# Simulation of a Combined Solar and Wind Power Farm. Economic analysis

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November 2015

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# 1 INTRODUCTION

This document deals with simulation of a combined power system, where solar and wind act as power sources. The solar radiation, wind speed and load are generated stochastically. The power system is equipped with an energy storage device. The system is connected to the utility grid to balance the power. Fig. 1.1 shows the main components in the power system.

The main reason for the present work is to perform economic analysis in respect of wind power capacity, solar power capacity at different locations and the advantage to use energy storages.

As for wind power  a study is conducted, where the aim is to find the lowest cost threshold for energy import, given that wind power becomes economically viable.

Energy storages in combinations with wind power as well as solar power have been investigated in order to find out if  such a combination  can result in economic advantages.

To evaluate the difference regarding the economic circumstances for solar power plants in respect of the geographic location, a  study has been done with a large span regarding the locations. Nairobi, Kenya in south to Kiruna, Sweden  in north.

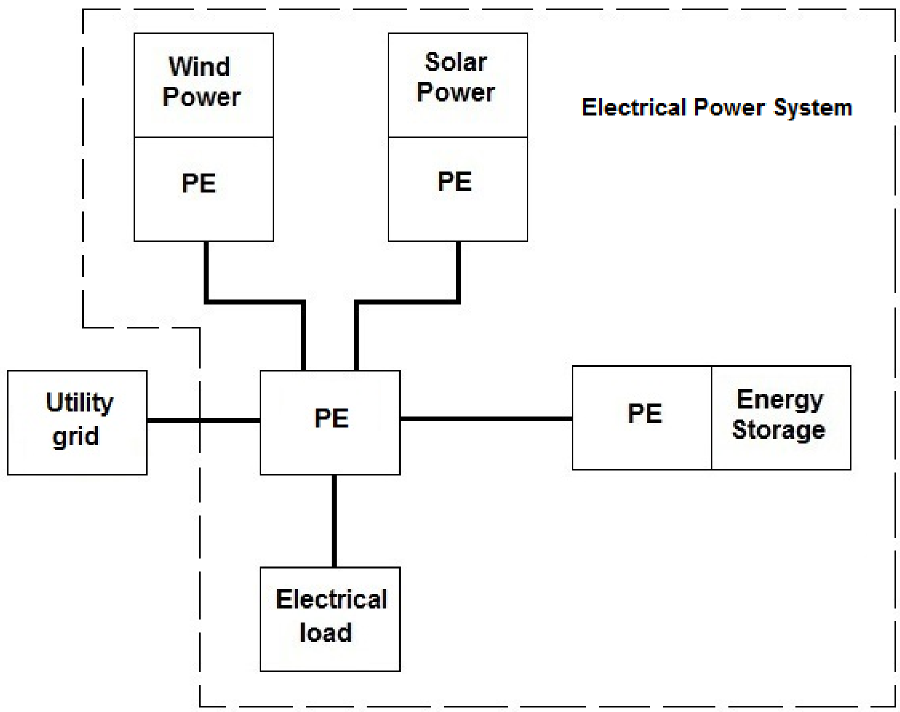


Fig. 1.1.  The main components in the combined power system.

Subsystems in the power system according to Fig. 1.1:

***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.
***Electrical load***: Active and reactive local electrical load.
***PE***: Power electronics for electrical adaptation.

# 2 SIMULATION SYSTEM

The simulation system is described in [1].

# 3 SIMULATION PARAMETERS

## 3.1 Solar power equipment

- Solar cell area: See section 3.11.
- Total efficiency for solar power production: 13.54 %
- Solar cell surface relative to zenith: 0 °
- Solar cell surface relative to south: -- °

## 3.2 Wind power equipment

- Number of wind turbines: 3 - 8
- Maximum power per turbine: 2000 kW
- Maximum rotation speed: 30 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%
- Air temperature: 15 ° C
- Air pressure: 1013 mbar
- Rotation speed control
- $\lambda_{ref}$ ($\lambda$-value that gives Cp – max): 9

### 3.3 Loaded power

An area with a mix of power consumers with the following annual power consumption (see [3):

- Industrial area, annual power consumption: 5 GWh
- Commercially center, annual power consumption: 5 GWh
- Residential area, annual power consumption: 10GWh

### 3.4 Energy storage

- Charging/discharging efficiency: 80%
- Maximum charge level: Varied between 0 - 0.5479 GWh
- Minimum charge level: 0 % of maximum charge level
- Initial charge level: Mean value between maximum charge level and minimum charge level
- Self-discharge: 0

### 3.5 Locations

Table 3.I. Locations and corresponding coordinates.

| Location | Latitude (degrees) | Longitude (degrees) |
| --- | --- | --- |
| Göteborg, Sweden | 57.7 | 12.0 |
| Kiruna, Sweden | 67.8 | 20.2 |
| München, Germany | 48.8 | 11.3 |
| Malaga, Spain | 36.7 | -4.4 |
| Nairobi, Kenya | -1.3 | 36.8 |

### 3.6 Wind speed

- Weibull parameters, A = 6.3, C = 1.9. The reason for this choice is treated in [4]. At a height over the ground of 80 m (wind turbine height over the ground) this results in:
  - Wind speed mean value: 6.35 m/s
  - Wind speed standard deviation: 1.14 m/s

### 3.7 Time resolution

- 600 sec

### 3.8 Simulation cycles per simulation process

- 200

### 3.9 Corresponding simulation time

- 365 days

### 3.10 Cloudiness

The cloudiness for different locations has been estimated according to:

$$\text{Cloudiness(location)} = 100 - \frac{365}{12} \times \frac{\text{Sun hours(location)}}{\text{Sun hours over horizon (location}} \times 100 \qquad (3.1)$$

where:

- Cloudiness(location): Estimates annual cloudiness (%) for the location
- Sun hours(location): Sum of “Sunshine per day” (hours). See Table 3.II.
- Sun hours over horizon(location): See Table 3.III.

In Table 3.II is given a row named “Sum”. This row corresponds to the values for parameter “Sun hours(location)” according to (3.1).

Table 3.II. Average number of daily hours of sunshine.

| **Month** | **Göteborg**<br><br>**Sunshine per day (hours)** | **Kiruna**<br><br>**Sunshine per day (hours)** | **München**<br><br>**Sunshine per day (hours)** | **Malaga**<br><br>**Sunshine per day (hours)** | **Nairobi**<br><br>**Sunshine per day (hours)** |
|---|---|---|---|---|---|
| January | 1 | 0 | 2 | 5 | 9 |
| February | 2 | 1 | 3 | 6 | 9 |
| Mars | 3 | 3 | 4 | 7 | 8 |
| April | 5 | 5 | 5 | 7 | 7 |
| May | 7 | 8 | 6 | 9 | 6 |
| June | 8 | 9 | 7 | 11 | 5 |
| July | 8 | 8 | 8 | 11 | 4 |
| August | 7 | 5 | 7 | 11 | 4 |
| September | 5 | 4 | 6 | 8 | 6 |
| October | 3 | 2 | 4 | 7 | 7 |
| November | 2 | 1 | 2 | 6 | 7 |
| December | 1 | 0 | 2 | 5 | 8 |
| **Sum** | **52** | **46** | **56** | **93** | **80** |

Table 3.III gives the values for parameter “Sun hours over horizon(location)” according to (3.1).

Table 3.III. Total annual number of hours, when sun is over horizon.

| **Location** | **Sun hours over horizon (location)** |
|---|---|
| Göteborg | 4381 |
| Kiruna | 4062 |
| München | 4394 |
| Malaga | 4369 |
| Nairobi | 4377 |

Table 3.IV gives the estimated cloudiness values as results of (3.1).

Table 3.IV. Estimated cloudiness as results of (3.1).

| **Location** | **Cloudiness (%)** |
|---|---|
| Göteborg | 64 |
| Kiruna | 66 |
| München | 61 |
| Malaga | 35 |
| Nairobi | 44 |

### 3.11 Solar cell area

As a measure of solar cell area is used the term “Area Unit”. This is defined according to:

1 area unit corresponds to the effective solar cell area, that in Göteborg, Sweden, with a cloudiness of 64 % (see Table 3.IV) and solar power equipment according

to section 3.1, produces an annual energy of 20 GWh. This corresponds to an area of $34.9 \times 10^4$ $m^2$. Or a a square surface of 591 m × 591 m.

## 4 NUMBER OF WIND TURBINES. ECONOMIC ANALYSIS

An economic analysis is done according to the following:

- No solar power
- No energy storage
- Number of wind turbines is evaluated with respect to economic optimization

The following expression is valid:

$$K_{tot} = N \times K_{wind} - E_{year} \times K_{Imp} + Imp \times K_{Imp} - Exp \times K_{Exp} \quad (4.1)$$

where:

$K_{tot}$: Total annual cost for the wind power farm
N: Number of wind turbines
$K_{wind}$: Total annual cost per wind turbine
$E_{year}$: Annual consumed energy = 20 GWh
$K_{Imp}$: Price per energy unit for imported energy
$K_{Exp}$: Price per energy unit for exported energy
Imp: Annual imported energy
Exp: Annual exported energy

For calculation of $K_{wind}$, information given in [8] has been used. In the related document the following is mentioned:

- Reference turbine cost: 9 MSEK / MW
- Infrastructure cost: 3 MSEK / MW
- Operation and Maintenance: 0.15 SEK / kWh

To calculate $K_{wind}$ the following has been assumed:

Investment cost (turbine cost + infrastructure cost): 24 MSEK (2 × Reference turbine cost + 2 × Infrastructure cost)
Turbine live time: 20 year
Operation and Maintenance: 0.6 MSEK / year (0.15 SEK/kWh)

This gives:

$$K_{wind} = \frac{24\ \text{MSEK}}{20\ \text{year}} + 0.6\ \text{MSEK / year} \tag{4.2}$$

This results in $\underline{K_{wind} = 1.8\ \text{MSEK / year}}$
The parameter $K_{Imp}$ has been assigned the values 0.40, 0,45 and 0.50 MSEK / GWh. The parameter $K_{Exp}$ has been assigned $K_{Exp} = K_{imp}$.

Table 4.I lists simulation results regarding produced annual energy and exported/imported annual energy for different number of wind turbines.

Table 4.I. Exported and imported energy. Solar = 0. No energy storage.

| **Wind (turbines)** | **Wind (GWh)** | **Export (GWh)** | **Import (GWh)** |
|---|---|---|---|
| 3 | 11.49 | 3.624 | 11.61 |
| 4 | 15.29 | 6.297 | 10.61 |
| 5 | 19.30 | 9.333 | 9.741 |
| 6 | 23.21 | 12.64 | 9.216 |
| 7 | 27.16 | 15.89 | 8.603 |
| 8 | 31.24 | 19.58 | 8.264 |

Fig. 4.1 – Fig. 4.2 illustrate exported resp. imported energy vs wind turbines. A polynomial adaptation is done. This is illustrated by red curves.

