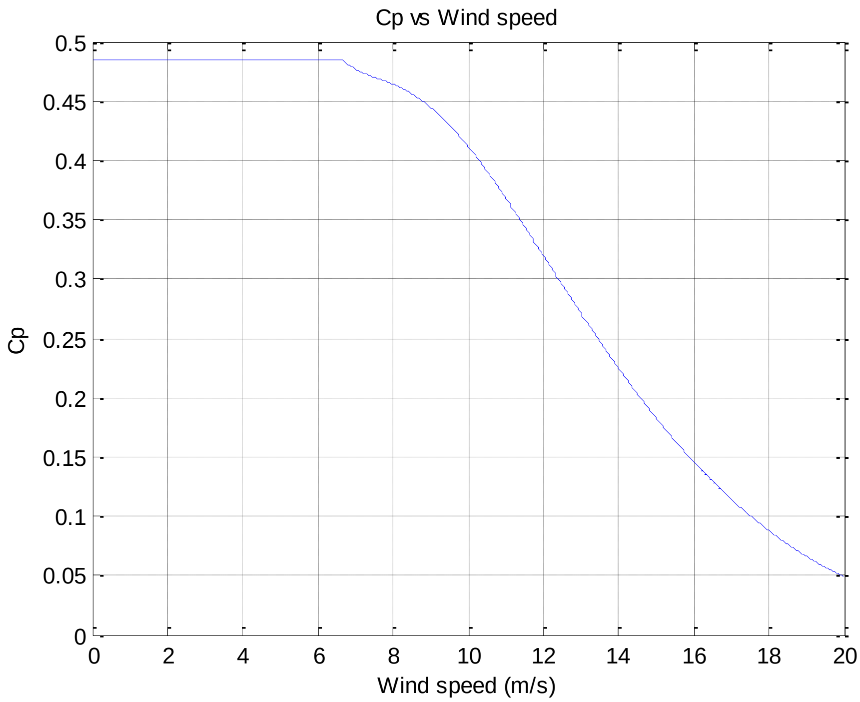

Fig. 8. As λ is decreased for rotor speeds exceeding the rotor speed limit the consequence will be a decreasing C_p - value.

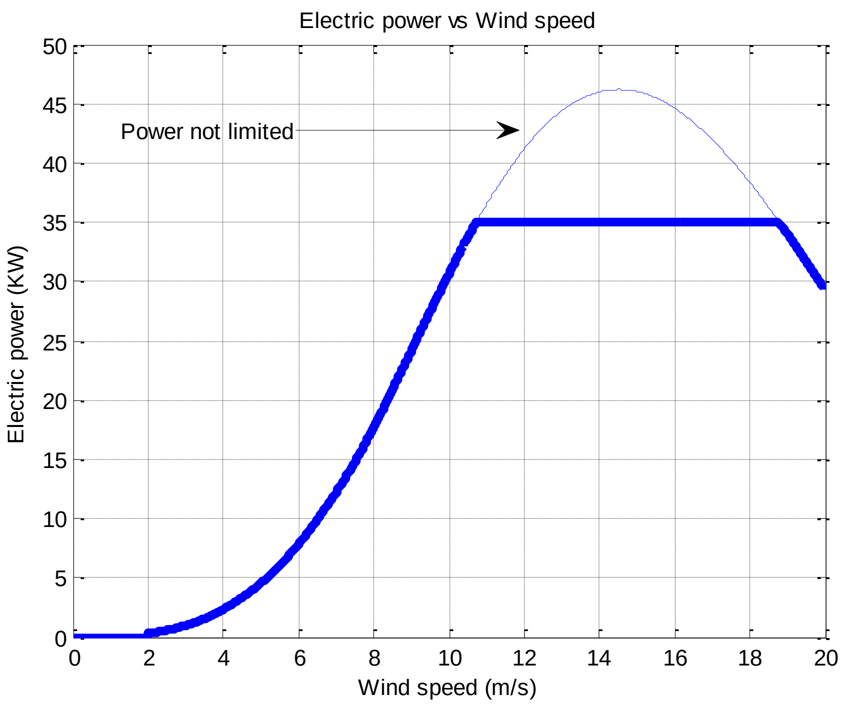

Fig. 9. As λ is decreased for rotor speeds exceeding the rotor speed limit the consequence will be a decreasing C_p - value. The rough curve represents limited power.

Generated reactive power is a function of the “Phase Angle”.

Equ. 13 $S = P + jQ$

Equ. 14 $P = |S| \times \cos \varphi$

Equ. 15 $Q = |S| \times \sin \varphi$

Where: S: Apparent power
P: Active power
Q: Reactive power
φ: Phase angle

2.3.2 *Example*

Fig. 10 shows an example of generated power with input parameters (among others) according to:

