Simulation of a Solar Power Farm

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Content

1 INTRODUCTION

This document deals with simulation of an autonomous power system, where solar acts as power source. The solar radiation 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.

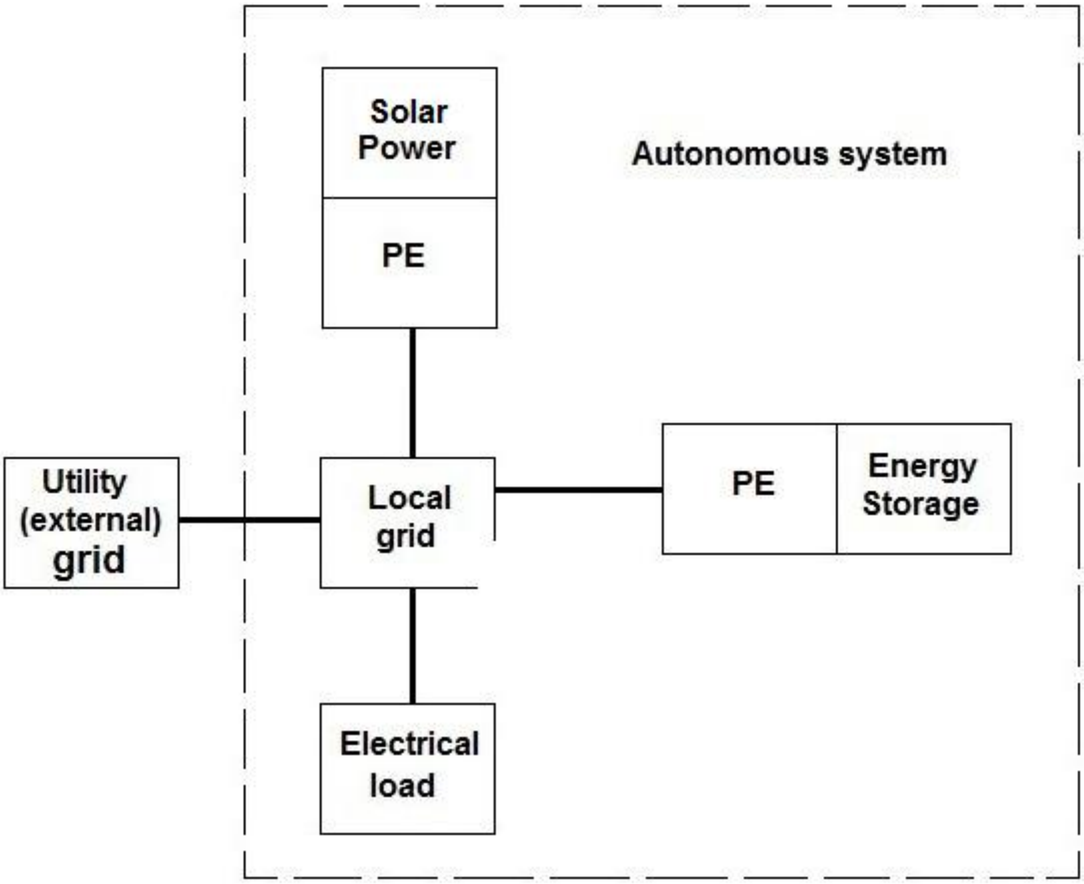

Fig. 1. The main components in the autonomous power system.

Subsystems in the power system according to Fig. 1:

Solar Power: Solar 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

Table I. The modules in the simulation system.

System Modules	Function
Extinction_make	Stochastic extinction coefficient
Sun_Intensity	Solar radiation based on extinction coefficient, time, date and solar panel direction
Sun_panel_generator	Electrical solar power based on solar radiation
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	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.