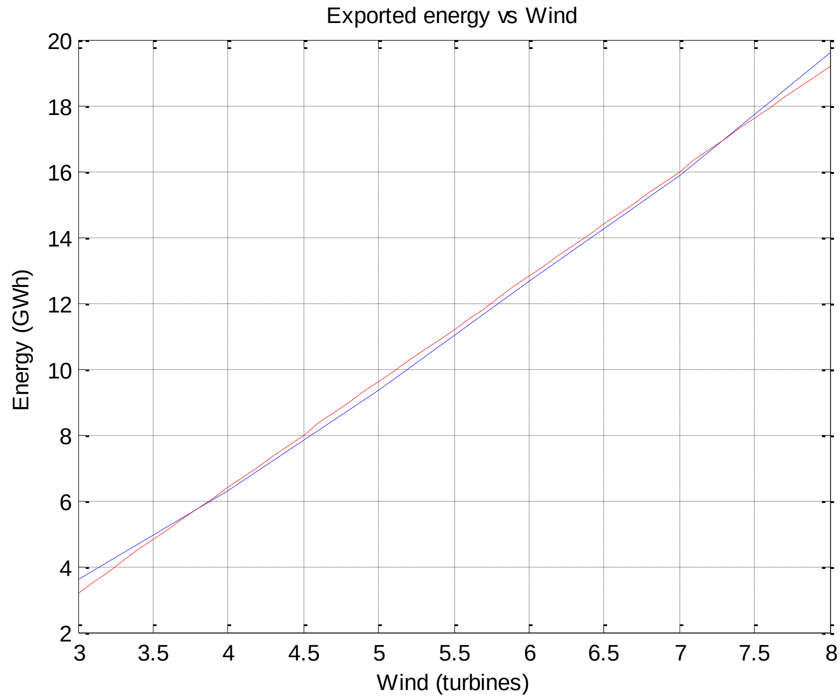


Fig. 4.1. Exported energy vs Wind. No solar. No energy storage. Red kurve is a polynomial adaptation with the degree of 1. c0 = -6.4, c1 = 3.2.

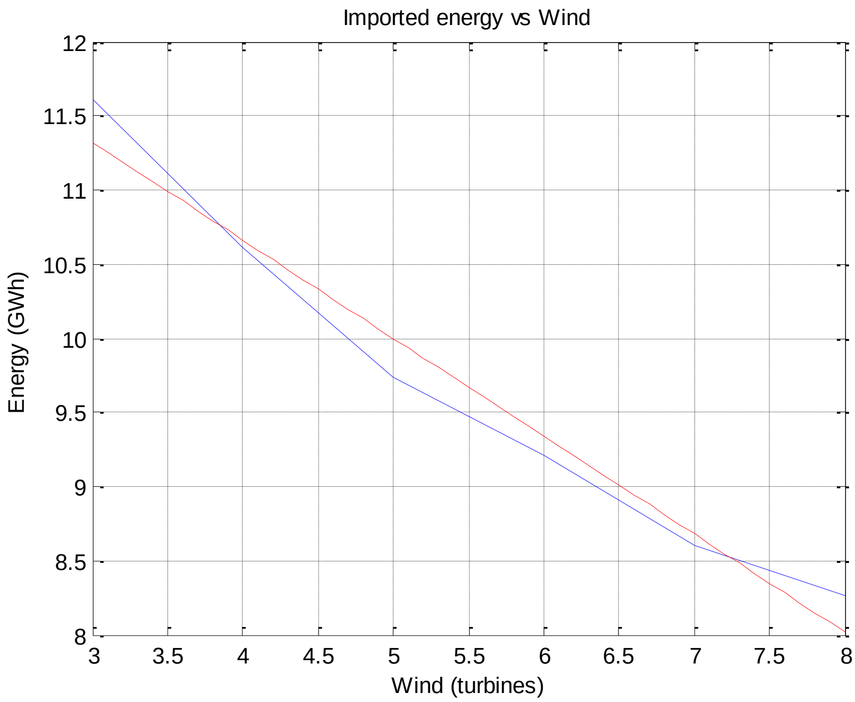


Fig. 4.2. Imported energy vs Wind. No solar. No energy storage. Red kurve is a polynomial adaptation with the degree of 1. c0 = 13.3, c1 = -0.66.

The result after adaptation of exported/imported energy and use of (4.1) and is illustrated in Fig. 4.3.

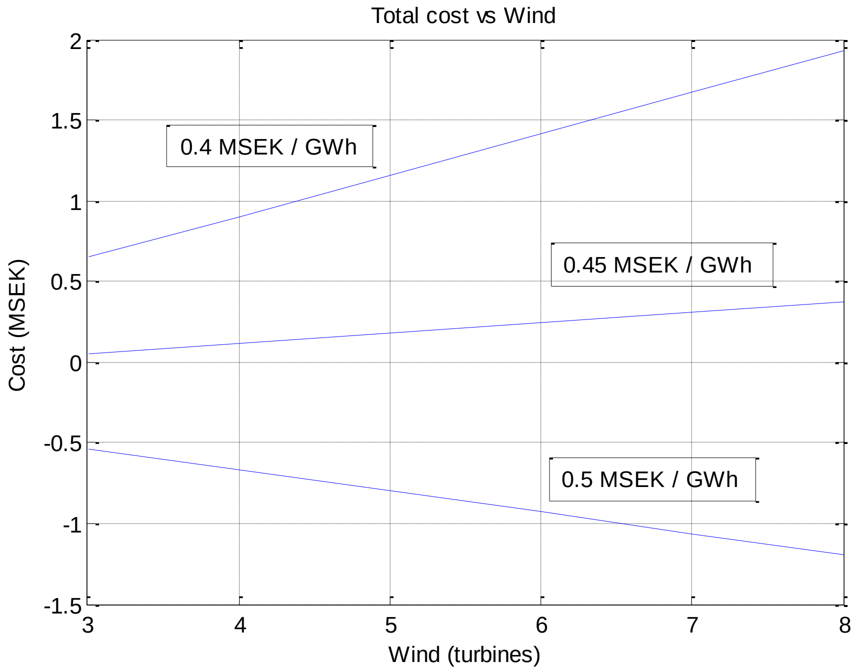


Fig. 4.3. Total cost vs Wind. 3 values of parameter $K_{imp}$. Parameter $K_{exp} = K_{imp}$.

## Conclusion of analysis

According to Fig. 4.3, parameter $K_{imp}$ must be at least 0.5 MSEK / GWh, or 0.5 SEK / kWh, for profitable investment of wind turbines. Otherwise the turbine cost has to be reduced (parameter $K_{wind}$).

If parameter $K_{imp}$ = 0.5 SEK / kWh, the annual profit will be about 0.9 MSEK for 6 installed wind turbines, or about 18 MSEK over 20 years. This corresponds to a return of:

$$\text{Return} = 100 \times \frac{0.9}{6 \times \text{Kwind}} \ \% \qquad (4.3)$$

$K_{wind}$ = 1.8 MSEK / year gives:

Return = 8.3 %

# 5 WIND TURBINES AND ENERGY STORAGE. ECONOMIC ANALYSIS.

An economic analysis is done according to the following:

- No solar power
- 6 wind turbines
- Capacity of energy storage is evaluated with respect to economical optimation

The following expression is valid:

$$K_{tot} = N \times K_{wind} + Storage \times K_{storage} - E_{year} \times K_{Imp} + + Imp \times K_{Imp} - Exp \times K_{Exp} \quad (5.1)$$

where:

| | |
|---|---|
| $K_{tot}$: | Total annual cost for the wind power farm |
| N: | Number of wind turbines = 6 |
| $K_{wind}$: | Total annual cost per wind turbine = 1.8 MSEK / turbine (see section 4) |
| Storage: | Storage capacity (units). See (5.2) - (5.3). |
| $K_{storage}$: | Total annual cost per storage unit |
| $E_{year}$: | Annual consumed energy = 20 GWh |
| $K_{imp}$: | Price per energy unit for imported energy = 0.5 MSEK / GWh (see section 4) |
| $K_{Exp}$: | Price per energy unit for exported energy = 0.5 MSEK / GWh (see section 4) |
| Imp: | Annual imported energy |
| Exp: | Annual exported energy |

The storage capacity in GWh resp in unit is defined according to (5.2) and (5.3).

$$E_{day} = \frac{20 \text{ GWh}}{365} \quad (5.2)$$

where $E_{day}$ corresponds to the daiy mean energy consumption.

$$Storage\ (GWh) = E_{day} \times Storage\ (unit) \quad (5.3)$$

where:

Storage (GWh): Storage capacity in GWh

Storage (unit): Storage capacity in units

Table 5.I lists simulation results regarding exported / imported annual energy and the difference between exported and imported energy for different storage capacities.

Table 5.I. Exported and imported energy. Solar = 0.

| **Storage (units)** | **Storage (GWh)** | **Export (GWh)** | **Import (GWh)** | **Difference Export – Import (GWh)** |
|---|---|---|---|---|
| 0 | 0 | 12.64 | 9.216 | 3.4240 |
| 0.1 | 0.0055 | 11.98 | 9.021 | 2.9590 |
| 0.5 | 0.0274 | 11.51 | 8.866 | 2.6440 |
| 1 | 0.0548 | 11.67 | 8.190 | 3.4800 |
| 3 | 0.1644 | 10.06 | 7.031 | 3.0290 |
| 5 | 0.2740 | 9.010 | 5.832 | 3.1780 |
| 7 | 0.3836 | 8.181 | 5.111 | 3.0700 |
| 10 | 0.5479 | 6.958 | 4.338 | 2.6200 |

Fig. 5.1 – Fig. 5.2 illustrate exported / imported annual energy. A polynomial adaptation with the degree of 1 is done. This is shown by red curves.

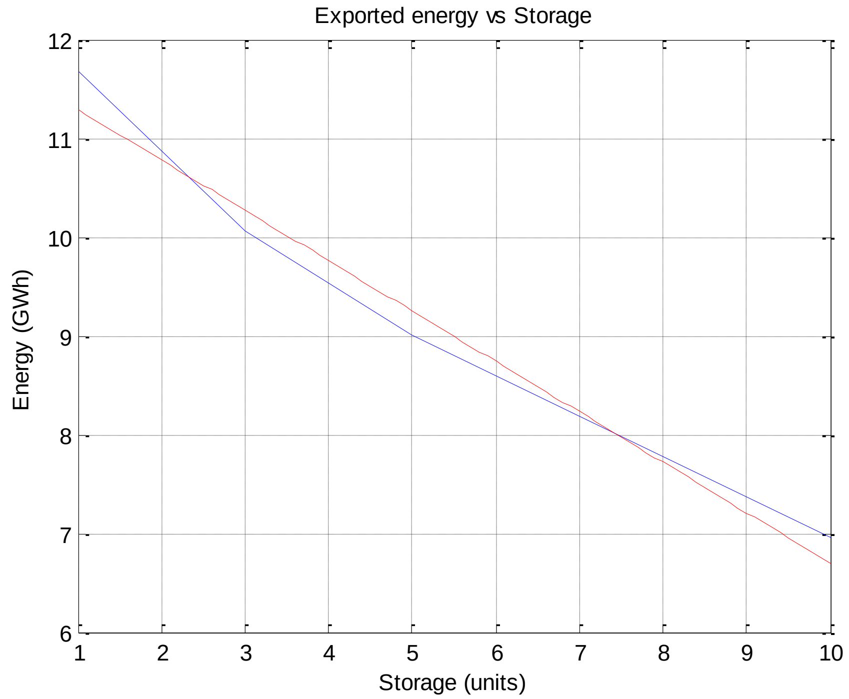


Fig. 5.1. Exported energy vs Storage. 6 turbines. No solar. Red kurve is a polynomial adaptation with the degree of 1. c0 = 11.8, c1 = -0.51.