- Number of wind turbines: 1
- Maximum power per wind turbine: 3000 kW

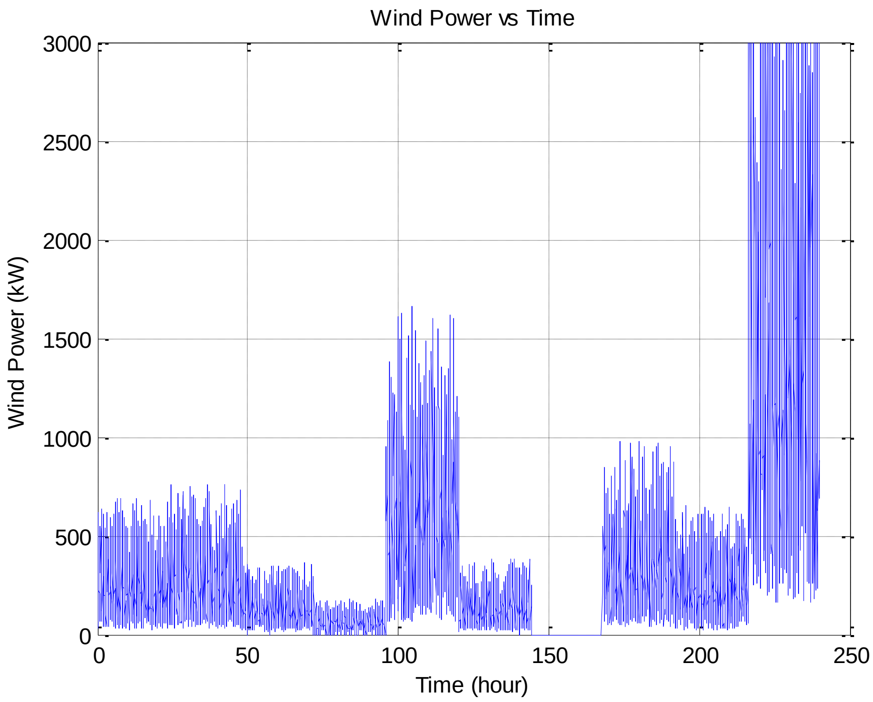

Fig. 10. Generated active wind power with input parameters according to the list above.

2.3.3 Input/Output parameters

Input parameters to the module:

- Number of wind turbines in the wind power farm
- Optimal value of tip speed ratio
- Maximum power per wind turbine
- Maximum rotation speed of wind turbine
- Total efficiency of wind turbine
- Phase angle

- Air temperature
- Air pressure
- Turbine rotor diameter
- Maximum wind speed for power production
- Minimum wind speed for power production

Output parameter from the module:

- Active wind power
- Reactive wind power
- Apparent wind power

2.4 Module Load_make

2.4.1 General description

The program module “Load_make” calculates stochastic electrical load, consisting of two components, active power and reactive power:

Equ. 16 $S = P + jQ$

Where: S: Apparent power
P: Active power
Q: Reactive power

Equ. 17 $P = |S| \times \cos \varphi$

Equ. 18 $Q = |S| \times \sin \varphi$

Where: φ: Phase angle

$|S|$ is divided into two Gaussian distributed power components:

$|S| = S_L + S_H$

Where: S_L: Low frequency power component
S_H: High frequency power component

Equ. 19 $S_L = F1$

Equ. 20 $S_H = F2 \times S_L$

Where: F1 and F2 are Gaussian distributed functions.

A description of the module is given in [1] and [3].

2.4.2 Examples

Fig. 11 shows an area consisting of 4 industrial complexes, 1 commercially center and 12 residential complexes.

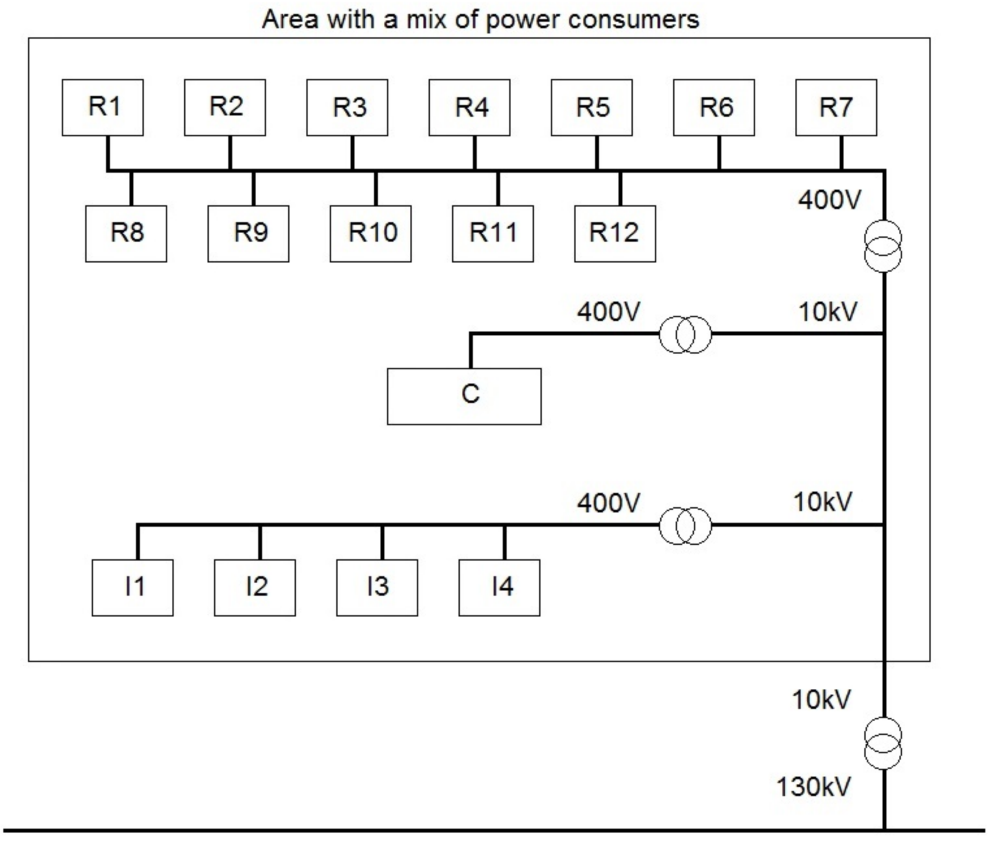

Fig. 11. An area with a mix of power consumers.

Abbreviations in Fig. 11 are according to:

- I1 – I4: 4 industrial complexes
- C: Commercially center
- R1 –R12: 12 residential complexes

A simulation is done with following assumptions:

Model for industrial area

- Annual power consumption: 1 GWh
- Phase angle, time 06 - 21 (day time): +40°
- Phase angle, time 21 – 06 (night time): + 5°

Model for commercially center

Annual power consumption 0.5 GWh and a phase angle of - 5°.

