Solar and Wind Power

Ingemar Mathiasson

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Department for Energy and Environment

Division of Electric Power Engineering

Chalmers University of Technology

Content

1 INTRODUCTION

This document deals with the analysis of a small electrical power system, aimed for use in a pivat household. The system has three main components:

- Wind power unit
- Solar power unit
- Energy storage unit
- Extra auxiliaries to produce deficit energy
- Electrical load

The system is connected to the utility grid to balance the power. This means that the utility grid can be used for importing power deficit and for exporting excess power. Section 2 describes the basic structure of the system.

The study is based on simulations where solar radiation, wind speed and electrical load are generated stochastically under given prerequisites. The simulation system is briefly described in section 3.

In this study wind power turbine “Skystream 3.7”, manufactured by Xzeres, USA, has been used for wind power production. This turbine can be regarded as a good example of powerful turbines for private usage.

Some questions that have been investigated:

- Appropriate alignment of solar panels in vertical respective horizontal direction
- Impact of wind power as a part in the system
- Impact of solar power as a part in the system
- Impact of energy storage as a part in the system
- Need of extra auxiliaries to produce deficit energy

The study is consistently based on simulations corresponding a time period of one year (365 days). This means that the study is focused on the annual result for all cases studied.

2 THE STUDY OBJECT

The object to study is a small electrical power producing system with wind and power as power sources. The system is aimed for use in a pivat household.

The solar power system is built up according to following specification:

- Photovoltaic solar cell panels
- Total effective solar cell area: 50 m^2 resp. 100 m^2
- Total efficiency for solar power system: 13.54 %
- Solar cell material: Silicon

The intention is to install the solar panels on a house roof according to Fig 2.1. The angle φ in this figure corresponds to the angle between the surface normal of the solar cell panels and direction to zenith.

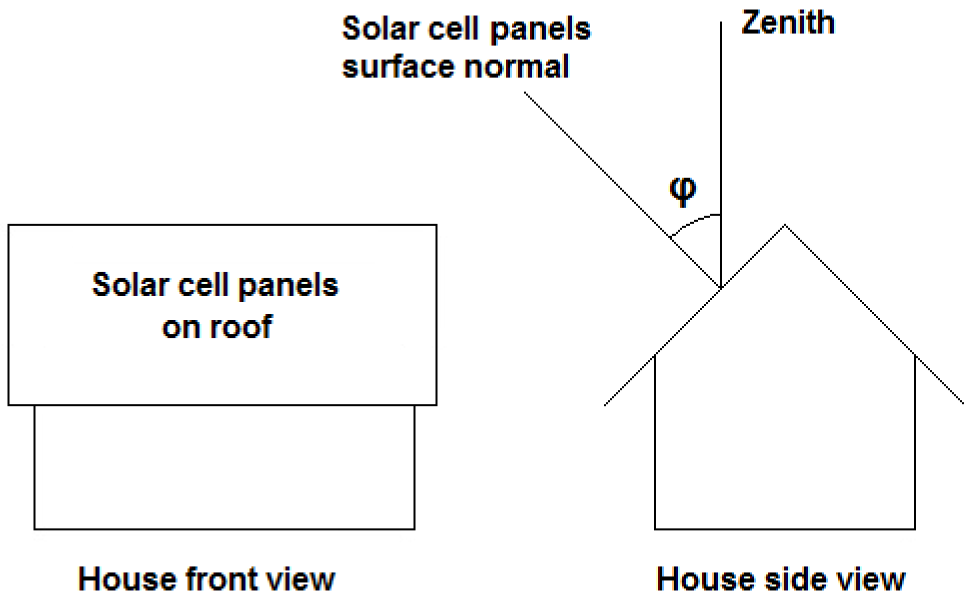

Fig. 2.1. Installation of solar cell panels on a house roof.

Fig 2.2 illustrates the installation in the horizontal plane. The angle β corresponds to the angle between the surface normal of the solar cell panels and direction to south.

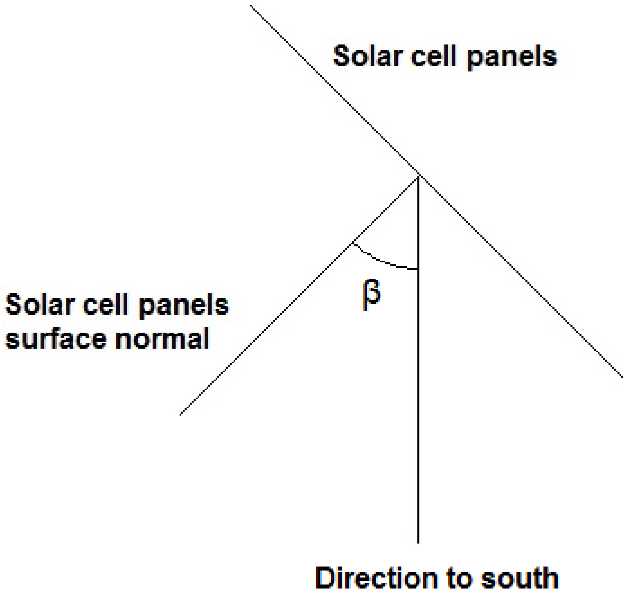

Fig. 2.2. Installation of solar cell panels in in the horizontal plane.

<u>The wind power system is built up according to following specification</u>:

- Wind power turbine: “Skystream 3.7”, manufactured by Xzeres, USA
- Maximum power per turbine: 2.4 kW
- Total efficiency for wind power system beyond the influence of Cp (see section 4): 80 %

Fig 2.3 shows an image of the wind power turbine “Skystream 3.7”. For more information regarding the wind power turbine see [5] and [6].

Fig. 2.3. Image of the wind power turbine “Skystream 3.7”.

3 THE SIMULATION SYSTEM

Fig 3.1 shows the main components in the power system.

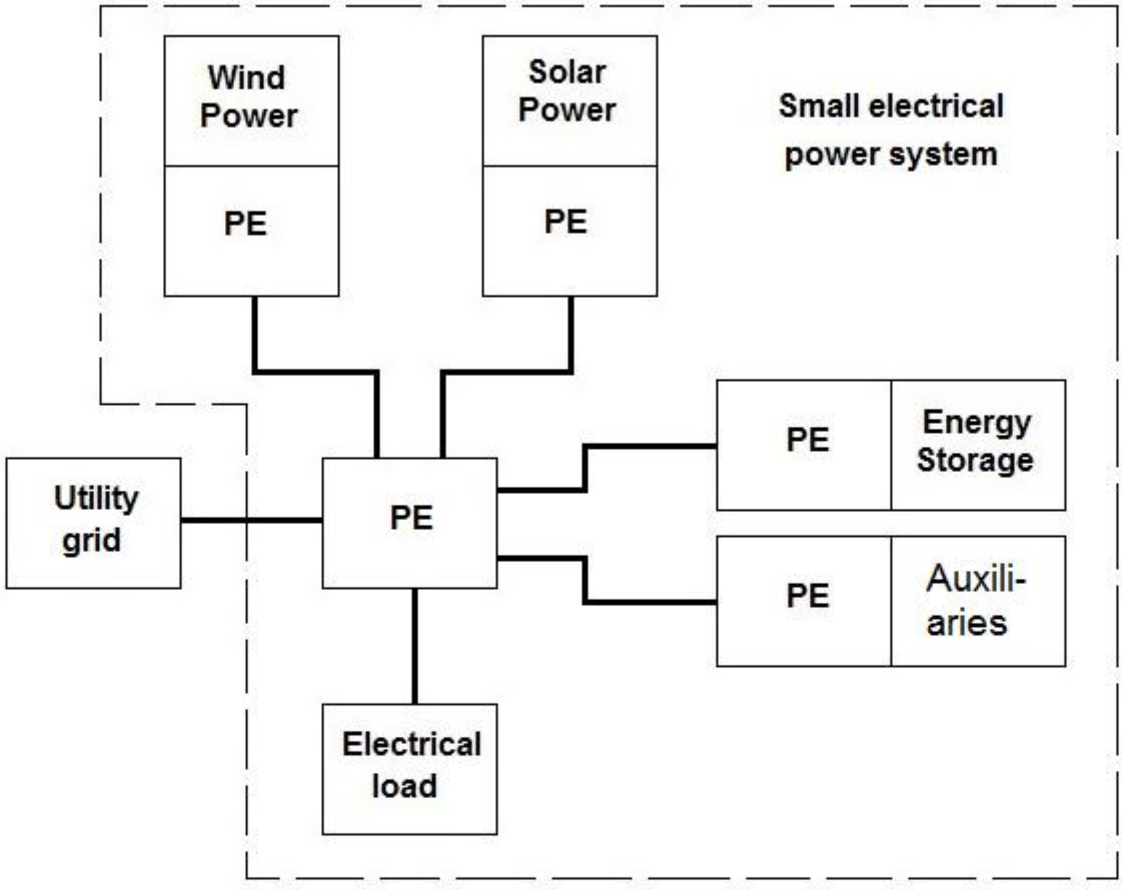

Fig. 3.1. The main components in the power system.

Subsystems in the power system according to Fig 3.1:

Wind Power: Wind power plant.
Solar Power: Solar power plant.
Utility grid: Power grid with facility to handle situations of energy deficit and energy surplus.
Energy storage: Storage device with two purposes: 1) To store surplus energy. 2) To supply energy to the local grid to meet an energy deficit.
Auxiliaries: Equipment to produce deficit energy. This can be regarded as a complement to the possibility of energy balance from the utility grid
Electrical load: Active and reactive local electrical load.
PE: Power electronics for electrical adaptation.

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

Table I. The modules in the simulation system.

