Simulation of a Small Solar and Wind Power Farm

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June 2015

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Content

1 INTRODUCTION 2
2 THE STUDY OBJECT 3
3 THE SIMULATION SYSTEM 5
4 MODULE WIND_TURBINE 8
5 SIMULATIONS 11
5.1 SOME BASIC PARAMETERS 11
5.2 WIND SPEED 11
5.3 SOLAR POWER 12
5.4 ELECTRICAL LOAD 14
5.5 TESTS WITH VARYING ANGLE Β. PART 1 15
5.6 TESTS WITH VARYING ANGLE Φ 21
5.7 TESTS WITH VARYING ANGLE Β. PART 2 21
5.8 TESTS WITH VARYING STORAGE CAPACITY 22
5.9 TESTS WITH VARYING NUMBER OF TURBINES 25
6 CONCLUSIONS 29
6.1 TESTS WITH VARYING ANGLE Β AND ANGLE Φ 29
6.2 TESTS WITH VARYING STORAGE CAPACITY 29
6.3 TESTS WITH VARYING NUMBER OF TURBINES 29
7 REFERENCES 30

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
- 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

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.

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

- Photovoltaic solar cell panels
- Total effective solar cell area: 50 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. 1. The angle φ in this figure corresponds to the angle between the surface normal of the solar cell panels and direction to zenith.

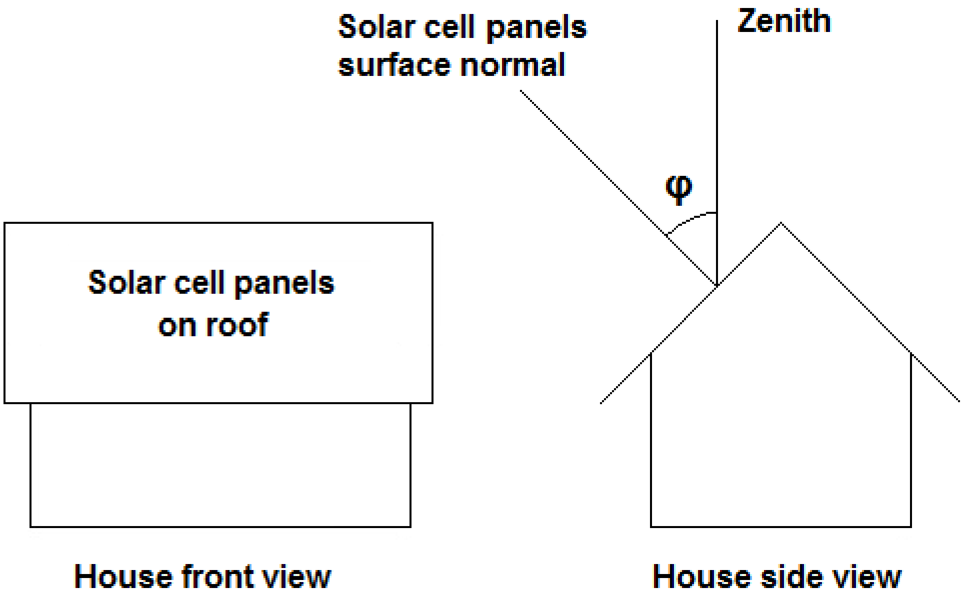

Fig. 1. Installation of solar cell panels on a house roof.

Fig. 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.

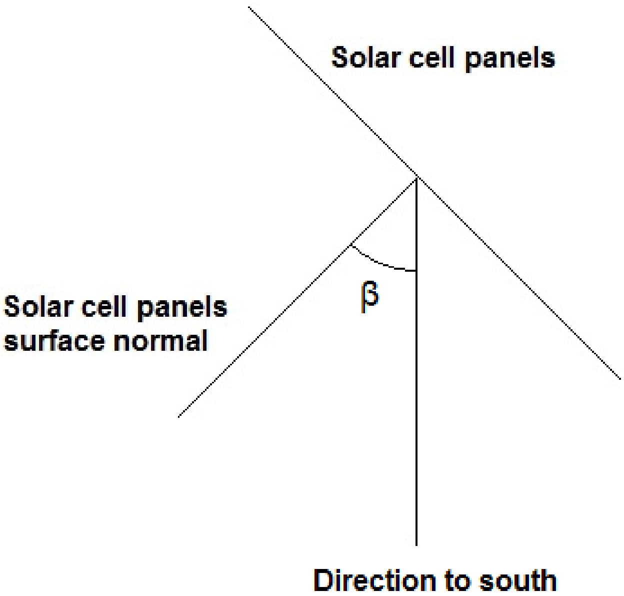

Fig. 2. Installation of solar cell panels in in the horizontal plane.

<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. 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. 3. Image of the wind power turbine “Skystream 3.7”.

3 THE SIMULATION SYSTEM

Fig. 4 shows the main components in the power system.

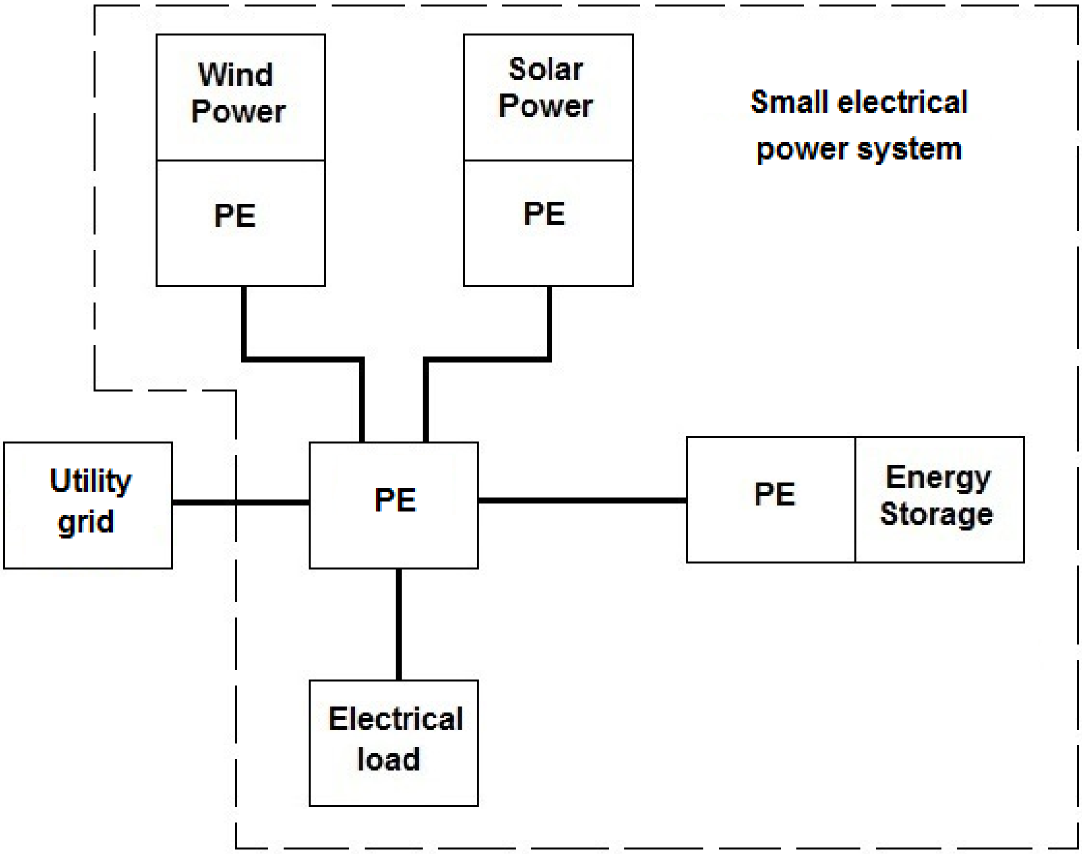

Fig. 4. The main components in the power system.

Subsystems in the power system according to Fig. 4:

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.
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. 5. The loop is repeated “N” times. Evaluation of the simulation is presented in the form of statistical parameters.