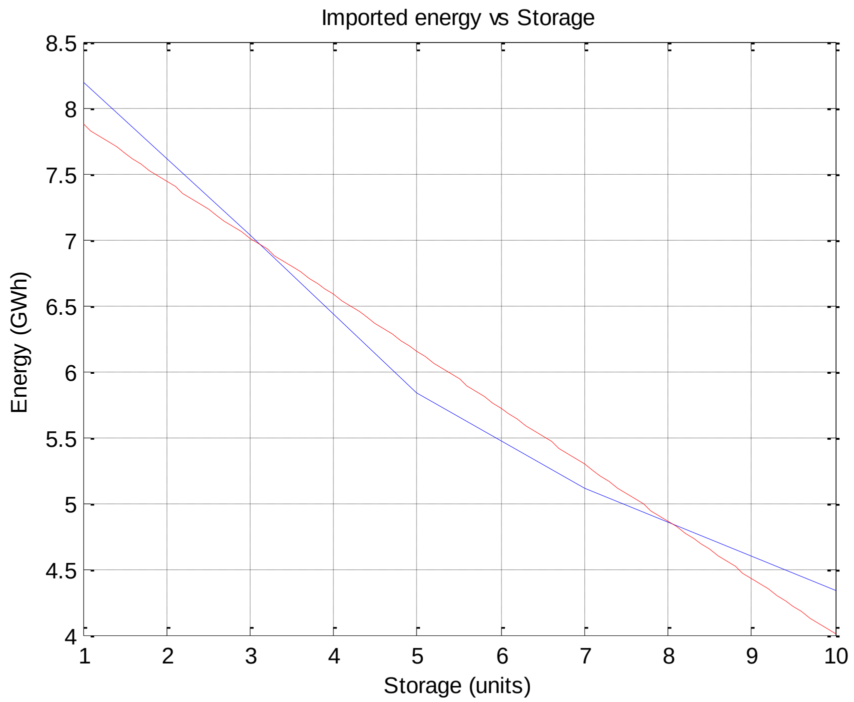


Fig. 5.2. Imported energy vs Storage. 6 turbines. No solar. Red kurve is a polynomial adaptation with the degree of 1. c0 = 8.3, c1 = -0.43.

Fig. 5.3 – Fig. 5.4 illustrate the difference between exported and imported annual energy vs storage capacity.

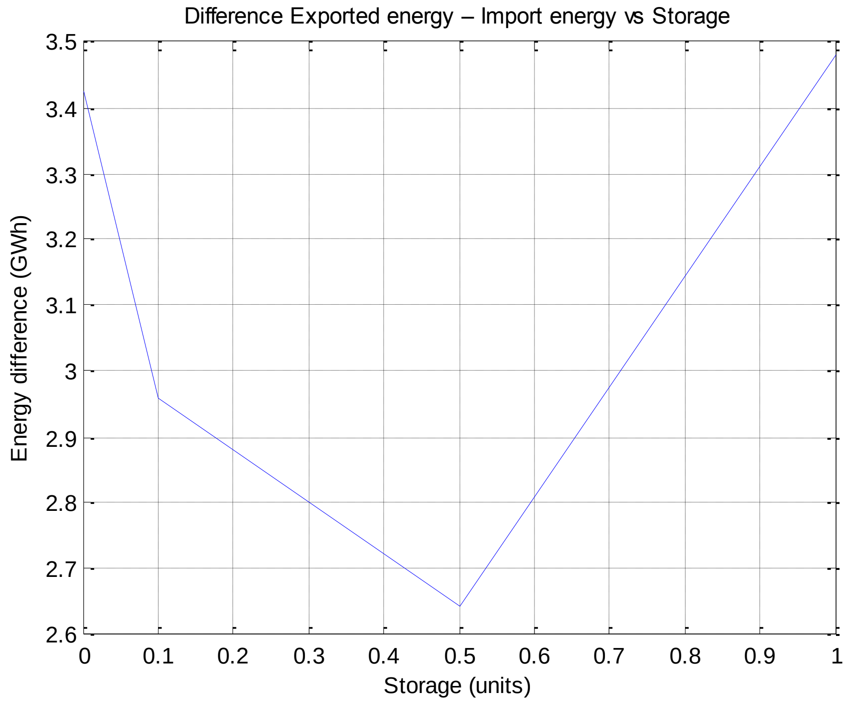


Fig. 5.3. Difference Exported energy – Import energy vs Storage. 6 turbines. No solar.

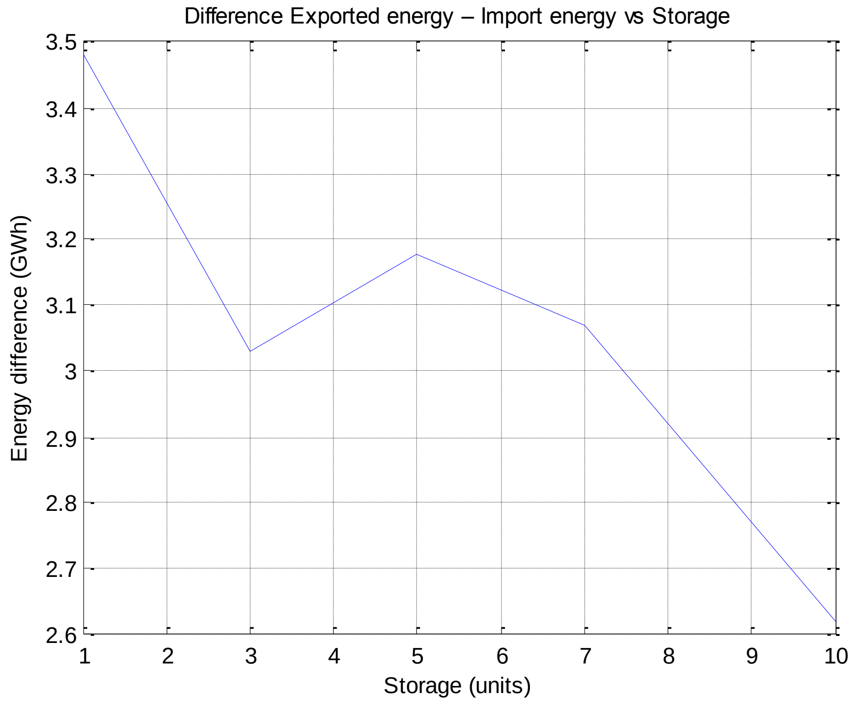


Fig. 5.4. Difference Exported energy – Import energy vs Storage. 6 turbines. No solar.

Conclusion of analysis

As can be observed in Fig. 5.3 and Fig. 5.4 there is no increase of the difference between exported and imported annual energy when an energy storage is used. A marginal increase is found for a storage capacity of 1 unit. But this can be neglected. There is no economical reason to involve an energy storage in the system, based on present energy producers (6 wind turbines with total annual production of about 23 GWh) and present energy consumers (annual consumption of 20 GWh). Since the simulation result is very clear, this conclusion can be regarded as applicable for a general power plant, where wind is the power source. This presumes access of a utility grid for power balance.

# 6 ECONOMIC ANALYSIS. 5 LOCATIONS. ENERGY COST 0.5 SEK

## 6.1 Introduction

An economic analysis is done with different parameter combinations according to Table 6.I

Table 6.I. Different parameters used for economic analysis.

| Location | Number of wind turbines | Energy storage (units) | Solar cell area (units) |
|---|---|---|---|
| Göteborg, Kiruna, München, Malaga and Nairobi | 6 turbines with total annual power production of about 23 GWh | 0 | 0, 0.0625, 0.125, 0.25, 0.5 and 1 units |

### *6.1.1 Annual solar farm cost*

In the following analysis a parameter, named "$K_{SOLAR}$", is essential. This parameter defines the total annual solar farm cost, including investment cost and operating cost for a specific solar cell area. The parameter has been estimated by using information in [9].

According to [9] the following costs were valid for solar energy 2014:

- South Germany: About 8.4 $ct_{EUR}$ / kWh
- South Spain: About 5.4 $ct_{EUR}$ / kWh

These values correspond to parameter "$ct_{EUR}$_per_kWh" below.

As representatives of the areas “South Germany  resp. South Spain” have been chosen:

- South Germany → München
- South Spain → Malaga

Parameter $K_{SOLAR}$ has been calculated by the following expression:

$$K_{SOLAR} = ct_{EUR}\_per\_kWh \times ct_{EUR}\_to\_SEK \times Solar\_annual \times 10^{-6} \quad (6.1)$$

where:

| | |
|---|---|
| $K_{SOLAR}$: | Total annual cost (MSEK) when Solar cell area = 1 unit |
| $ct_{EUR}$_per_kWh: | Solar power cost ($ct_{EUR}$/kWh). This is 8.4 in South Germany and 5.4 in South Spain |
| $ct_{EUR}$_to_SEK: | Conversion factor from $ct_{EUR}$ to SEK. This is assigned to the value 0.1 |
| Solar_annual: | Annual solar energy production (kWh) |

Simulations with a solar cell area = 1 unit result in annual solar energy and corresponding values of parameter $K_{SOLAR}$ according to Table 6.II.

Table 6.II. Parameters in (6.1) and corresponding resulting $K_{solar}$

| Location | $ct_{EUR}$_per_kWh ($ct_{EUR}$) | $ct_{EUR}$_to_SEK | Solar_annual (kWh) | $K_{SOLAR}$ (MSEK) |
|---|---|---|---|---|
| München | 8.4 | 0.1 | $27.26 \times 10^6$ | 22.9 |
| Malaga | 5.4 | 0.1 | $50.42 \times 10^6$ | 27.2 |
| | | | $K_{SOLAR, MEAN}$ | 25.0 |

The value “$K_{SOLAR,MEAN}$” = 25, according to Table 6.II is in the following applied for all geographic locations in question as a “reference value” for parameter $K_{SOLAR}$.

An estimation of parameter KSOLAR, based on information according to [9], is presented in Table 6.III. The estimation is based on the assumption that the cost, relative cost 2015, will be reduced about 25% to 2025, and about 50% to 2050.

Table 6.III. Estimated value of $K_{SOLAR}$.

| Year | Value of parameter $K_{SOLAR}$ |
|---|---|
| 2015 | 25 |
| 2025 | 19 |
| 2050 | 12 |

*6.1.2 Economic analysis*

The vectors according to Table 6.IV are defined. Vectors have dimension 6.