System Modules	Function
Wind_make	Stochastic wind speed
Wind_turbine	Electrical wind power
Extinction_make	Stochastic extinction coefficients
Sun_intensity	Solar irradiation
Sun_panel_generator	Electrical solar power
Load_make	Stochastic load
Connect_gen_load	Handling of electrical power status as a result of power production and power consumtion
Storage_distribution	Handling of the process regarding energy storage and usage of utility grid
Power_evaluate	Statistic evaluation of total simulation

The simulation flowchart is illustrated in Fig. 3.2. The loop is repeated “N” times. Evaluation of the simulation is presented in the form of statistical parameters.

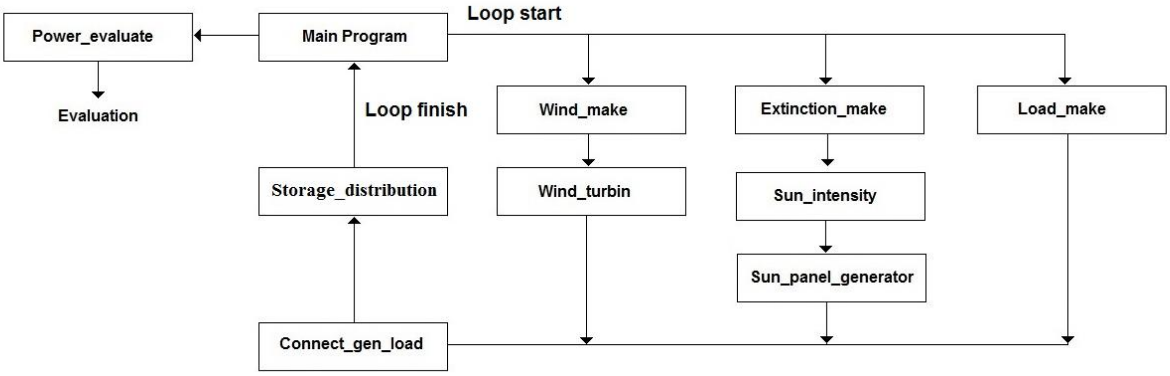

Fig. 3.2. Simulation flowchart. The loop repeated “N” times.

The simulation system is described in [1] that deals about an autonomous power system consisting of wind power and solar power. More detailed information can also be find in [2] - [4]. Regarding module “Wind_turbine”: A special version has been used in this study. This version is described in section 4, below.

4 MODULE WIND_TURBINE

The module has been adapted for wind turbine Skystream 3.7, manufactured by Xzeres, USA.

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. 1 $$\text{Pw} = \frac{\mathbf{Cp} \times \boldsymbol{\rho} \times \mathbf{A} \times \mathbf{V}^{3} \times \mathbf{Pfw} \times \mathbf{Nt}}{\mathbf{2}}$$

Where:

Pw: Generated active wind power (W)
$C_p(V)$: Power coefficient
ρ: Air density (kg/m^3)
A: Rotor sweeping area (m^2)
V: Wind speed (m/s)
Pfw: Wind turbine efficiency excluding Cp: 80 %. This parameter includes generator and power electronics
Nt: Number of wind power turbines in the farm

The air density (ρ) is calculated according to:

Equ. 2 $$\rho = \frac{1.293}{1+0.00367\times\text{Tair}} \times \frac{\text{Pair}}{1013}$$

Where:

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

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

Equ. 3 $$A = \boldsymbol{\pi} \times \frac{\mathbf{D}^{2}}{\mathbf{4}}$$

Where: D: Rotor diameter

Power coefficient Cp(V) for "Skystream 3.7" has been measured up as presented in [5]. Fig 4.1 shows the connection between Cp and wind speed.

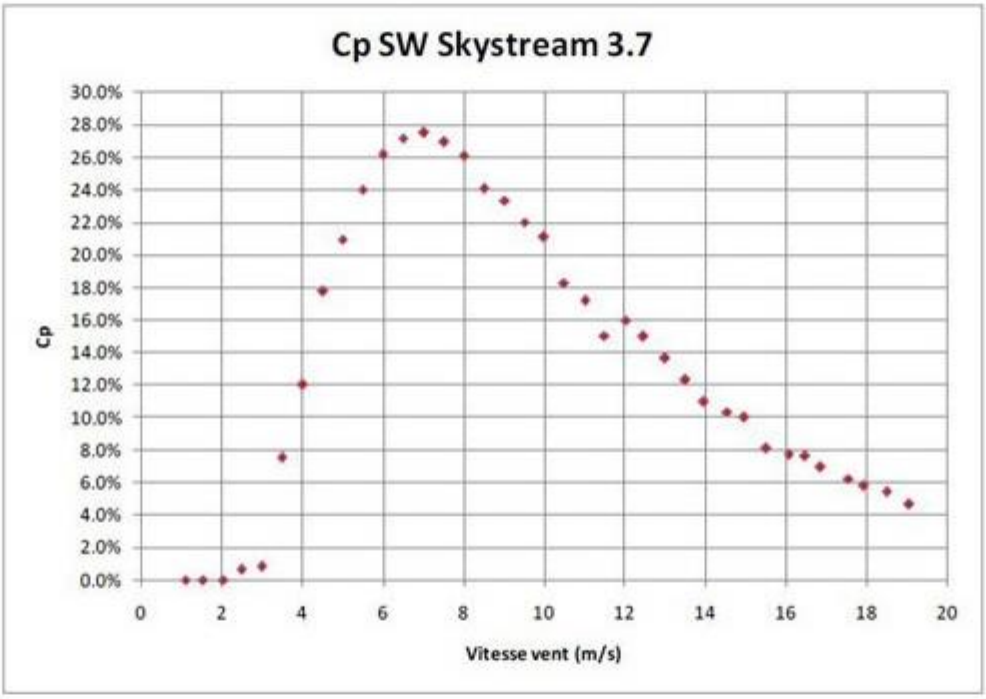

Fig. 4.1. Power coefficient Cp vs wind speed. This curve is presented in [5].

In this study the curve according to Fig 4.1 has been adapted to a polynomial of degree 10. Fig 4.2 illustrates a comparison between measured and adapted values.

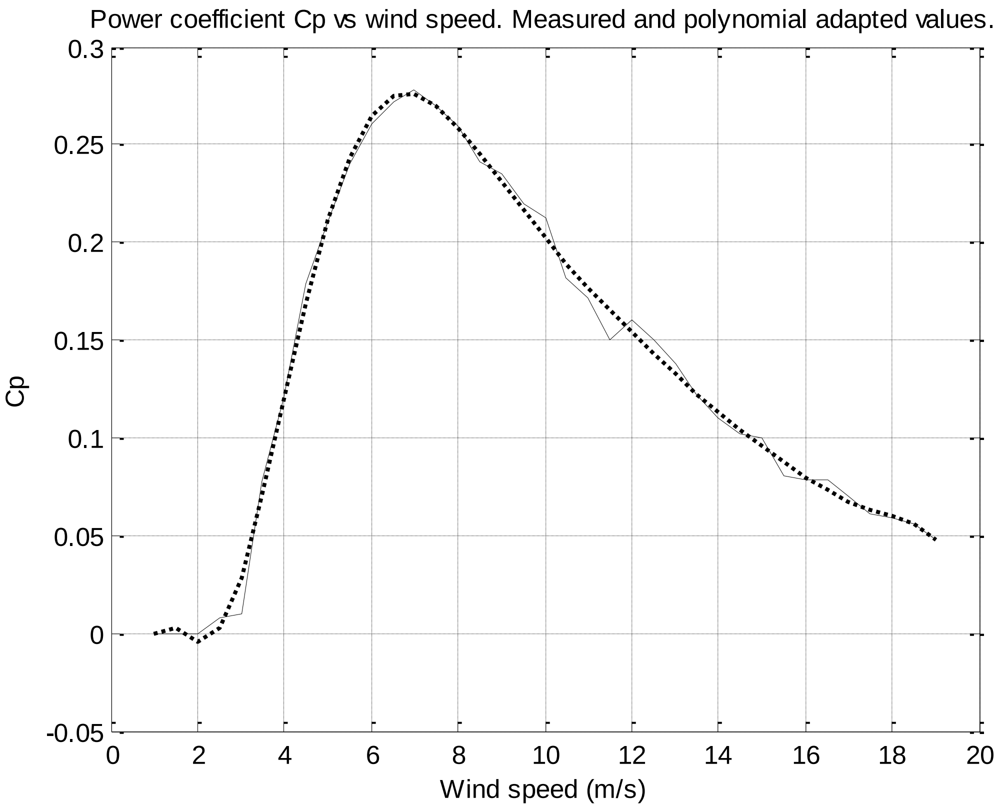

Fig. 4.2. Power coefficient Cp vs wind speed. Measured and polynomial adapted values. Solid curve: Measured values. Dotted curve: Adapted values.

<u>Some turbine related parameters in this study</u>:

- Rotor diameter: 3.72 m
- Tair: 15 °C
- Pair: 1013 mbar
- Maximum output power from turbine: 2.4 kW
- Minimum wind speed for output power: 3.5 m/s
- Maximum wind speed has been limited to 19 m/s. This due to lack of available measurement values concerning the parameter Cp
- Wind power efficiency <u>excluding</u> Cp: 80 % but <u>including</u> generator and power electronics
- Turbine height over ground: 10 m

5 SIMULATIONS

5.1 Some basic parameters

- Time resolution: 10 minutes
- Corresponding start time for simulation: 00.00, March 20
- Corresponding simulation time 365 days
- Number of repeating cycles for each simulation (parameter N according to Fig 3.2): 200
- Location for power system: longitude = 11.968°, latitude = 57.710°. This corresponds to Göteborg, Sweden

5.2 Wind speed

The following Weibull parameters have been used:

- A = 6.3
- C = 1.9

Fig 5.1 and Fig 5.2 show examples of simulated wind speeds. Fig 5.1 illustrates the total time range, while Fig 5.2 illustrates a small part of the total range.