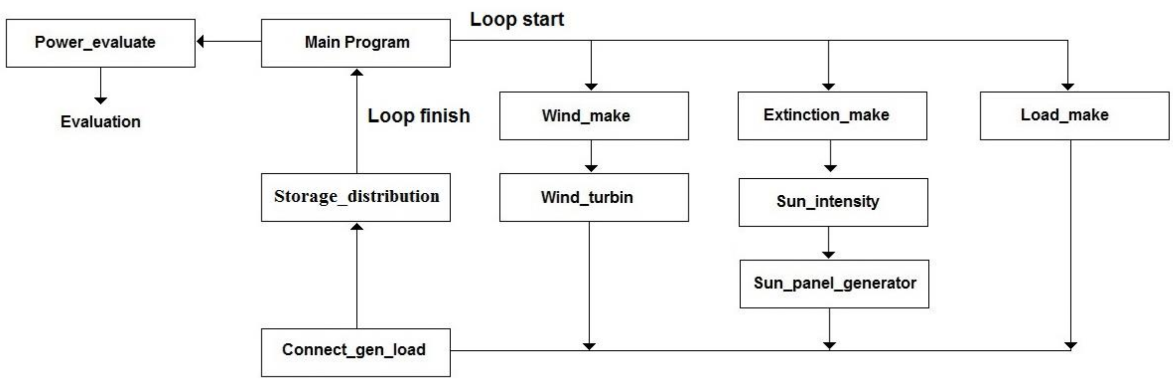

Fig. 5. Simulation flowchart. The loop repeated “N” times.

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

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

Where:

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

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

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

Where: D: Rotor diameter

Power coefficient Cp(V) for "Skystream 3.7" has been measured up as presented in [5]. Fig. 6 shows the connection between Cp and wind speed.

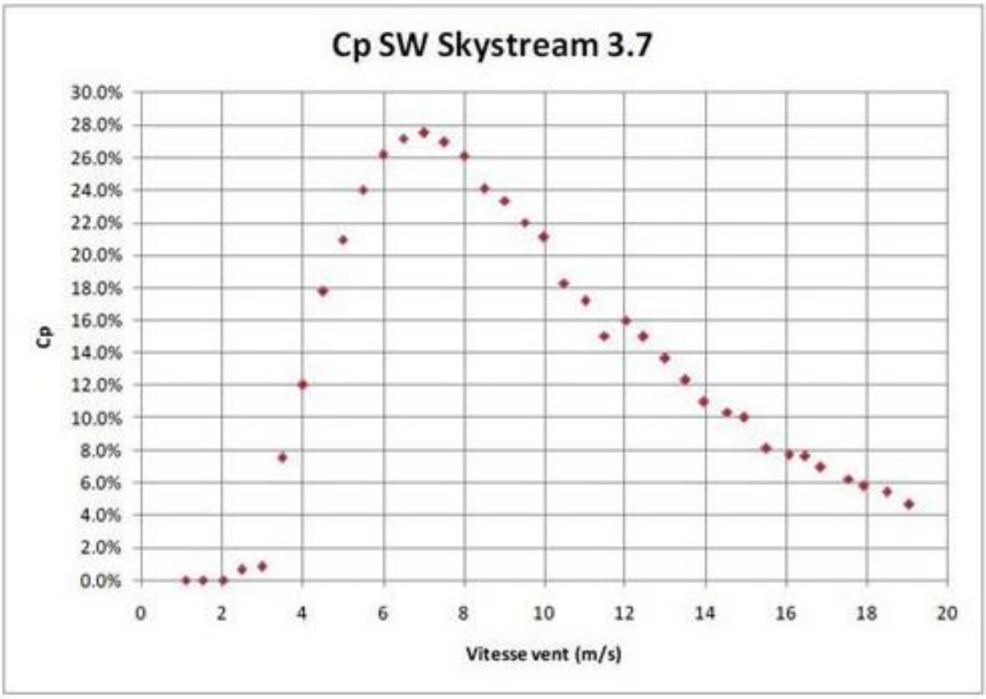

Fig. 6. Power coefficient Cp vs wind speed. This curve is presented in [5].

In this study the curve according to Fig. 6 has been adapted to a polynomial of degree 10. Fig. 7 illustrates a comparison between measured and adapted values.

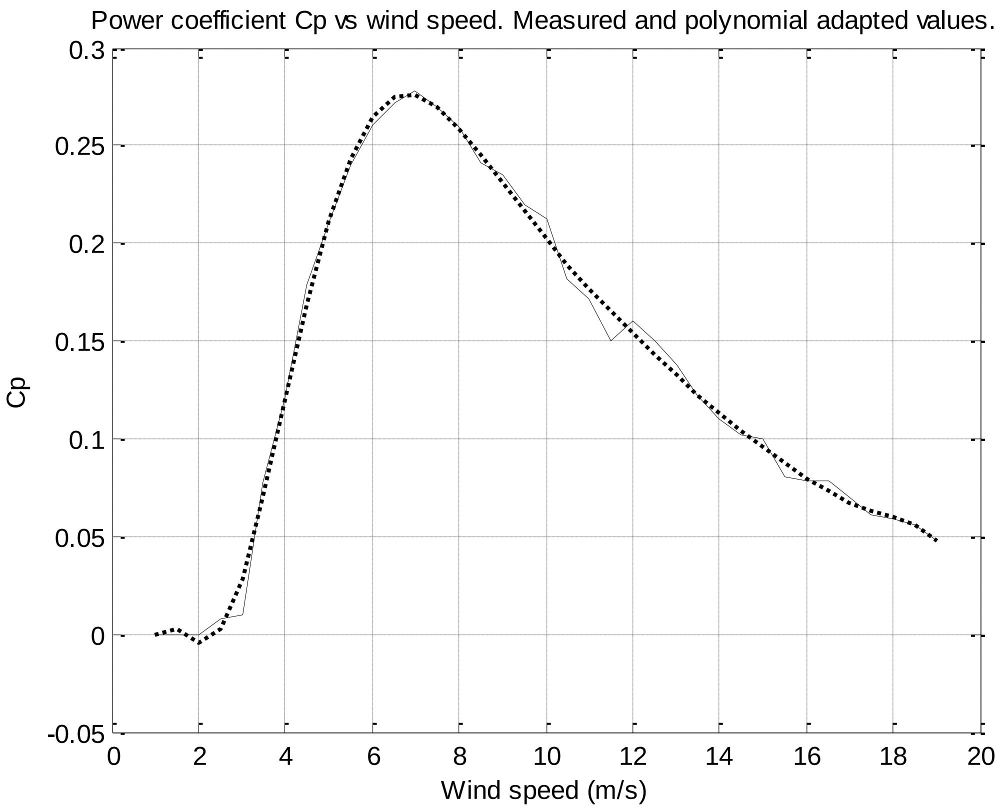

Fig. 7. Power coefficient Cp vs wind speed. Measured and polynomial adapted values. Solid curve: Measured values. Dotted curve: Adapted values.

Some turbine related parameters in this study:

- Rotor diameter: 3.72 m
- Tair: 15 ºC
- 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 excluding Cp: 80 % but including 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 in Fig. 5): 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. 8 and Fig. 9 show examples of simulated wind speeds. Fig. 8 illustrates the total time range, while Fig. 9 illustrates a small part of the total range.

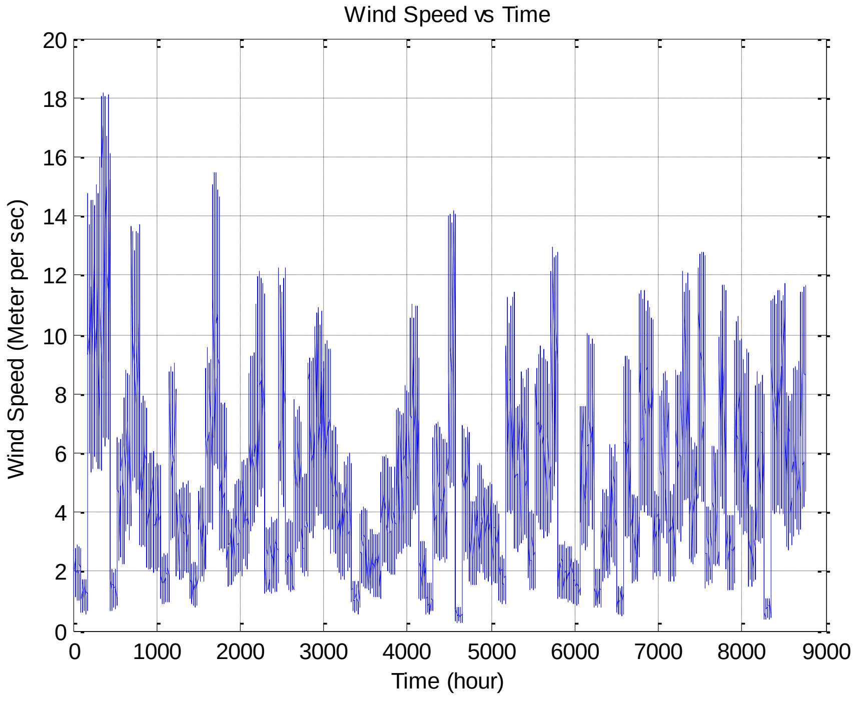

Fig. 8. Example of simulated wind speed for 365 days (8760 hours).

