Design and feasibility study of PV systems in Kenya

- A case study

Master's Thesis within the Sustainable Energy System programme

JONAS BARMAN

Department of Energy and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Report no. T2011-347

MASTER’S THESIS

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JONAS BARMAN

SUPERVISOR

Erik Pihl

EXAMINER

Erik Ahlgren

Department of Energy and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY

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Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

Solar power has the ability to play a main role in the electrification of the developing world. Autonomous energy systems based on solar photovoltaic is, for some cases, a feasible alternative to a grid connection. Solar power can also be used as a complement to a weak grid, for facilities that requires a higher reliability of power.

The main objectives of this thesis were to present one backup energy system for a grid connected facility, based on existing but non-operational solar panels, and to present a cost-effective autonomous energy system, with a good reliability, for an upcoming school. An investment analysis for each case shows the feasibility of the proposed systems. A second objective was to investigate if it is feasible to attach reflectors to solar panels.

If a V-shaped set of reflectors, with a surface area nine times larger than the panels, are attached to solar panels, and the panels are twisted four times a year, the annual energy generation is expected to increase with 65 %, compared with a fixed installation without reflectors.

The results from the investment analysis show that using solar power as a backup energy system can be economically favourable, if it leads to an enhanced business with increased income. The proposed complemented system, to the studied case with existing solar panels, has a payoff time of less than six months.

For the upcoming school facility, the results from this thesis shows that it is mainly the interest rate and the assumed future electricity price, used for the investment analysis, that decides if an autonomous energy system, based on solar PV:s, economically can compete with a grid connection. If both the interest rate and the price increase for electricity are set to 10 % per year, an autonomous system is very economical. The Net Present Value (NPV) of a grid connection is 120 500 SEK, while the NPV of an autonomous system based on solar power is 54 800 SEK.

The conclusion from the results in this thesis is that already today solar power is a cost-effective energy source, for countries with much solar insolation and a weak grid. However, it is very important that the system is designed for the specific facility and that the required maintenance is communicated with the operator in order to get a reliable system that will be in operation throughout its expected lifetime.

Key words: Solar power, Autonomous energy systems, Backup energy, Reflectors

Contents

Preface

This thesis is based on a case study in Nairobi, Kenya. The case study was financed by SIDA's Minor Field Study scholarship. I would like to thank SIDA and Chalmers representative Erik Ahlgren for giving me the opportunity to do this case study.

I would also like to thank Per-Olof Hansson at Gothenburg University, chairman of the organisation Global Relations, for the guidance and help with several contact persons in Kenya.

Finally I would like to thank my supervisor Erik Pihl for all the help with laboratory work, discussions and the writing of the report.

Göteborg April 2011

Jonas Barman

1 Introduction

The electricity demand in the world's developing countries is increasing rapidly and it is a great challenge to meet this demand, without affecting the climate and the environment. The main energy source for power production in the world today is fossil fuels. However, with threatening climate change the use of these must arguably decrease. The power generation is globally the largest source of green-house gases and, preferably, the generation should be shifted to more renewable sources. There are a lot of alternatives to fossil fuels, but the cost is in most cases higher than for conversion of fossil fuels. Grid-connected wind power is one of the most economic renewable energy sources. Solar power is often regarded as one of the most promising energy sources for the future, but it is today one of the most expensive sources, due to high investment costs. However the price has steadily decreased and in some countries, like Greece, grid connected solar panels is today economically feasible if the cost of electricity from the grid is higher than 1.5 SEK/kWh (1). In places with a lot of solar radiation and a weak existing power grid, specifically for off-grid locations, solar power is regarded as a cost-effective solution (2).

Even though the solar panels are the most obvious part of a solar power system it must be seen as a whole system with power production, energy storage, charge regulation and inverters. Hence, the system must be well developed and suited for its special purpose. Many systems, especially in the developing world are neither in operation nor fully utilised.

1.1 Background

This thesis focuses on two different facilities, an operating internet café, named Cyber Relations, and an upcoming boarding school, named Global Secondary School. The internet cafe, founded by the charity organisation Global Relations, is a project aiming to generate local income. Global Relations is operating in the slums of Nairobi and the upcoming school facility is one of Global relations ongoing project in the area.

In November 2009 six solar panels was installed at the Cyber Relations internet café. Each panel was connected directly to charge a laptop with DC current, hence the laptop batteries were charged during sunny weather. However due to low battery capacity, the laptops could not be used during cloudy days or after the sunset. The solution was to charge the laptops and the rest of the facility with electricity from the grid instead. The problem is that the electrical grid of Kenya is quite weak and the internet café therefore suffers from occasional power blackouts. If the internet café could have a back-up energy system, based on the solar panels, which can supply at least the laptops with electricity. Okong'o, the manager of the internet café, believes that the income could increase with 830 SEK per month (3). The increased income is, both due to the possible occupation during blackouts, but also due to customer satisfaction and trust that there is power at the Cyber Relations, even during power blackouts. It would also lead to reduced electricity consumption from the national grid.

This thesis involves two cases; one practical part, focusing on the development of a backup energy system for the internet café, and one theoretical part that deal with a feasibility study and the design of a cost-efficient autonomous energy system for the upcoming secondary school.

Global Relations, the organization behind the upcoming school facility and the founder of the internet café, sees sustainable development and renewable energy as an important part of their work. For the school, the vision is to be independent of fossil energy or electricity from the grid and have a cost-effective energy system with a low ecological footprint and a good reliability.

1.2 Objective

The two main objectives of this thesis are: 1) to present one backup energy system for the internet café, Cyber Relations, based on the existing solar panels and 2) to design a cost-effective energy system with a low ecological footprint and a good reliability and performance for the upcoming Global Secondary School. The goal is to show, with an investment- analysis and performance analysis, that the PV systems can be a feasible and qualitative alternative to a grid-connection. Another objective is to investigate if it is economically advisable to attach reflectors to solar panels in order to increase the power output, or to reduce the required amount of panels.

1.3 Study design

This thesis involves six main studies that has been analyzed and evaluated in order to fulfil the main objectives of the report. The first three studies mainly involve measurements and calculations of the power generation of existing solar panels at the internet café. The results and conclusions of those subjects were used as a base for the forth to sixth studies. Study four to six involves the design and analyzes of the energy systems for the two cases; a backup system for the internet café and an autonomous system for the school facility.

The first study was the measurement of the generated power from the existing solar panels at the internet café. The results were use to evaluate the accuracy of the available climate data and the electrical specifications of solar panels.

The second study involves the installation angle and maintenance of solar panels. The results here were used to see how the installation angle and lack of maintenance affects the power generation.

The third study describes how the usage of reflectors for solar panels can affect the power generation. This involves designing of a simple attachment of reflectors, elaboration of reflections at a metal surface and a calculation of the expected enhancement due to reflectors. The result was then used in the design part of the thesis, but is also a main conclusion itself, whether it is advisable to install reflectors to solar power systems.

The fourth study was the dimensioning of a few alternative systems for each one of the two cases. This means dimensioning the energy loads, the expected generation, the energy storage with a charge controller and a power inverter.

The fifth study was to analyze the dimensioned systems. The expected annual generation and system efficiency, the capacity of delivering power during periods of low radiation and the robustness of the system during unexpected circumstances were analyzed. The results were used to evaluate which system is the most reliable.

The sixth and last study was an investment analysis of the alternative systems for the two cases. The designed solar power systems were compared with a grid-connection. The results are used to discuss whether solar power can be a feasible alternative to the national grid in Kenya.

The report starts with a description of the method used to fulfil the objectives. The next three chapters (Chapter 3, 4 and 5) handle a theoretical background to the thesis. Chapter 3 is describing the prerequisites for using sustainable energy systems in Kenya Chapter 4 is a technical description of the equipment used for autonomous energy systems. Chapter 5 is a theoretical description of how energy systems can be dimensioned and compared form a cost- and performance perspective.

Chapter 6 deals with a problem definition and a description of the two studied cases. The laboratory work is described in Chapter 7. The data and assumptions used for the calculations and dimensioning are presented in Chapter 8. Chapter 9 gives the results of the laboratory work and Chapter 10 shows the results from the cost- and performance analysis. Chapter 11 discusses and analyzes the results in order to give conclusions in Chapter 12.

2 Method

This thesis is based on a field study in Kenya. The thesis focuses on two cases, an internet café with existing solar panels and an upcoming school facility. In the field study measurements were done on the solar panels of the internet café, to get accurate data, valid for the location. Laboratory work with solar PV has been done at Chalmers to see how angles and reflectors affect the power output.

Different sources of climate data for Nairobi has been studied and compared, in order to evaluate which data to use. A literature study was done within the field of stand-alone power systems. Scientific articles were studied to evaluate equations and methods for the dimensioning of solar power systems.

Since climate data varies between different sources, the field study includes measurements of the actual generation from solar panels in Nairobi. From these results, which was compared with literature concerning solar radiation, conclusions could be drawn, of which data source that should be used in the thesis, for the dimensioning of the energy systems. Measurements were also done to evaluate the importance of maintenance of solar panels. The generation by the panels at the internet café was measured before and after cleaning the panels. The laboratory work is further described in Chapter 7.

To evaluate if it is economic to use reflectors the expected increased generation from attached reflectors has been calculated. The reflections (η_{surf}) from a metal surface was analyzed in a laboratory test, see Chapter 7.3.1. The attachment of the reflectors was designed to suit the panels and the solar path throughout the year, see Figure 1. The required size and cost of the reflectors was evaluated for the cost-comparison. The design of the attachment is described in Appendix F.

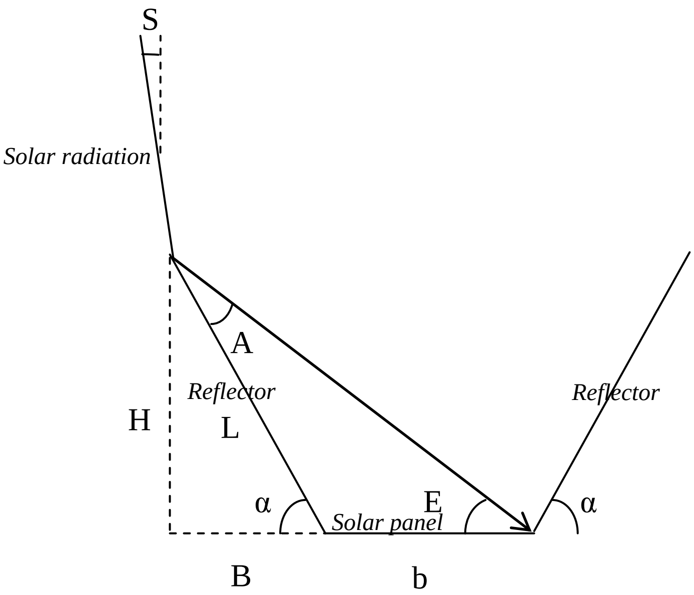


Figure 1 The proposed attachment of reflectors.