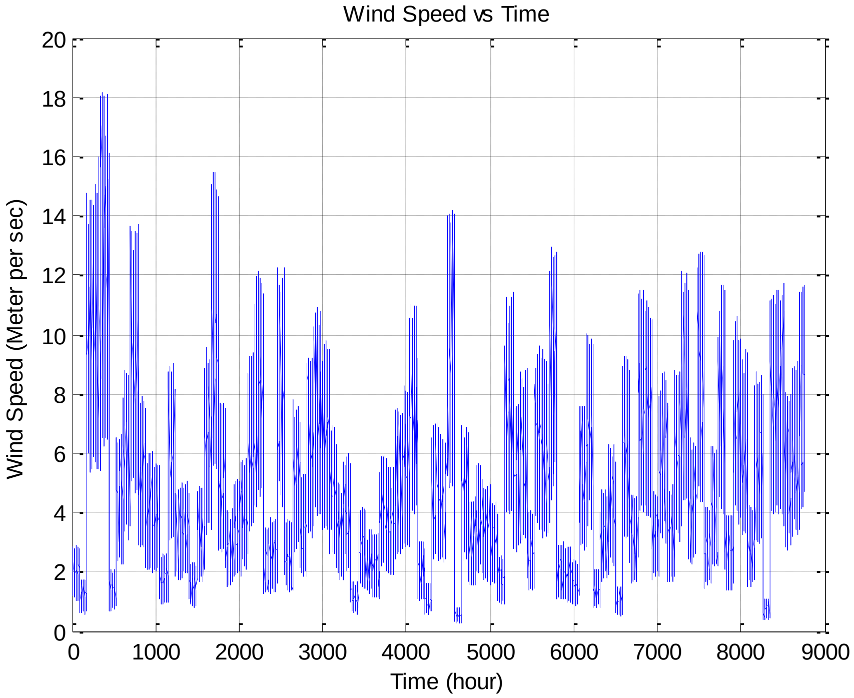

Fig. 5.1. Example of simulated wind speed for 365 days (8760 hours).

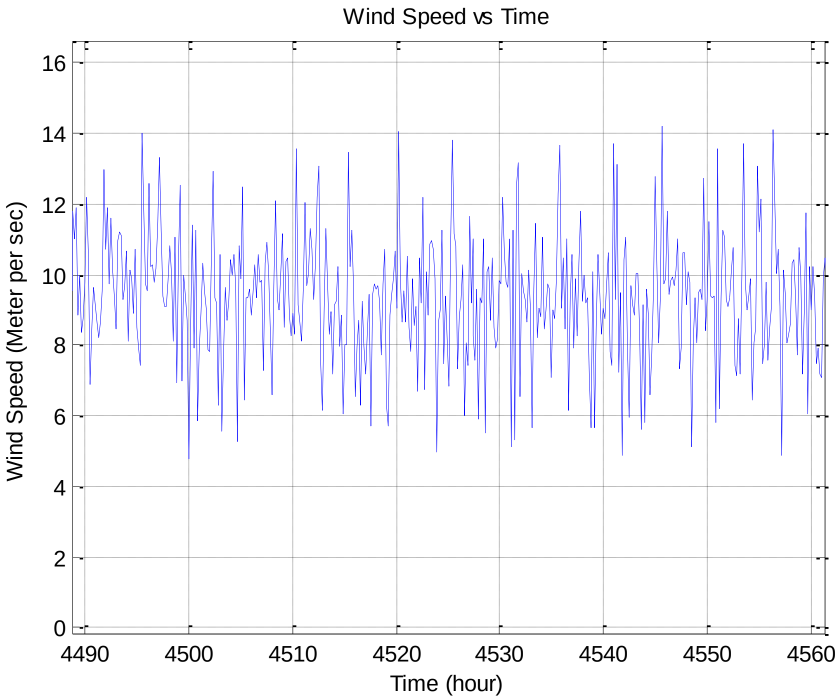

Fig. 5.2. Example of simulated wind speed. Part of the total time range.

5.3 Solar power

Cloudiness probability: 65 %.

Fig 5.3 and Fig 5.4 show examples of simulated solar powers. Fig 5.3 illustrates the total time range, while Fig 5.4 illustrates a small part of the total range.

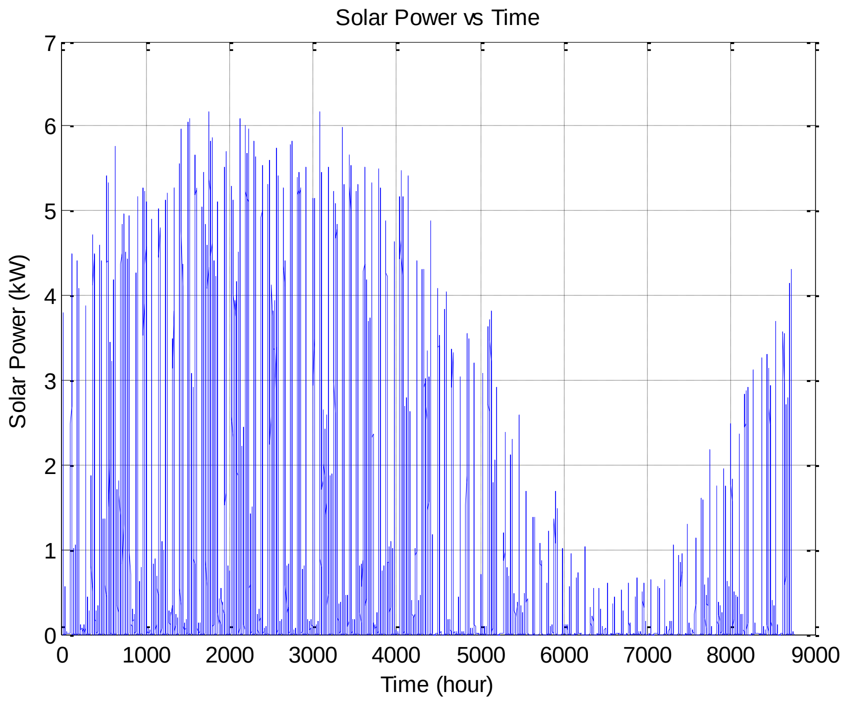

Fig. 5.3. Example of simulated solar power for 365 days (8760 hours).

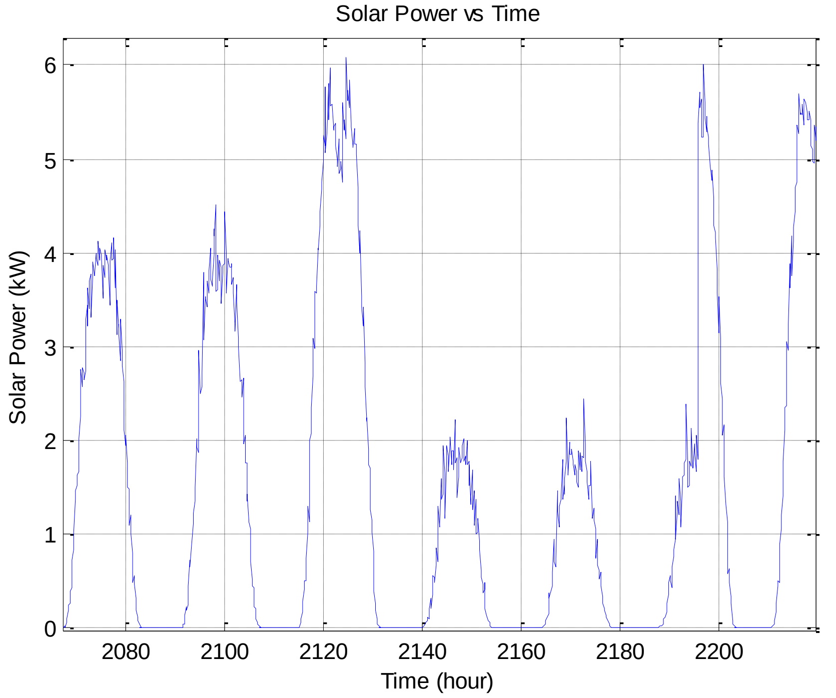

Fig. 5.4. Example of simulated solar power. Part of the total time range.

5.4 Electrical load

The following applies to the electrical load:

- Type of load: Residential
- Annual energy consumption: 10 000 kWh

Fig 5.5 and Fig 5.6 show examples of simulated solar powers. Fig 5.5 illustrates the total time range, while Fig 5.6 illustrates a small part of the total range.

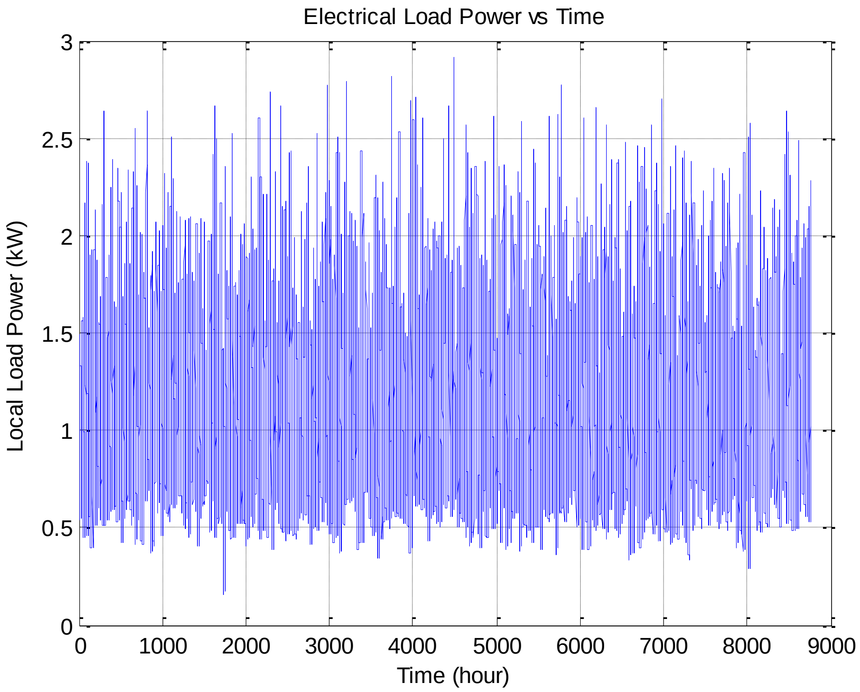

Fig. 5.5. Example of simulated electrical load power for 365 days (8760 hours).