Table 6.IV. Vector definition.

| Vector | Function | Specification |
|---|---|---|
| Solar-cell-area | Solar cell area in units | - |
| Exported-energy | Exported energy in GWh | - |
| Imported-energy | Imported energy in GWh | - |
| Excess-energy-A | Excess energy in GWh | See (6.2) |
| Excess-energy-B | Excess energy in GWh | See (6.3) |
| Gross-profit | Gross profit in MSEK | See (6.4) |
| Operating-cost | Investment cost and operating cost for a specific solar cell area (units) in MSEK | See (6.5) |
| Net-profit | Net profit in MSEK | See (6.6) |
| Percentage-profit | Profit in percentage | See (6.7) |

(6.2) - (6.7) give additional specification about the defined vectors. Index "n" is valid in the region between 1 – 6.

Excess energy A(n) = Exported energy (n) - Imported energy(n) (6.2)

Excess energy B(n) = Excess energy A (n) - Excess energy A (1) (6.3)

With reference to (6.3):

Since "Excess energy A(1)" is a result of only wind power production, then "Excess energy B", is the same as the increase of annual excess energy as a result of solar power complement. Thus, this parameter can be used as a measure of the economic effect of the solar power.

Gross profit(n) = Energy cost × Excess energy B(n) (6.4)

Where:

Energy cost: Energy rate for export/import of energy (MSEK/GWh)

Operating cost(n) = $K_{SOLAR}$ × Solar cell area(n) (6.5)

Net profit(n) = Gross profit(n) – Operating cost(n) (6.6)

$$\text{Percentage profit(n)} = \frac{\text{Net profit(n)}}{\text{Operating cost(n)}} \times 100 \qquad (6.7)$$

Vector Solar-cell-area is defined according to Table 6.V.

Table 6.V. Vector Solar-cell-area.

| Position | Value (units) |
|---|---|
| 1 | 0 |
| 2 | 0.0625 |
| 3 | 0.125 |
| 4 | 0.25 |
| 5 | 0.5 |
| 6 | 1 |

(6.5), $K_{SOLAR}$ according to Table 6.III and solar cell areas according to Table 6.V give values for operating cost according to Table 6.VI.

Table 6.VI. Vector Operating-cost. Year 2015, 2025 and 2050.

| **Position** | **Value (MSEK))** | | |
|---|---|---|---|
| | **$K_{SOLAR}$ = 25 (2015)** | **$K_{SOLAR}$ = 19 (2025)** | **$K_{SOLAR}$ = 12 (2050)** |
| 1 | 0 | 0 | 0 |
| 2 | 1.5625 | 1.1875 | 0.7500 |
| 3 | 3.1250 | 2.3750 | 1.5000 |
| 4 | 6.2500 | 4.7500 | 3.0000 |
| 5 | 12.5000 | 9.5000 | 6.0000 |
| 6 | 25.0000 | 19.0000 | 12.0000 |

## 6.2 Power plant at Göteborg

The results of simulations follow according to Table 6.VII.

Table 6.VII. Simulation result Göteborg.

| Solar cell area (Unit) | Solar energy (GWh) | Exported energy (GWh) | Imported energy (GWh) | Excess energy A (GWh) | Excess energy B (GWh) |
|---|---|---|---|---|---|
| 0 | 0 | 12.64 | 9.216 | 3.4240 | 0 |
| 0.0625 | 1.253 | 13.31 | 9.228 | 4.0820 | 0.6580 |
| 0.125 | 2.506 | 14.25 | 8.668 | 5.5820 | 2.1580 |
| 0.25 | 5.017 | 16.43 | 8.227 | 8.2030 | 4.7790 |
| 0.5 | 10.02 | 21.27 | 7.904 | 13.3660 | 9.9420 |
| 1 | 19.98 | 30.59 | 7.580 | 23.0100 | 19.5860 |

The result of economic analysis follows according to Table 6.VIII.

Table 6.VIII. Economic analysis Göteborg. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -1.2335 | -78.9440 | -0.8585 | -72.2947 | -0.4210 | -56.1333 |
| 0.125 | -2.0460 | -65.4720 | -1.2960 | -54.5684 | -0.4210 | -28.0667 |
| 0.25 | -3.8605 | -61.7680 | -2.3605 | -49.6947 | -0.6105 | -20.3500 |
| 0.5 | -7.5290 | -60.2320 | -4.5290 | -47.6737 | -1.0290 | -17.1500 |
| 1 | -15.2070 | -60.8280 | -9.2070 | -48.4579 | -2.2070 | -18.3917 |

Annual profit and percentage profit are plotted according to Fig. 6.1 and Fig. 6.2.

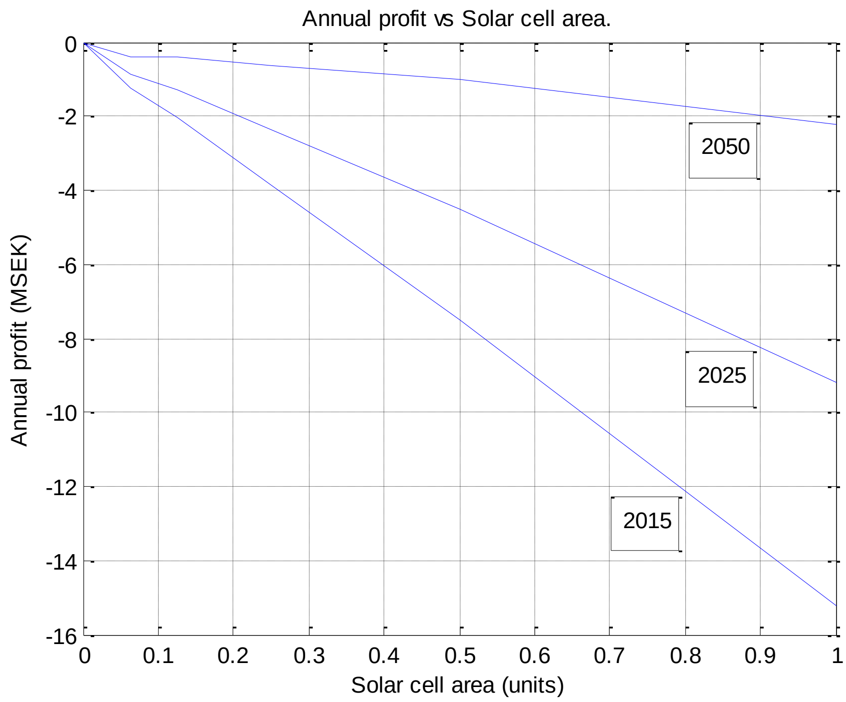


Fig. 6.1. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

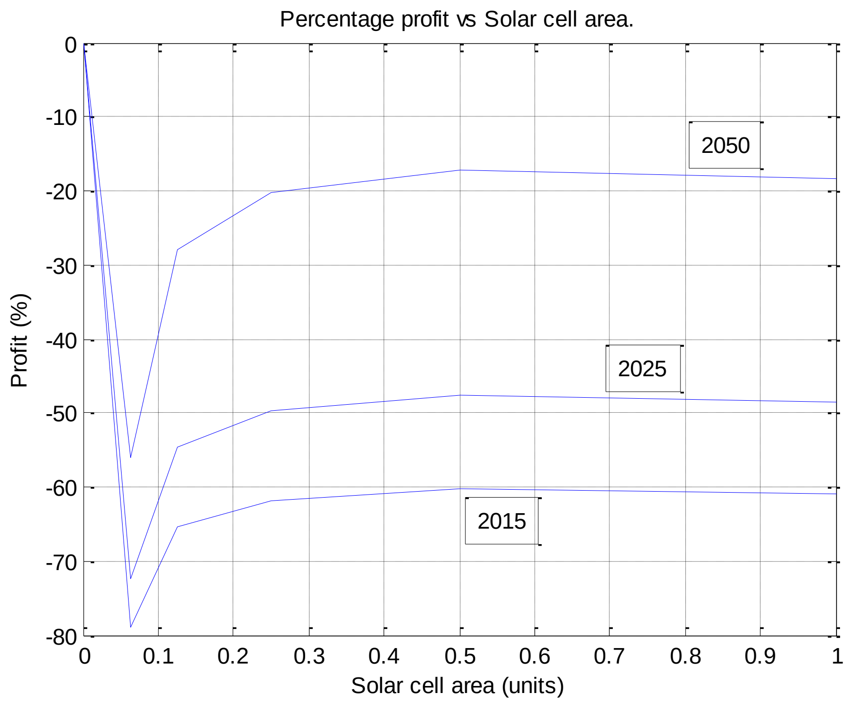


Fig. 6.2. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

## 6.3 Power plant at Kiruna

The results of simulations follow according to Table 6.IX.

Table 6.IX. Simulation result Kiruna.

| Solar cell area (Unit) | Solar energy (GWh) | Exported energy (GWh) | Imported energy (GWh) | Excess energy A (GWh) | Excess energy B (GWh) |
|---|---|---|---|---|---|
| 0 | 0 | 12.64 | 9.216 | 3.4240 | 0 |
| 0.0625 | 0.8571 | 13.27 | 9.381 | 3.8890 | 0.4650 |
| 0.125 | 1.704 | 13.61 | 9.159 | 4.4510 | 1.0270 |
| 0.25 | 3.412 | 14.90 | 8.727 | 6.1730 | 2.7490 |
| 0.5 | 6.867 | 18.21 | 8.300 | 9.9100 | 6.4860 |
| 1 | 13.63 | 24.61 | 8.070 | 16.5400 | 13.1160 |

The result of economic analysis follows according to Table 6.X.

Table 6.X. Economic analysis Kiruna. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -1.3300 | -85.1200 | -0.9550 | -80.4211 | -0.5175 | -69.0000 |
| 0.125 | -2.6115 | -83.5680 | -1.8615 | -78.3789 | -0.9865 | -65.7667 |
| 0.25 | -4.8755 | -78.0080 | -3.3755 | -71.0632 | -1.6255 | -54.1833 |
| 0.5 | -9.2570 | -74.0560 | -6.2570 | -65.8632 | -2.7570 | -45.9500 |
| 1 | -18.4420 | -73.7680 | -12.4420 | -65.4842 | -5.4420 | -45.3500 |

Annual profit and percentage profit are plotted according to Fig. 6.3 and Fig. 6.4.