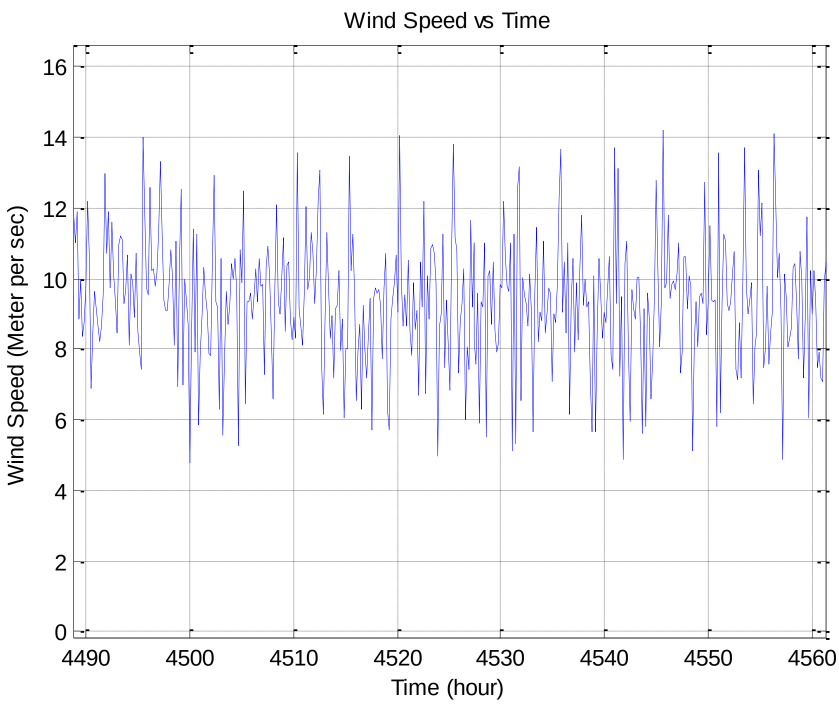

Fig. 9. Example of simulated wind speed. Part of the total time range.

5.3 Solar power

Cloudiness probability: 65 %.

Fig. 10 and Fig. 11 show examples of simulated solar powers. Fig. 10 illustrates the total time range, while Fig. 11 illustrates a small part of the total range.

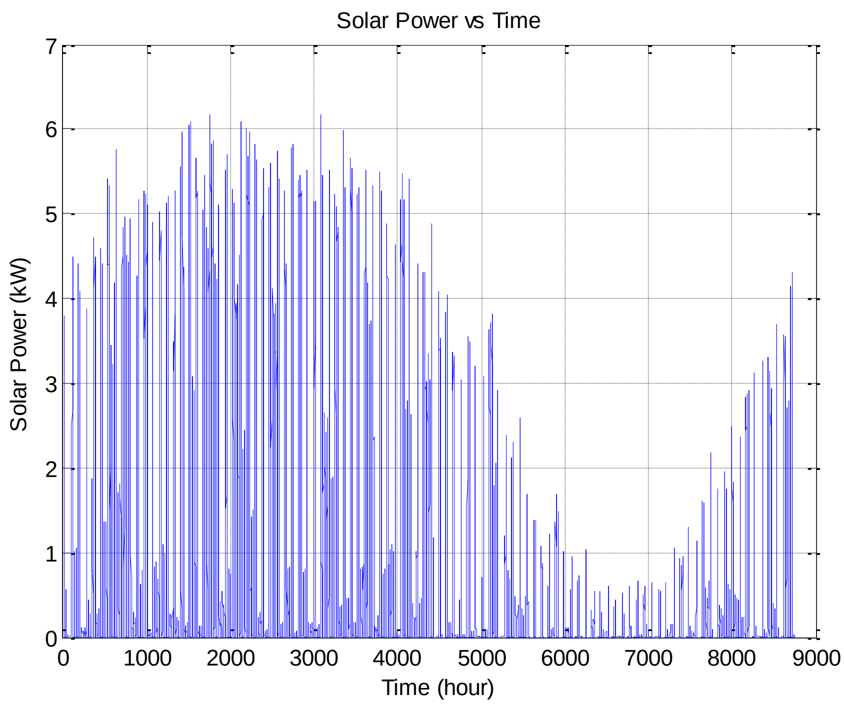

Fig. 10. Example of simulated solar power for 365 days (8760 hours).

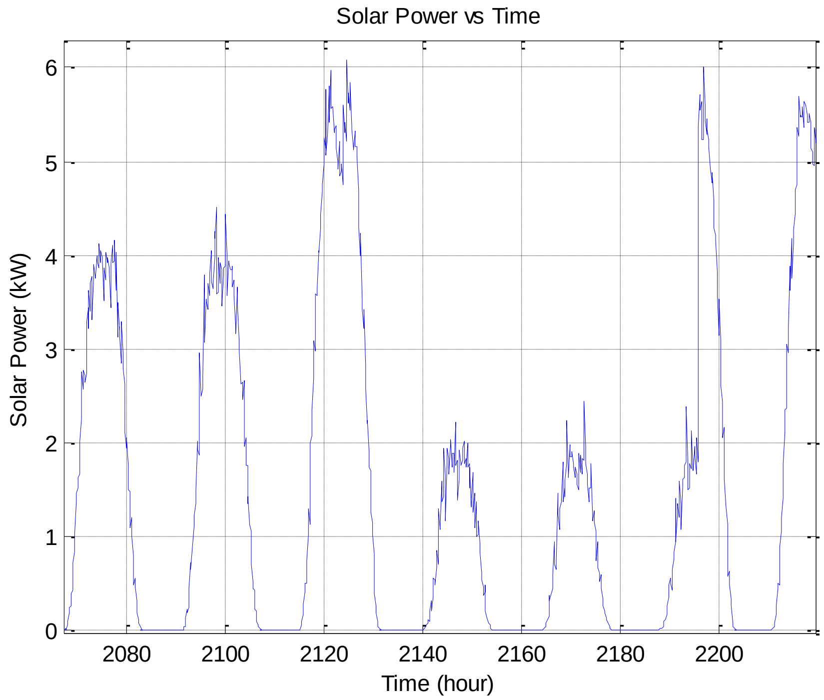

Fig. 11. Example of simulated solar power. Part of the total time range.

5.4 Electrical load

The following applies to the electrical load:

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

Fig. 12 and Fig. 13 show examples of simulated solar powers. Fig. 12 illustrates the total time range, while Fig. 13 illustrates a small part of the total range.