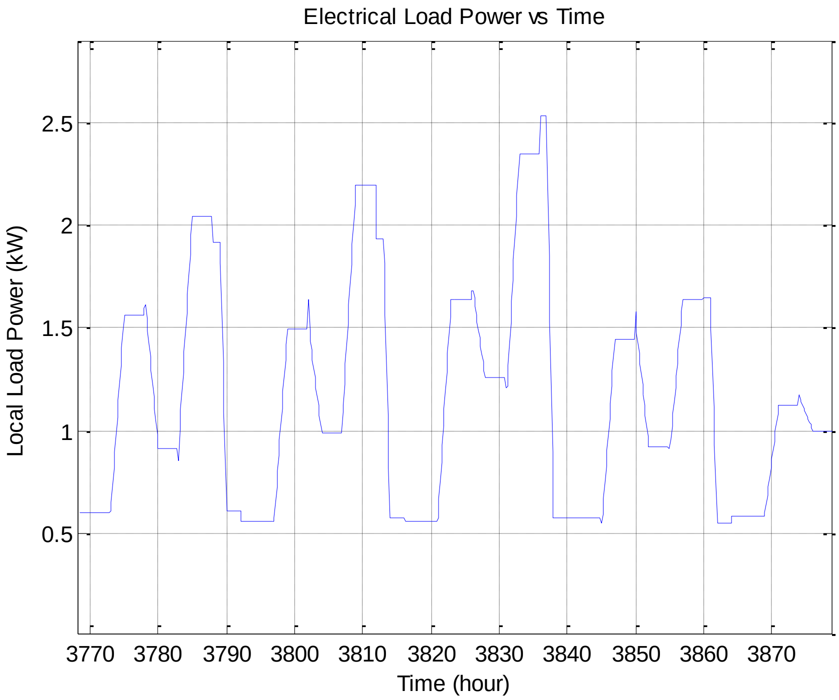

Fig. 5.6. Example of simulated electrical load power. Part of the total time range.

5.5 Tests with varying angle β

Simulations have been performed with varying angle β and fixed angle φ = 45 º. Angle β is the angle between surface normal of solar cell panels and direction to south. Angle φ is the angle between surface normal of solar cell panels and direction to zenith. Table II lists the simulation results.

Table II. Simulation results. φ = 45 º.

Angle relative to south (degrees)	**Annual solar energy (kWh)**
0	3746
22.5	3643
45	3322
90	2272
135	1145
180	617.9

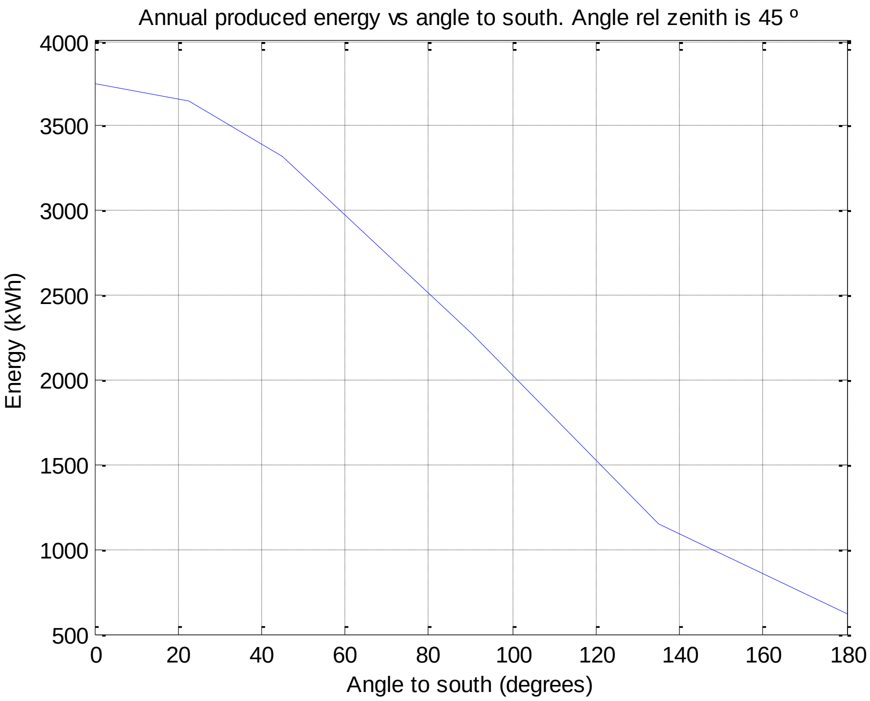

Fig. 5.7. Annual produced energy vs angle β. Angle φ is 45 º.

5.6 Tests with varying angles β and φ

Simulations have been performed with varying angles β and φ. Angle β is the angle between surface normal of solar cell panels and direction to south. Angle φ is the angle between surface normal of solar cell panels and direction to zenith. Table III and Table IV list the simulation results.

Table III. Simulation results. β = 0 º.

Angle relative to zenith (degrees)	**Annual solar energy (kWh)**
35	3742
40	3767
45	3746
50	3717

Table IV. Simulation results. β = 5 º.

Angle relative to zenith (degrees)	**Annual solar energy (kWh)**
35	3728
40	3746
45	3746
50	3714

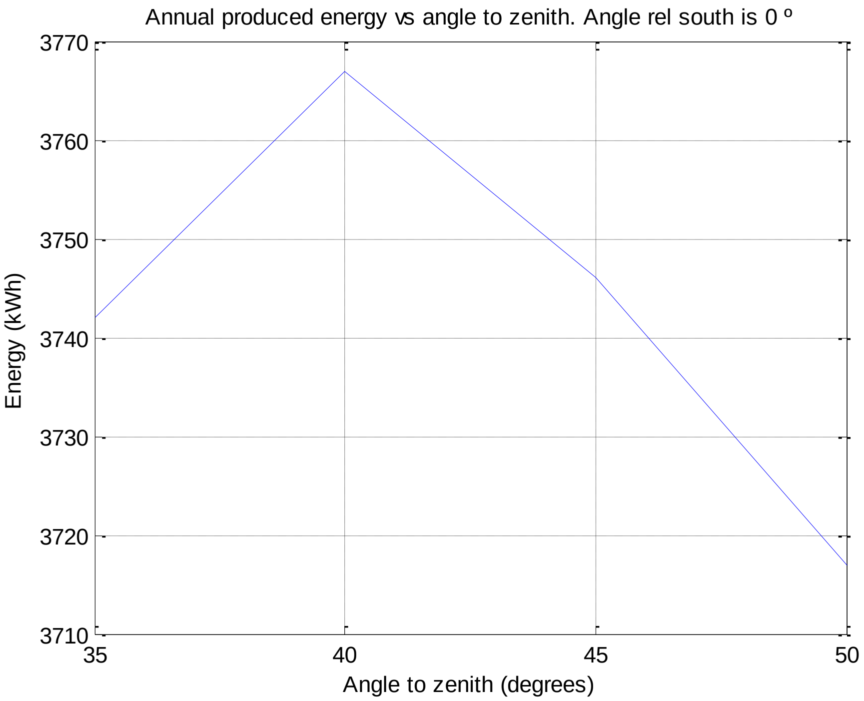

Fig. 5.8. Annual produced energy vs angle φ. Angle β is 0 º.

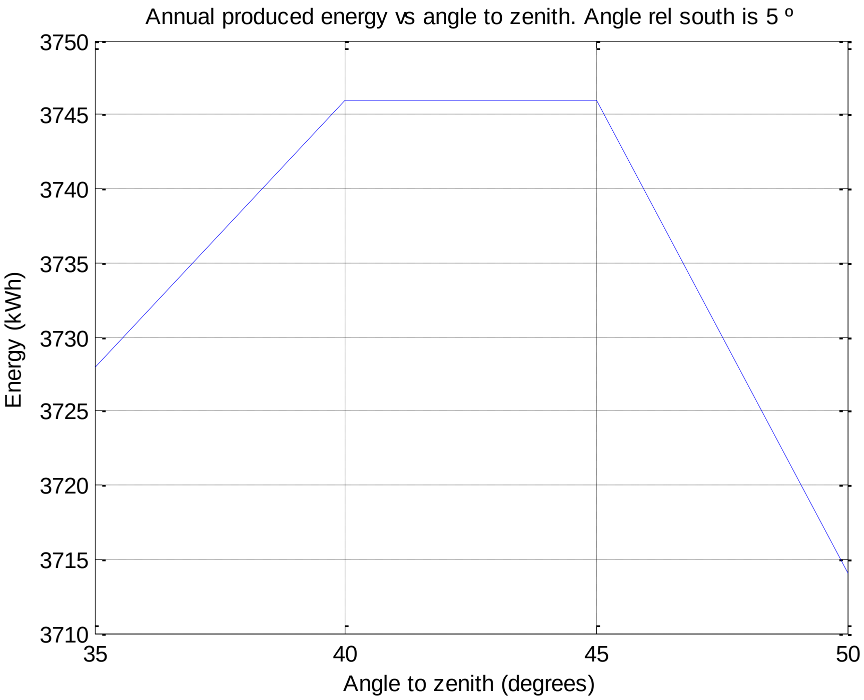

Fig. 5.9. Annual produced energy vs angle φ. Angle β is 5 º.