Geometrical theory was used to evaluate Equation 1, which was used to calculate the expected increased generation for different solar paths.

$$E = 2 * \alpha - S - 90 \quad (1)$$

The angle E means that the reflections will add as an extra light source with the incoming angle E. The increased radiation (R), during solar noon, was calculated with Equation 2.

$$R = \cos(90 - E) * \eta_r * \eta_{surf} \qquad (2)$$

The reflection efficiencies (η_r) are evaluated from the results of an experiment by (4).

When the increased generation over one full day should be estimated, the solar height and the varying generation over the day are included. Equation 3 was evaluated to estimate the increased generation over one full day (R_F).

$$R_F = R * \eta_{6r} + R * \eta_{5r} + R * \eta_{0r} \qquad (3)$$

η_{6r} is the part of the total daily generation that occurs during the time when all the six panels fully can absorb reflections. η_{5r} is the part of the generation that occurs when five of the panels are affected by the reflectors. η_{0r} is the part of the generation that occurs when none of the panels are affected by the reflections.

Reflectors lead to an increased temperature, which results in decreased efficiency. The estimated increased temperature (ΔT) and the decreased efficiency per ΔT gives the decreased efficiency.

In order to recommend and present a cost-effective energy system, based on solar panels, a few alternative systems have been designed and compared.

The systems are designed by estimating the power consumption throughout the year and adapting the power generation to the load. The month with lowest values of insolation was used for dimensioning the generation, in order to cover the electricity demand for every month of the year. Attached reflectors were included in some of the alternatives to give conclusions if reflectors should be recommended to solar power systems. Some of the alternatives use a Maximal Power Point Tracker (MPPT) charge controller, while other uses a regular Pulse Width Modulations (PWM) controller. This gives a conclusion of which investment is preferred.

The dimensioning of the energy storage differs for the two cases. For the case of the internet café, the energy system mainly works as a backup system during power blackouts. The energy storage was dimensioned to cover the energy demand during one day with a generation at a low level. The low level is defined as the tenth lowest daily irradiation that occurs during one year of climate data. The dimensioning for the school case is based on the expected generation during a *single-day scenario* and a *five-day scenario*. The *single-day scenario* is the lowest expected daily irradiation from one year climate data and the *five-day scenario* is the lowest expected insolation during a period of five days. For the school facility the energy storage was dimensioned to cover the demand at all times, but some of the loads are allowed to be reduced during periods of low generation. This is regulated by reducing the lighting when the battery capacity reaches a level of 70 % and by turning off the charge of two third of the computers when the battery capacity reaches a level of 60 %. The consumption during periods of low generation is therefore dependent of the capacity of the energy storage, since the loads will be reduced at a certain capacity level. The required capacity is in its turn dependent of the consumption. To solve this problem, iteration calculations have been done in Matlab. At first the required capacity during the *single-day scenario* is calculated, see Appendix K, and in order to see if this capacity is enough for the *five-day scenario,* another calculation in Matlab was done, see Appendix L.

The expected annual generation and the supply of power, to the loads, during periods of low solar radiation, have been analyzed and used as a value of performance for the alternative systems.

In case of a period of low insolation, the alternative energy systems, designed for the school facility, will supply the loads with power during different periods of time. The Matlab calculations are used to calculate how long time the computers in the school can be fully used during the *five-day scenario*. This gives a value of performance for the alternative systems.

Sensitivity analyses were done to evaluate the robustness of the alternative systems. The robustness of the alternative systems is checked by calculating the Depth of Discharge (DOD) of the battery bank, during periods with low generation, when both the generation and the battery capacity are reduced with 20 %.

To see if the alternative systems, designed for the school facility, can withstand the *single-day scenario* and the *five-day scenario*, with a 20 % decreased insolation and a 20 % decreased battery capacity, the Matlab calculations was used. For the *single-day scenario* the required capacity was calculated, with the decreased insolation and reduced capacity. The result was compared with the capacity of the dimensioned energy storage. The expected DOD for the *five-day scenario,* with the decreased insolation and reduced capacity, was received directly from the Matlab calculations.

For the economic point of view an investment analysis was done for both cases. The payoff time and the Net Present Value (NPV) were used. The economic and expected lifetime of the system affects the result. A lifetime of 25 years was used for the NPV calculation. The expected interest rate and future electricity price affect the results a lot. The investment analysis was done with interest rates of 10 and 20 % and with an increased electricity price of 5 or 10 % per year.

3 Prerequisites for sustainable energy in Kenya

This chapter describes the prerequisites for using sustainable energy sources for electricity generation in Kenya. At first the current energy situation is described. This includes the power generation and infrastructure and autonomous energy systems. The climate conditions in the country are of great importance for the profitability of using sustainable energy sources, like solar power. The second section includes theory and data of solar insolation and the solar path.

3.1 The current energy situation in Kenya

The current energy consumption in Kenya is mainly the usage of biomass for cooking and lightning. About 97 % of the energy supply was from biomass at the year of 2000. The high consumption of firewood and charcoal has led to severe deforestation. The firewood together with farm residues are mainly used in rural areas, where about 80 % of the population in Kenya lives. The urban population uses mainly charcoal and kerosene. LPG and electricity is almost only used within the cities (5). Sources from 2002 estimated that about 4 % of the rural population and 48 % of the urban population had access to electricity. Those values place Kenya among the countries with lowest electricity supply in the world (6).

In Nairobi most dwellings are connected to the electricity grid, even within the slum, see **Fel! Hittar inte referenskälla.**2. The primarily usage is for lightning, radio and television, while cooking rarely is powered by electricity.

Figure 2 Most dwellings in Nairobi are connected to the electricity grid.

3.1.1 Electricity generation

The electricity generation in Kenya has increased with more than four times between 1980 and 2008. The generation was 6.8 TWh during year 2008, which gives a value of 184 kWh per capita. Among other African countries Kenya is on the upper half when it comes to electricity generation. To compare with other African countries the value for South Africa, which generates almost 50 % of Africa's electricity, was 5 400 kWh per capita. On the other hand Chad generated 10 kWh per capita the same year, which is among the lowest values in the world. To compare with the western world Sweden generated 15 600 kWh per capita that year (7)

Kenya's most important source of electricity is hydropower, see Figure 3. Several oil fired plants have been built the recent years to cover the increasing demand and to decrease the dependency of hydropower, which in case of a drought can decrease a lot (8). Kenya is, except for a small power plant in Ethiopia, the only country in Africa with geothermal power, see Figure 4. Biomass and municipal waste serves a small share of the generation.

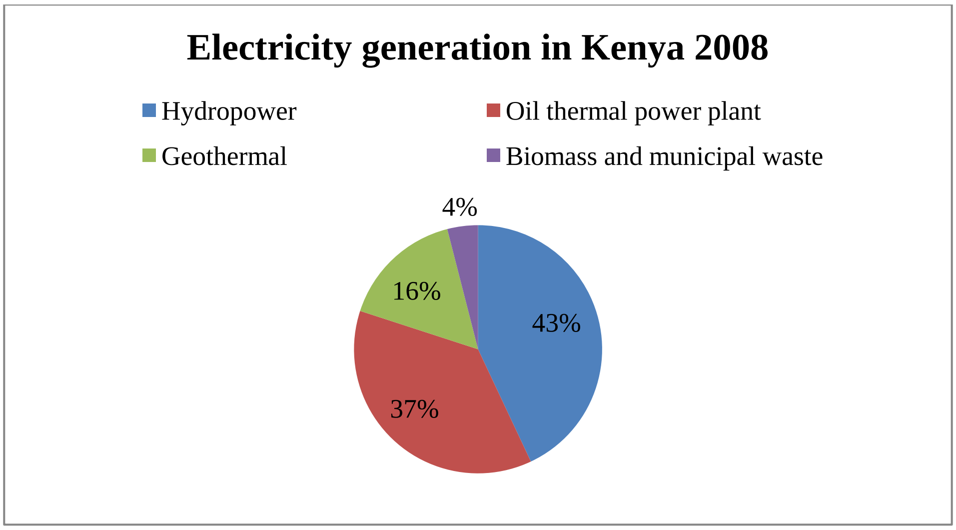


Figure 3 Electricity generation in Kenya 2008 (7).

The World Bank have reported that they will finance a 280 MW increased generation from geothermal power. The main purpose is to increase the access to electricity without increasing Kenya's oil dependency (9). Wind power stands for a very small share of the generation, but large turbines have recently been installed in a mountainous and windy area outside Nairobi, see Figure 4.

Figure 4 Wind turbines outside Nairobi. *Figure 5 Geothermal power in Rift valley.*

3.1.2 Electricity infrastructure

The Kenyan national grid consists of 220 kV and 132 kV transmission lines. There are plans to build a 400 kV transmission line from Mombasa to Nairobi to reduce the transmission losses. Kenya Power and Lightning Company (KPLC) operate the national grid. KPLC also own the right to distribute and sell the electricity to customers in the whole of Kenya. The main power lines goes from Mombasa at the coast, via Nairobi to Kisumo near Lake Victoria. The northern part of the country is not connected to the national grid. There are interconnections with Tanzania in the south and Uganda in the west. There are also plans to interconnect with Ethiopia in the north.

The hydropower stations are mainly located northeast of Nairobi in the Central Highlands. One hydropower station operates north of Kisumo in the western part of the country. The Geothermal power plants lie in the Rift Valley northwest of Nairobi. The oil fired power plants operates in Nairobi and Mombasa (8).

Some of the dwellings connected to the grid have an electricity meter with electricity bills, while others have prepaid meters. For the prepaid meters a code is purchased from a retail store. The code is used to charge the accessible electricity through the meter, see Figure 6. The electricity price was 0.78 SEK/kWh at September 2010 but rose to 1 SEK/kWh at December 2010 (3).