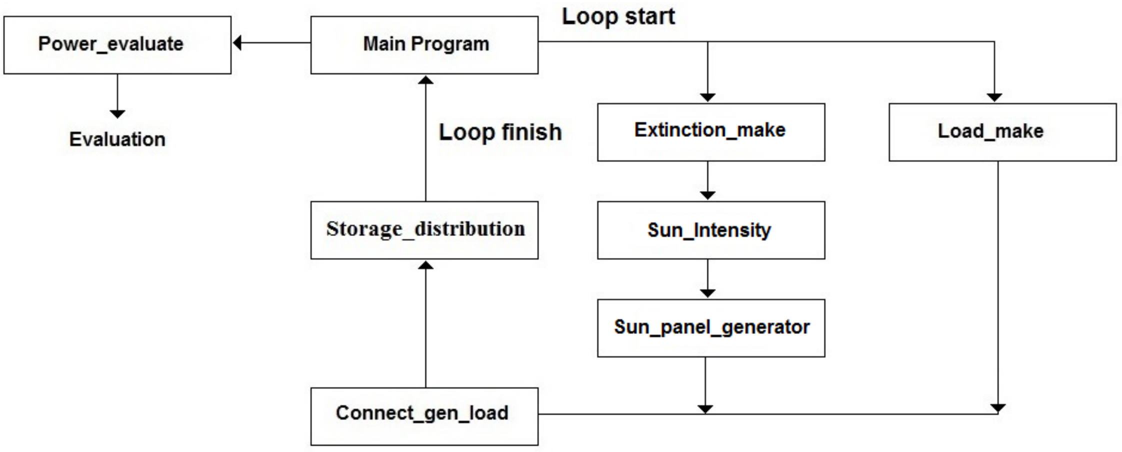

Fig. 2. Simulation flowchart. The loop repeated “N” times.

These modules are described in [1] that deals about an autonomous power system consisting of both wind power and solar power. More detailed information can also be find according to:

[2] Extinction coefficient
[3] Electrical load

3 SIMULATION OF A SOLAR POWER FARM

Simulation of a wind power farm has been performed with 200 simulation cycles per simulation process. The time resolution was 60 seconds, except in cases where the simulation length corresponds to 365 days. For these cases, the time resolution was selected to 600 seconds.Regarding power production, power load and energy storage the following has been in question:

Power production

- Solar cell area: See 3.1
- Total efficiency for solar power production: 13.54 %
- Solar cell surface relative to south: 0°
- Solar cell surface relative to zenith: 0°

Power Load

An area with a mix of power consumers 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 Solar cell area

The following adoption is taken: The solar power plant shall produce more energy, than equivalent load during following conditions:

- Location: Göteborg, Sweden
  - Latitude: 57.710º
  - Longitude: 11.968º
- Cloudiness: 65%
- Period: March 20 to 29 (around spring equinox)

Simulation results with mean values and standard deviations and with different solar cell areas follow according to Table II.

Table II. Simulation result for different solar cell areas.

Solar cell area (m^2)	**Energy, mean (MWh) (10 days)**	**Energy, st.dev. (MWh) (10 days)**
7×10^5	471	116
8×10^5	561 (538)	145
9×10^5	636 (606)	152

Outgoing from simulation results with solar cell area = 7×10^5 m^2, one would obtain the following:

Solar cell area 8×10^5 : Energy, mean = 471 / 7 × 8 = 538 MWh
Solar cell area 9×10^5 : Energy, mean = 471 / 7 × 9 = 606 MWh

These values are in parentheses in Table II. 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: 554 MWh

St.dev: 12 MWh

This means that an area of 9×10^5 m^2 could be suitable to meet the approach above.

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. 1 $$\text{Storage capacity} = \frac{20\ \text{GWh}}{365} \times N$$

Where:

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

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

The conditions according to section 3.1 are in question with a solar cell area of $9 \times 10^5\ \text{m}^2$.

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

St_cap (N):	Storage capacity in terms of parameter N. See Equ. 1.
St_cap/E_{gen_day}:	See below. Equ. 2.
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 III. 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 (%)**
1	0.84	0.647	36.3	24.6	13.4
2	1.68	0.637	35.1	14.6	6.4
3	2.52	0.625	40.5	9.3	4.9
4	3.36	0.606	41.2	5.5	2.3
5	4.2	0.628	36.8	5.0	0.85
6	5.04	0.618	38.8	3.1	0.18
7	5.88	0.626	37.8	2.73	7.3×10^{-2}
8	6.72	0.626	40.2	1.8	0
9	7.56	0.626	44.2	0.71	0
10	8.4	0.616	45.2	0.73	0
11	9.24	0.621	46.5	0.56	0
12	10.1	0.626	48.2	0.17	0
13	10.9	0.614	48.0	0.28	0
14	11.8	0.615	49.8	3.6×10^{-2}	0
15	12.6	0.632	49.2	6.3×10^{-2}	0
16	13.4	0.619	48.8	8.4×10^{-2}	0
17	14.3	0.633	49.5	4.0×10^{-2}	0
18	15.1	0.623	50.0	0	0
19	16.0	0.600	50.0	0	0
20	16.8	0.626	50.0	0	0
21	17.6	0.631	50.0	0	0
22	18.5	0.629	50.0	0	0
23	19.3	0.632	50.0	0	0
24	20.2	0.616	50.0	0	0
25	21.0	0.631	50.0	0	0
30	25.2	0.615	50.0	0	0
40	33.6	0.626	50.0	0	0
50	42.0	0.624	50.0	0	0