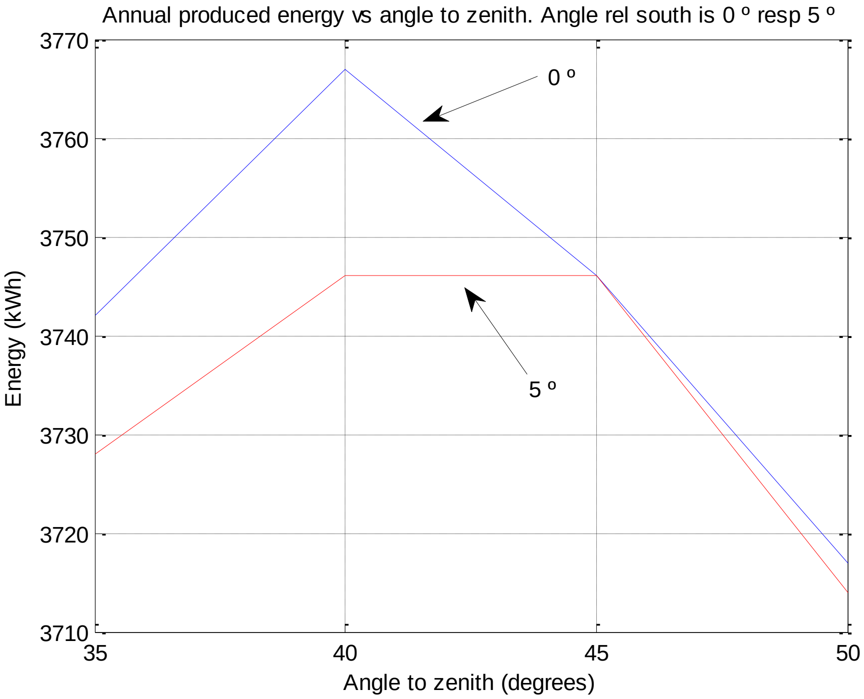

Fig. 5.10. Annual produced energy vs angle φ. Angle β is 0 resp 5 º.

5.7 Tests with varying number of turbines

Simulations have been performed with varying number of turbines.

- No energy storage
- No solar power

Table V. Simulation results with varying values of wind turbines.
Storage capacity N = 0.

Number of turbines	Exported energy (kWh)	Imported energy (kWh)	Exported - Imported (kWh)
0	0	9994	-9994
1	344.3	7326	-6982
2	1831	6122	-4291
3	3899	5471	-1572
4	6199	5088	1111
5	8648	4788	3860
6	11400	4509	6891
7	13640	4393	9247

Fig 5.11 shows the difference between exported and imported energy vs number of turbines.

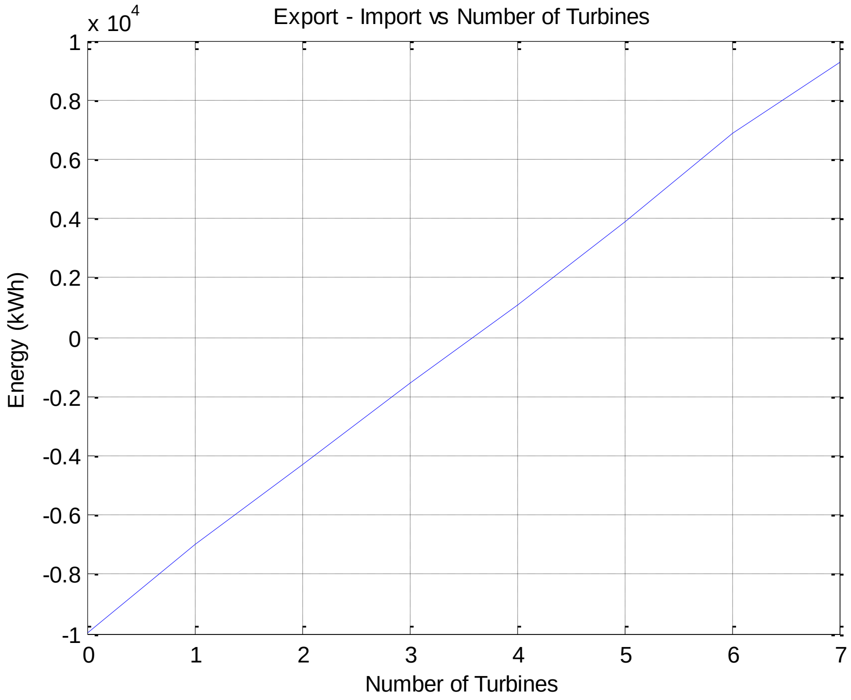

Fig. 5.11. Exported energy – Imported energy vs Number of Turbines.

Fig 5.12 shows imported energy vs number of turbines.

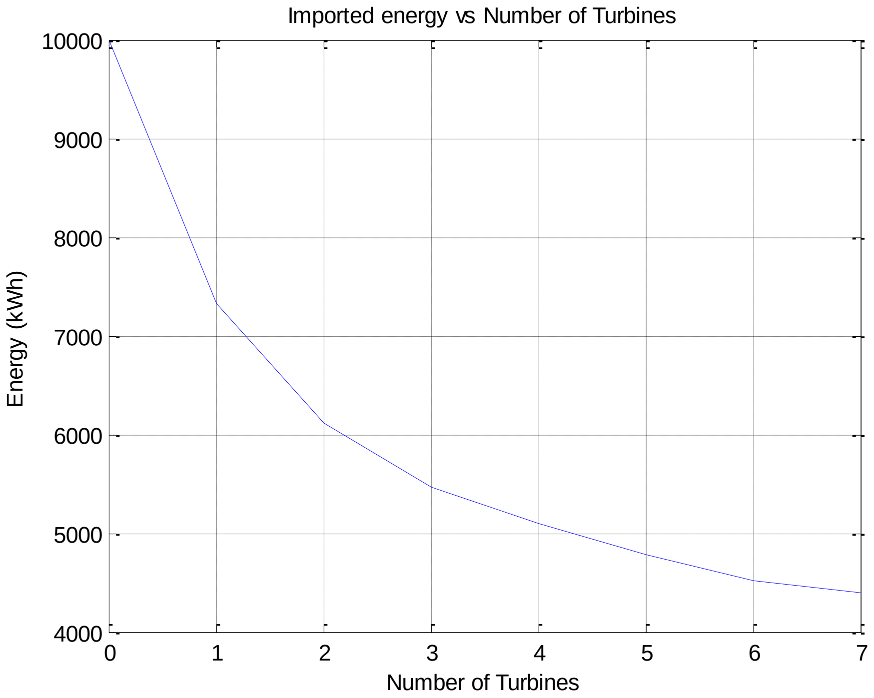

Fig. 5.12. Imported energy vs number of Turbines.

5.8 Tests with varying area of solar cells

Simulations have been performed with varying area of solar cells.

- No energy storage
- Number of wind turbines = 4

Table VI. Simulation results with varying area of solar cells.

Solar cell area (m^2)	**Exported energy (kWh)**	**Imported energy (kWh)**	**Exported - Imported (kWh)**
0	6199	5088	1111
25	7345	4350	2995
50	9127	4087	5040
100	12360	3968	8392
200	19520	3835	15685
400	33850	3680	30170

Fig 5.13 shows the difference between exported energy and imported energy vs solar cell area.

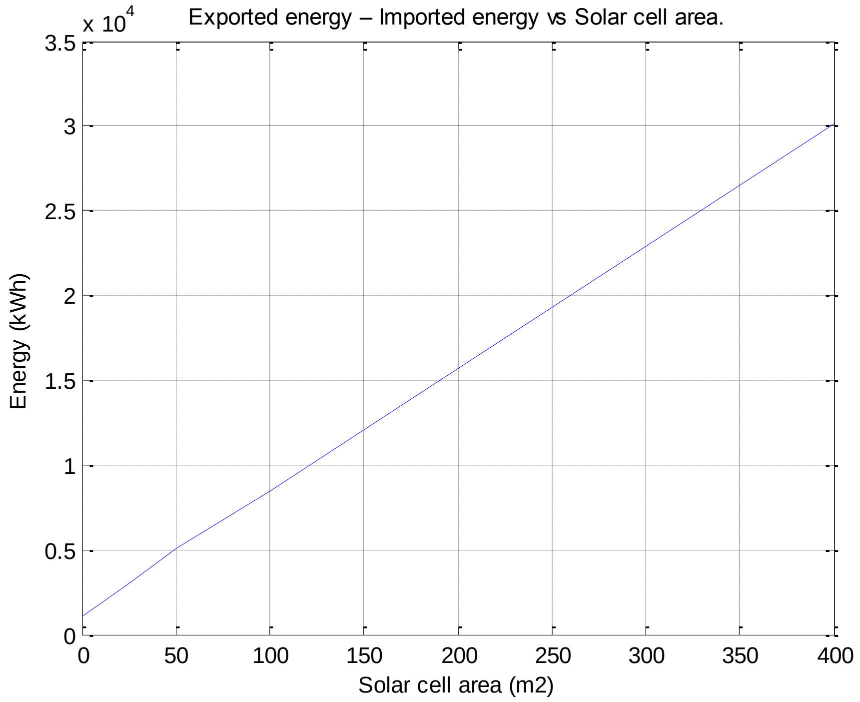

Fig. 5.13. Exported energy – Imported energy vs Solar cell area.

Fig 5.14 shows imported energy vs solar cell area.