Figure 6 Electricity meter for pre-paid electricity bill.

The quality of the Kenyan electricity grid is poor. A usual week may have 1-3 blackouts in Nairobi (3). Most often the blackout occurs for the whole district. Neighbouring districts about one kilometre away, though, usually are not affected by the same blackouts. To solve these problem facilities highly dependent of electricity often uses energy storage systems or back-up generators, see Figure 7.

Figure 7 Diesel generator at a hotel used to prevent power blackouts from the electricity grid.

3.1.3 Autonomous energy systems

It was previously described that the quality of the national grid is rather poor and that large parts of the country lack of grid connection. A solution to this has been to use autonomous energy systems for a single facility or a whole village.

The conventional power source for autonomous energy systems has historically been a diesel or petrol generator, supplying the local load with electricity. The technology is mature and the investment cost is rather low. The noise and exhaust gases are a problem and alternatives have been developed. Solar power is regarded as one of the best options for rural electrification, especially in sub-Saharan Africa (10).

The installation rate of SHS systems in Kenya is about 20 000 systems annually. About 150 000 Solar Home Systems (SHS) was installed in Kenya in year 2000. Of those, though, about 21 % were not operating. Nieuwenhout, et al. reports that many of the system that were not operating, was systems that had been donated (2). A study from Guatemala showed that even if the operators were educated in the maintenance of the systems, 45 % of the systems were not in operation five years after installation.

A regular 12-voltage SHS include, one solar panel of about 50 peak watt (W_p), a charge regulator and a battery with the capacity of about 100 Ah. Larger systems can also include an inverter to get the opportunity to use alternating current devises. A SHS can supply a few lamps, a radio and sometimes a TV and a small fridge (2). The SHS is mainly used for small businesses in the rural Kenya where there's no access to the national grid, see Figure 8.

Figure 8 Solar panel and solar collector is used to support a small camp in rural Kenya with power and hot water.

3.2 Climate conditions in Nairobi

Renewable energy sources generate energy from natural sources like solar radiation and kinetic energy in the wind. The local climate conditions determine if a certain energy source is profitable.

Nairobi is located about 1° south of the equator in the central part of Kenya. The altitude is about 1800 meters above sea level, which gives a generally cool climate compared with the rest of the region. There is one wet season considered as "the long rain" between March and May. April usually gets the most rain with an average of 15 rainy days. "The short rain" occurs between October and December. "The short rain" often has much less precipitation than "the long rain". From June to September the weather is often chilly and cloudy, but with few rainy days. January and February are sunny and hot months with little rain. Nairobi seldom meets high wind speeds and the average wind speed is about 3 m/s (11).

The climate conditions are affecting the type of power source to consider in a small sustainable energy system. Solar power is preferable in places with much sunshine, while wind turbines might be a better option for windy location.

3.2.1 Solar insolation

The surface of the sun, with a temperature of about 5 800 Kelvin, is emitting electromagnetic radiation. The energy is spread out in the universe and when the radiation reaches the outside of the earth's atmosphere the mean energy content is 1367 W/m^2, named the solar constant. About 40 % of this radiation reaches the surface of earth; the rest is reflected or absorbed by the atmosphere (12). The maximum radiation is about 1 100 W/m^2, this is in places near the equator, like Kenya.

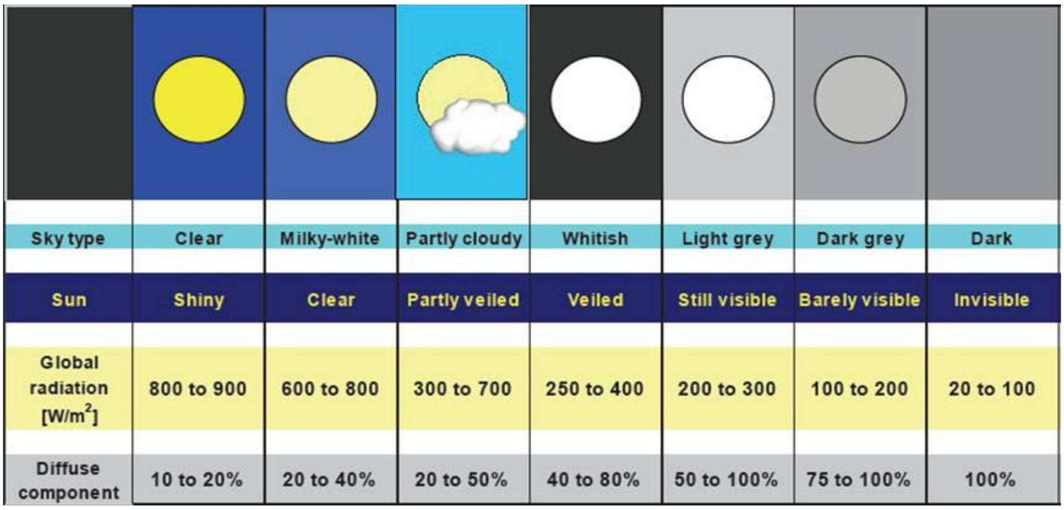
The solar insolation determines how much energy a solar panel can generate. Nairobi's location close to the equator gives good circumstances for solar power. The annual irradiation is about 2 100 kWh/m^2 for a horizontal surface, which can be compared to Gothenburg in Sweden that gets about 900 kWh/m^2. However, on a national level Nairobi gets among the lowest level of annual solar insolation. Some places in the western part of the country receive an annual irradiation above 2 500 kWh/m^2 (13).

The global horizontal radiation (W/m^2) and the daily insolation (I_d), expressed in (Wh/m^2), for the first 5 days of each month at year 2000 is presented in Appendix A (14). The daily insolation varies between 2 380 and 7 160 Wh/m^2. The lowest values are during the first days of June, which is considered as a cloudy month. The highest insolation is between December and March, with February at the top, see Table 1 Mean values for daily insolation (Wh/m^2) at a horizontal surface in Nairobi. Data for average daily insolation for different months is also available from (13). This data is based on satellite images using the HelioSat-2 method (15). Another source of climate data is the program (16). For Nairobi the values from (13), (14) and (16) are presented in Table 1 Mean values for daily insolation (Wh/m^2) at a horizontal surface in Nairobi below.

Table 1 Mean values for daily insolation (Wh/m^2) at a horizontal surface in Nairobi.

Month	Wh/m^2 day from (13)	Wh/m^2 day from (14)	Wh/m^2 day from (16)
January	6 670	5 690	6 450
February	7 020	6 500	6 610
March	6 730	5 990	6 350
April	5 910	4 940	5 270
May	5 250	5 060	4 650
June	4 620	4 520	4 300
July	4 250	5 200	3 810
August	4 540	4 610	4 000
September	5 820	4 800	5 270
October	6 050	5 300	5 610
November	5 720	4 650	5 270
December	6 340	5 720	6 030
Year	5 740	5 250	5 300

The solar intensity is dependent of the weather. The solar radiation can vary from down to 20 W/m^2 up to at least 900 W/m^2, see Figure 9.



Sky type	Clear	Milky-white	Partly cloudy	Whitish	Light grey	Dark grey	Dark
Sun	Shiny	Clear	Partly veiled	Veiled	Still visible	Barely visible	Invisible
Global radiation [W/m^2]	800 to 900	600 to 800	300 to 700	250 to 400	200 to 300	100 to 200	20 to 100
Diffuse component	10 to 20%	20 to 40%	20 to 50%	40 to 80%	50 to 100%	75 to 100%	100%

Figure 9   Solar radiation during different weather conditions (17).

The lowest insolation is very important for the design of the energy storage of a solar power system. As previously shown in Appendix A the data from (14) very seldom shows a daily value of lower then 3 000 Wh/m^2. Figure 10, with data from (13) shows the probability for low values of daily insolation. In the figure it is seen that values under 2 000 Wh/m^2 rarely occurs.

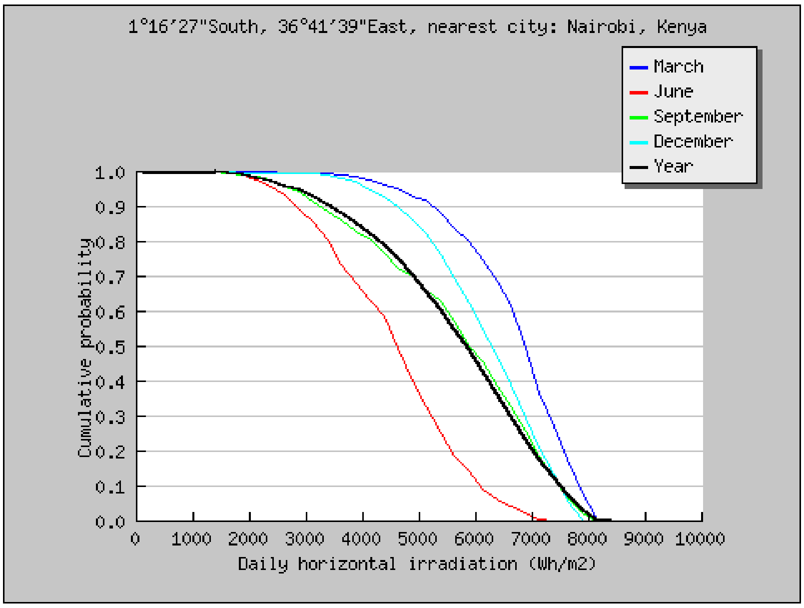


Figure 10   Cumulative probability of Daily horizontal irradiation (Wh/m^2) (13).

Data of solar radiation is also given by the program Meteonorm (16). The daily horizontal global radiation is showed in Figure 11. Remarkable are the lowest values, which can reach down to below 500 Wh/m^2. This varies a lot from the values received from (13) and (14).