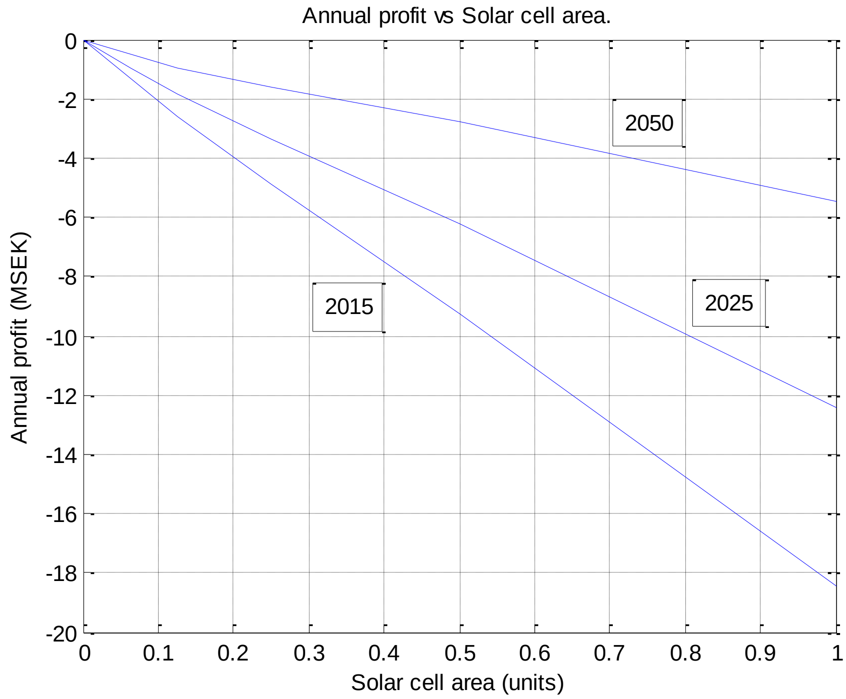


Fig. 6.3. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

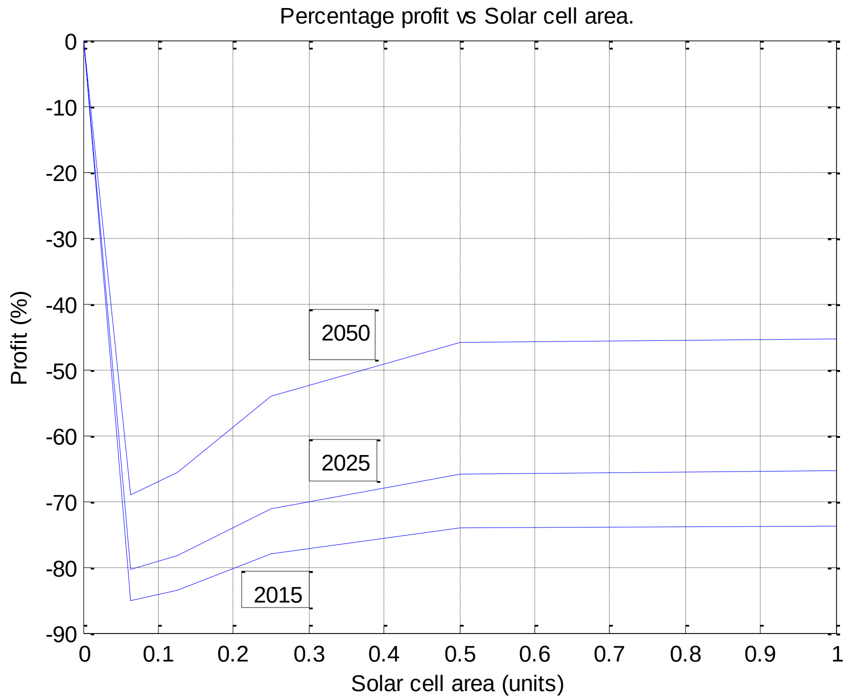


Fig. 6.4. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

## 6.4 Power plant at München

The results of simulations follow according to Table 6.XI.

Table 6.XI. Simulation result München.

| Solar cell area (Unit) | Solar energy (GWh) | Exported energy (GWh) | Imported energy (GWh) | Excess energy A (GWh) | Excess energy B (GWh) |
|---|---|---|---|---|---|
| 0 | 0 | 12.64 | 9.216 | 3.4240 | 0 |
| 0.0625 | 1.715 | 13.58 | 8.952 | 4.6280 | 1.2040 |
| 0.125 | 3.408 | 14.68 | 8.436 | 6.2440 | 2.8200 |
| 0.25 | 6.820 | 17.70 | 7.805 | 9.8950 | 6.4710 |
| 0.5 | 13.67 | 24.20 | 7.344 | 16.8560 | 13.4320 |
| 1 | 27.30 | 37.65 | 6.997 | 30.6530 | 27.2290 |

The result of economic analysis follows according to Table 6.XII.

Table 6.XII. Economic analysis München. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -0.9605 | -61.4720 | -0.5855 | -49.3053 | -0.1480 | -19.7333 |
| 0.125 | -1.7150 | -54.8800 | -0.9650 | -40.6316 | -0.0900 | -6.0000 |
| 0.25 | -3.0145 | -48.2320 | -1.5145 | -31.8842 | 0.2355 | 7.8500 |
| 0.5 | -5.7840 | -46.2720 | -2.7840 | -29.3053 | 0.7160 | 11.9333 |
| 1 | -11.3855 | -45.5420 | -5.3855 | -28.3447 | 1.6145 | 13.4542 |

Annual profit and percentage profit are plotted according to Fig. 6.5 and Fig. 6.6.

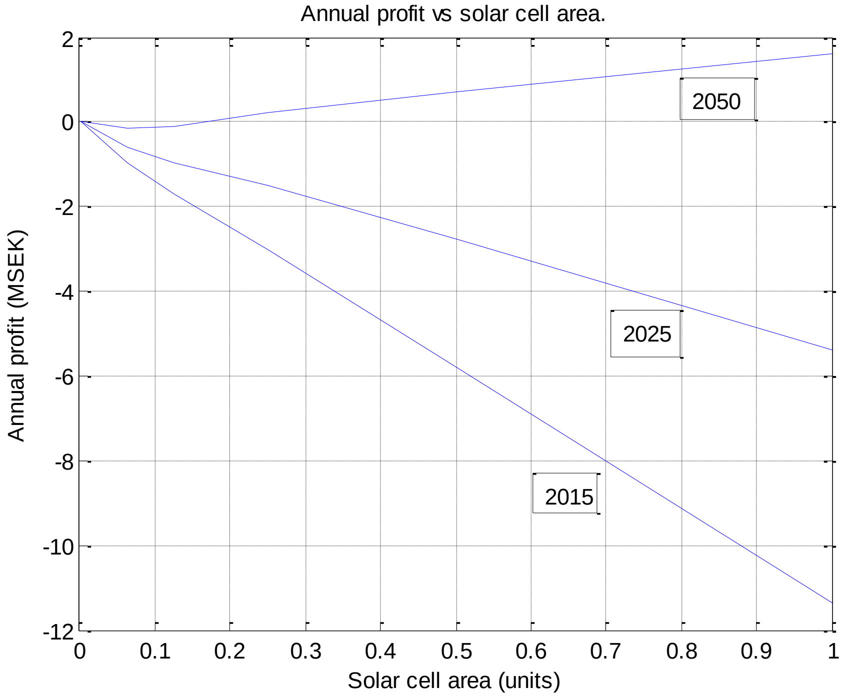


Fig. 6.5. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

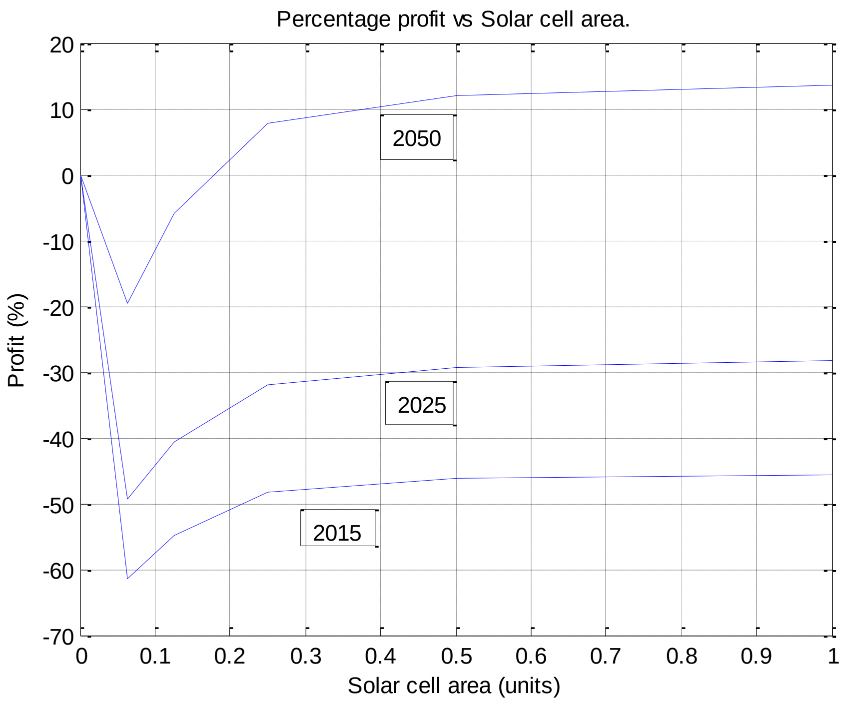


Fig. 6.6. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

### 6.5 Power plant at Malaga

The results of simulations follow according to Table 6.XIII.

Table 6.XIII. Simulation result. Malaga.

| Solar cell area (Unit) | Solar energy (GWh) | Exported energy (GWh) | Imported energy (GWh) | Excess energy A (GWh) | Excess energy B (GWh) |
|---|---|---|---|---|---|
| 0 | 0 | 12.64 | 9.216 | 3.4240 | 0 |
| 0.0625 | 3.150 | 14.27 | 8.206 | 6.0640 | 2.6400 |
| 0.125 | 6.304 | 16.59 | 7.454 | 9.1360 | 5.7120 |
| 0.25 | 12.60 | 22.45 | 6.782 | 15.6680 | 12.2440 |
| 0.5 | 25.20 | 34.52 | 6.409 | 28.1110 | 24.6870 |
| 1 | 50.43 | 59.36 | 6.103 | 53.2570 | 49.8330 |

The result of economic analysis follows according to Table 6.XIV.

Table 6.XIV. Economic analysis Malaga. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -0.2425 | -15.5200 | 0.1325 | 11.1579 | 0.5700 | 76.0000 |
| 0.125 | -0.2690 | -8.6080 | 0.4810 | 20.2526 | 1.3560 | 90.4000 |
| 0.25 | -0.1280 | -2.0480 | 1.3720 | 28.8842 | 3.1220 | 104.0667 |
| 0.5 | -0.1565 | -1.2520 | 2.8435 | 29.9316 | 6.3435 | 105.7250 |
| 1 | -0.0835 | -0.3340 | 5.9165 | 31.1395 | 12.9165 | 107.6375 |

Annual profit and percentage profit are plotted according to Fig. 6.7 and Fig. 6.8.