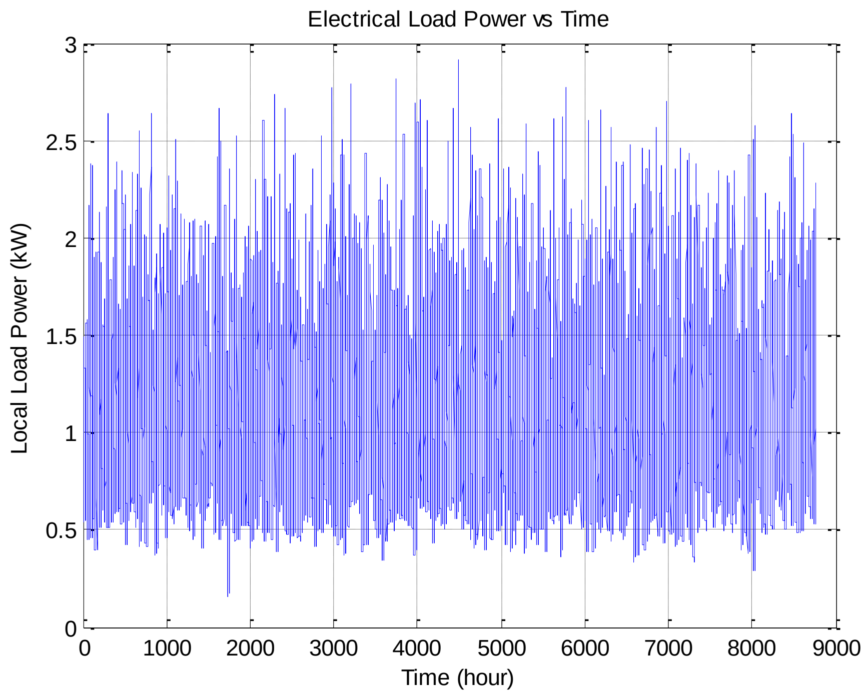

Fig. 12. Example of simulated electrical load power for 365 days (8760 hours).

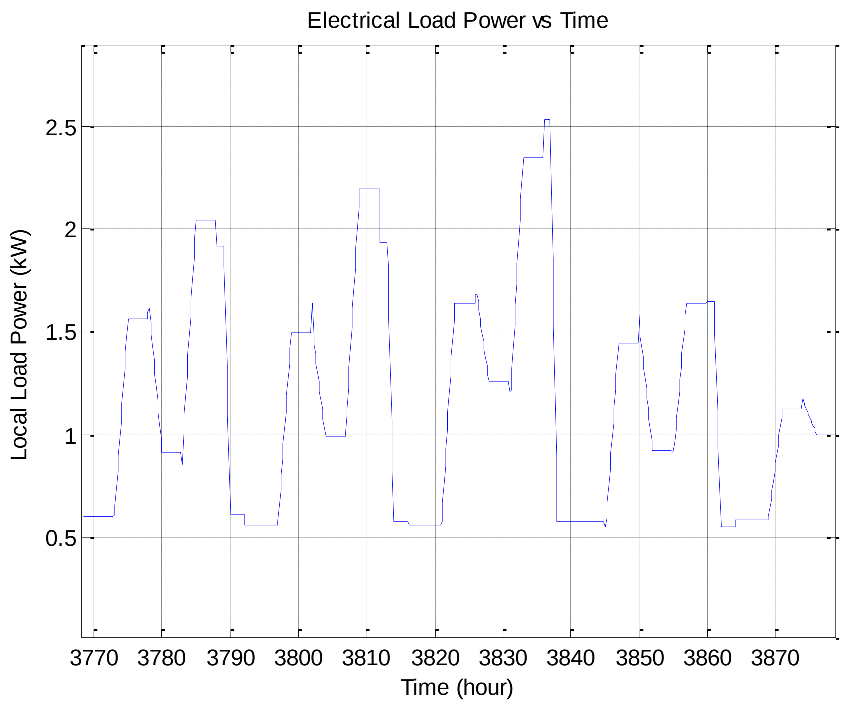

Fig. 13. Example of simulated electrical load power. Part of the total time range.

5.5 Tests with varying angle β. Part 1

Simulations have been performed with varying angle β and fixed angle φ = 45 º. The angle β corresponds to the angle between the surface normal of the solar cell panels and direction to south. The angle φ corresponds to the angle between the surface normal of the solar cell panels and direction to zenith. See section 2.

- Number of wind power turbines: 1
- Energy storage: 0 kWh

Table II and Table III lists the simulation results with the following output parameters:

- Angle relative to south: β
- Wind speed: Mean value of wind speed
- Electrical load: Mean value for annual consumed load
- Wind energy: Mean value for annual produced wind energy
- Solar energy: Mean value for annual produced solar energy
- Wind + Solar energy: Mean value for annual produced wind energy and solar energy
- Exported energy: Mean value for annual exported excess energy
- Imported energy: Mean value for annual imported energy deficit

- Import / (Exp+Imp): Mean value of relation between exported energy and the sum of exported and imported energy
- Export / Generated: Mean value of relation between exported energy and produced energy
- Import / Generated: Mean value of relation between imported energy and produced energy

Table II. Simulation results. φ = 45 º.

Angle relative to south (degrees)	**Wind speed (m/s)**	**Electrical load (kWh)**	**Wind energy (kWh)**	**Solar energy (kWh)**	**Wind + Solar energy (kWh)**
- 180	5.3	10000	2785	615	3400
- 135	5.3	10000	2775	183	2958
- 90	5.2	10000	2753	728	3481
- 45	5.2	9998	2765	2126	4891
0	5.3	9994	2761	3744	6505
22.5	5.2	10000	2762	4313	7075
35	5.2	9999	2756	4461	7217
40	5.2	9994	2752	4489	7241
42.5	5.2	9994	2752	4498	7250
45	5.3	9997	2815	4524	7339
47.5	5.2	10000	2755	4533	7288
50	5.2	10000	2763	4515	7277
55	5.3	9998	2818	4496	7314
67.5	5.2	9998	2758	4342	7100
90	5.2	10000	2782	3818	6600
135	5.3	9994	2779	2109	4888

Table III. Simulation results. $\varphi = 45$ º.

Angle relative to south (degrees)	Exported energy (kWh)	Imported energy (kWh)	Import/ (Exp+Imp) (%)	Export/ Generated (%)	Import/ Generated (%)
- 180	476	6904	93.5	13.9	206.1
- 135	390	7228	94.9	13.0	249.0
- 90	642	6944	91.5	18.4	202.1
- 45	1502	6437	81.1	30.7	132.4
0	2641	6030	69.5	40.6	93.1
22.5	3062	5917	65.9	43.3	84.0
35	3162	5882	65.0	43.8	81.9
40	3183	5868	64.8	44.0	81.4
42.5	3192	5867	64.8	44.0	81.2
45	3223	5815	64.3	43.9	79.7
47.5	3209	5855	64.6	44.0	80.7
50	3194	5856	64.7	43.9	80.8
55	3193	5807	64.5	43.7	79.8
67.5	3040	5866	65.9	42.8	83.0
90	2610	5920	69.4	39.5	90.1
135	1325	6296	82.6	27.1	130.0

Some plots based on Table II and Table III:

- Fig. 14 illustrates the relationship between annual solar energy and angle β
- Fig. 15 illustrates the relationship between total annual energy and angle β
- Fig. 16 illustrates the relationship between annual exported energy and angle β
- Fig. 17 illustrates the relationship between annual imported energy and angle β
- Fig. 18 illustrates the relationship between “annual exported energy relative annual produced energy” and angle β
- Fig. 19 illustrates the relationship between “annual imported energy relative annual produced energy” and angle β

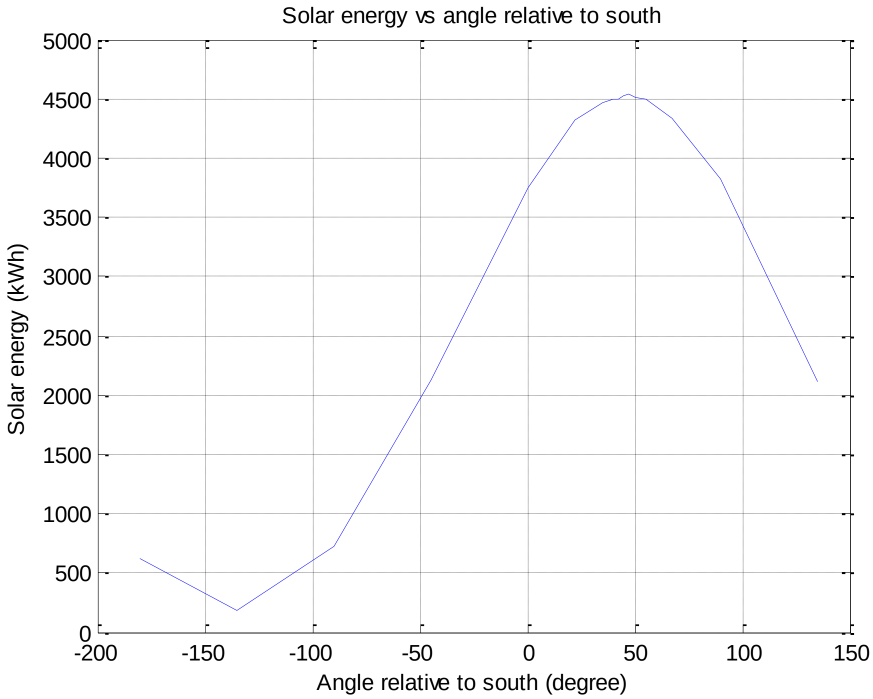

Fig. 14. Annual solar energy vs angle β.