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

St_cap (N)	**Storage mean (%)**	**Storage std.dev (%)**	**Storage max (%)**	**Storage min (%)**
1	48.1	9.9	100	10
2	54.5	15.8	100	10
3	55.1	18.8	100	10
4	54.8	19.0	100	10
5	56.3	17.8	100	10
6	56.7	15.2	100	10
7	59.4	15.7	100	10
8	57.2	13.1	100	12.6
9	57.6	11.3	100	17.4
10	57.5	11.2	100	21.5
11	57.5	10.3	100	23.7
12	56.9	9.3	100	25.2
13	56.4	8.5	100	30.4
14	55.6	8.2	100	31.8
15	56.6	7.1	100	31.0
16	56.6	7.5	100	34.1
17	56.9	7.0	100	33.6
18	56.5	6.6	95.2	32.4
19	55.7	6.0	97.6	35.3
20	56.5	5.8	94.8	37.9
21	56.2	5.2	96.3	39.2
22	56.0	5.4	87.7	38.4
23	56.2	5.0	91.9	40.8
24	56.0	4.8	82.9	41.0
25	56.2	4.6	82.6	40.7
30	55.7	3.6	82.2	44.3
40	55.5	3.1	76.7	46.9
50	55.4	2.0	69.3	47.8

Depending on stochastic variations, deviates the generated energy levels slightly between each simulation. See Fig. 3. The mean value for all simulations is 0.624 GWh. The standard deviation is 0.01 GWh.

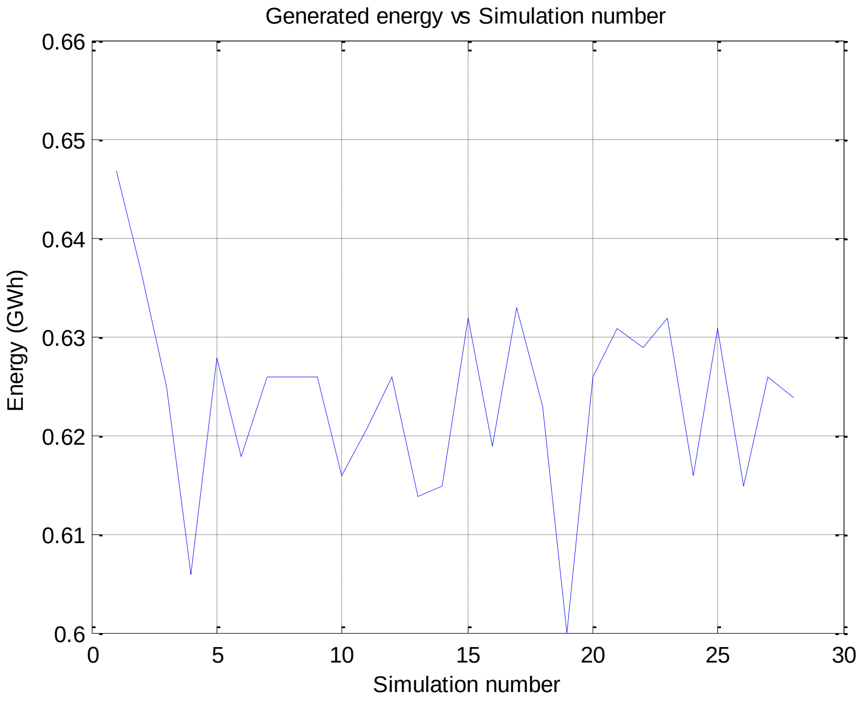

Fig. 3. Stochastic variations of the generated energy.

The following definition is done:

Equ. 2. $\mathrm{St\_cap}/\mathrm{E}_{\mathrm{gen\_day}} = \dfrac{\text{Storage capacity}}{\mathrm{E}_{\mathrm{gen\_day}}}$

Where:

Storage capacity: Storage capacity (GWh)

$\mathrm{E}_{\mathrm{gen\_day}}$: Mean value of energy production per day = $\dfrac{0.652\ \mathrm{GWh}}{10}$

Table III lists the values of parameter $\mathrm{S\_cap}/\mathrm{E}_{\mathrm{gen\_day}}$.