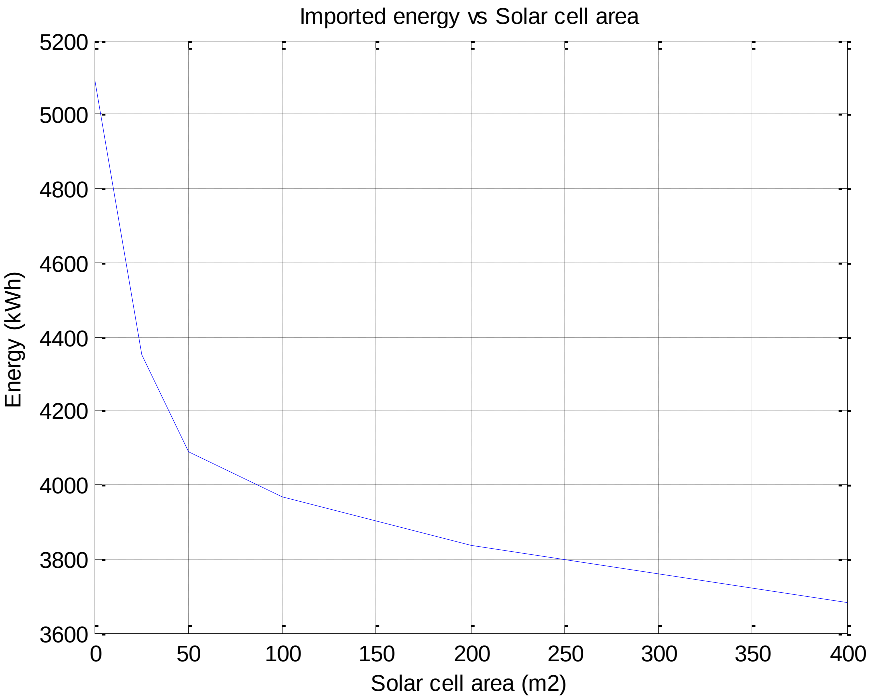

Fig. 5.14. Imported energy vs Solar cell area.

5.9 Tests with varying storage capacity

Simulations have been performed with varying storage capacity.

- Number of wind power turbines = 4
- Solar cell area = 100 m^2
- Angle β: 0 º
- Angle φ = 40 º

A parameter “N” is defined according to:

Equ. 4. $$\text{Storage capacity(N)} = N \times \frac{\textbf{Annual consumed energy}}{\textbf{365}}$$

Where “Annual consumed energy” = 10 000 kWh

Table VII shows simulation results with varying storage capacity and storage initiation = 0.5 × N. Min storage = 0.5 × N. “Storage initiation” corresponds to the value at simulation start. “Min storage” corresponds to the minimum accepted storage value.

Table VII. Simulation results with varying storage capacity.
Storage initiation = 0.5 × N. Min storage = 0.5 × N.

Storage capacity (N)	**Exported energy (kWh)**	**Imported energy (kWh)**	**Exported - Imported (kWh)**
0	12360	3968	8392
0.5	11370	2850	8520
1	10800	2343	8457
2	10450	1709	8741
4	9531	1088	8443
8	9154	677.2	8477
16	8763	332.2	8431
32	8183	140.0	8043
64	7553	30.80	7522
128	6464	19.41	6445

Fig 5.15 shows imported energy vs storage capacity. Storage initiation = 0.5 × N. Min storage = 0.5 × N.

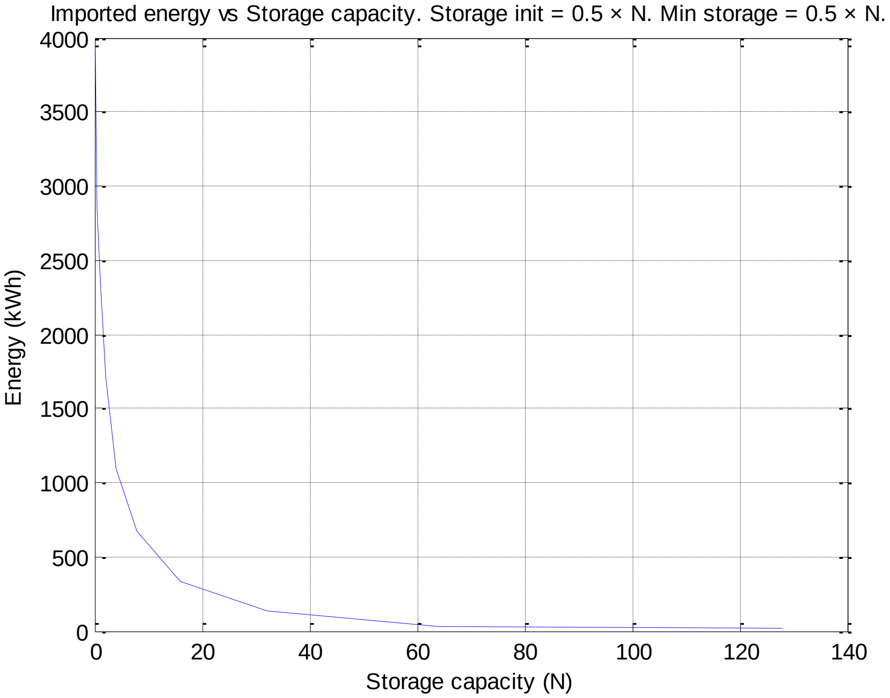

Fig. 5.15. Imported energy vs Storage capacity. Storage initiation = 0.5 × N. Min storage = 0.5 × N.

Table VIII shows simulation results with varying storage capacity and storage initiation = N. Min storage = 0.5 × N. “Storage initiation” corresponds to the value at simulation start. “Min storage” corresponds to the minimum accepted storage value.

Table VIII. Simulation results with varying storage capacity.
Storage init = N. Min storage = 0.5 × N.

Storage capacity (N)	Exported energy (kWh)	Imported energy (kWh)	Exported - Imported (kWh)
0	12360	3968	8392
0.5	11330	2859	8471
1	10860	2329	8531
2	10480	1706	8774
4	9584	1073	8511
8	9267	653.7	8613
16	9016	312.1	8704
32	8707	117.5	8590
64	8621	7.2	8614
128	8628	0	8628

Fig 5.16 shows imported energy vs storage capacity. Storage initiation = N. Min storage = 0.5 × N.

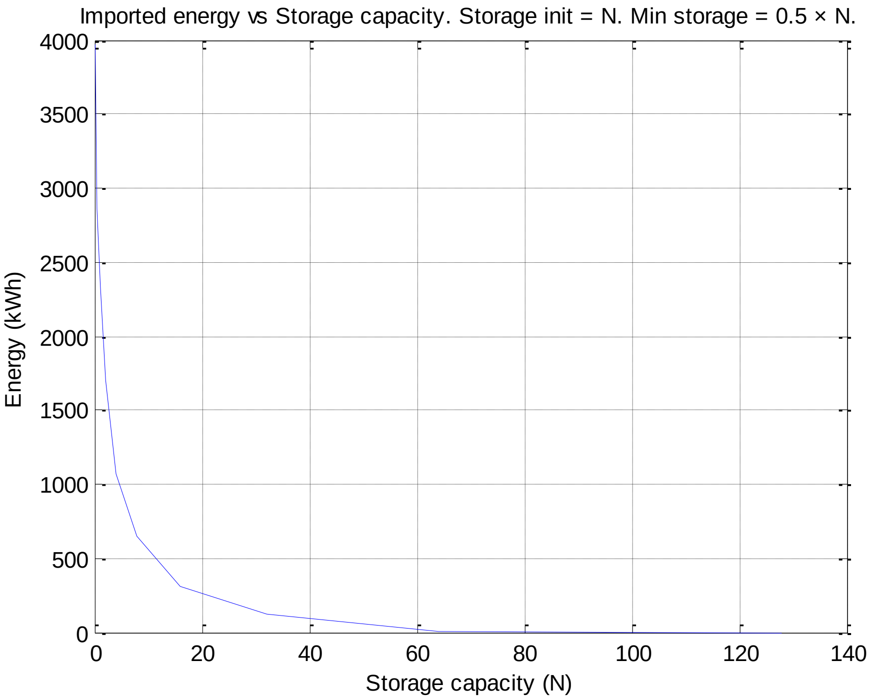

Fig. 5.16. Imported energy vs Storage capacity. Storage initiation = N. Min storage = 0.5 × N.

Fig 5.17 illustrates imported energy vs storage capacity for storage initiations N resp. 0.5. The difference is only marginal and can be neglected.

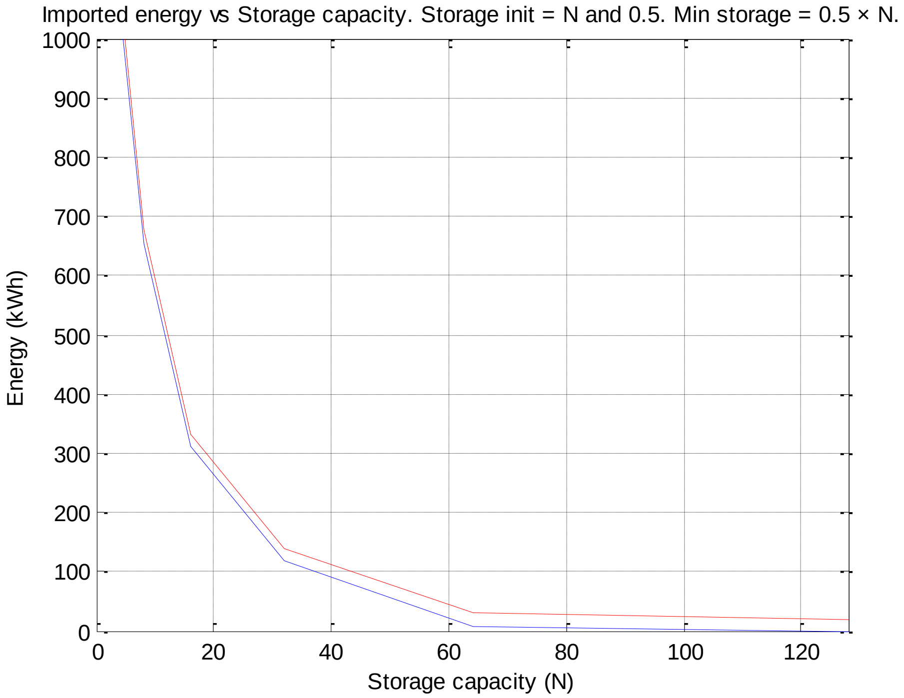

Fig. 5.17. Imported energy vs Storage capacity. Storage initiation = N resp. 0.5. Min storage = 0.5 × N. Red curve: Storage initiation = 0.5.