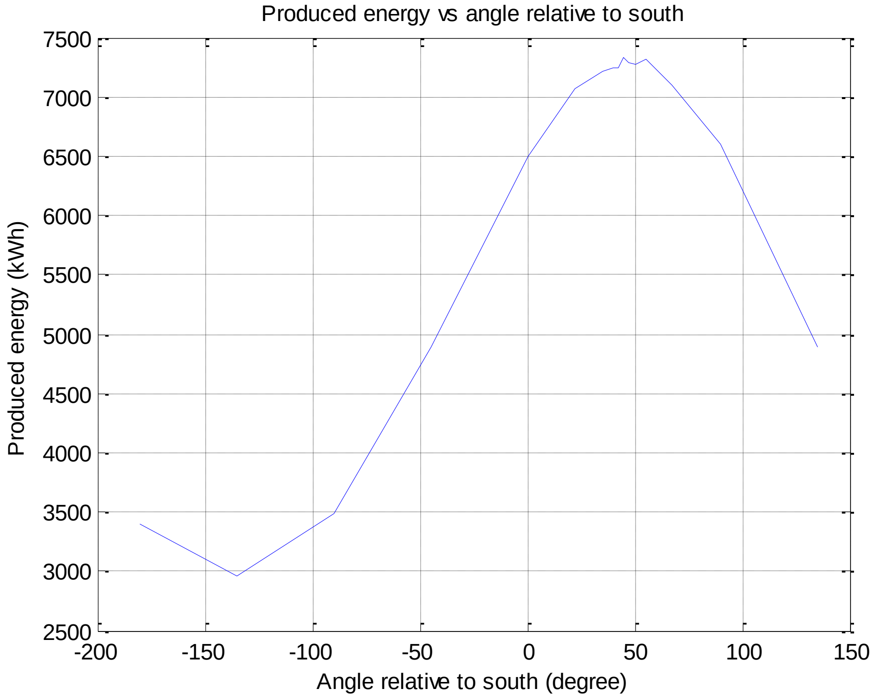

Fig. 15. Annual produced energy vs angle β.

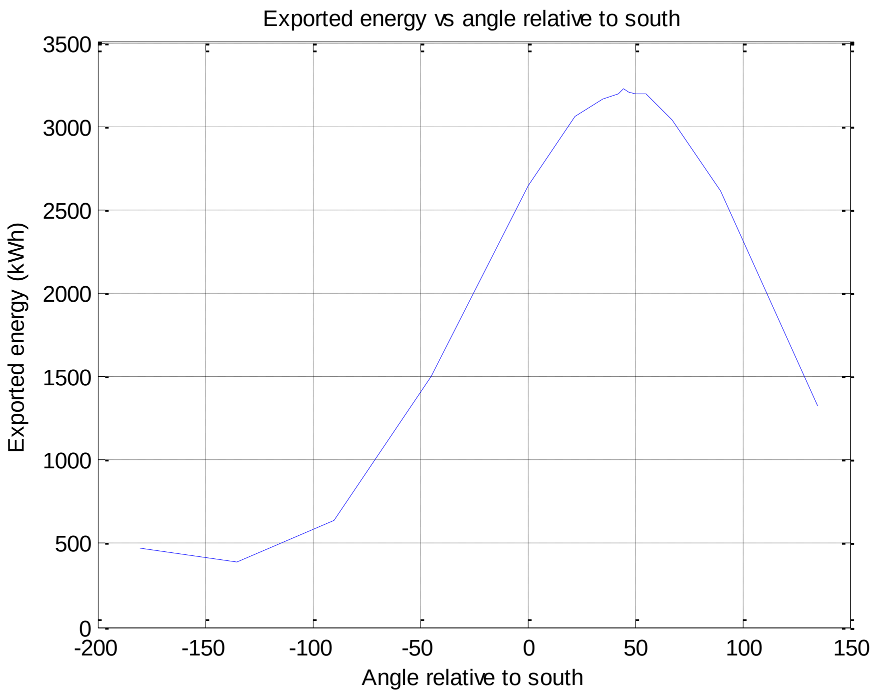

Fig. 16. Annual exported energy vs angle angle β.

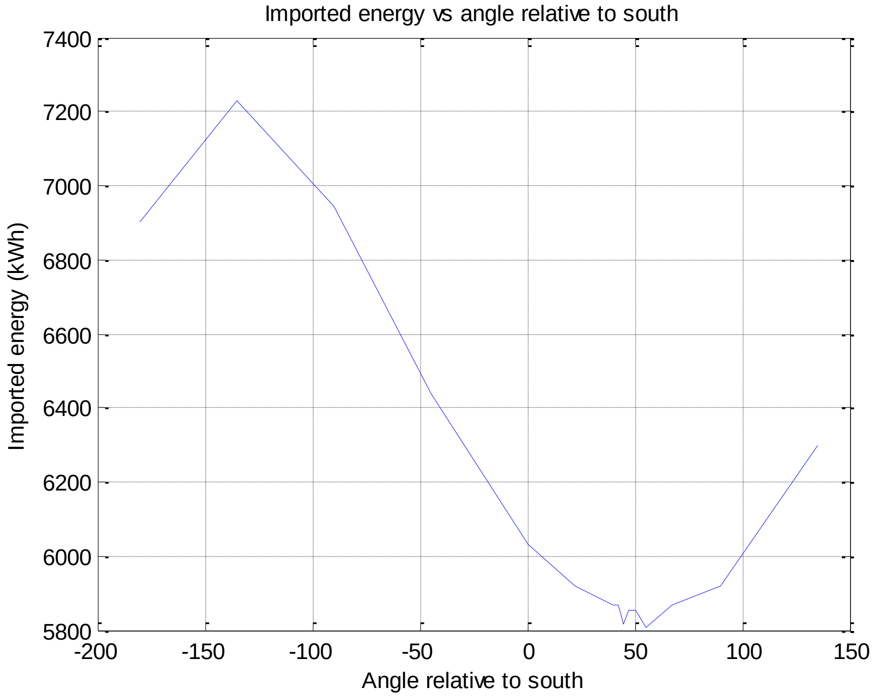

Fig. 17. Annual imported energy vs angle angle β.

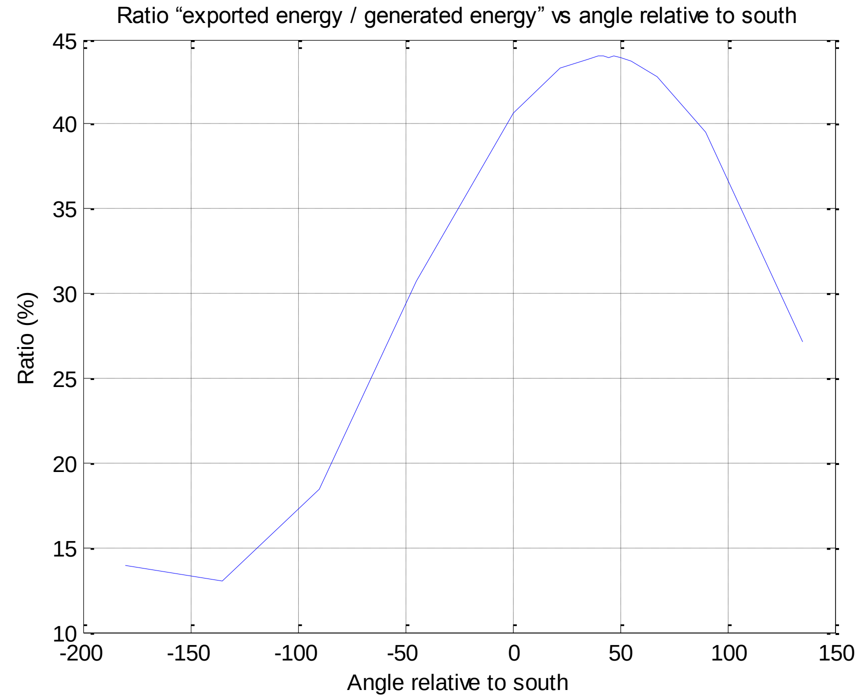

Fig. 18. Ratio “annual exported energy / annual generated energy” vs angle angle β.