Model for residential area.

Annual power consumption 0.5 GWh and a phase angle of + 5°.

The output result is related to total power consumption of all consumers. This corresponds to the connection point at the 130 kV-line in Fig. 11.

A simulation result regarding active power for 10 days is illustrated in Fig. 12.

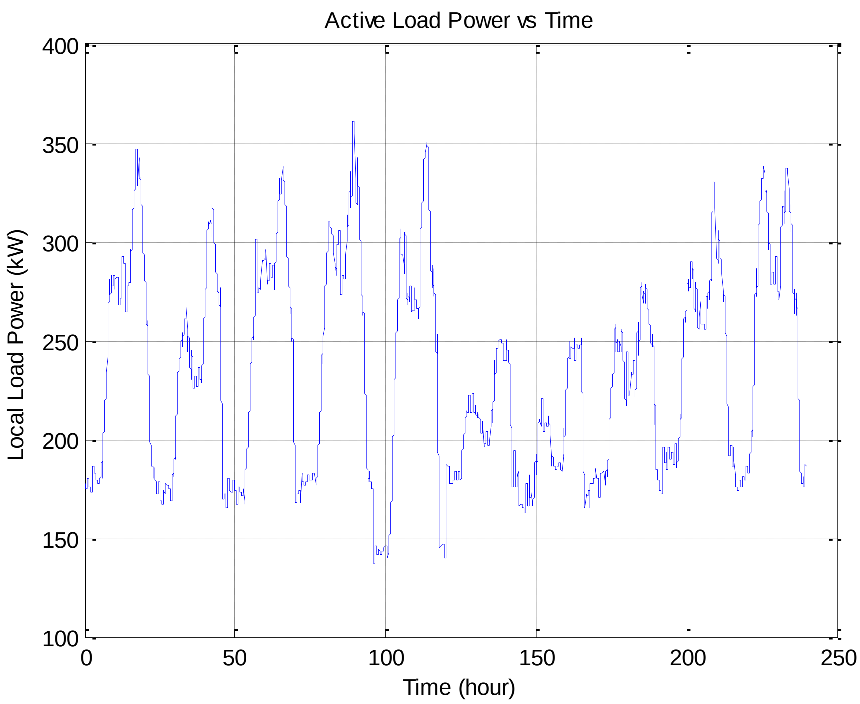

Fig. 12. Simulated active power consumption during 10 days for an area of mixed power consumers.

2.4.3 Input/Output parameters

Input parameters to the module:

- Annual power consumption, industrial area
- Annual power consumption, residential area
- Annual power consumption, commercially center
- Phase angle, industrial area, time 06 - 21 (day time)
- Phase angle, industrial area, time 21 – 06 (night time)
- Phase angle, residential area
- Phase angle, commercially center

Ouput parameters from the module:

- Statistically load of active power
- Statistically load of reactive power
- Statistically load of apparent power

2.5 Module Connect_Gen_load

A description of module "Connect_Gen_load" is given in [1].

2.6 Module Storage_distribution

2.6.1 General description

The program module "Storage_distribution" perform handling of the process regarding energy storage and usage of utility grid. Two modes are defined:

- Charging / Discharging of energy storage
- Exporting/Importing energy via utility grid

2.6.2 Examples

Fig. 13, Fig. 14 and Fig. 15 illustrate simulation examples on related values regarding Energy Storage level, Exported Active Power and Imported Active Power.

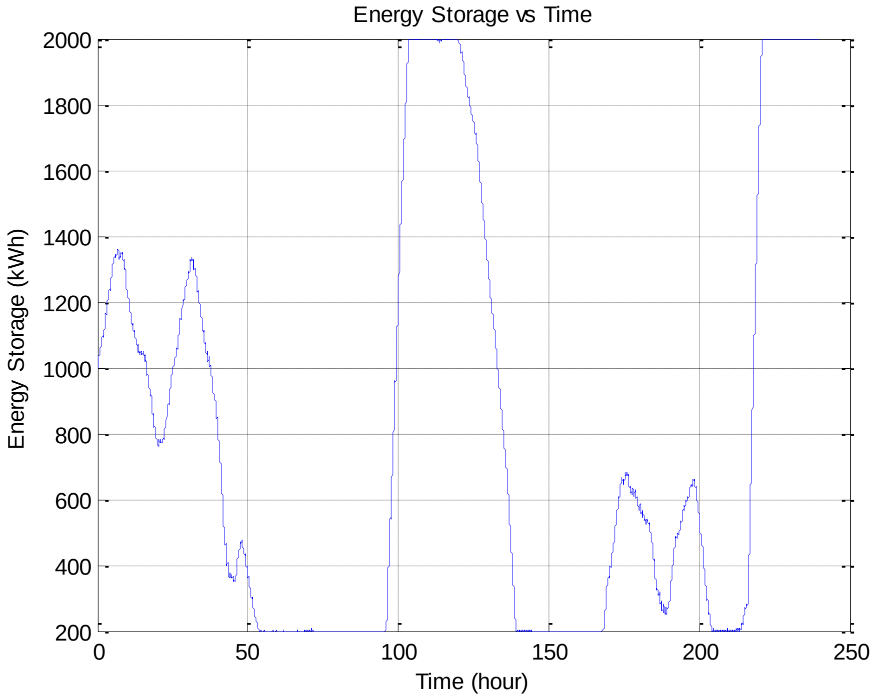

Fig. 13. Simulated example on Energy Storage level.