Fig. 4 illustrates the Relation between Storage capacity and Generated energy per day vs Storage capacity expressed in parameter N.

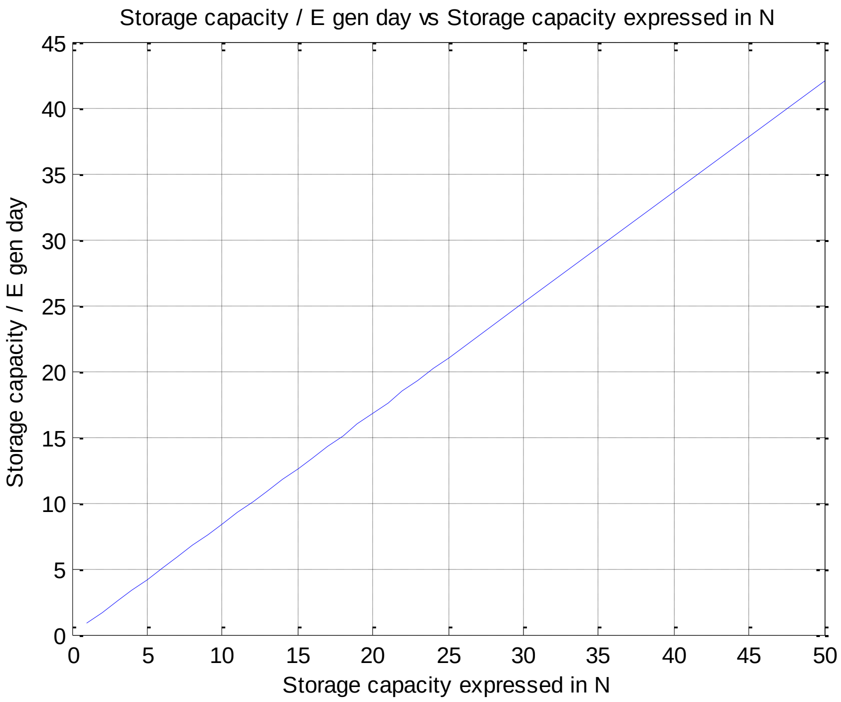

Fig. 4. Relation between Storage capacity and Generated energy per day vs Storage capacity expressed in N..

Additional figures:

- The relation between Exported/Imported energy and Generated energy during 10 days vs Storage capacity expressed in parameter N is illustrated in Fig. 5 rep Fig. 6.

- Maximum/Minimum used Storage level vs Storage capacity expressed in parameter N is illustrate in Fig. 7 resp Fig. 8.

- Standard deviation of Storage level vs Storage capacity expressed in parameter N is illustrated in Fig. 9.

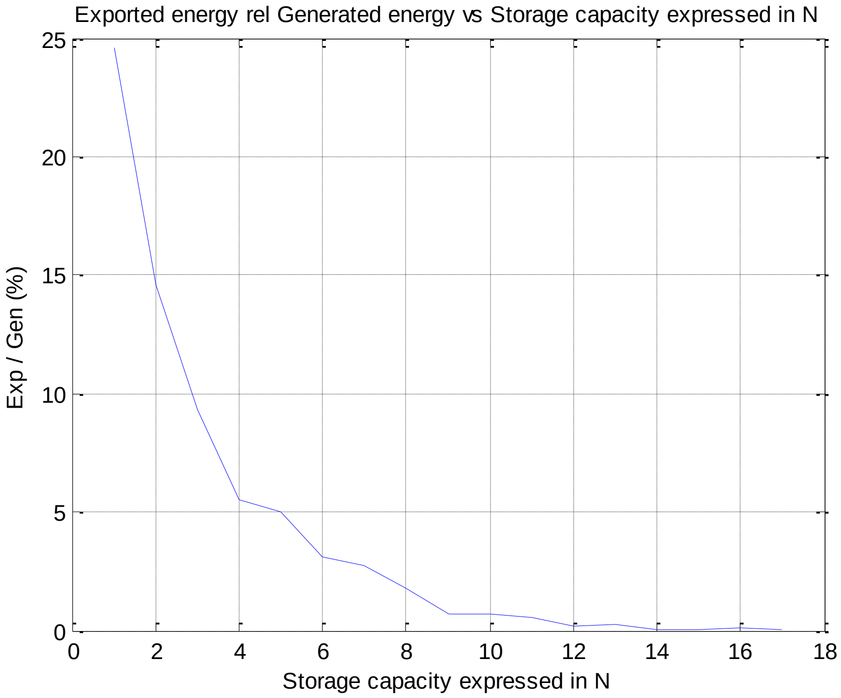

Fig. 5. Relation between Exported energy and Generated energy during 10 days vs Storage capacity expressed in parameter N.