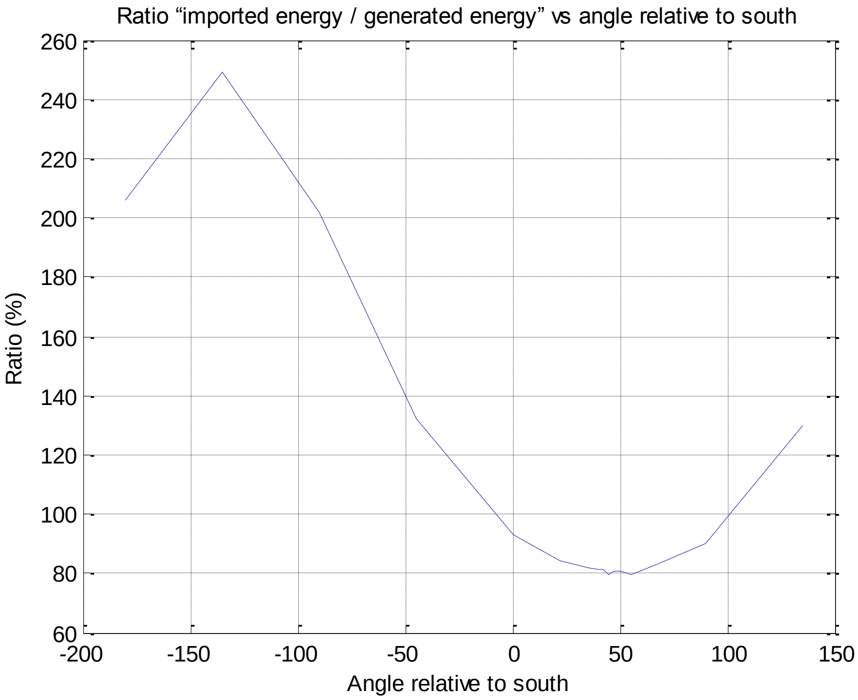

Fig. 19. Ratio “annual import energy / annual generated energy” vs angle angle β.

5.6 Tests with varying angle φ

Simulations have been performed with varying angle φ and fixed angle β = 45 º. These tests are performed to make a more precise evaluation regarding the optimal angles β and φ regarding maximum solar power.

- Number of wind power turbines: 1
- Energy storage: 0 kW

Table IV. Simulation results. β = 45 º.

Angle relative to zenith (degrees)	Wind speed (m/s)	Electrical load (kWh)	Wind energy (kWh)	Solar energy (kWh)	Wind + Solar energy (kWh)
40	5.2	9999	2770	4464	7234
47.5	5.2	9998	2750	4555	7304
50	5.3	9994	2796	4541	7338

Table V. Simulation results. β = 45 º.

Angle relative to zenith (degrees)	Exported energy (kWh)	Imported energy (kWh)	Import/ (Exp+Imp) (%)	Export/ Generated (%)	Import/ Generated (%)
40	3165	5862	64.9	43.8	81.4
47.5	3233	5861	64.4	44.3	80.5
50	3230	5819	64.3	44.0	79.6

5.7 Tests with varying angle β. Part 2

Simulations have been performed with varying angle β and fixed angle φ = 47.5 º. These tests are performed to make a more precise evaluation regarding the optimal angles β and φ regarding maximum solar power.

- Number of wind power turbines: 1
- Energy storage: 0 kW

Table VI. Simulation results. φ = 47.5 º.

Angle relative to south (degrees)	Wind speed (m/s)	Electrical load (kWh)	Wind energy (kWh)	Solar energy (kWh)	Wind + Solar energy (kWh)
42.5	5.2	10000	2763	4533	7296
47.5	5.3	10000	2768	4532	7300
50	5.2	9994	2752	4516	7268

Table VII. Simulation results. φ = 47.5 º.

Angle relative to south (degrees)	**Exported energy (kWh)**	**Imported energy (kWh)**	**Import/ (Exp+Imp) (%)**	**Export/ Generated (%)**	**Import/ Generated (%)**
42.5	3217	5861	64.6	44.1	80.7
47.5	3207	5848	64.6	43.9	80.5
50	3193	5856	64.7	43.9	80.9

5.8 Tests with varying storage capacity

Simulations have been performed with varying storage capacity.

- Number of wind power turbines: 4
- Angle β: 45.0 º
- Angle φ = 47.5 º

A parameter "N" is defined according to:

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

Where "Annual consumed energy" = 10 000 kWh

Table VIII lists the simulation results with the following output parameters:

- Storage capacity (N): Storage capacity expressed in parameter "N"
- Storage capacity (kWh): Storage capacity expressed in kWh
- Wind + Solar energy: Mean value of annual energy production
- Exported energy: Mean value of annual exported excess energy
- Imported energy: Mean value of annual imported energy deficit
- Import / (Exp+Imp): Mean value of the relation annual imported energy and the sum of annual exported and imported energy
- Storage level Mean: Mean value of annual storage level

Table VIII. Simulation results with varying values of storage capacity. 4 wind turbines.

Storage capacity (N)	**Storage capacity (kWh)**	**Wind + Solar energy (kWh)**	**Exported energy (kWh)**	**Imported energy (kWh)**	**Import/ (Exp+Imp) (%)**	**Storage level Mean (%)**
0	0	15680	9675	4023	29.6	-
0.1	2.74	15820	9421	3641	28.1	74.8
0.5	13.7	15590	8598	3052	26.4	74.9
1	27.4	15630	8240	2652	24.6	76.5
2	54.8	15700	7717	2069	21.4	78.7
3	82.2	15700	7394	1766	19.6	79.3
4	110	15570	7007	1506	18.0	79.8
5	137	15530	6786	1331	16.7	80.5

Some plots based on Table VIII:

- Fig. 20 illustrates the relationship between Exported energy and Storage capacity (N)
- Fig. 21 illustrates the relationship between Imported energy and Storage capacity (N)
- Fig. 22 illustrates the relationship between the ratio “Imported energy / (Exported energy +Imported energy)” and Storage capacity (N)

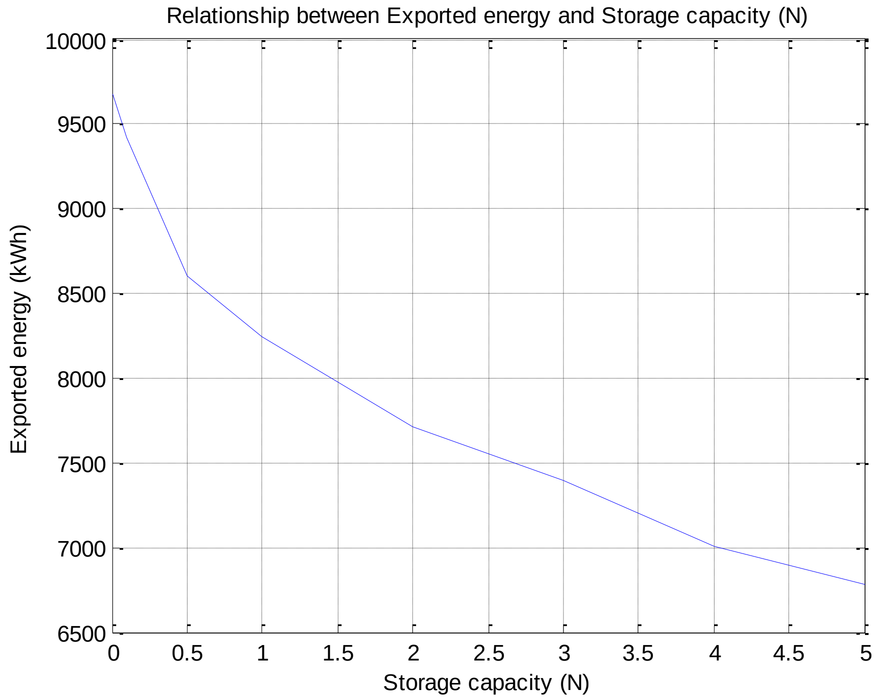

Fig. 20. Relationship between Exported energy and Storage capacity (N).