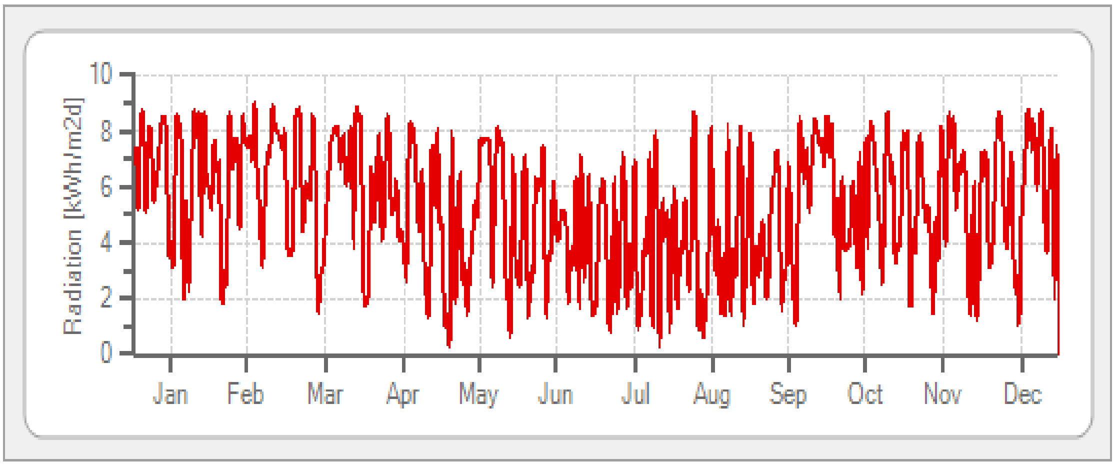


Figure 11 Global Horizontal Radiation (kWh/m² day) for Dagoretti in Nairobi (16).

3.2.2 Sun path for Nairobi

When the earth orbits the sun the relative tilt changes with an angle of about 47° between the extreme points, which occurs December 21st and June 21st. Nairobi's location 1° south of the equator means that the solar angle will be 1° north of the perpendicular line to the horizontal plane at solar noon the 21st of March and 23rd of September. Since solar time and real time differs a bit noon at solar time for Nairobi is about 12.30 (18).

Data for average daily insolation for surfaces at different angles during different months is available at (13). The solar panels at the internet café are placed in a south south-west direction with an angle of 20°. The estimated power production for a 1 000 W_p solar panel placed at a horizontal position is compared with a similar panel placed in the same direction as the solar panels of the internet café is showed in Appendix C.

4 Technology for sustainable power sources

The power generation from renewable sources, especially solar, is developing rapidly. The efficiency of photovoltaic increase at the same time as new production methods pushes down the prices. The demand for energy storage is increasing rapidly, hence forcing this development forward. This chapter describes the technology of power generation with photovoltaic cells and methods to increase or optimize the power generation from them. Energy storage with focus on lead-acid batteries is also described, which includes charge regulation and power inverters.

4.1 Photovoltaic cells

In 1838, Edmund Becquerel noticed that a small voltage is created between two metals placed in a semi-conducting electrolyte that is exposed for light (19). This is the working principle for photovoltaic cells.

4.1.1 Different types of solar cells

There are different types of solar cells; the most common group is the silicon cells. The silicon cell with highest efficiency is the mono-crystalline cell, where the atoms are symmetric placed within the structure. As mentioned before this gives a high efficiency, however it is also very costly to manufacture this symmetric structure (20). Commercial silicon cells have an efficiency of 14 - 17 %. A less expensive alternative is the polycrystalline cell, where the structure is less symmetric and less complex. Here the efficiency is about 13 - 15 % (21).

Another type of silicon solar cell is the thin film cell based on amorphous silicon that is sprayed on a transparent surface. The main difference from crystalline cells is the amount of silicon needed. For thin film cells a very thin layer of silicon is required, but another material like glass, for holding the silicon together, is required. Because of the low amount of silicon needed, the required energy for manufacturing and thereby the production cost of those cells can be very low (20). Today the efficiency of the commercial thin film cells is 5 - 7 %. But the expectations are high and in laboratories efficiencies of around 13 % have been reached (21). Within the thin film technology other materials than silicon are used, such as copper, indium, gallium and selenide, for so-called CIGS cells, or cadmium and telluride, for CdTe cells. However a problem is the toxicity of cadmium and telluride and the scarcity of indium (20).

4.1.2 Electricity generation in a cell

Silicon, the most common semi-conductor, has the atomic number 14 and has four valence electrons. In the silicon structure each atom share its valance electrons with four other atoms to create a stabile structure. But if a photon hits the atoms, the binding breaks and an electron is realised, the material gets electrically charged. To increase the conductivity the silicon can be doped with other materials to change the structure. A photovoltaic silicon cell is divided in two parts, called the n-type and the p-type. The part that is exposed to light is the n-type, which is doped with phosphorus. Phosphorous has five valance electrons so there will be an extra electron for each phosphorous atom in the doped structure. The lower part of the silicon cell is doped with bor, which has three valence electrons. In this part missing electrons, which can be called “holes” are created. At the upper part of the silicon cell thin contacts are attached to conduct the electricity. The backside of the cell is covered with a metal-layer that conducts the charge from this side (20).

When photons with energy content higher than 1.1 electron voltage (eV), the band gap for silicon, hits the silicon cell the energy will be transformed to electricity. The structure of a n-type silicon together with a p-type, also called a pn-junction, forces all released electrons to the same direction If a load is connected between the upper and lower contact a current will conduct through the load (19). Only photons with a wavelength under 1100nm have an energy content of 1.1 eV, which is required to release an electron. Photons with less energy can’t be used. If the energy content is higher than 1.1 eV, only 1.1eV will be used, the rest will be unwanted excess heat in the cell. Because of this not all sunlight can be used; the theoretical efficiency is about 29 % (20). To gain higher efficiencies multi-layer cells can be used.

The voltage from a single solar cell is about 0.5 V, which often is too low to connect to a load. To increase the voltage several cells are serial connected. To get a solar cell applicable to a 12 voltage system, 33 – 36 cells are connected. This gives an open circuit voltage of about 20 V (20). When a load is connected the voltage drops according to the characteristic I-V curve for solar cells, see Figure 12. The voltage for the series connected cells is about 15 V when a load is connected.

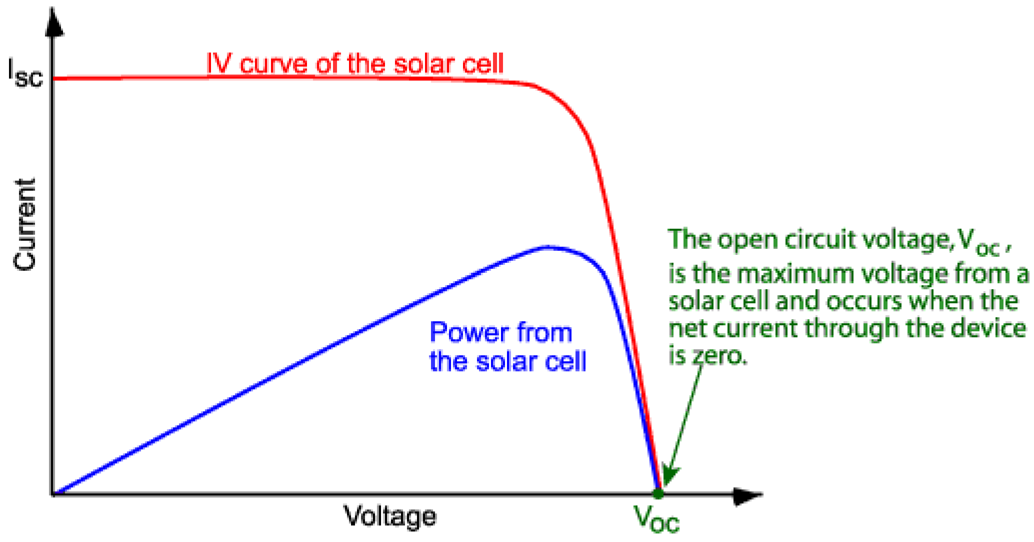


Figure 12 The characteristic I-V curve for solar cells (18).

In Figure 12 it can be seen that the power output from the cell depends on the operating voltage. The size of the short-circuit current (I_{sc}) is directly dependent of the solar radiation, so if the radiation is doubled the I_{sc} is doubled. The optimal operating voltage thereby depends of the actual radiation. The power production in relation to the product of the short-circuit current and the open-circuit voltage is called the *Fill Factor* (18).

4.1.3 Factors affecting the power generation

The angle of the incident light will affect the amount of power produced by a solar cell. The amount of photons hitting a horizontal surface decreases with the angle from the perpendicular normal line according to the cosine law. Experiments and models shows that the power generated by a solar cell decreases even more than expected by the cosine law, especially for angles >30° from the normal line. The reason is mainly that the reflection from the coating will increase with steeper incident angles. The decreased generation due to reflections is 11 % and 50 % for 60° respectively 80° from the normal line (4).

The temperature of a solar cell affects the shape of the IV curve. Higher temperature means increased internal energy losses and an increased band gap for the semi-conducting material. This leads to a decreased V_{oc} and a slightly increased I_{sc}, see Figure 13. The maximum power output, the highest product of the current and voltage in the curve, is lower for a high temperature solar cell. The efficiency of the cell will decrease with about 0.4 %/°C (22). An increased temperature also means higher stress on a panel, which decreases the lifetime by a factor of two for about every 10°C.

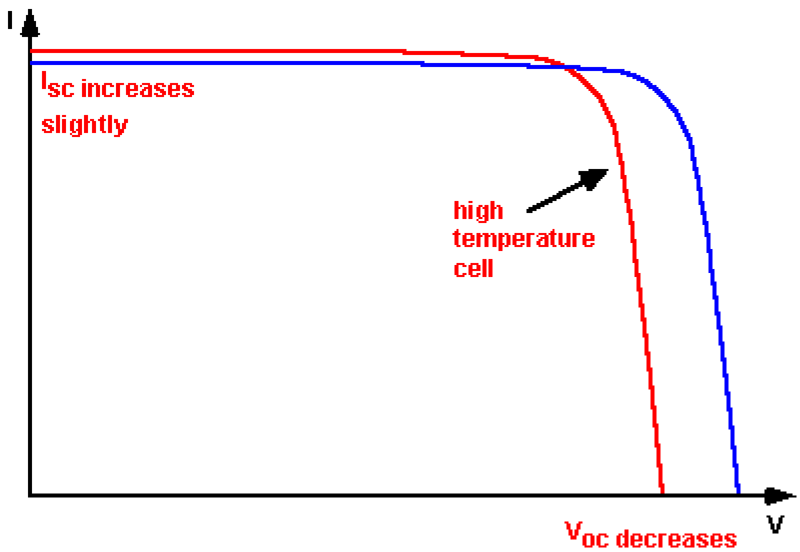


Figure 13 The IV curves dependence of the temperature (18).