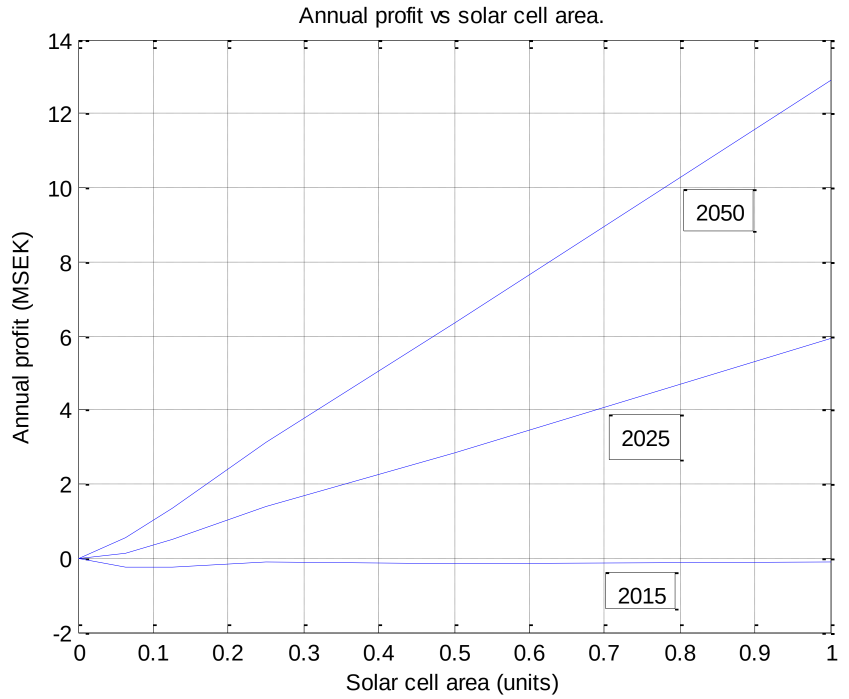


Fig. 6.7. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

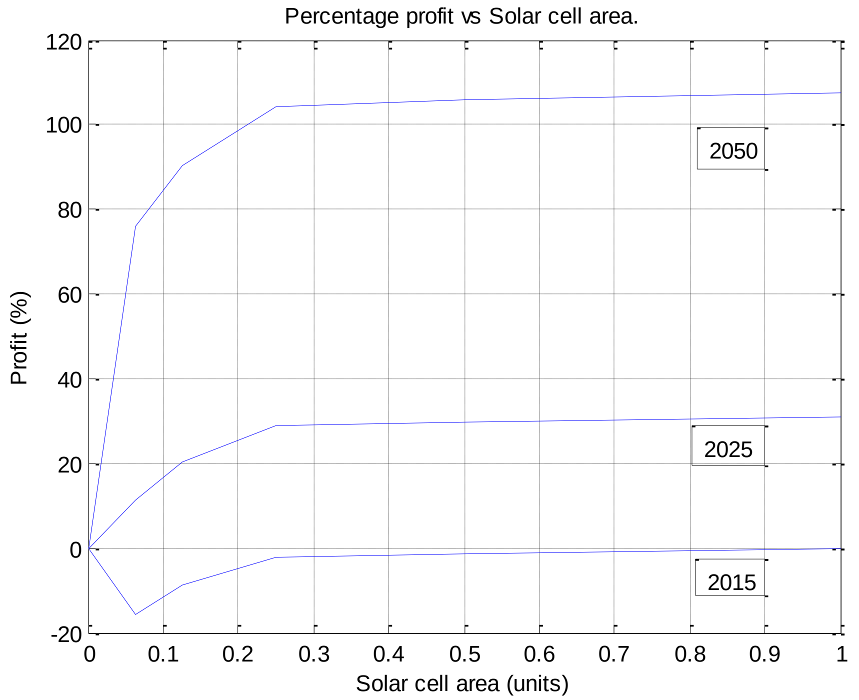


Fig. 6.8. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

### 6.6 Power plant at Nairobi

The results of simulations follow according to Table 6.XV.

Table 6.XV. Simulation result. Nairobi.

| Solar cell area (Unit) | Solar energy (GWh) | Exported energy (GWh) | Imported energy (GWh) | Excess energy A (GWh) | Excess energy B (GWh) |
|---|---|---|---|---|---|
| 0 | 0 | 12.64 | 9.216 | 3.4240 | 0 |
| 0.0625 | 3.894 | 14.58 | 7.778 | 6.8020 | 3.3780 |
| 0.125 | 7.785 | 17.76 | 7.141 | 10.6190 | 7.1950 |
| 0.25 | 15.57 | 25.32 | 6.670 | 18.6500 | 15.2260 |
| 0.5 | 31.20 | 40.72 | 6.338 | 34.3820 | 30.9580 |
| 1 | 62.28 | 71.77 | 6.140 | 65.6300 | 62.2060 |

The result of economic analysis follows according to Table 6.XVI.

Table 6.XVI. Economic analysis Nairobi. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | 0.1265 | 8.0960 | 0.5015 | 42.2316 | 0.9390 | 125.2000 |
| 0.125 | 0.4725 | 15.1200 | 1.2225 | 51.4737 | 2.0975 | 139.8333 |
| 0.25 | 1.3630 | 21.8080 | 2.8630 | 60.2737 | 4.6130 | 153.7667 |
| 0.5 | 2.9790 | 23.8320 | 5.9790 | 62.9368 | 9.4790 | 157.9833 |
| 1 | 6.1030 | 24.4120 | 12.1030 | 63.7000 | 19.1030 | 159.1917 |

Annual profit and percentage profit are plotted according to Fig. 6.9 and Fig. 6.10.

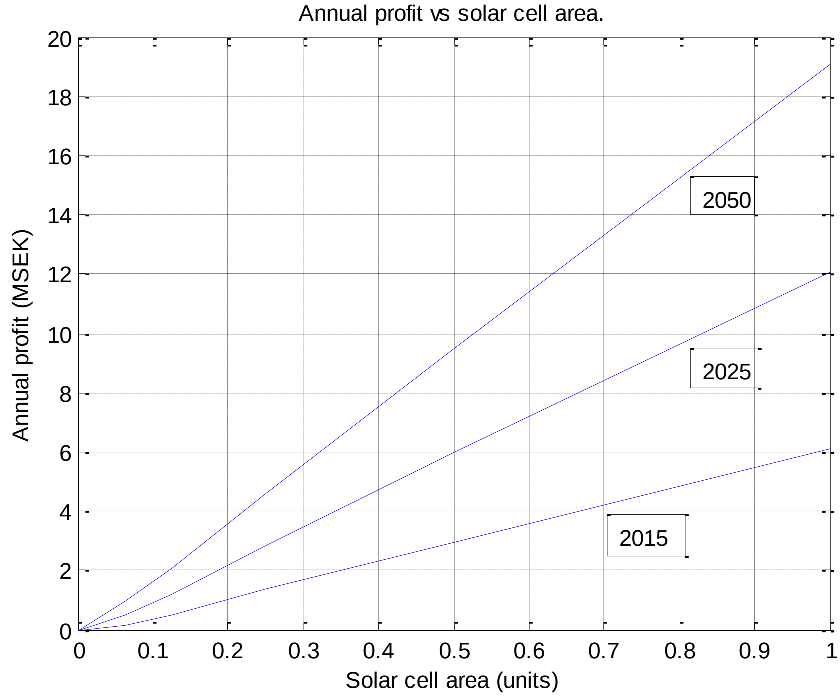


Fig. 6.9. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

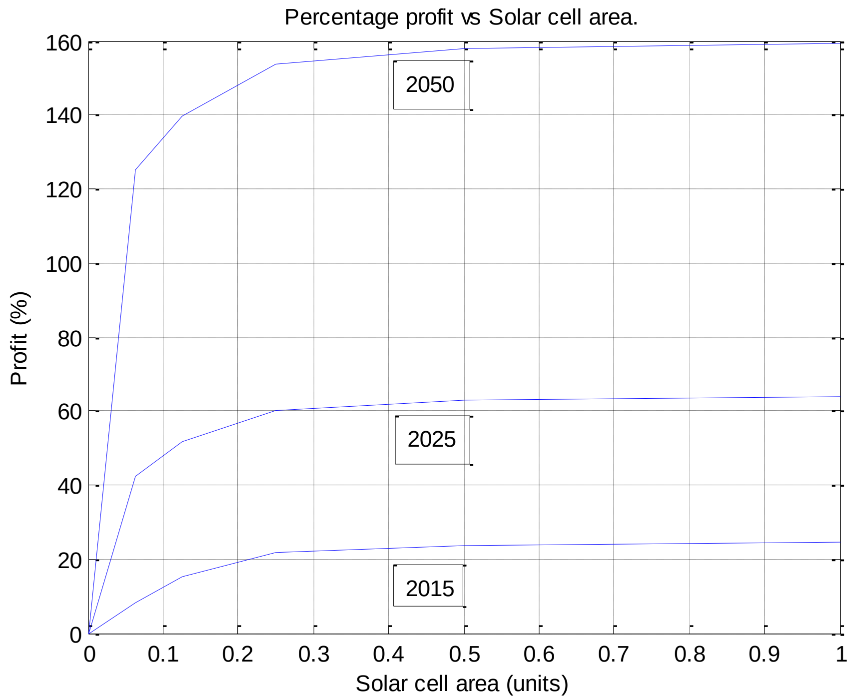


Fig. 6.10. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

## 6.7 Conclusion of analysis and an energy cost of 0.5 SEK per kWh

The analysis has been done with the adoption of an energy price of 0.5 SEK per kWh. The result is:

- Göteborg and Kiruna. The analysis results in an economic loss with solar energy supplementation in all cases. This applies during the total time interval year 2015 to year 2050.

- München. The analysis results in an economic loss with solar energy supplementation during the time interval 2015 to 2025. Year 2050, the predicted costs for solar energy systems have been reduced enough to give an economic profit with solar energy supplementation.

- Malaga. The analysis shows a potential financial loss with solar energy supplementation year 2015. This is just marginal, and based on prediction of costs for solar energy systems, it is a financial gain with solar production supplementation from year 2025. The analysis results in a percentage profit of about 30 % year 2025 and a percentage profit of over 100 % year 2050.

- Nairobi. The analysis shows a significant financial profit when a solar energy system is added in the power plant. For year 2015, the percentage profit is more than 20 %. For year 2025 more than 60 % and for year 2050 about 160 %.

# 7 ECONOMIC ANALYSIS. 5 LOCATIONS. ADAPTED ENERGY COST

According to chapter 6, and the current solar energy cost for the year 2015, it is only in Nairobi, as there is an economic benefit to supplement the wind power systems with solar energy systems. Malaga can be regarded as a limit case in this regard. A critical parameter in this regard is the current energy costs. This chapter deals with the situation where the energy costs have been adapted. The adjustment has been made according to the following principle:

“Choose for each location an individual energy cost, which for solar energy cost of year 2015, provides an economic benefit for supplementing of solar energy to existing wind energy”.

The individual energy costs have been chosen according to Table 7.I.

Table 7.I. Adapted energy costs. Göteborg, Kiruna, München and Malaga.

| **Location** | **Göteborg** | **Kiruna** | **München** | **Malaga** |
|---|---|---|---|---|
| **Energy cost (SEK) per kWh** | 1.3 | 2.0 | 1.0 | 0.6 |

Economic analyzes have been done with energy costs as in Table 7.I. The results are presented in section 7.1 - 7.4. The simulation results presented in chapter 6 have been used as inputs for the economic analyzes.

## 7.1 Power plant at Göteborg

The result of economic analysis follows according to Table 7.II.

Table 7.II. Economic analysis Göteborg. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -0.7071 | -45.2544 | -0.3321 | -27.9663 | 0.1054 | 14.0533 |
| 0.125 | -0.3196 | -10.2272 | 0.4304 | 18.1221 | 1.3054 | 87.0267 |
| 0.25 | -0.0373 | -0.5968 | 1.4627 | 30.7937 | 3.2127 | 107.0900 |
| 0.5 | 0.4246 | 3.3968 | 3.4246 | 36.0484 | 6.9246 | 115.4100 |
| 1 | 0.4618 | 1.8472 | 6.4618 | 34.0095 | 13.4618 | 112.1817 |

Annual profit and percentage profit are plotted according to Fig 7.1 and Fig 7.2.