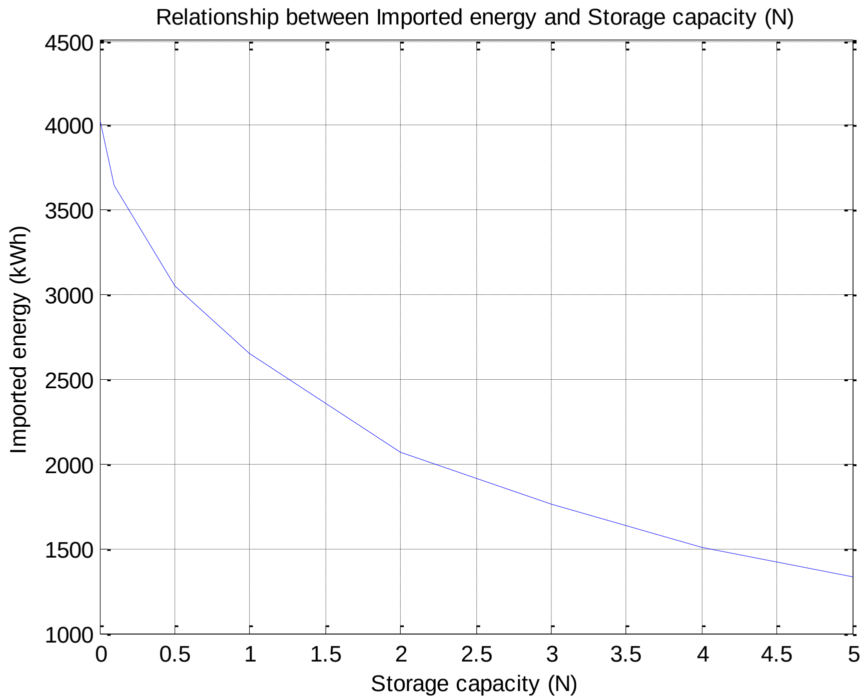

Fig. 21. Relationship between Imported energy and Storage capacity (N).

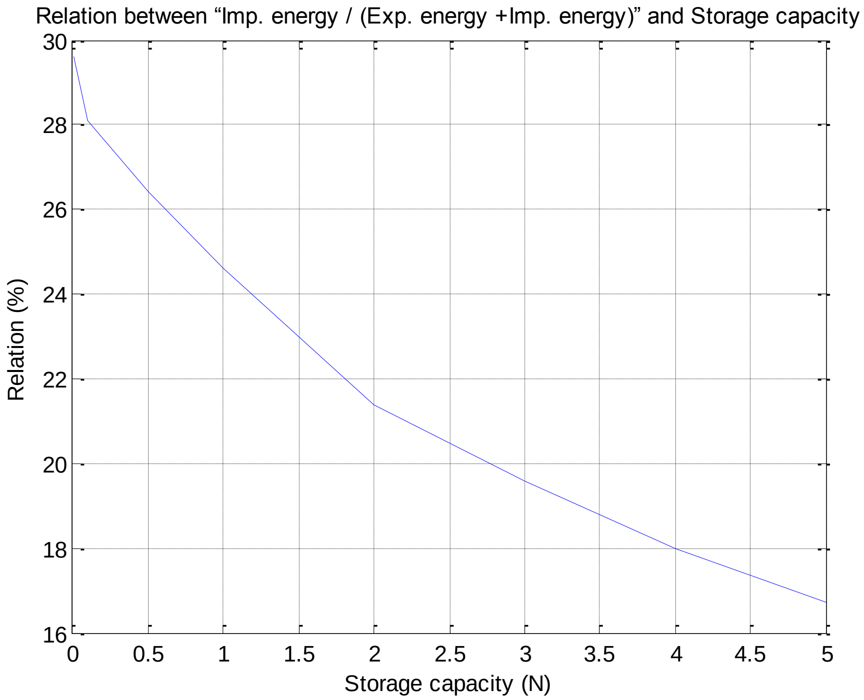

Fig. 22. Relationship between the ratio "Imported energy / (Exported energy +Imported energy)" and Storage capacity (N).

5.9 Tests with varying number of turbines

Simulations have been performed with varying number of turbines.

- Storage capacity: N = 0 resp N = 3
- Angle β: 45.0 º
- Angle φ = 47.5 º

Table IX and Table X lists the simulation results with the following output parameters:

- Wind + Solar energy: Mean value of annual energy production
- Exported energy: Mean value of annual exported excess energy
- Imported energy: Mean value of annual imported energy deficit
- Import / (Exp+Imp): Mean value of the relation annual imported energy and the sum of annual exported and imported energy

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

Number of turbines	Wind + Solar energy (kWh)	Exported energy (kWh)	Imported energy (kWh)	Import/ (Exp+Imp) (%)
0	4545	2421	7550	75.7
1	7328	3203	5733	64.2
2	10050	4981	4862	49.4
3	12780	7160	4353	37.9
4	15590	9589	4041	29.8
5	18630	12310	3753	23.6
6	21060	14590	3635	20.2

Table X. Simulation results with varying values of wind turbines.
Storage capacity N = 3 (82.2 kWh).

Number of turbines	Wind + Solar energy (kWh)	Exported energy (kWh)	Imported energy (kWh)	Import/ (Exp+Imp) (%)
0	4526	137	5608	97.6
1	7316	808	3499	81.3
2	10120	2550	2448	49.2
3	12780	4782	2044	30.3
4	15590	7299	1774	19.9
5	18630	10100	1544	13.6
6	21060	12450	1472	10.8

Some plots based on Table IX and Table X:

- Fig. 23 illustrates the relationship between Generated energy and Number of turbines. Storage capacity N =0 (in principle the same for N = 3)
- Fig. 24 illustrates the relationship between Exported energy and Number of turbines. Storage capacity N =0 resp N = 3
- Fig. 25 illustrates the relationship between Imported energy and Number of turbines. Storage capacity N =0 resp N =3
- Fig. 26 illustrates the relationship between the ratio “Imported energy / (Exported energy +Imported energy)”. Storage capacity N =3 resp N = 3

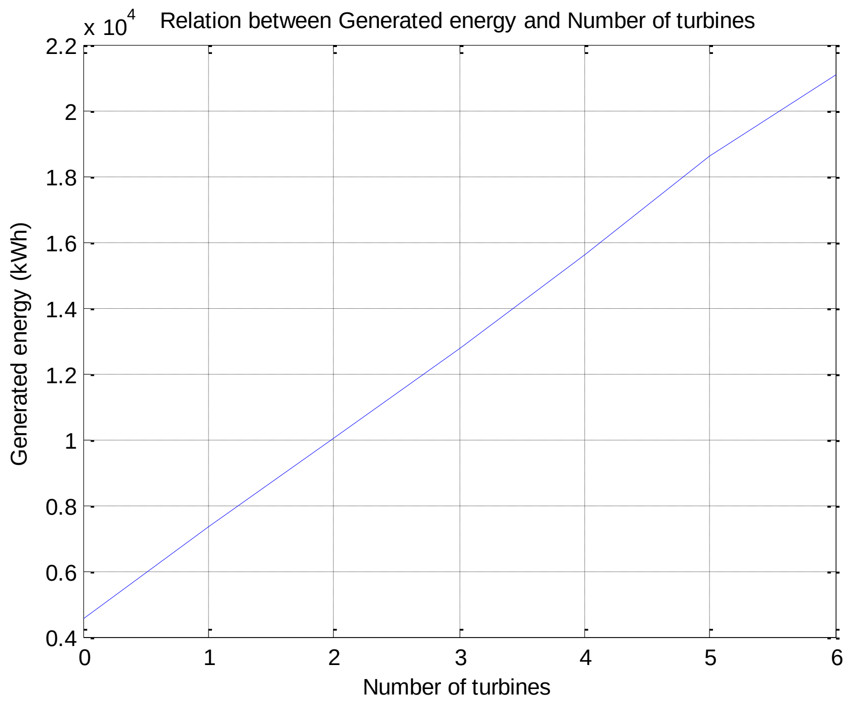

Fig. 23. Relationship between Generated energy and Number of turbines. Storage capacity N =0 (in principle the same for N = 3).