The heat energy of solar cells comes from the solar radiation. Since only 10-15 % is converted to electricity, excess heat will be produced, as previously described. The materials used for the panel affect the temperature. If the excess heat energy easily can be transmitted to the surrounding the temperature will be lower (18).

As previously described, solar cells are series connected to increase the output voltage. There is one important disadvantage of this; the mismatch effects. Since serial connection means same current trough all cells, mismatch occurs when the current produced in each cell differs. The cell producing the lowest current will decide the effect. This means that if one of the cells is shadowed the generation will drop for the whole panel (18).

The specified power for a PV panel is rated with perpendicular solar radiation of 1000 W/m^2 and a temperature of 25° C. Seen over a whole year, radiation of this level might only occur during a few hours. This means that a lot more capacity must be installed when it comes to solar power, compared with i.e. a diesel generator, in order to obtain the same annual energy generation (23).

4.1.4 Technologies to increase or optimize the electricity generation

The generated current is direct proportional to the incoming radiation, as described in Chapter 4.1. So an increased incoming radiation means higher output.

The radiation can be reflected with mirrors or other material and focused to the solar cells. The increased output varies a lot between different designs and for each design it varies during the year due to radiation angle. One design is the ARCHIMEDES system, which is a solar tracing panel with V-formed concentrators. The system is built up with solar cells covering 50% of the area and reflectors covering the other 50 %. The enhancement of the effective radiation is about 1.5 -1.6 times, but varies depending on the weather conditions since only direct sunlight is reflected as modelled. The tracking system is increasing the output with another 1.25 – 1.35 times. To decrease the cell temperature, aluminium fins at the rear part of the panels are used (24). A more simple method is to use a fixed panel with a plane reflector, which (25) has done measurement of the annual generation with. Two panels are considered, one with and one without one plane reflector. The reflector has the same width (W) as the panel. The length of the reflector (L) is equal to the length of the panel plus the width on both sides of the panel (L+2W). The extended length is required to reflect radiation when the sun not is perpendicular to the attachment The reflector is tilted once a month and is modelled to reflect light on the whole panel during three hours before and three hours after noon. The cost of the reflector is about 5 % of the cost of the panel. The power output increases over the year with about 22 %. The negative impact of the reflector is an increased cell temperature. The surface temperature increases with about 10°C, compared with the panel without reflector.

Another important way to increase the power output and lower the investment cost for a stand-alone system is to make sure that the power supply is equal to the power consumption. If the consumption gets lower than the estimated value, the investment will be higher than needed.

4.2 Energy storage

There are today several opportunities to store energy; electrochemical, flywheel, compressed air or superconducting coil can be used.

For a small stand-alone system in Kenya the flywheel technology is too immature and requires technical maintenance. It is also generally too large for this application. The compressed air requires a closed shaft or another enclosure that is not available in this case. The superconducting coil could have been an alternative, but the specific energy is too small and high effect is not required. The electrochemical batteries, see Figure 14, are the most mature and the most economical option for a small scale energy system (26).

With a battery, chemical energy is converted to electricity. Primary batteries are nonreversible and can only be discharged once. Secondary, also called rechargeable batteries can be recharged. During both discharge and recharge a part of the energy is converted to heat. The discharge to recharge efficiency is therefore 70-80 % (27). The main properties that are important for rechargeable batteries are the energy content, the power output and the amount of discharge and recharge cycles it can provide. Those properties differ among different types of batteries and among different versions of the type of battery. The state-of-charge (SOC) describes the amount of energy left in the battery compared to the full capacity, i.e. if SOC = 0.7, 70 % of the capacity is left and 30 % has been used. The C-rate is the time the battery is charged or discharged within. A C-rate of 1 means that the whole capacity is discharged within one hour, while a C-rate of 0.1 means that it is discharged during ten hours. Battery manufacturer uses different C-rates for the rating of the specific capacity. It is often called discharge rate, where 10 hours discharge rate equals a C-rate of 0.1 (27).

Figure 14 Lead-Acid batteries and a charge regulator used for a small solar power system.

4.2.1 Lead-acid batteries

The Lead-acid is the most common battery. It is a mature and relatively low-cost technology. It is, though, the battery with least energy per volume and weight. Within the lead-acid technology several versions are available. For automobiles shallow-cycle batteries are used. Only a high power output is required to start the engine, so the battery only requires a small amount of energy. For other applications, such as a stand-alone energy system, a deep-cycle version with long life time is preferable. One such battery is the flooded traction battery; popular in PV systems. Among the flooded lead-acid batteries the lead-antimony, open vent battery is the most widespread. The advantage is the deep-cycle capacity and that it is a robust battery that can handle abused charging. The drawback is loss of electrolyte when recharging, which means that it has to be maintained by filling battery water. It also needs to be placed in a ventilated space. There are also the more expensive sealed lead-acid batteries called Valve-Regulated Lead Acid (VRLA). The advantage is that they require less maintenance and that the life length can be longer. There are two types of VRLA batteries. The first one is the gelled battery, which is using a gel as electrolyte. Those can be placed in a closed environment but requires controlled slow charging at constant voltage and temperature. There is also a type called absorbed glass matte (AGM) that has similar properties as the gelled type, but without limits for charging time (26). The efficiency of the AGM batteries is 80 % and the efficiency of the flooded type is 75 % (28). Lead-acid batteries are available with different capacities, with terminal voltage normally of 2, 4, 6, 12 or 24V (27).

4.2.2 Battery characteristics

The Charge/Discharge (C/D) voltages for a battery cell differ with the type of battery, but for all types of batteries the voltage depends of the SOC. A fully charged battery has a higher voltage than an empty one. During recharge the voltage is higher than during discharge.

The C/D ratio defines the required Ah (ampere-hour) input over the required Ah output. A C/D ratio of 1.2 means 20 % more Ah for charge than for discharge. The energy efficiency is dependent on this but it also includes the different voltages for charge and discharge. The round-trip energy (   ) is calculated by Equation 4, where   is the discharge voltage and   is the charge voltage (27).

(4)

Another efficiency to consider is the charge efficiency, which is the Ah being chemically stored between the plates over the Ah charged to the battery. This efficiency is almost 100 % with low SOC but then decreases to 0% as the SOC goes to 100 %. The curve is dependent of the C-rate, with lower efficiency for high C-rate. This means that it is inefficient to fully charge the battery, especially with a high C-rate. The energy that is not charging the battery is converted to heat. To prevent overheating it is therefore important that the charge is decreased when the battery is almost fully charged. A small current, called trickle charging, is though required to maintain the battery at a fully charged level, since batteries self-discharges. The self-discharge is generally lower than 1 % of the capacity, per day, but it increases a lot with high working temperatures (27).

The temperature affects the performance of a battery in many ways. As just mentioned, the self-discharge increases with higher temperature. The C/D ratio increase with increased temperature. The charge and discharge efficiency is decreased for low temperatures. The charge efficiency is also decreased for temperatures above 20°C. The optimal temperature differs for different types of batteries and different applications but it is usually in the range of 10 - 25°C (27).

The life time of a battery varies with type and version. For example a lead-acid battery usually last for 500 – 1000 cycles. The life time can quickly be reduced if the battery is overcharged or deeply discharged. For a flooded lead-acid the total life time in full Wh cycles can be two or three times higher if the SOC is kept above 90 % instead of 50 % (26). Deep-cycle batteries often have a specification showing the expected life time with different Depth of Discharge (DOD), see Figure 15.

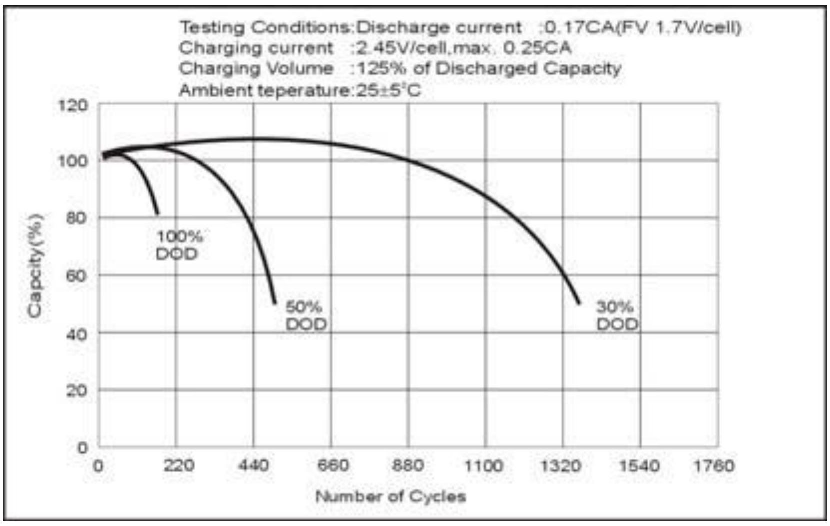


Figure 15 Expected lifetime of a sealed lead-acid battery with differnet DOD (29).

4.2.3 Charge regulator

To prevent the battery from overcharging or deep discharging in a small power system a charge regulator is required. A simple controller only have the opportunity to switch off the charging power when the battery reaches a certain voltage, deep discharge must be avoided in other ways. For a lead-acid battery the charge regulator uses maximum charge until the gassing in the cells starts. The charge is then gradually reduced to the trickle-charge rate. This is called a multiple charge rate and is applied in modern controllers.

The charge controllers have developed a lot the recent years and today some controllers have the possibility to increase the power output from a solar panel. As described in Chapter 4.1, there is a maximum power point for each certain level of radiation. The Maximum Power Point Tracking (MPPT) controller is able to adapt the voltage level from the panel, so the panel can operate at the optimal point (B) at all times. A regular charge controller operates at a voltage level slightly above the battery voltage (A), see Figure 16.