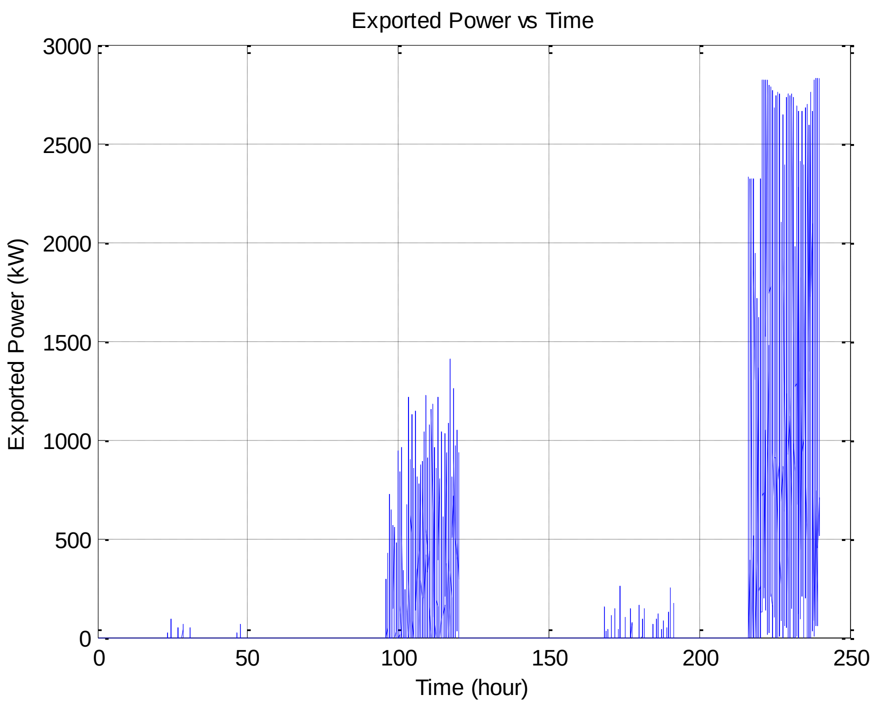

Fig. 14. Simulated example on Exported Active Power to utility grid vs Time.

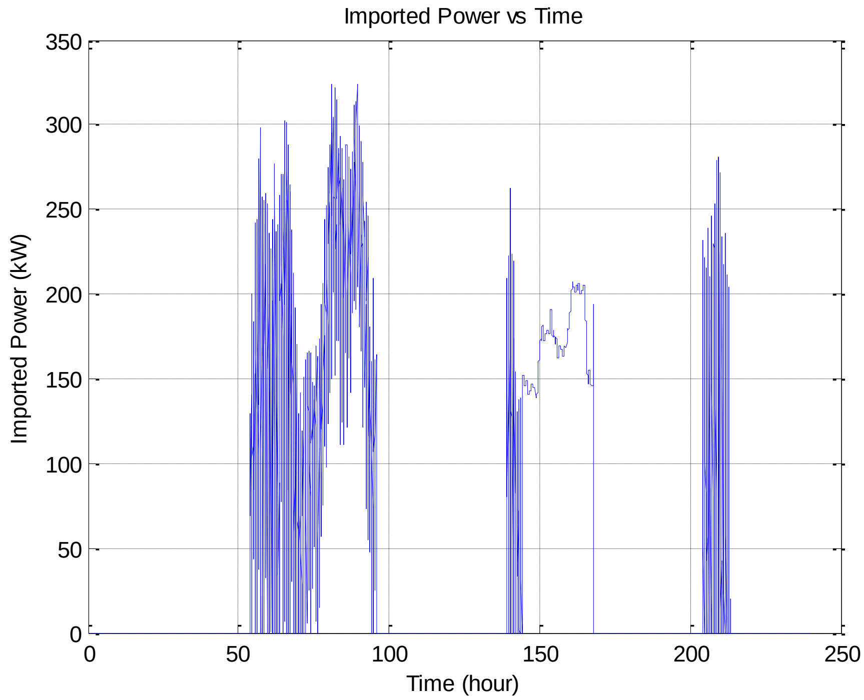

Fig. 15. Simulated example on imported Active Power from utility grid vs Time.

2.6.3 Input/Output parameters

Input parameters to the module:

- Charging/discharging efficiency
- Initial charge
- Maximum charge
- Minimum charge
- Self-discharge
- Net Power from module “Connect_Gen_load”

Output parameters from the module:

- Energy Storage level
- Exported Power to utility grid
- imported Power from utility grid

2.7 Module Power_evaluate

The program module “Power_evaluate” perform evaluation of the simulation based on all simulation repeats. The result is presentated in the form of statistical parameters.

3 SIMULATION OF A WIND POWER FARM

Simulation of a wind power farm has been performed with 200 simulation cycles per simulation process. Time resolution was 60 sec. Regarding wind speed, power generation, power load and energy storage, the following has been in question:

<u>Wind speed</u>

- Weibull paramers, A = 6.3, C = 1.9. These values correspond to predicted mean values for a time period of 1 year according to [2].
- Hight over the ground: 80 m. The Weibull parameters above were predicted from measurements at a heght over the ground of 18.5 m. At a hight over the ground of 80 m the following was simulated (see section 2.2):

- Wind speed mean value: 6.35 m/s
- Wind speed standard deviation: 1.14 m/s

Power generation

- Number of wind turbines: 4, 5 and 6. See section 3.1.
- Maximum power per turbine: 2000 kW
- Maximum rotation speed: 85 rpm
- Minimum wind speed for power: 4 m/s
- Maximum wind speed for power 25 m/s
- Wind turbine height over the ground: 80 m
- Rotor diameter: 80 m
- Turbine efficiency: 85%
- λ_{ref} (λ-value that gives Cp – max): 9
- Air temperature: 15 ° C
- Air pressure: 1013 mbar
- $C_p(\lambda)$: According to Equ. 9

Power Load

- An area with a mix of power consumers according to Fig. 11 with the following annual power consumption:
- Industrial area, annual power consumption: 5 GWh
- Commercially center, annual power consumption: 5 GWh
- Residential area, annual power consumption: 10GWh

Energy storage

- Charging/discharging efficiency: 80%
- Maximum charge level: See section 3.2
- Minimum charge level: 10 % of maximum charge level
- Initial charge level: Mean value between maximum charge level and minimum charge level
- Self-discharge: 0

3.1 Numbers of turbines

The following approach is taken: The turbines shall produce more energy, than equivalent load during a given time period.