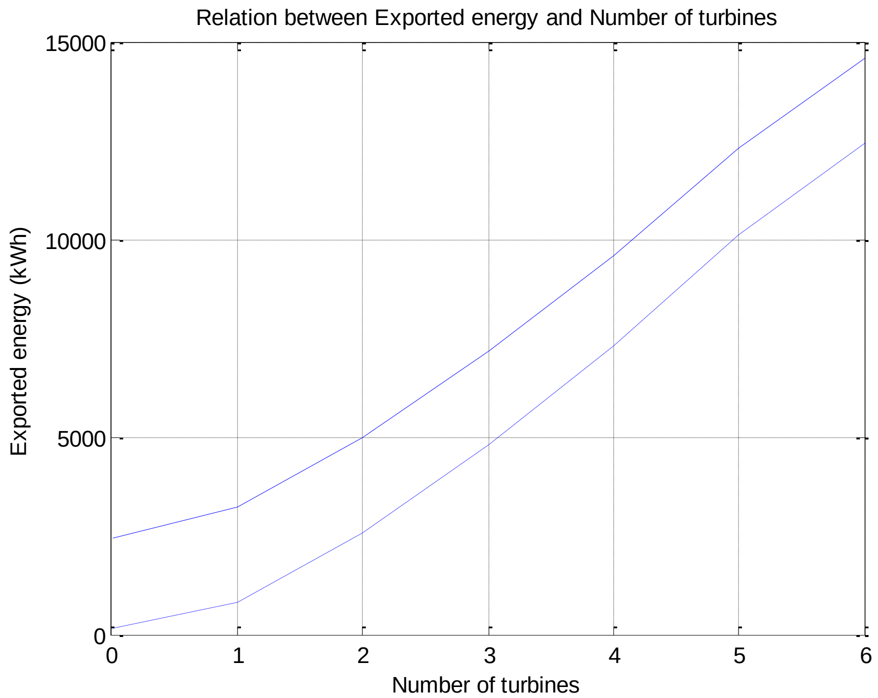

Fig. 24. Relationship between Exported energy and Number of turbines.
Solid curve: Storage capacity N = 0. Dashed curve: Storage capacity N = 3.

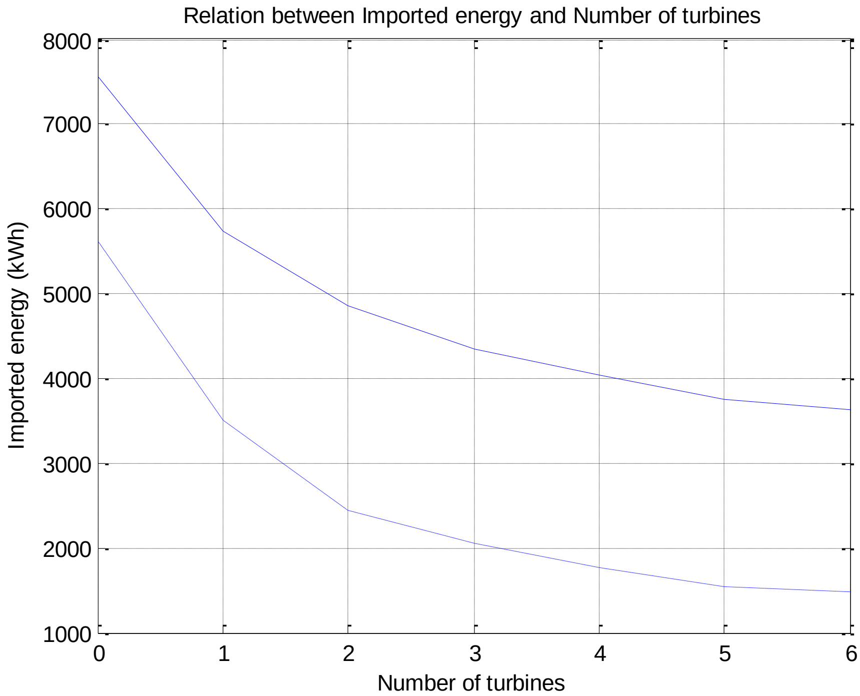

Fig. 25. Relationship between Imported energy and Number of turbines. Solid curve: Storage capacity N = 0. Dashed curve: Storage capacity N = 3.

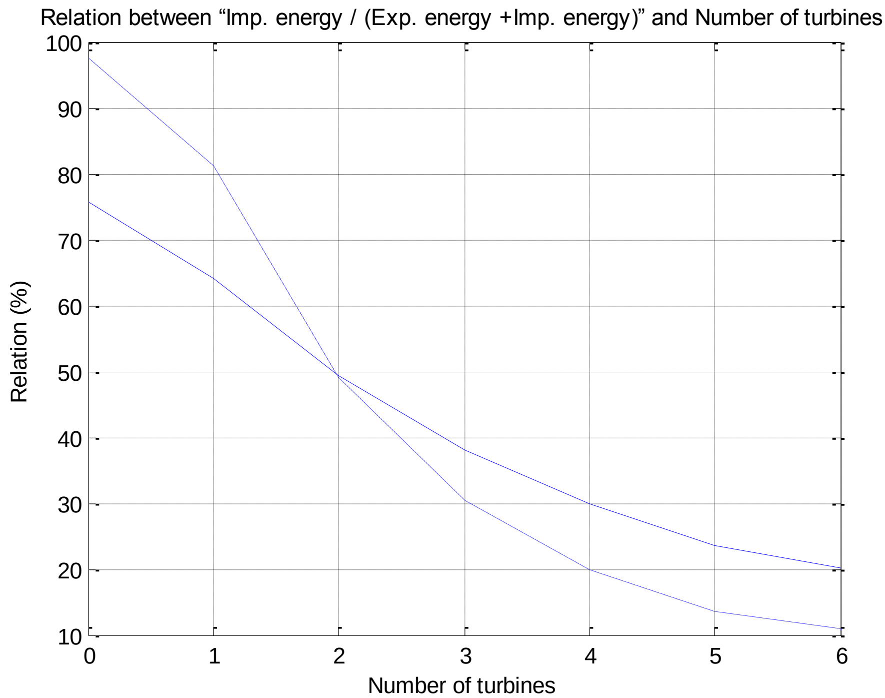

Fig. 26. Relationship between the ratio "Imported energy / (Exported energy +Imported energy)" and Number of turbines. Solid curve: Storage capacity N = 0. Dashed curve: Storage capacity N = 3.

6 CONCLUSIONS

6.1 Tests with varying angle β and angle φ

The optimal angles β and φ have been found to be about 47.5°.

The performance of the system with regard to solar energy, is reasonable dependent on the angle β, provided that we talk about differences in the order of ± 20 degrees from the optimal angle, that is around 47.5 °. For an angle of 27.5 °, the annual solar energy has been reduced about 3.6 %. For an angle of 67.5 °, the annual solar energy has been reduced about 4.2 %. However this reducing effect will accelerate. For an angle of 10 degrees, the annual solar energy has been reduced about 12 %. And for an angle of 85 degrees, the annual solar energy has been reduced about 13 %.

The reduction of produced solar energy in the event of inappropriate angle β will of course decrease the amount of exported energy and increase the amount of imported energy.

6.2 Tests with varying storage capacity

Exported energy as well as Imported energy will decrease when the Storage capacity is increased. The relation between “Imported energy / (Exported energy +Imported energy)” will decrease when the Storage capacity is increased. This relation decreases from 29.6 % to 16.7 % when the storage capacity increases from N = 0 to N = 5. Imported energy decreases from 4023 kWh to 1331 kWh.

6.3 Tests with varying number of turbines

It is difficult to draw any definite conclusions based on the tests. Whether to invest in increased capacity of the storage unit alternative to invest in increased production capacity regarding wind generators will be a tradeoff with respect to the pricing which can be expected for the sale / purchase of electric energy. However, the made tests give a good indication of the problem to design an optimal small scale power system for home usage. A lot of economic considerations have to be taken into account.

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