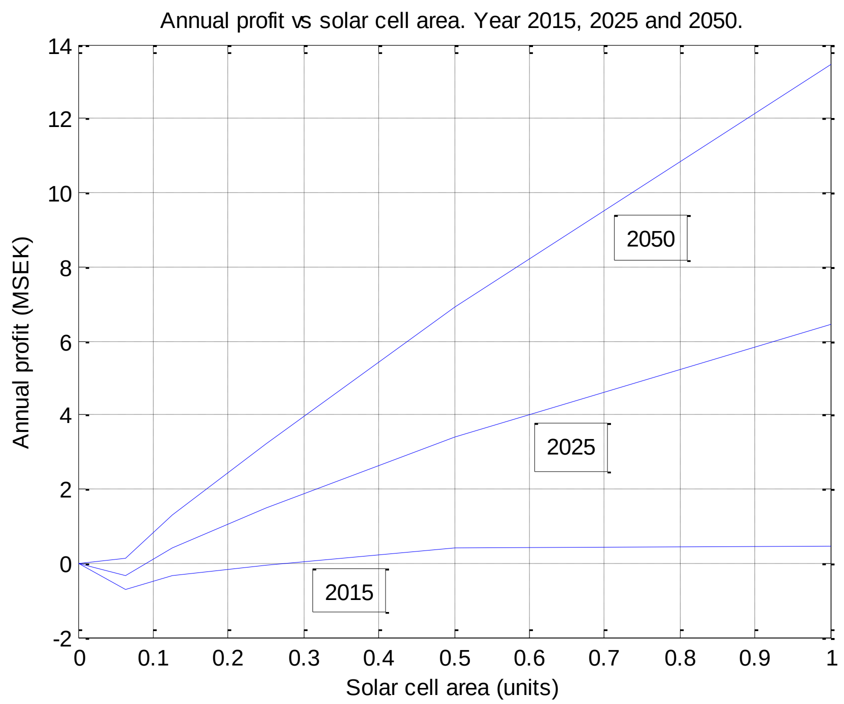


Fig. 7.1. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

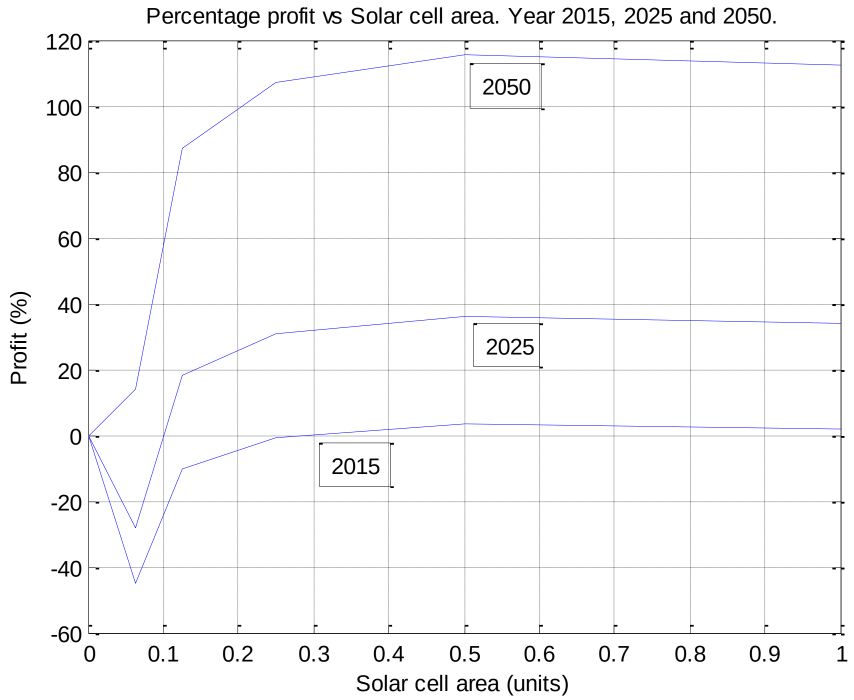


Fig. 7.2. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

## 7.2 Power plant at Kiruna

The result of economic analysis follows according to Table 7.III.

Table 7.III. Economic analysis Kiruna. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -0.6325 | -40.4800 | -0.2575 | -21.6842 | 0.1800 | 24.0000 |
| 0.125 | -1.0710 | -34.2720 | -0.3210 | -13.5158 | 0.5540 | 36.9333 |
| 0.25 | -0.7520 | -12.0320 | 0.7480 | 15.7474 | 2.4980 | 83.2667 |
| 0.5 | 0.4720 | 3.7760 | 3.4720 | 36.5474 | 6.9720 | 116.2000 |
| 1 | 1.2320 | 4.9280 | 7.2320 | 38.0632 | 14.2320 | 118.6000 |

Annual profit and percentage profit are plotted according to Fig 7.3 and Fig 7.4.

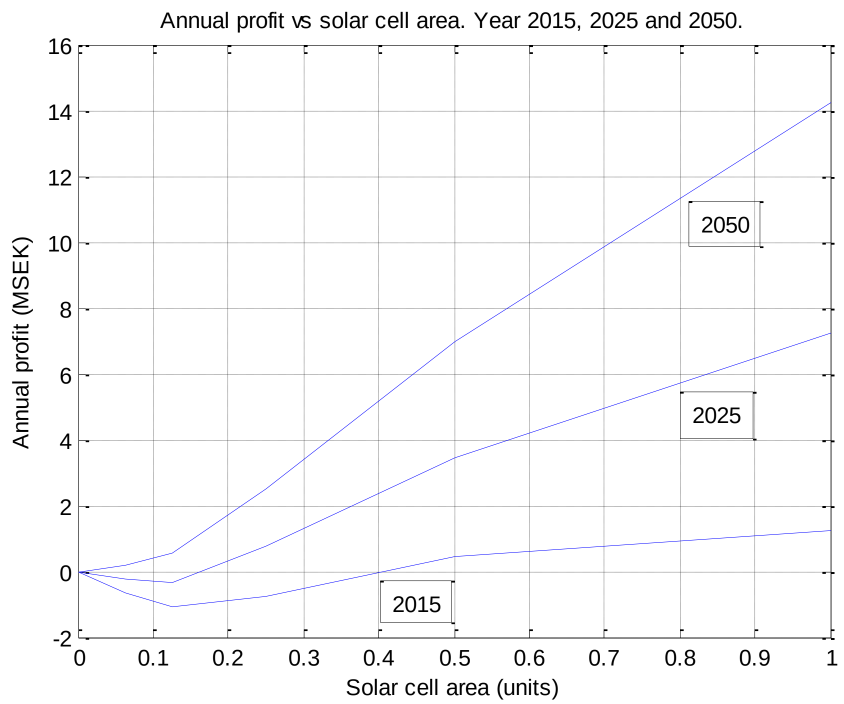


Fig. 7.3. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

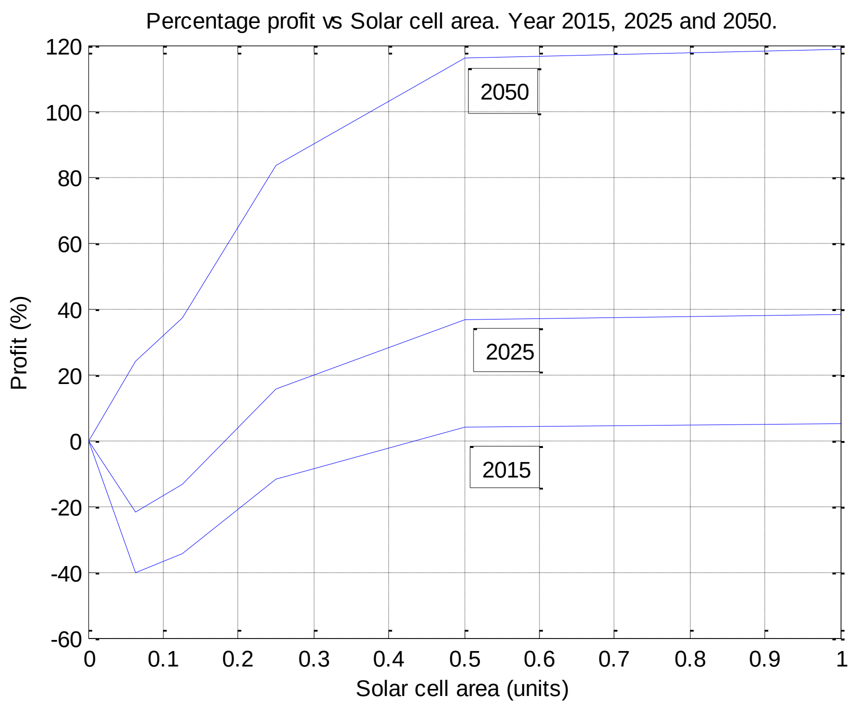


Fig. 7.4. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

## 7.3 Power plant at München

The result of economic analysis follows according to Table 7.IV.

Table 7.IV. Economic analysis München. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | -0.3585 | -22.9440 | 0.0165 | 1.3895 | 0.4540 | 60.5333 |
| 0.125 | -0.3050 | -9.7600 | 0.4450 | 18.7368 | 1.3200 | 88.0000 |
| 0.25 | 0.2210 | 3.5360 | 1.7210 | 36.2316 | 3.4710 | 115.7000 |
| 0.5 | 0.9320 | 7.4560 | 3.9320 | 41.3895 | 7.4320 | 123.8667 |
| 1 | 2.2290 | 8.9160 | 8.2290 | 43.3105 | 15.2290 | 126.9083 |

Annual profit and percentage profit are plotted according to Fig 7.5 and Fig 7.6.