Simulation results with mean values and standard deviations and with different numbers of turbines follow according to Table III.

Table III. Simulation result for different numbers of turbines.

Number of turbines	Energy, mean (MWh) (10 days)	Energy, st.dev. (MWh) (10 days)
4	509 (517)	185
5	642 (647)	221
6	776	266

Outgoing from simulation results with six turbines, one would obtain the following:

Mean, 4 turbines: 776 / 6 × 4 = 517
Mean, 5 turbines: 776 / 6 × 5 = 647

These values are in parentheses in Table III. Values outside and inside parentheses does not match completely (as would be expected). The difference is due to the large standard deviation. Despite the 200 simulation cycles, the mean values spread slightly between different simulation processes.

The simulated energy consumption during 10 days is:

Mean: 555 MWh

St.dev: 12 MWh

This means that a number of 5 turbines could be suitable to meet the approach above.

Maximum power consumtion has been simulated to 4.9 MW. This to compare with maximum available power from 5 turbines of 5 × 2 MW = 10 MW.

3.2 Capacity of energy storage

The storage capacity has been related to the annual power consumption of totally 20 GWh (industrial area 5 GWh + commercially center 5 GWh + residential area 10 GWh) according to the following:

Equ. 21 Storage capacity = $\frac{20\ \text{GWh}}{365} \times N$

Where:

N:	Number of days
Storage capacity:	This corresponds to the mean value of energy consumption (GWh) during N days.

Table IV and Table V show some simulation results for varying values of parameter N. Each simulation consists of 200 simulation cycles. 5 turbines have been used.

With respect to certain parameters in Table IV and Table V:

St_cap (N):	Storage capacity in terms of parameter N. See Equ. 21.
St_cap/E_{gen_day}:	See below. Equ. 22.
Generator:	Genarated energy during 10 days.
Imp/(Exp+Imp):	Relation between imported energy and the sum of imported and exported energy during 10 days.
Exp/Gen:	Relation between exported energy and generated energy during 10 days.
Imp/Gen:	Relation between imported energy and generated energy during 10 days.
Storage, mean and std.dev:	Mean value and standard deviation of used storage level relative to total storage capacity.
Storage, max and min:	Maximum and minimum level of used storage level relative to total storage capacity.

Table IV. Simulation results with varying values of parameter N.

St_cap (N)	St_cap/ E_{gen_day}	Generator (GWh)	Imp/ (Exp+Imp) (%)	Exp/Gen (%)	Imp/Gen (%)
0.1	0.084	0.649	45.0	44.7	49.1
0.5	0.42	0.659	42.0	37.9	34.4
1	0.84	0.626	43.3	28.8	30.4
2	1.68	0.691	34.1	22.6	12.7
3	2.52	0.656	38.7	16.4	13.8
4	3.36	0.654	35.8	12.4	9.58
5	4.2	0.654	34.0	9.98	6.13
6	5.04	0.665	34.8	8.56	4.48
7	5.88	0.653	36.5	7.45	3.58
8	6.72	0.658	36.2	5.69	5.35
9	7.56	0.641	39.5	3.73	3.41
10	8.4	0.654	39.2	2.65	2.05
11	9.24	0.639	42.0	2.26	0.678
12	10.1	0.658	40.5	2.29	1.74
13	10.9	0.658	44.0	1.23	1.1×10^{-2}
14	11.8	0.670	42.5	1.26	0
15	12.6	0.648	46.8	0.593	0
16	13.4	0.646	46.0	0.838	0
17	14.3	0.680	45.5	0.703	0
18	15.1	0.673	47.8	0.358	0
19	16.0	0.634	49.0	8.68×10^{-2}	0
20	16.8	0.630	49.2	6.45×10^{-2}	0
21	17.6	0.653	48.2	0.146	0
22	18.5	0.625	49.8	1.76×10^{-2}	0
23	19.3	0.623	49.2	2.44×10^{-2}	0
24	20.2	0.674	49.2	7.85×10^{-2}	0
25	21.0	0.659	49.2	6.67×10^{-2}	0
26	21.9	0.665	49.5	2.86×10^{-2}	0
27	22.7	0.642	50.0	0	0
28	23.5	0.645	50.0	0	0
29	24.4	0.659	49.8	3.20×10^{-2}	0
30	25.2	0.631	50.0	0	0
35	29.4	0.646	50.0	0	0
40	33.6	0.672	50.0	0	0
45	37.8	0.643	50.0	0	0
50	42.0	0.632	50.0	0	0
60	50.4	0.663	50.0	0	0
70	58.8	0.653	50.0	0	0
80	67.2	0.664	50.0	0	0
90	75.6	0.635	50.0	0	0
100	84.0	0.660	50.0	0	0

Table V. Simulation results with varying values of parameter N.