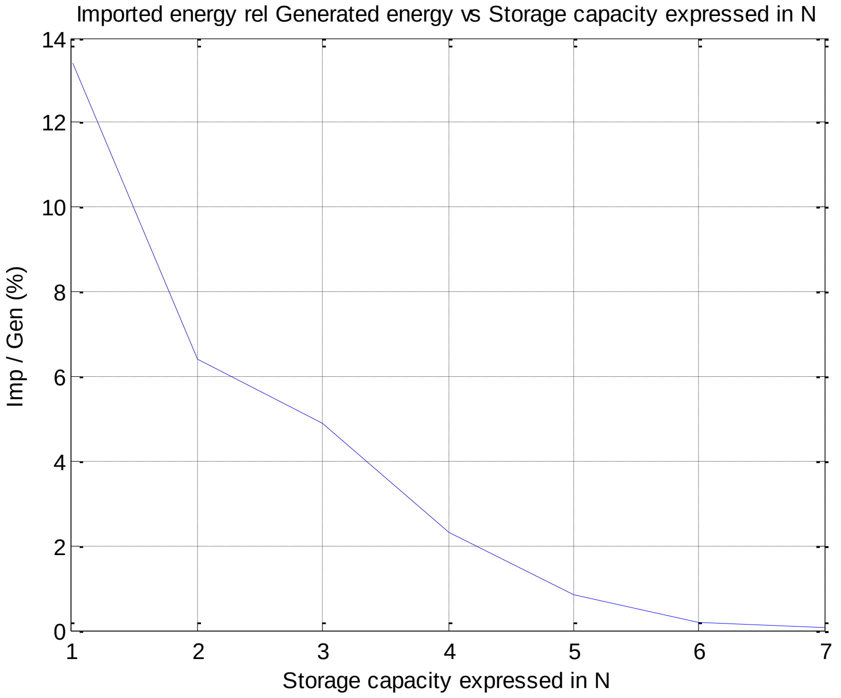

Fig. 6. Relation between Imported energy and Generated energy during 10 days vs Storage capacity expressed in parameter N.

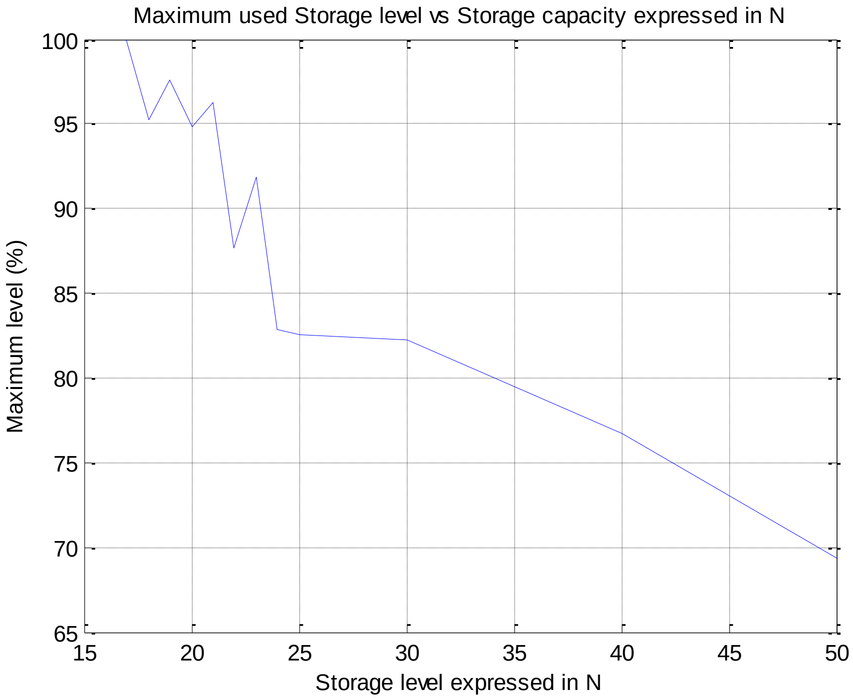

Fig. 7. Maximum used Storage level vs Storage capacity expressed in parameter N.