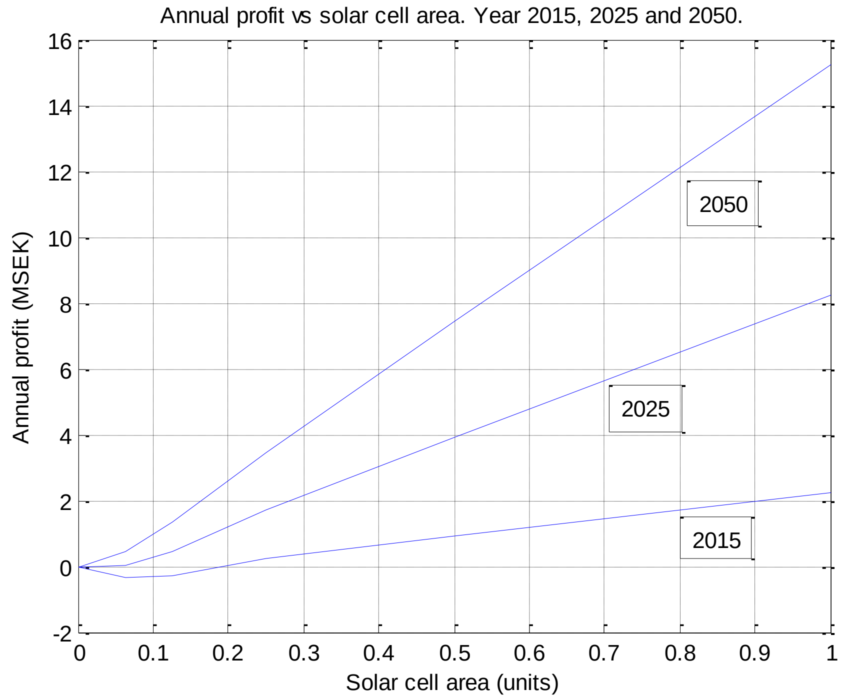


Fig. 7.5. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

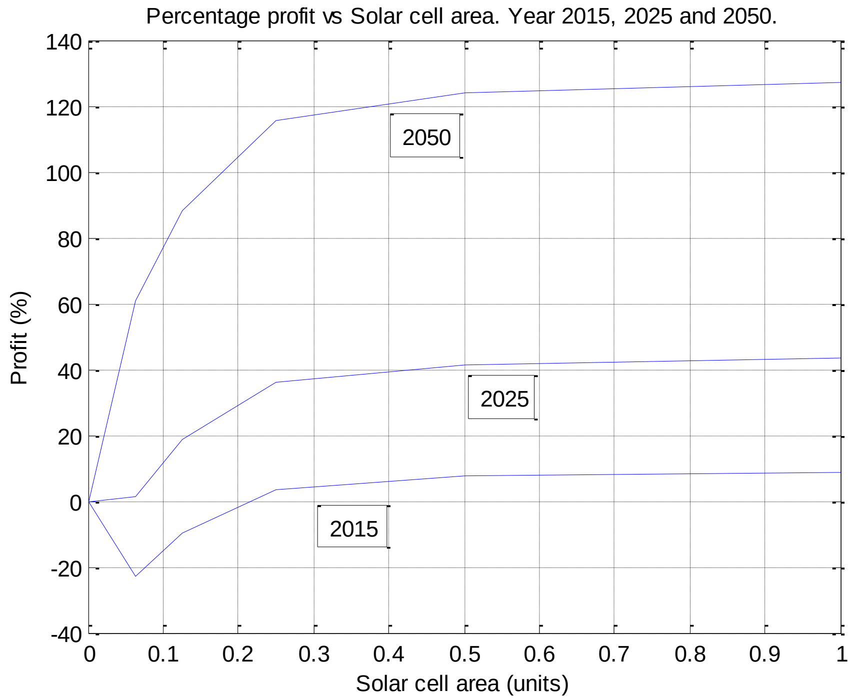


Fig. 7.6. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

### 7.4 Power plant at Malaga

The result of economic analysis follows according to Table 7.V.

Table 7.V. Economic analysis Malaga. Year 2015, 2025 and 2050.

| Solar cell area (Unit) | Year 2015 | | Year 2025 | | Year 2050 | |
|---|---|---|---|---|---|---|
| | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) | Annual profit (MSEK) | Percent. profit (%) |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0.0625 | 0.0215 | 1.3760 | 0.3965 | 33.3895 | 0.8340 | 111.2000 |
| 0.125 | 0.3022 | 9.6704 | 1.0522 | 44.3032 | 1.9272 | 128.4800 |
| 0.25 | 1.0964 | 17.5424 | 2.5964 | 54.6611 | 4.3464 | 144.8800 |
| 0.5 | 2.3122 | 18.4976 | 5.3122 | 55.9179 | 8.8122 | 146.8700 |
| 1 | 4.8998 | 19.5992 | 10.8998 | 57.3674 | 17.8998 | 149.1650 |

Annual profit and percentage profit are plotted according to Fig 7.7 and Fig 7.8.

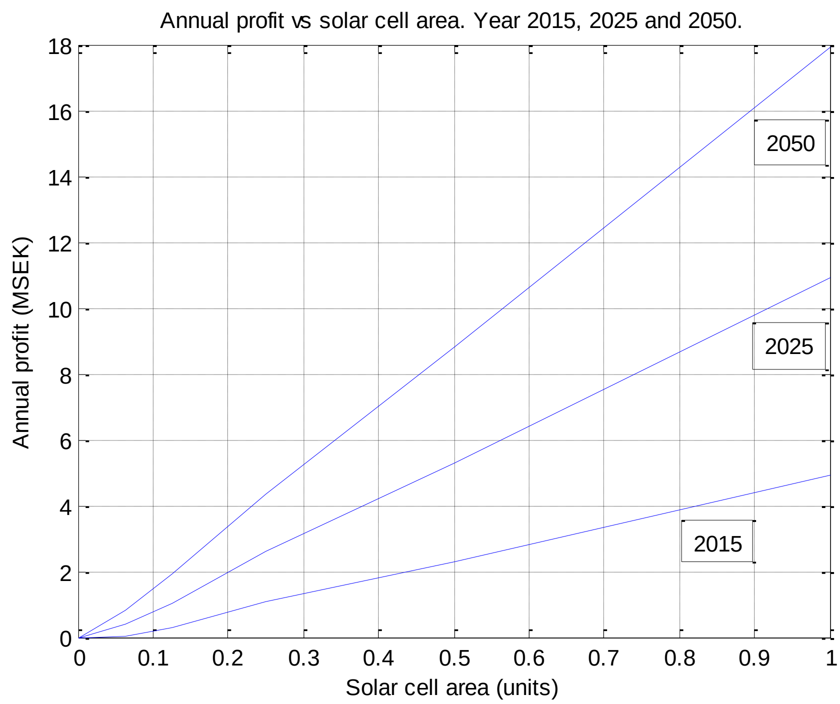


Fig. 7.7. Annual profit vs solar cell area. Year 2015, 2025 and 2050.

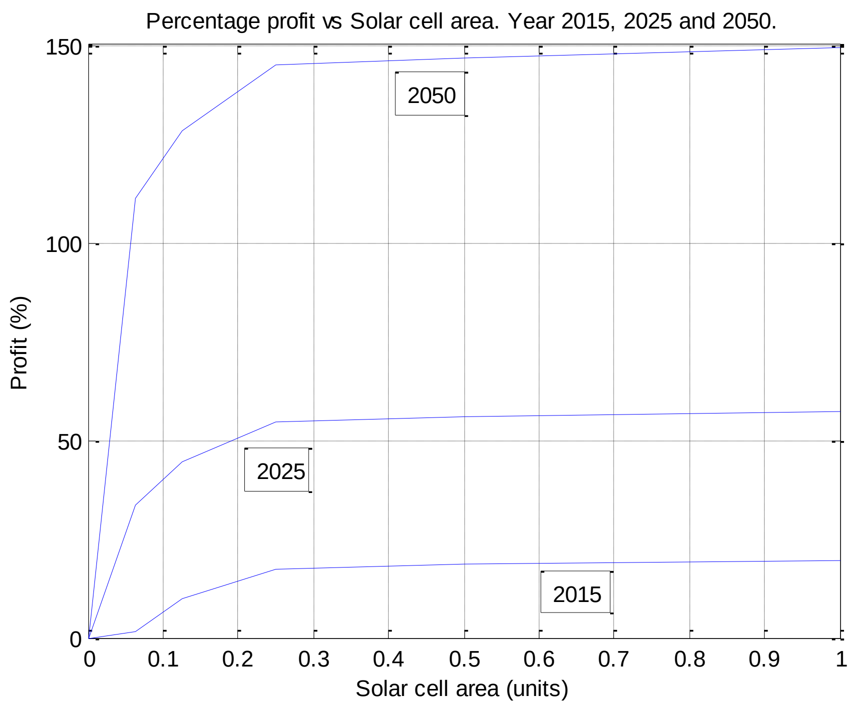


Fig. 7.8. Percentage profit vs Solar cell area. Year 2015, 2025 and 2050.

## 7.5 Conclusion of analysis and adapted energy costs

The analysis has been done with adapted energy cost, individual for each location. The result is:

- Göteborg. Energy cost 1.3 KSEK per kWh. The analysis results in an economic profit with solar energy supplementation according:
  - 2015: Some percentage
  - 2025: More than 30 %
  - 2050: More than 110 %

- Kiruna. Energy cost 2.0 KSEK per kWh. The analysis results in an economic profit with solar energy supplementation according:
  - 2015: Some percentage
  - 2025: More than 30 %
  - 2050: More than 110 %

- München. Energy cost 1.0 KSEK per kWh. The analysis results in an economic profit with solar energy supplementation according:
  - 2015: About 10 %
  - 2025: More than 40 %
  - 2050: More than 120 %

- Malaga. Energy cost 0.6 KSEK per kWh. The analysis results in an economic profit with solar energy supplementation according:
  - 2015: About 20 %
  - 2025: About 60 %
  - 2050: About 150 %

# 8 CONCLUSION OF ECONOMIC ANALYSIS

## 8.1 Wind power. Energy cost

According to Fig. 4.3, parameter $K_{imp}$ must be at least 0.5 MSEK / GWh, or 0.5 SEK / kWh, for profitable investment of wind turbines. Otherwise the turbine cost has to be reduced (parameter $K_{wind}$).

## 8.2 Wind power. Energy storage

There is no economical reason to involve an energy storage in the system, based on investigated energy producers (6 wind turbines with total annual production of about 23 GWh) and present energy consumers (annual consumption of 20 GWh). Since the simulation result is very clear, this conclusion can be regarded as applicable for a general power plant, where wind is the power source. This presumes access of a utility grid for power balance.

## 8.3 Economic analysis. 5 locations

The investigation regarding geographic location shows a significant relationship between energy costs and economic reasons to complete a wind power plant with solar power. To get an economic profit for adding solar energy, assuming solar energy costs for 2015, the following energy costs must be valid:

- Göteborg: 1.3 SEK / kWh
- Kiruna: 2.0 SEK / kWh
- München: 1.0 SEK / kWh
- Malaga: 0.6 SEK / kWh

Regarding Nairobi an energy cost of 0.5 SEK / kWh results in an economic profit of more than 20 %.

Table 8.I shows the approximate percentage profit for for Göteborg (Gö), Kiruna (Ki), München (Mü), Malaga (Ma) and Nairobi (Na) for energy cost 0.5 SEK / Kwh and individual energy cost for each location. The individual cost is adapted to get an economic profit for adding solar energy, assuming solar energy costs for 2015.

Table 8.I. Approximate percentage profit for Göteborg (Gö), Kiruna (Ki), München (Mü), Malaga (Ma) and Nairobi (Na) for energy cost 0.5 SEK / Kwh and individual energy cost for each location.

| **Location** | **Gö** | | **Ki** | | **Mü** | | **Ma** | | **Na** |
|---|---|---|---|---|---|---|---|---|---|
| **Energy cost** | **0.5** | **1.3** | **0.5** | **2.0** | **0.5** | **1.0** | **0.5** | **0.6** | **0.5** |
| **Profit (%) 2015** | N | P | N | P | N | 10 | 0 | 20 | 20 |
| **Profit (%) 2025** | N | 30 | N | 30 | N | 40 | 30 | 60 | 60 |
| **Profit (%) 2050** | N | 110 | N | 110 | 10 | 120 | 100 | 150 | 160 |

Designation N: Negative
Designation P: Positive

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