St_cap (N)	Storage mean (%)	Storage std.dev (%)	Storage max (%)	Storage min (%)
0.1	48.9	14.7	100	10
0.5	50.8	14.6	100	10
1	50.5	17.9	100	10
2	59.5	18.8	100	10
3	58.0	21.6	100	10
4	60.4	22.1	100	10
5	60.6	20.9	100	10
6	61.3	21.3	100	10
7	61.4	20.9	100	10
8	61.7	20.3	100	10
9	61.1	16.9	100	10
10	61.7	15.7	100	10
11	60.3	16.6	100	10
12	60.7	16.0	100	10
13	60.4	13.6	100	10
14	61.1	13.2	100	14.2
15	59.4	11.6	100	11.6
16	59.7	12.6	100	12.4
17	59.4	10.9	100	19.1
18	59.4	10.2	100	22.4
19	58.4	9.55	100	23.5
20	57.6	8.81	100	23.8
21	58.6	9.12	100	23.5
22	57.4	7.89	100	23.5
23	57.5	8.55	100	33.3
24	58.7	8.09	100	30.6
25	58.1	8.12	100	28.3
26	58.0	7.94	100	34.8
27	57.4	7.14	91.0	31.5
28	57.3	6.38	96.7	32.2
29	57.6	6.97	100	29.8
30	56.7	6.87	98.8	30.0
35	57.0	5.36	85.6	36.3
40	57.2	4.46	83.5	41.4
45	56.4	4.00	80.2	41.5
50	56.3	3.72	75.8	43.0
60	56.4	3.27	76.0	45.7
70	56.1	2.92	72.1	46.5
80	56.0	2.65	69.8	46.9
90	55.7	2.01	64.9	47.1
100	55.8	1.72	64.4	47.6

Depending on stochastic variations, deviates the generated energy levels slightly between each simulation. See Fig. 16. The mean value for all simulations is 0.652 GWh. The standard deviation is 0.016.

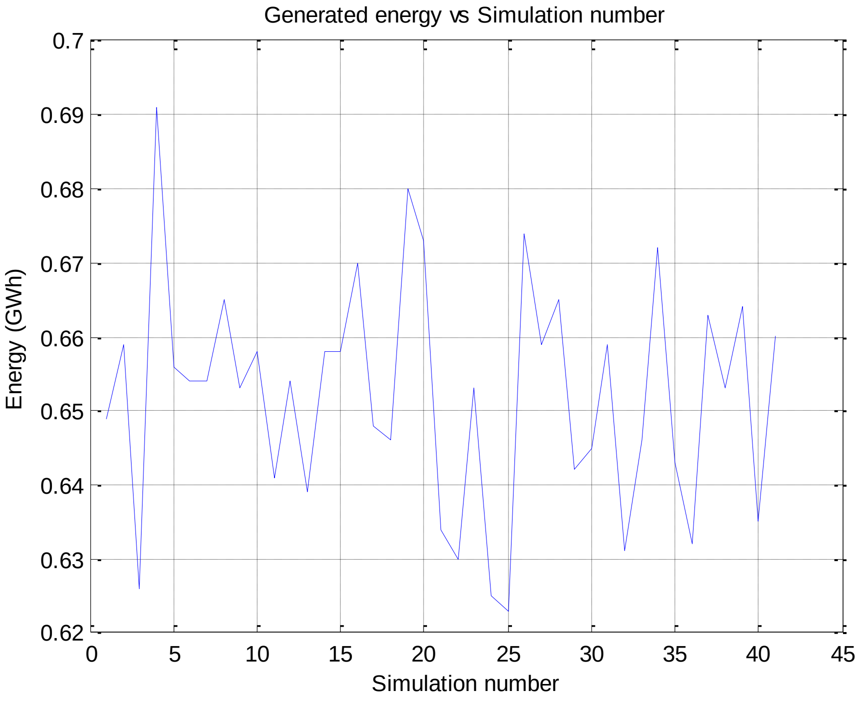

Fig. 16. Stochastic variations of the generated energy.

The following definition is done:

Equ. 22. $St\_cap/E_{gen\_day} = \frac{\text{Storage capacity}}{E_{gen\_day}}$

Where:

Storage capacity: Storage capacity (GWh)

E_{gen_day}: Mean value of energy production per day = $\frac{0.652 \text{ GWh}}{10}$

Table IV lists the values of parameter S_cap/E_{gen_day}.

Fig. 17 illustrates the Relation between Storage capacity and Generated energy per day vs Storage capacity.

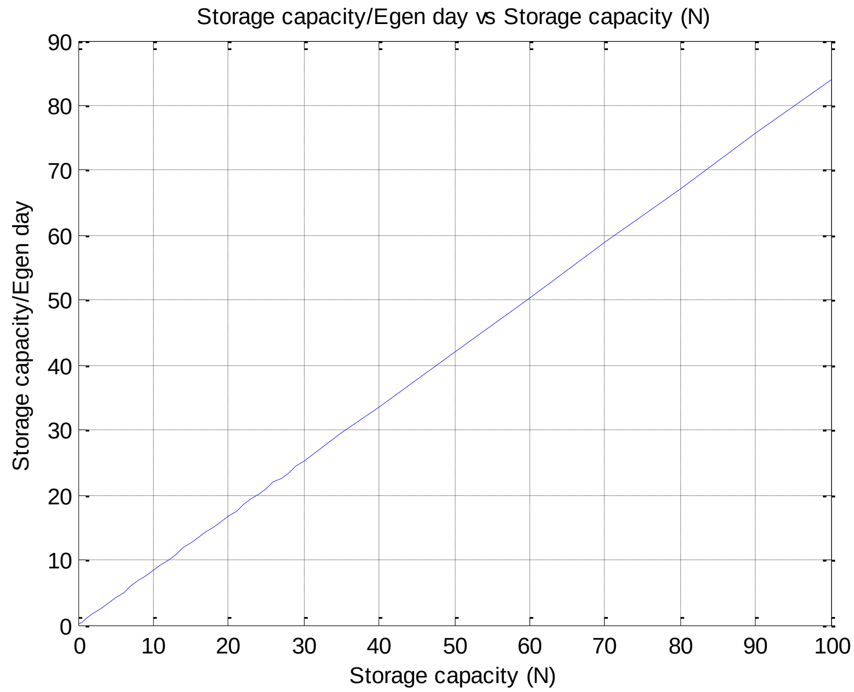

Fig. 17. Relation between Storage capacity and Generated energy per day vs Storage capacity.