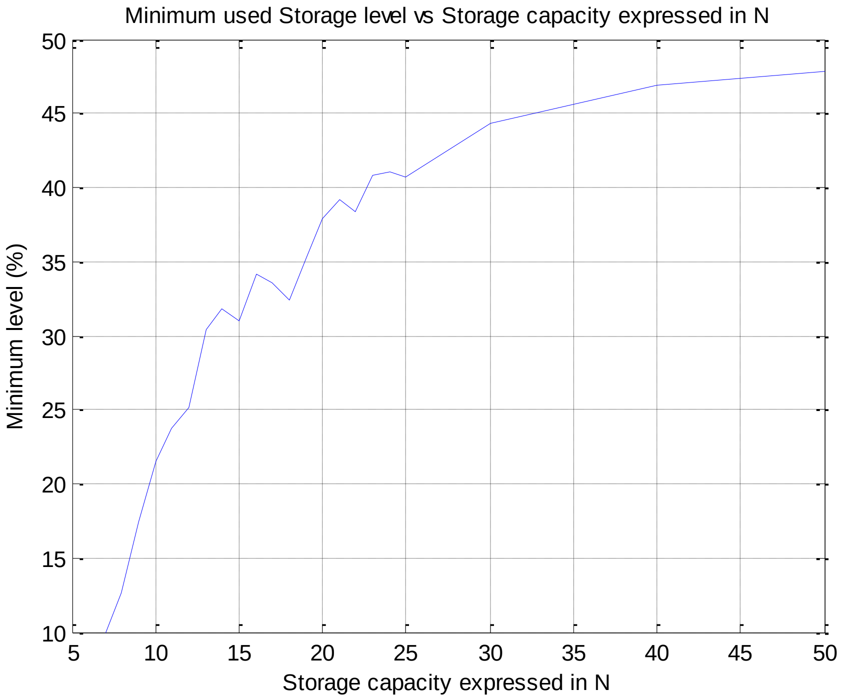

Fig. 8. Minimum used Storage level vs Storage capacity expressed in parameter N.

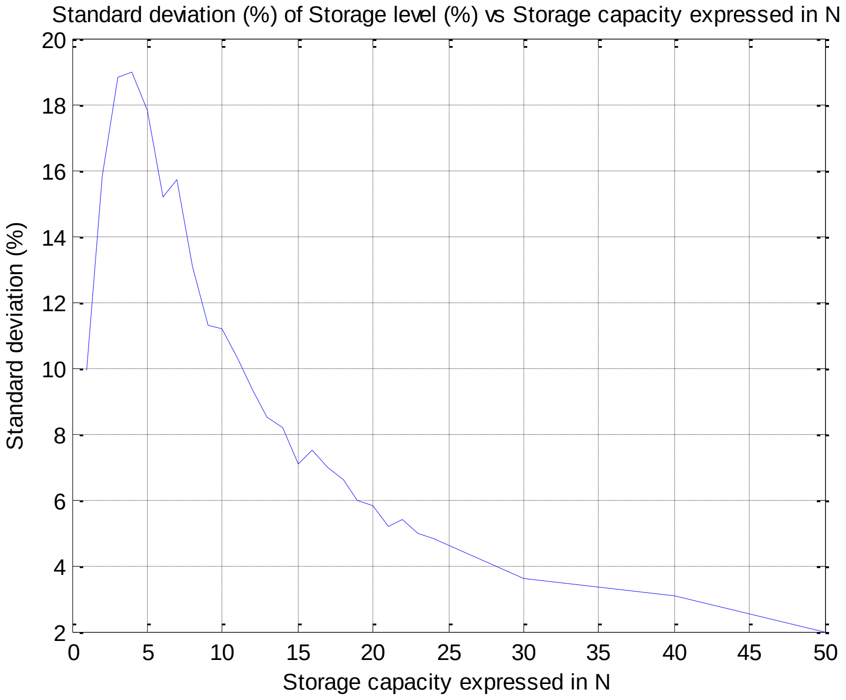

Fig. 9. Standard deviation of Storage level vs Storage capacity expressed in parameter N.