Table IX shows simulation results with varying storage capacity and storage initiation = N. Min storage = 0. “Storage initiation” corresponds to the value at simulation start. “Min storage” corresponds to the minimum accepted storage value. In addition to the information in Table VII and Table VIII, Table IX also presents statistics based on 200 simulations regarding storage level “mean”, “min” and standard deviation.

Table IX. Simulation results with varying storage capacity.
Storage initiation = N. Min storage = 0.

Storage capacity (N)	Exported energy (kWh)	Imported energy (kWh)	Exported - Imported (kWh)	Storage level Mean (%)	Storage level Min (%)	Storage level Std. dev (%)
0	12360	3968	8392	-	-	-
0.5	10810	2305	8505	55.9	0	3.9
1	10260	1770	8490	61.6	0	3.7
2	9584	1067	8517	67.0	0	4.1
4	9398	601.9	8796	74.7	0	4.3
8	8948	319.2	8629	80.3	0	4.9
16	8818	96.0	8722	86.8	0	5.4
32	8569	4.5	8564	91.7	0	4.6
64	8629	0	8629	95.7	23.0	2.8
128	8853	0	8853	98.1	64.7	1.2

Fig. 5.18 shows imported energy vs storage capacity for the information according to Table IX.

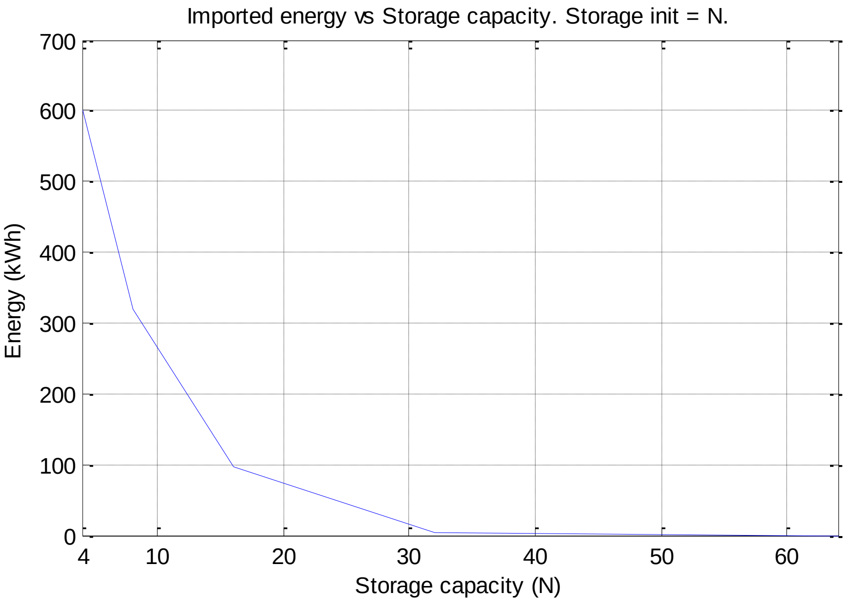

Fig. 5.18. Imported energy vs Storage capacity. Storage init = N. Min storage = 0.

Table X to Table XIV show the probability for need of “Extra auxiliaries” (if no connection to a utility grid is on hand) for different storage capacity as a function of accepted minimum storage level. Fig. 5.19 to Fig. 5.23 illustrate the corresponding information in graphs.

Table X. Simulation results with storage capacity N = 8.

Storage level Min (%)	**P Extra auxiliaries (%)**
5	94.5
10	97.0
15	98.0
20	98.5
25	99.5
30	100
35	100

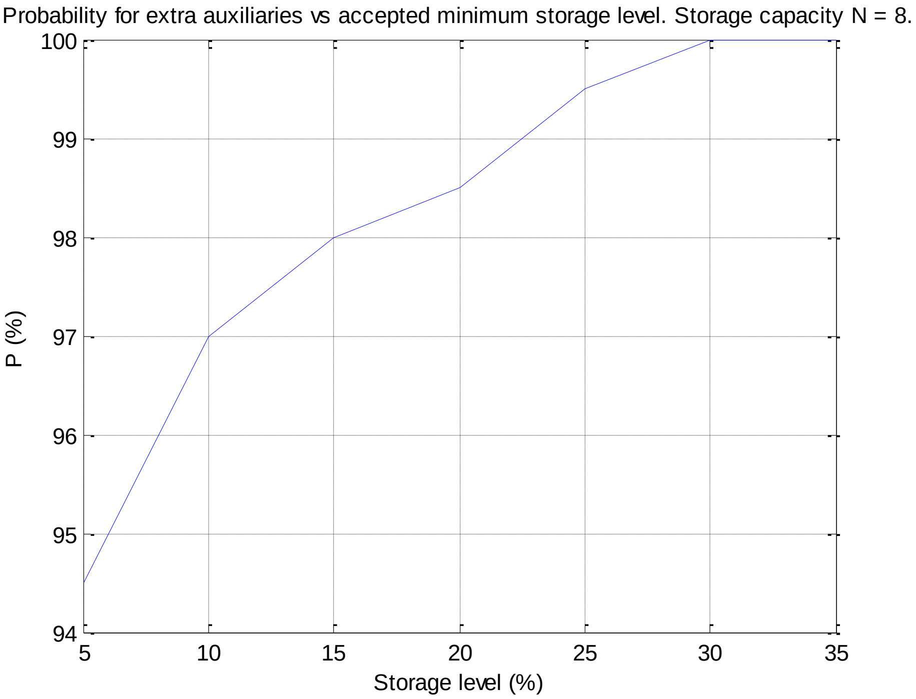

Fig. 5.19. Probability for need of extra auxiliaries vs accepted minimum storage level. Storage capacity N = 8.

Table XI. Simulation results with storage capacity N = 16.

Storage level Min (%)	**P Extra auxiliaries (%)**
5	44.2
10	47.2
20	59.8
30	70.4
40	81.9
50	92.0
60	99.5
65	100

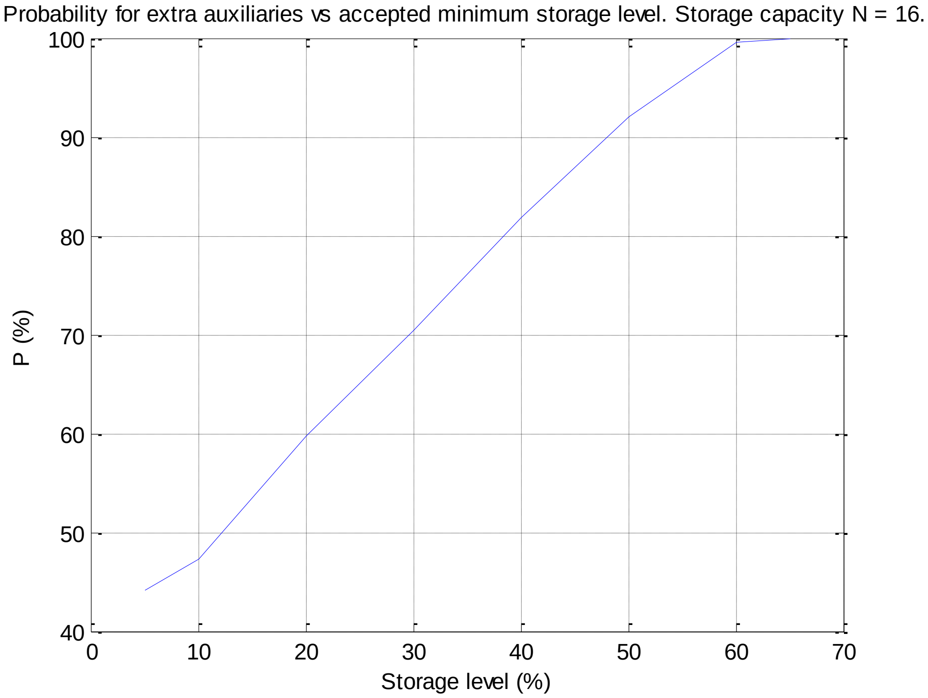

Fig. 5.20. Probability for need of extra auxiliaries vs accepted minimum storage level. Storage capacity N = 16.

Table XII. Simulation results with storage capacity N = 32.