<u>Additional figures</u>:

- The relation between Exported/Imported energy and Generated energy during 10 days vs Storage capacity is illustrate in Fig. 18 rep Fig. 19.
- Maximum/Minimum used Storage level vs Storage capacity is illustrate in Fig. 20 resp Fig. 21
- Standard deviation of Storage level vs Storage capacity is illustrated in Fig. 22.

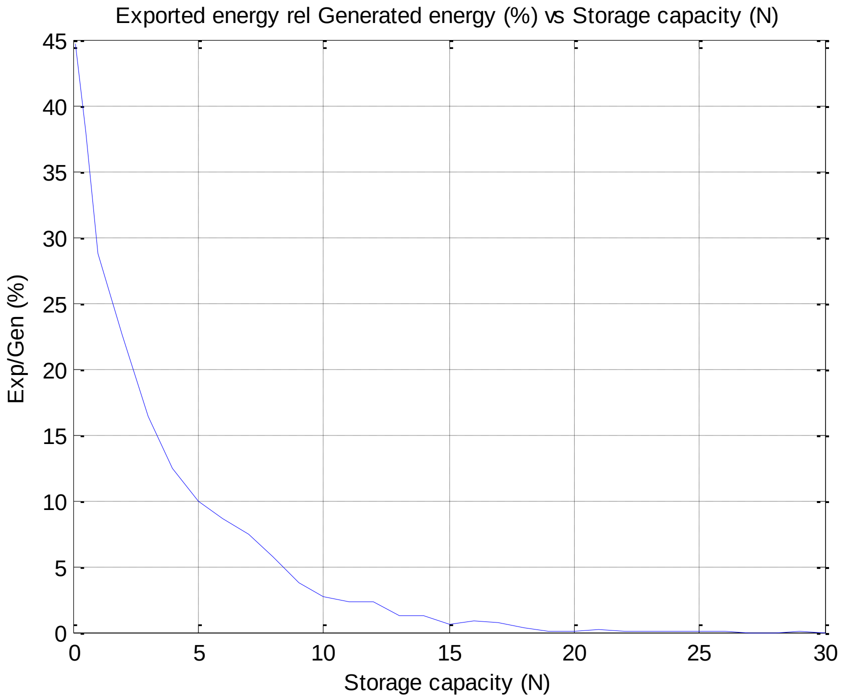

Fig. 18. Relation between Exported energy and Generated energy during 10 days vs Storage capacity.

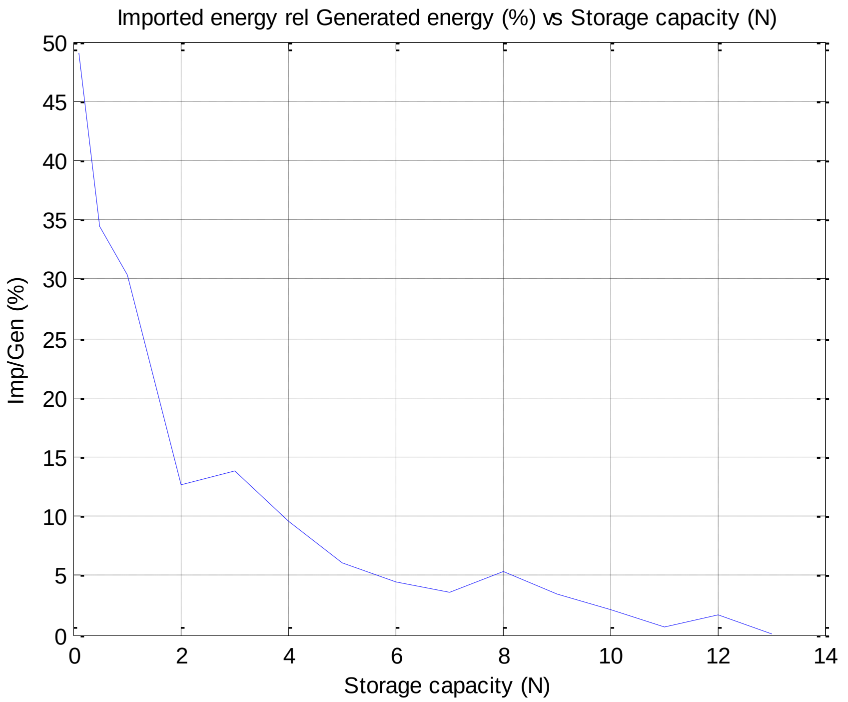

Fig. 19. Relation between Imported energy and Generated energy during 10 days vs Storage capacity.

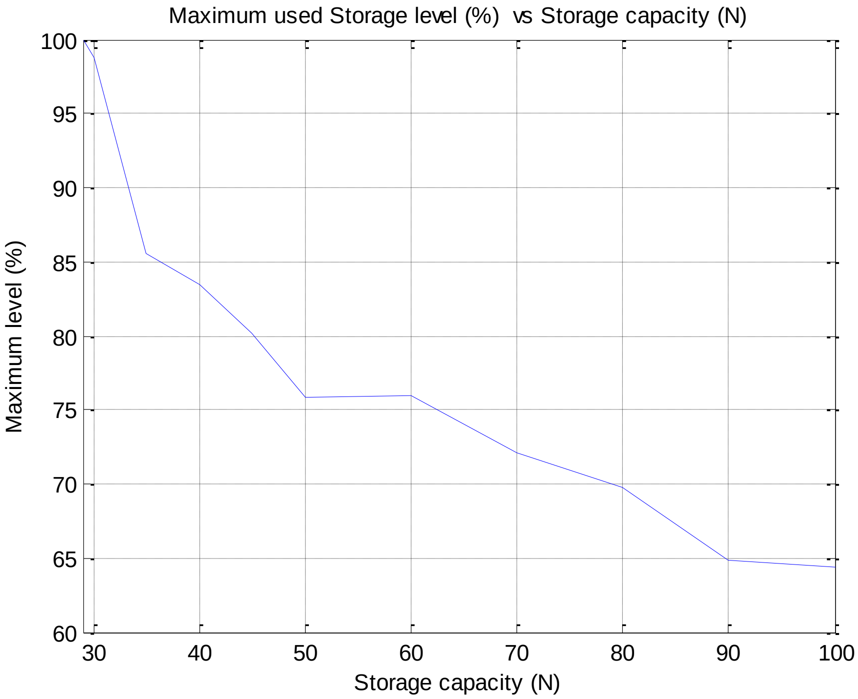

Fig. 20. Maximum used Storage level vs Storage capacity.