3.3 Simulation corresponding 365 days and different locations

Simulations corresponding a period of 1 year are perfomed during following conditions:

- Location: Göteborg, Sweden
  - Latitude: 57.710º
  - Longitude: 11.968º
  - Cloudiness: 65%
- Kiruna, Sweden
  - Latitude:
  - Longitude:
  - Cloudiness: 65%
- Location: Nairobi, Kenya
  - Latitude:
  - Longitude:
  - Cloudiness: 50%
- Total solar cell area of: 9×10^5 m^2 (see section 3.1)
- Energy storage: corresponding to N = 8 (see section 3.2))
- Consuming load: Same as above. Annual consumption of 20 GWh

Table V. Results of simulations corresponding to 365 days.

Loacation	Generated energy (GWh)	Consumed energy (GWh)	Exported energy (GWh)	Imported energy (GWh)
Göteborg	50.1	20.1	37.8	7.6
Kiruna	35.4	20.1	25.9	10.4
Nairobi	147.6	20.1	127.8	0.6

Table VI. Results of simulations corresponding to 365 days.

Location	Import / (Export + Import) (%)	Consumed / Generated (%)	Exported / Generated (%)	Imported / Generated (%)
Göteborg	17.1	40.7	75.1	15.6
Kiruna	29.0	57.7	72.9	30.0
Nairobi	0.4	13.6	86.5	0.4

3.4 Conclusion

3.4.1 Solar cell area

The folowing adoption was taken according to section 3.1: The solar power plant shall produce more energy, than equivalent load during following conditions:

- Location: Göteborg, Sweden
  - Latitude: 57.710º
  - Longitude: 11.968º
- Cloudiness: 65%
- Period: March 20 to 29 (around spring equinox)

It was found that a solar cell area of 9 × 10^5 m^2 was a suitable choice to fulfil the specified adoption. This is the circumstances regarding location Göteborg and a time period around spring equinox.

It is interesting to make a comparison with simulation results corresponding to a total year. According to this, the following applies:

Table VII. Genarated energy during 365 days and different solar cell areas.

Loacation	Generated energy (GWh) and solar cell area 9 × 10^5 m^2	Solar cell area to produce 20 GWh during 365 days
Göteborg	50.1	$9 \times 10^5\ m^2 \times \frac{20}{50.1} = 3.6 \times 10^5\ m^2$
Kiruna	35.4	$9 \times 10^5\ m^2 \times \frac{20}{35.4} = 5.1 \times 10^5\ m^2$
Nairobi	147.6	$9 \times 10^5\ m^2 \times \frac{20}{147.6} = 1.2 \times 10^5\ m^2$

3.4.2 Capacity of energy storage. Location Göteborg and a time period around spring equinox.

- To avoid import of energy deficit or use of “extra generator”, a storage capacity corresponding to at least “N = 8” is needed. This corresponds to (see Equ. 1, Table III, Table IV and Fig. 6):

  $$\text{Storage capacity} = \frac{20\ \text{GWh}}{365} \times 8 = 0.44\ \text{GWh}.$$

  This is the same as 8 days power consumption or 2.2 % of the annual power consumption.

  It also corresponds to 7 times the daily energy production.

- If the storage capacity exceeds about a level corresponding to “N = 18”, no excess energy is produced. This corresponds to (see Equ. 1, Table III, Table IV and Fig. 5):

  $$\text{Storage capacity} = \frac{20\ \text{GWh}}{365} \times 18 = 0.99\ \text{GWh}.$$

- To reduce the variations of the storage level, it is advantageous to use a high storage capacity. See Fig. 9.
- To reduce the use of low storage levels, it is advantageous to use a high storage capacity. See Fig. 8.

3.4.3 Capacity of energy storage. Location Göteborg, Kiruna, Nairobi and a time period of 365 days.

The energy capacity according to section 3.3 is 0.44 GWh. With this assumption the following implies (see also Table V and Table VI):

Table VIII. Generated and need of imported energy.

Loacation	Generated energy (GWh)	Imported / Generated (%)
Göteborg	50.1	15.6
Kiruna	35.4	30.0
Nairobi	147.6	0.4

The simulations show, that in spite of more total generated energy than corresponds to the annual consumption, there is a need of temporary complement of power for all locations.

4 REFERENCES

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

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

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