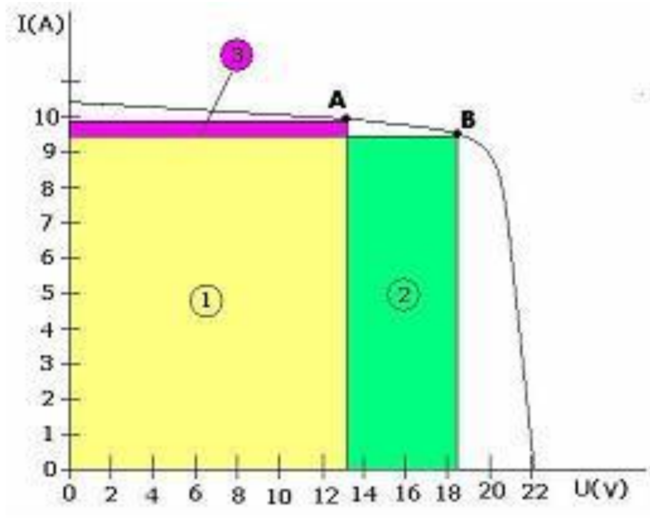


Figure 16 The operation point differs with a regular charge controller and a MPPT charge controller (30).

The lost power production is about 24 % with regular charge controller (30). It is though important to know that even with a MPPT controller the optimal operation point (A) only can be kept as long as all the power can be utilized to a load or to charge the batteries. A MPPT charge controller primarily supplies the load with power and charges the batteries with the excess energy (31).

4.2.4 Power inverter

Since solar panels generate direct current a power inerter will be needed in order to supply the loads with alternate current. The inverter must be able to handle the expected power level, but must also be compatible with the voltage of the supply and demand side.

There are two categories of power inverters. What differs is the output wave form. The true sine wave produces a high quality alternating current with a smooth sine curve, while the modified sine wave inverter produces a squared-off sine wave. The true sine wave is required for sensitive equipment like laser printers, TV or video games. These devices can be affected in quality by a modified sine wave inverter. Computers, however, are able to use the modified sine wave inverter (32).

5 Dimensioning and evaluation of solar power systems

The designing of a solar power system, as an autonomous system or as a backup system, requires calculations of the expected consumption, which together with the system efficiency gives the required generation. The system efficiency includes the efficiency of each devise in the system like; charge regulator, batteries and power inverter. The energy storage with charge regulator must be dimensioned to supply the loads with power during periods of low generation. Generation capacity and irradiation affects the required energy storage (33). To recommend one system, alternative systems should be designed and compared from a cost- and performance perspective. This chapter describes how solar power systems, in the thesis, were dimensioned and evaluated.

5.1 Dimensioning the solar power systems

Several methods and modelling programs have been developed in order to dimension autonomous solar PV systems. (34) presented a worksheet where loads are to be filled in, in order to dimension the required generation and storage capacity. Other articles describe how solar PV can be integrated in the electrical grid. (35) presents a MATLAB model that simulates the expected power generation of grid connected PV systems.

(2) claims that, which model to be used, depends of the specific country and the specific facility. In this thesis, the dimensioning of a backup energy system for an internet café with existing solar panels and the dimensioning of an autonomous energy system for an upcoming school facility uses conclusions from (2,) (34) and (35). Equations used to dimension the energy systems in this thesis, have been developed to suit the available data and prerequisites of the specific facilities, see Chapter 6.

5.1.1 Electricity demand

To be able to calculate the need of power producers the electricity demand must be clearly defined. The variations over the hours and days must be included to calculate the need of energy storage. The electrical specifications of the loads must be known. The worksheet, presented by (34), is separated between AC and DC loads . The current, voltage, usage time per day and days of usage per week are filled out. The maximal power and current is evaluated and the system efficiency is included to get the amp-hour load per day. If a direct current generating producer is to supply a load that operates with alternating current, a suitable power inverter is required. The efficiency of the inverter is about 85 % (36).

5.1.2 Power generation

To design a well functioning solar power system the expected energy production each day over the year must be estimated. Average values of solar radiation are used to see the expected generation over the year. Data of minimum expected radiation for each month is used to design a sufficient energy storage system. Accurate data for the specific location is required to give good output from the dimensioning, (37).

In case of dimensioning the amount of required panels either the month with maximal irradiation, the average irradiation or the month with minimal irradiation can be used. If the maximal irradiation is used all the generated energy will be consumed by the loads, but during other months the expected consumption must be lower or be decreased. If the month with the lowest value of irradiation is used the loads can be supplied with power throughout the year. During the other months, with higher values of irradiation, excess power will be generated (33).

The efficiency of a solar panel ( ), can be calculated if the rated peak power ( ) and the total panel area (is known. The efficiency is calculated by Equation 5 (36).

(5)

In Chapter 4.1 it is described that reflection losses occurs with high inclination angles, which is included as the absorption efficiency ( ). To calculate the expected daily power production (G) can be calculated if the daily insolation ( ) is known. Equation 6 is used in this thesis (33).

(6)

5.1.3 Energy storage

In the power grid, electricity is consumed simultaneously with generation, so the demand must match the supply. In a small stand-alone system, where both the generation and the consumption of electricity vary independently, energy storage is needed. (34) describes that the energy storage are to be dimensioned after a suggested time, during which there is no or low generation. For a facility that is highly dependent of power for its business, the capacity must be dimensioned after the yearly lowest generation that can occur within a period of i.e. five days. For a water irrigation system or water pumping system, the energy storage might not at all be needed (37). The allowed Depth of Discharge (DOD) must also be considered when the batteries are dimensioned. In Chapter 4.2.2 it was described that the lifetime of lead-acid batteries can be prolonged by avoiding deep discharge.

The required energy storage for a system is dependent both of the required performance and the expected generation. If the power generation is over dimensioned the energy storage capacity can be reduced (33). Another way to reduce the required energy storage is to adapt the power consuming devises to the supply (37). For example a certain load can be reduced during low generation.

Equation 7, based on the article of (34), is used to calculate the required battery capacity (in Ah for a certain system voltage ( ), with a given energy consumption (. The accepted Depth Of Discharge ( ) is included. The solar panels will generate a low amount of power (even during periods of cloudy weather. If reflectors are attached to the panels the increased generation ( ) is included. Of this generation there will be losses in the charge regulation ( ) and the battery bank (. If a PMW controller is used all the energy must pass the battery bank. There will also be losses from the power inverter ( ).

(7)

5.1.4 Charge controller

The required size of the charge controller depends of the total current that the proposed interconnection of solar panels will generate. In the case with reflectors the increased radiation must be counted for. A safety margin for the current generated by the panels and a margin for reflections must be included. (38) recommends a safety margin of 1.25 in the case of the generated current. The safety margin for the reflectors is dependent of the accuracy of the elaborations used to calculate the assumed increased generation.

When the required size is dimensioned the type of controller must be chosen. Like presented in Chapter 4.2.3 a Maximal Power Point Tracker (MPPT) charge controller will theoretically give higher system efficiency. (34) concluded that this is the case for autonomous systems and that it can be cost-effective to use this type of controller.

The current that the controller must be specified ( ) for is calculated by Equation 8, which was developed from (38).

(8)

Where ( ) is the number of solar panels connected in parallel and ( ) is the specified short-circuit current. ( ) is the safety margin for the current generated by the panels. In the case with reflectors the increased radiation ( ) and a margin for reflections ( ) are included.

5.1.5 Power inverter

Power inverters are sized after the maximal power they need to provide. The power inverter must be suitable with the voltage level of the batteries. It is also important to consider the efficiency of the inverter. The highest efficiency is usually reached when the inverter operates at 50 % of its rated power (39). As described in Chapter 4.2.4, the kind of devices that is connected to the system decides if a cheap modified sine wave inverter is enough, or if a more expensive true sine inverter is required.

5.2 Analysis of the energy systems

When alternative energy systems have been designed, they must be compared in order to recommend one of the systems for each case (34). The expected annual generation and the possibility of supplying loads with power during periods of low solar radiation are ways of describing the performance of the systems (33). Sensitivity analyses are used to evaluate the robustness of the alternative systems.

5.2.1 Annual generation and system efficiency

The expected annual generation is dependent of the solar insolation, the peak power of the solar panels and the system efficiency ( ). The efficiency of the systems is dependent of the chosen devices; charge regulator ( ), batteries ( ) and power inverter ( ). The system efficiency is also dependent of the share of the energy that goes through the batteries ( ). is set to 1 if all the energy goes through the batteries and to 0 if all the energy goes directly to the loads. For this thesis the increased radiation from reflectors (are also included in the system efficiency, resulting in possible system efficiencies of above 100 %. The system efficiency is given by Equation 9

(9)

The calculation of the expected annual generation is a development of the expected power production, described in Chapter 5.1.2. The average daily generation ( ) is used for solar data (16). Equation 10 is used to calculate the annual generation.

(10)

5.2.2 Energy supply during periods of low radiation

The method of calculating the required energy storage capacity is described in Chapter 5.1.3. Since batteries are available in certain capacities, the capacity will differ a bit from the demands. Equation 7 can be rewritten to Equation 11 in order to calculate the actual energy storage capacity for a battery voltage ( ), measured in hours ( ) that a certain load ( ) can be supplied with power.

(11)

5.2.3 Sensitivity analysis of the systems

A sensitivity analysis analyzes the robustness of the system. The following parameters were investigated:

- How changed weather conditions or decreased power production affect the system.

How a decreased energy storage capacity affects the system.

The robustness of the alternative systems is checked by calculating the DOD of the battery bank when both the generation and the battery capacity are reduced. The DOD is calculated with Equation 12, which originates from Equation 7.

(12)

If the power generation is dimensioned after the month with the lowest value of solar insolation and the actual insolation gets lower than this, the power supply to the loads will be lower than the average total consumption ( ). This means that the consumption must be reduced. Equation 13 is used to calculate how much a certain load, with the consumption ( ), must be reduced ( ) in percent, if the generation is (r) % lower than the system was dimensioned for.

(13)

5.3 Cost comparison of the systems

To evaluate whether investing in a solar power system is an economic option and which alternative is the most economic, a cost analysis must be done (34).

The payoff time is calculated by dividing the investment cost with the benefit each year. In case of an autonomous system the estimated energy consumption with the present electricity price is used as the benefit each year. If new investments are required during the payoff time, those are to be included in the investment cost.

The Net Present Value (NPV) is calculated with Equation 14.

(14)

- Cash flow the present year (Expenditures – Income)

- Interest rate

For the NPV calculations both the investment cost and the future costs is included. The expected life time for the devices in the systems is included in the analysis.