Storage level Min (%)	**P Extra auxiliaries (%)**
5	4.5
10	5.5
20	10.6
30	17.6
40	27.1
50	46.2
60	66.8
70	87.9
80	99.5
82	100

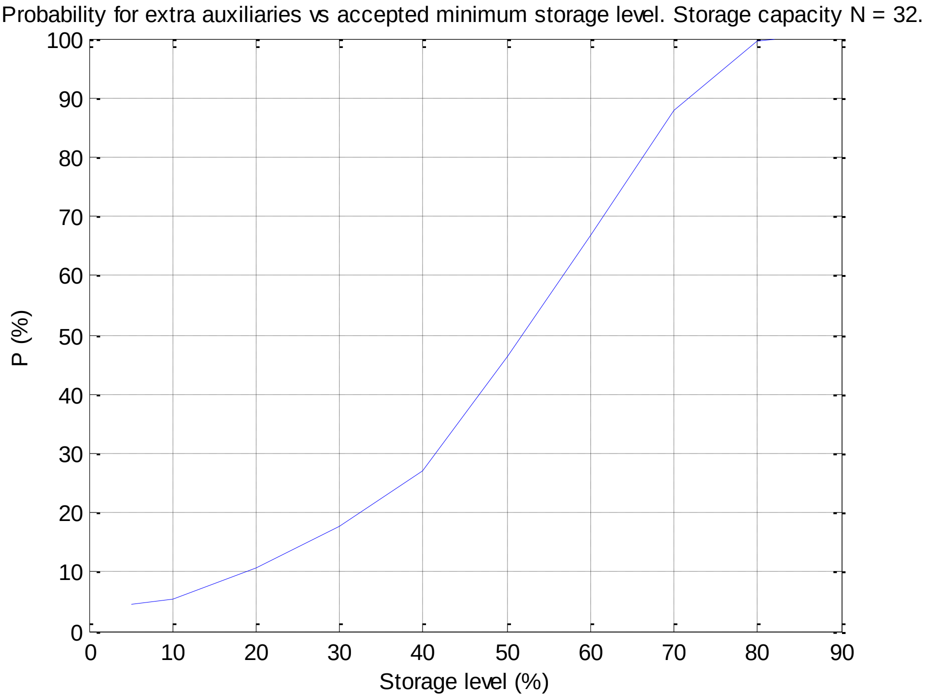

Fig. 5.21. Probability for need of extra auxiliaries vs accepted minimum storage level. Storage capacity N = 32.

Table XIII. Simulation results with storage capacity N = 64.

Storage level Min (%)	**P Extra auxiliaries (%)**
5	0
10	0
20	0
30	1.0
40	2.0
50	4.0
60	16.1
70	30.2
80	62.3
90	99.5
91	100

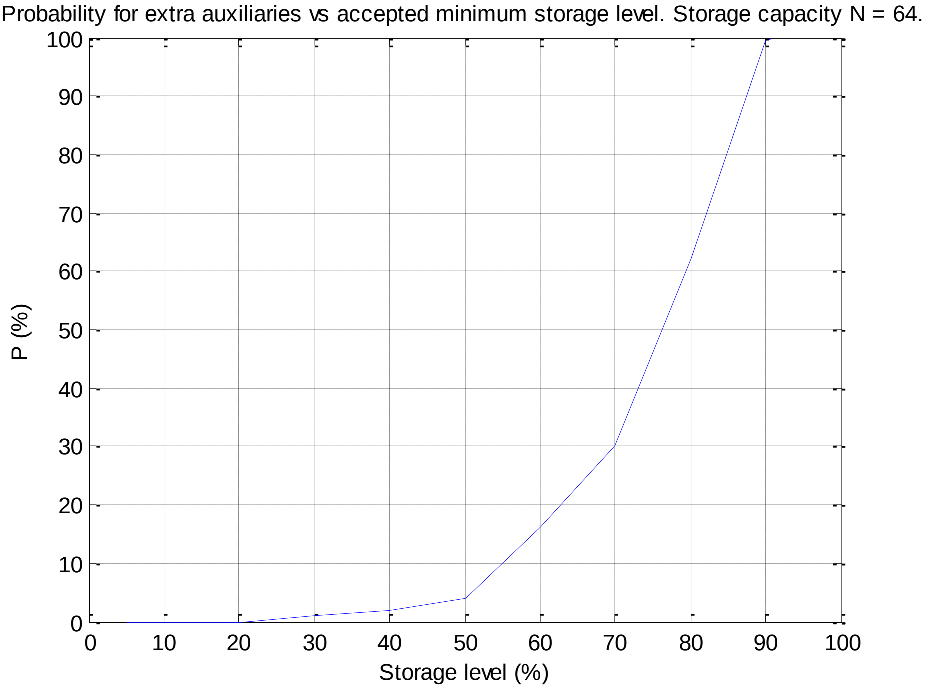

Fig. 5.22. Probability for need of extra auxiliaries vs accepted minimum storage level. Storage capacity N = 64.

Table XIV. Simulation results with storage capacity N = 128.

Storage level Min (%)	**P Extra auxiliaries (%)**
5	0
10	0
20	0
30	0
40	0
50	0
60	0
70	0.5
75	4.5
80	9.5
85	24.1
90	54.3
95	98.0
95.73	100

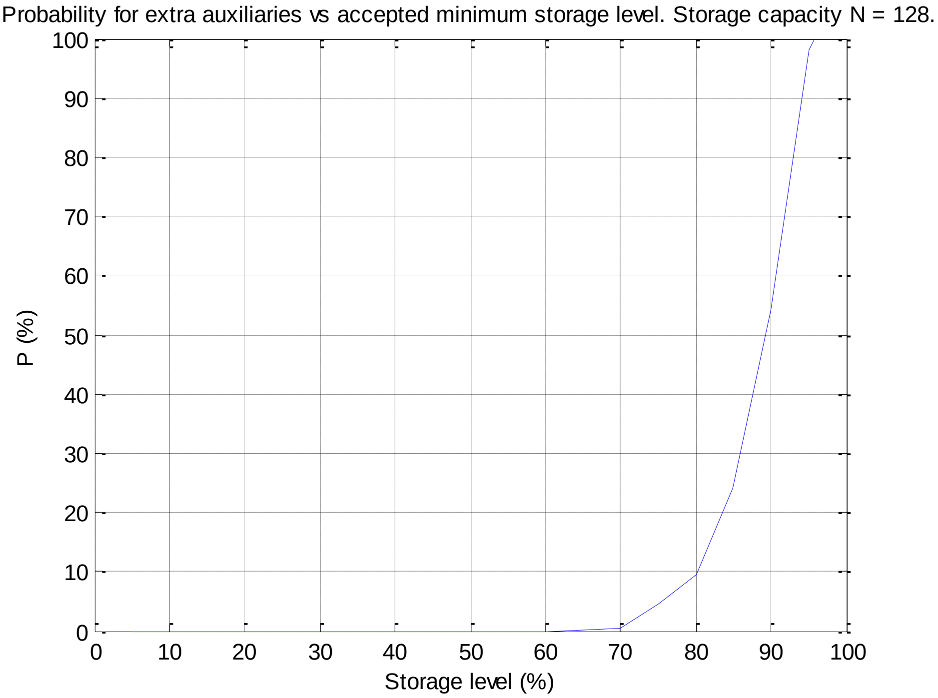

Fig. 5.23. Probability for need of extra auxiliaries vs accepted minimum storage level. Storage capacity N = 128.

6 CONCLUSION

6.1 Tests with varying angle β and fixed angle φ = 45º

See section 5.5.

The optimum angle β is 0º. Table XV shows the annual decrease of solar energy for varying values of angle β relative to 0º.

Table XV. Annual decrease of solar energy.

Angle β relative to 0 º (degrees)	**Annual decrease of solar energy (%)**
22.5	3
45	11
90	39
135	69
180	84

As can be observed, the generated solar energy will be reduced only marginally (3 %), if the angle deviates 22.5° relative to the south.

6.2 Tests with varying angles β and φ

See section 5.6.

The conclusion, based on simulations, is that the optimal angle φ (surface normal angle relative to zenith) is located in the region 40º - 45º.

6.3 Tests with varying number of turbines

See section 5.7.

The study is in first hand focused on the total need to import energy (use of auxiliaries) as a function of wind turbines in function. Fig. 5.12 shows the annual imported energy vs number of wind turbines in function. As can be observed the curve fall down quickly in the region 0 to 3 turbines. It tends to flat out at about 4 turbines. This can be a hint regarding the optimal number of turbines in respect of cost. A first simple conclusion, based on simulations, is that the optimal number of wind turbines are about 4. This corresponds to a total maximum wind power of 4 × 2.4 kW = 9.6 kW. This will be used as a suitable starting point for the further power plant design, that includes solar power and energy storage.

6.4 Tests with varying area of solar cells

See section 5.8.

The study is in first hand focused on the total need to import energy (use of auxiliaries) as a function of solar cell area in function. Fig. 5.14 shows the annual imported energy vs solar cell area in function. As can be observed the curve fall down quickly in the region 0 to 50 m^2. It tends to flat out at about 100 m^2. This can be a hint regarding the optimal solar cell area in respect of cost. A first simple conclusion, based on simulations, is that the optimal solar cell area is about 100 m^2.

6.5 Tests with varying storage capacity

See section 5.9.

The study gives information regarding the connection between energy storage and the probability for need of extra auxiliaries (if no connection to a utility grid is on hand) in combination with accepted minimum storage level. Suppose, for example the following:

- probability to need extra auxiliaries: 4 %
- minimum accepted storage level: 50 %

According to Table XIII, the storage capacity has to be at least N = 64.

Suppose:

- probability to need extra auxiliaries: 70 %
- minimum accepted storage level: 30 %

According to Table XI, the storage capacity has to be at least N = 16.

7 REFERENCES

[1] Mathiasson I. “Simulation of Autonomous Electric Power Systems”.
Chalmers University of Technology, Mars 2015.

[2] Mathiasson I. “Solar power. Statistical analysis of extinction coefficients”.
Chalmers University of Technology, June 2015.

[3] Mathiasson I. “Wind power. Statistical analysis of wind speed”.
Chalmers University of Technology, January 2015.

[4] Mathiasson I. “Modelling of an electrical load”.
Chalmers University of Technology, February 2015.

[5] “Experimental Test Site for Small Wind Turbines of Narbonne.
Test Report no. 15 version 4 of Mars, 25 2010.
Skystream Grid Connected Wind Turbine”.
Sud Eoliennes Technologie, Mars 2010.

[6] “Marknadsöversikt små vindkraftverk i Sverige”.
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