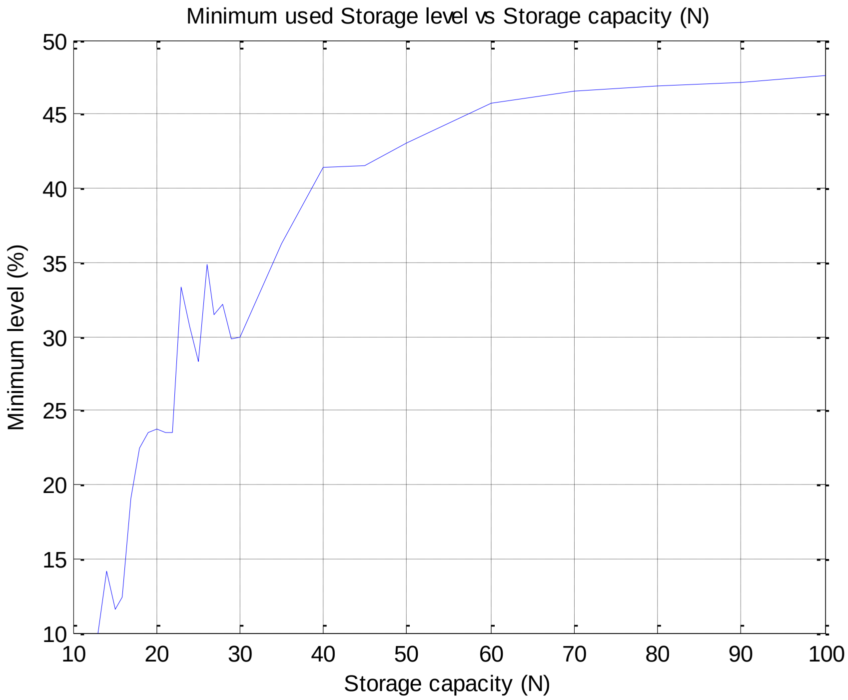

Fig. 21. Minimum used Storage level vs Storage capacity.

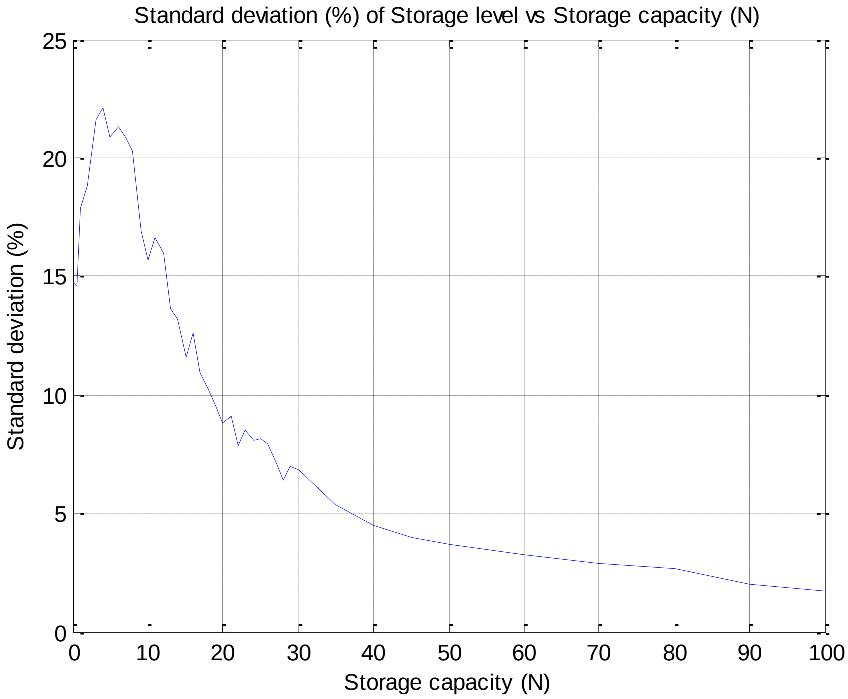

Fig. 22. Standard deviation of Storage level vs Storage capacity.

3.3 Conclusion

3.3.1 Numbers of turbines

To fulfil the approach, that the turbines shall produce more energy than equivalent load during a given time period, at least 5 turbines are needed.

3.3.2 Capacity of energy storage

- To avoid import of energy deficit or use of “extra generator”, a storage capacity corresponding to at least “N = 14” is needed. This corresponds to (see Equ. 21, Table IV, Table V and Fig. 19):

  $$\text{Storage capacity} = \frac{20\ \text{GWh}}{365} \times 14 = 0.767\ \text{GWh}.$$

  This is the same as 14 days power consumption or 3.84 % of the annual power consumption.

  It also corresponds to 11.8 times the daily energy production.

- If the storage capacity exceeds about a level corresponding to “N = 30”, no excess energy is produced. This corresponds to (see Equ. 21, Table IV, Table V and Fig. 18):

  Storage capacity = $\frac{20\ \text{GWh}}{365}$ × 30 = 2.47 GWh.

- To reduce the variations of the storage level, it is advantageous to use a high storage capacity. See Fig. 22.

- To reduce the use of low storage levels, it is advantageous to use a high storage capacity. See Fig. 21.

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