Important aspects to the investment analyses are the interest rate and the future electricity price. The interest rate for microfinance, including fees, taxes and security deposit, depends of the business and the loan time. The interest rate for loans >24 months varies from 17 – 64 % per year (40). The benchmark interest rate, controlled by the Central bank of Kenya, was in March 2011 5.75%, but has been around 10 % just a few years ago (41).

The electricity price in Kenya is rather low, when compared on an international level. The electricity price in December was 1 SEK/kWh (3).

6 Description and prerequisites of the cases and the suggested systems

This thesis focuses on two different facilities, an operating internet café and an upcoming boarding school. The internet café, named Cyber Relations, is a project driven to generate income for an organisation operating in the slums of Nairobi. The school is a project driven by Swedish students in cooperation with the same organisation that is operating the internet café. This chapter describes the background and approach to the cases. The proposed alternative systems for each case are presented.

6.1 Internet café

In November 2009, six solar panels, with a total peak power of 360 W, were installed at the internet cafe. Each one of the panels was connected directly to charge a laptop with DC current. The laptop batteries were charged during sunny weather, but, due to low battery capacity, the laptops could not be used during cloudy days or after sunset. The battery capacity of one type of laptop was immediately ruined, when it was connected to the panels.

To increase the safety of the system and the possible usage time of the laptops, they were connected to the electrical grid instead. The solar panels are therefore not in operation. The electrical grid of Kenya is rather weak and the internet café suffers from occasional power blackouts. A usual week there might be one to three blackouts. How long time the blackout holds differs, the most common blackout only holds for around 5-15 minutes. Three to four times a month the blackout can last for one whole day. The blackout leads to income loss, but also decreased customer satisfaction (3).

If the internet café could have a back-up energy system that can supply at least the laptops with electricity, (3) believes that the income could increase with 830 SEK per month. The increased income is from the possible occupation during blackouts, but also due to customer satisfaction and trust that there is power at the Cyber Relations.

The present solar power system at the internet café is desired to be complemented, in order to be a functioning backup energy system that won't ruin the laptop batteries (3). It is desired to use the solar panels for electricity backup, at least for a part of the loads, during blackouts in the national grid. If the solar panels can be operational, the amount of electricity demand from the grid will be reduced.

6.1.1 Electricity demand

Cyber Relations consists of six laptops and seven stationary computers. The internet café also has a TV with a Nintendo Wii, a printer, a scanner and a server for the internet connection. The opening hours are 9– 21 everyday and it is often fully occupied from 14 – 20.

The total power consumption usually varies between 600 and 840 W. Of this consumption the laptops and the server consumes about 150 W. The daily consumption for the whole facility varies between 6 and 9 kWh (3).

6.1.2 Installed solar panels

The solar panels, from Kenital Solar, are placed at a brick roof with a south south-west direction and angle of 20°. The electrical specifications (at 25°C, 1000 W/m^2 and AM 1.5) for the panels are:

Peak power (P)	*60 Wp*
Short-circuit current	*4.5 Amps*
Open-circuit voltage	*21.6 V*
Voltage at max power	*17 V*
Current at max power	*3.6 Amps*

The dimensions of the panels are 1200 x 550 mm so the panel area (A_p) is 0.66 m^2 per panel. Each panel consists of 36 mono-crystalline cells that totally cover (A_c) 0.50 m^2.

6.1.3 Suggested backup energy systems

To use the present solar panels for a backup energy system at the internet café, the system must be complemented. Energy storage, controlled by a charge regulator and a power inverter is required. For the internet café four different alternatives have been designed and compared with each other and the *Zero case,* where no investment is done. Each alternative is given a *short name*. The dimensioning of the alternative systems is presented in Appendix G. The different alternatives are:

- *12V*
  - A 12V system with a simple charge controller from Kenital Solar. All the panels are connected in parallel to the *KS 45* charge controller. Two 100 Ah AGM batteries are connected in parallel to a 12 V system. A 300 W 12VDC/220VAC inverter is used. The total cost is 5 000 SEK.

- *24V*
  - A 24V system with a simple charge controller from Kenital Solar. The panels are series connected in pairs. The three pairs are connected in parallel to the *Time K20* charge controller. Two 100 Ah AGM batteries are connected in series to a 24 V system. A 300 W 24VDC/220VAC inverter is used. The total cost is 4 200 SEK.

- *36V*
  - A 36V solar panel connection with a MPPT charge controller and a 24 V battery bank. The panels are series connected in two groups of three panels. The two groups are connected in parallel to the *Morningstar Sunsaver 15 A MPPT Charge Controller*. Two 100 Ah AGM batteries are connected in series to a 24 V system. A 300 W 24VDC/220VAC inverter is used. The total cost is 5 000 SEK.

- *36V Reflectors*
  - A 36V solar panel connection with reflectors attached and a MPPT charge controller that is regulating the charge of a 24 V battery bank. The panels and the reflectors are tilted four times a year as described in Chapter 9.3. The panels are series connected in two groups of three panels. The two groups are connected in parallel to the *Tristar MPPT-45 Charge Controller*. The batteries

are connected in series to a 24 V system. A 500 W 24VDC/220VAC inverter is used. The total cost is 6 800 SEK.

For all the alternatives a switch is installed to make it possible to charge the laptops with power from the grid. The other loads in the facility are connected to the grid, but in case of excess power some of the loads can be connected to the solar power.

A sketch of the proposed system is presented in Figure 17.

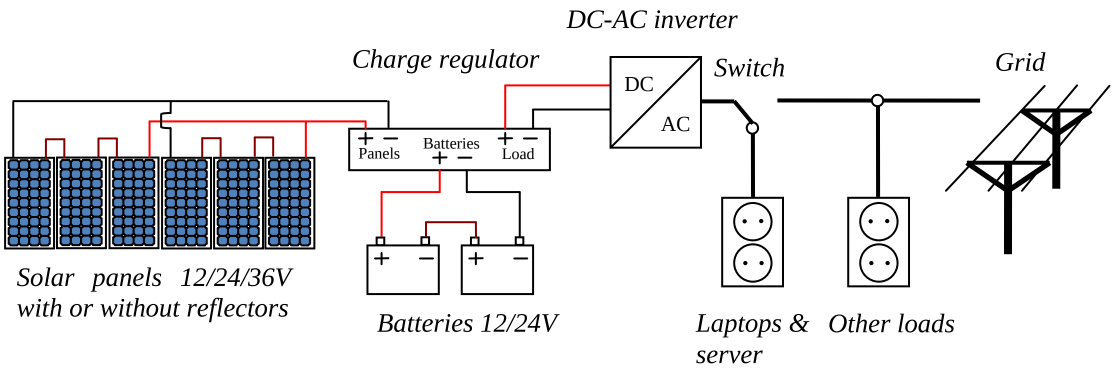


Figure 17 The proposed backup energy system suggested for the internet café.

6.2 Upcoming secondary school

A school facility in a developing country like Kenya differs a lot from school facilities in the western world. The buildings are often very simple and many of them lack electricity. For this upcoming school, named Global Secondary School, sustainability and cost-effectiveness is strived for. To create a good working atmosphere for the students and to enable activities during the dark times, electricity is requested. The Global Secondary School is meant to be a boarding school with about 200 students. The facility consists of ten classrooms, a kitchen, two dormitories and a sanitary building. The classrooms will together cover a size of 500 square meters, the kitchen covers 30 square meters, the sanitary building 20 square meters and the dormitories will have a total area of 400 square meters. The classrooms regular use is during 9.00 – 17.00, Monday to Friday.

The aim for the planned Global Secondary School is to have a cost-effective energy system with a low ecological footprint and a good reliability.

The school facility can be connected to the national grid for a single connection fee of about 5 000 SEK. This is called the *base-case*. The electricity price is then 1 SEK/kWh and it has been increasing a lot the recent year (3). The electricity generation, described in Chapter 3.1.1, shows that oil-fired power plant has been on the margin in the Kenyan electricity market the last years. To see if an autonomous system can be economically competitive, to a grid connection, different alternative systems have been designed and analyzed. Except for the environmental issue, the poor quality of the grid, with occasional power blackouts, is also a reason to investigate is an autonomous system is feasible.

To design an autonomous energy system, that can fulfil the electricity demand at all times, is very costly, since a large energy storage capacity is required (34). For this facility it can be accepted that the lights are reduced to 50 % of its rated power, during periods of low electricity generation. During some days, the charging of ten of the laptops can be allowed to be switched off to decrease the consumption even more. To regulate this, lights are reduced when the storage capacity is below 70 %. The charge for the ten laptops is switched of when the storage capacity is below 60 %. To prevent a state where the loads are switched on and off frequently, the lighting is reset to full power when the capacity is 75% and the all laptops are charged again when the capacity is 65 %.

The lighting, mobile charging and the fans operate with direct current, while an inverter must be used for the other loads. The fans only operate when the batteries are fully charged. Thereby the fans work as a dump load.

6.2.1 Electricity demand

During the regular education time the whole facility is lit up. Two of the classrooms, covering 100 square meters, will be used four hours longer on weekdays and will also be used twelve hours per day on weekends. The kitchen and dormitories will be lit up during four hours in the evening every day. The sanitary house will be lit up 24 hours per day. 15 laptops are supposed to be used during eight hours per day. Loudspeakers should be installed and fans will be operating in case of available extra power. The electricity system should also supply a side business, where mobile phones will be charged. Possible additional equipment is also considered. The electricity consuming equipment will thereby be:

- Lightning for all building during operational time
- 15 computers á 25 W used eight hours every day
- Radio and loudspeaker equipment, used one hour on weekdays
- Charging of 100 mobile phones per day
- Additional equipment, consuming 20 W all year around
- Fans operating in case of additional power

To be able to design a sustainable system the estimated electricity consumption must be well defined. The consumption is defined for daytime (9.00-17.00) and night-time (17.00 – 9.00). The calculations and estimations of the consumption are specified in Appendix H. The electricity consumption is shown in Table 2.

Table 2 Electricity consumption for the school facility during different periods

Consumption	Weekdays 9 – 17 (kWh/day)	Weekdays 17 – 9 (kWh/day)	Weekends 9 – 17 (kWh/day)	Weekends 17 – 9 (kWh/day)
Full power	7.61	2.05	4.26	2.05
50% lighting	5.57	1.31	3.82	1.31
50% lighting & only 5 laptops	3.57	1.31	1.82	1.31

The average consumption is 8.70 kWh per day. The yearly consumption is about 3 200 kWh.

6.2.2 Suggested autonomous energy systems

The dimensioning of the energy system of the school facility varies from the dimensioning of the system for the internet café. The school facility requires a whole system. There is no increased income or other surplus, like in the case of the internet café. The investment of an autonomous system, with free energy generation, must compete with the grid connection fee and its electricity price. Three alternative autonomous systems have been compared with each other and the *grid connection*.

The available area, which can be used for installation of solar panels, is very large in comparison with the electricity demand; therefore a low efficiency panel can be used. The most important is to choose a panel with a low cost per W rated power. It is though important to consider that if reflectors are used efficient panels might be preferred, since they require a smaller reflector area.

As described in Chapter 5.1.2 it the solar panels should dimensioned after the expected generation in July, the month with lowest values of insolation, in order to supply the loads with power all months. The amount of panels required is dimensioned after the average or weekday consumption. The autonomous system consists of solar panels, charge regulator, a battery bank and a power inverter and each system is dimensioned after the method described in Chapter 5.1. Equipment is found on the local market or by international suppliers, which then includes shipping. In all the autonomous systems AGM batteries are chosen due to its long lifetime and high efficiency (26) & (28). MPPT charge controllers are chosen since the efficiency is much higher than the efficiency of a PMW controller. The MPPT charge controller also has the advantage that the power can be fed directly to the load, bypassing the batteries, see Chapter 4.2.3. This results in an even higher efficiency. The dimensioning of the alternative systems is presented in Appendix I. The installation cost is estimated to 1 000 SEK, based on an electrician work fee of 50 SEK/day (3).

The different alternative autonomous systems for the school facility are:

- *Grid connection*
  - The facility is supplied with electricity from the national grid. The connection fee is 5000 SEK and the electricity price is 1 SEK/kWh the first year.

- *Thin film Modules*
  - An autonomous system with 22 pieces of 130 W thin film modules connected in parallel. The amount of panels is dimensioned after the average daily consumption. Six 100 Ah AGM batteries with a *Tristar MPPT-45* charge regulator is used. An 800 W modified sine wave inverter is used. The total cost is 44 000 SEK.

- *Thin film Modules with reflectors*
  - An autonomous system with V-shaped reflectors attached to the 14 pieces of 130 W thin film modules connected in parallel. The amount of panels is dimensioned after the average daily consumption. Six 100 Ah AGM batteries with a *Tristar MPPT-60* charge regulator is used. An 800 W modified sine wave inverter is used. The total cost is 41 800 SEK.

- *Crystalline solar modules with reflectors*

- An autonomous system with V-shaped reflectors attached to the 230 W crystalline solar panels, which are connected in series three by three. The amount of panels is dimensioned after the daily consumption on weekdays, which leads to a higher generation than for the other cases. Six 100 Ah AGM batteries with an *OutBack FlexMax 80* charge regulator is used. An 800 W modified sine wave inverter is used. The total cost is 47 400 SEK.

7 Laboratory work

In this chapter the laboratory work that has been done in the thesis is described. The first part describes how radiation data and theoretical generation from the panels has been critically reviewed, by measuring the $I_{sc,}$ generated by the solar panels at the internet café, during different occasions. The second part describes the method used to measure and investigate opportunities to optimize the generation from existing solar panels. The third part describes the laboratory work with reflectors.

7.1 Measurements of the generated current from the panels

Accurate climate data and technical specifications are required to design a good solar energy system, like described in Chapter 5. In Chapter 3.2.1 data from SWEREA European Commission and Meteonorm shows the daily average insolation for each month (14), (13) and (16). SWEREA presents data of how the insolation varies from day to day (14). Meteonorm gives graphical data of how the insolation varies over the year (16). From this data, shown in Figure 11, the minimal daily insolation for each month is graphically evaluated. The result is presented in Appendix B.

Measurements of the short-circuit current (I_{SC}) and the open-circuit voltage (V_{OC}) has been done, at the installed solar panels at the internet café during periods with different weather.

7.1.1 Measurement of generation during a sunny day

The six panels at the internet café have the same electrical characteristics. To see if this also holds in reality, the I_{SC} and the V_{OC} was measured for all of the panels at the same time. The panels are numbered 1-6 with 1 at the rear and 6 in the front, see

Figure 18 The six solar panel on the roof of the internet café were cleaned to see if it would increase the power output

. The measured values were compared with the specified theoretical values.

To estimate the potential of the panels the short-circuit current from panel 1 and panel 6 was measured every half an hour during a sunny day. At 16.30 it was observed that a tree was shadowing a part of Panel 1. The tree was moving and the shadow was changing.

7.1.2 Measurement of generation during changing weather

In Chapter 3.2.1 it is described how the weather affects the radiation, see Figure 9. In the same chapter it is shown that the expected insolation during days with low radiation, cloudy days with changing visible strength of the shadows, is varying a lot between different data sources. To evaluate which data is most accurate, a measurement of the I_{SC} during a day with changing weather was done. The strength of the shadows is used to give a value of the weather. Figure 18 shows how the shadows changed during the measurement. This gives a figure of how large insolation (Wh/m^2) that can be expected for a full day of a certain weather with that shadow strength.

Figure 17   The generated current was measured during one day of changing weather.

7.2 Optimal installation and maintenance of the solar panels

For a fixed installation of solar panels it is important that the angle of the panels is the optimal for the location. For the installed panels it is important to regularly clean the panels. Analyze was done to see how the tilted attachment of the panels at the internet café affect the generation over the year. A measurement of the I_{SC} before and after cleaning the panels has also been done to see how often the panels must be maintained.

7.2.1 Optimal installation angle

In Chapter 4.1.3 it was described that the incident angle of light affects the generation. As described in Chapter 3.2.2 the sun path differs over the year and that the optimal angle for a fixed solar panel in Nairobi is 1° in a north direction. To see how the expected generation would change if the solar panels are placed in a horizontal location instead of the 20° in a south south-west direction, like the existing panels at the internet café, a web-based modelling tool has been used (13). From this tool the expected power generation each month, for a 1 kW_p solar panel with the two installation angles, are given.

7.2.2 Maintenance of the panels

The six solar panels at the internet café, which were installed in November 2009, had never been cleaned. To see how the current generation was affected by dirt covering the panels a measurement was done. The I_{SC} was measured before and after cleaning the panels and the difference gave a result of the value of maintaining the system. The measurement was done a clear day. The radiation first was measured to be almost constant within the short period that the measurements were done. The voltage from the panels was not measured, since it is the generated current that is directly proportional to the radiation, which is reduced by dirt covering the panels, see Chapter 4.1.4. The difference between cleaned and dirty panels can be seen in

Figure 18 The six solar panel on the roof of the internet café were cleaned to see if it would increase the power output

. The effect of water covering the panel was also tested by pouring water at one of the panels. The I_{SC} was measured for the dry and the wet panel.

Figure 18 The six solar panel on the roof of the internet café were cleaned to see if it would increase the power output

7.3 Reflectors

In Chapter 4.1.4 it was described that reflectors can increase the power generation from a solar panel. To see whether it is feasible to do this at the internet café or at the school facility, laboratory work and calculations have been done.

7.3.1 Reflections from a metal surface

A laboratory test was done to see how a reflector of aluminum increases the I_{SC} for a solar cell. The cell and the reflector, with the same sizes, were aimed towards the light source, both with 45° angle and at the same distance from the light source, see Figure 20.

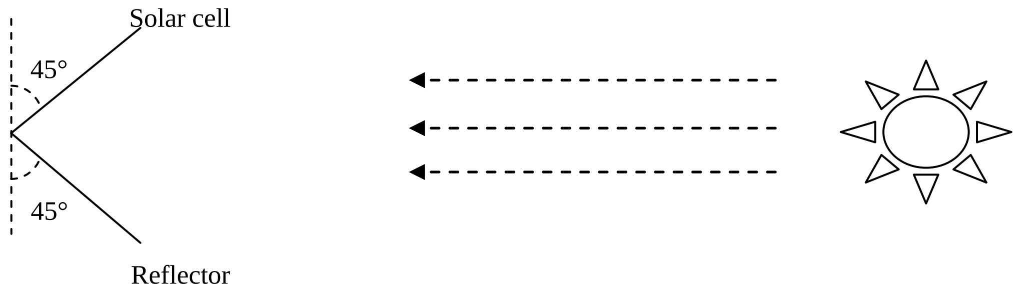


Figure 20 Laboratory test with a reflector and a solar cell.

To see how different angles of the reflector affects the generation, a test was done with the solar cell placed perpendicular against the light source while the aluminum surface was placed at different angles (α), see Figure 21 below.

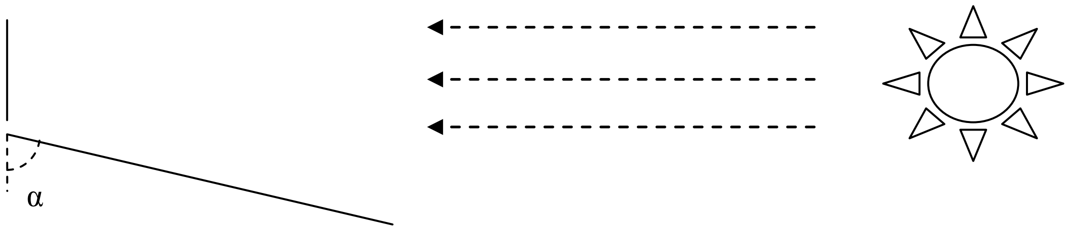


Figure 21   Laboratory test with the reflector attached with different angles.

It should be considered that a lamp was used for the laboratory test. This is not a light source that focuses the light straight towards the solar cell and the reflector. The result can therefore differ a bit from the reality when the sun is the light source. The results are therefore mainly used for the design, to give an idea how different angles of a reflector affect the generated current.

7.3.2 Design of the attachment

The design of the attachment is based on the results given by the articles, described in Chapter 4.1.4, and the result from the laboratory work. The design is also based on the knowledge of the suns movement, described in Chapter 3.2.2, whit a solar height differing 47° over the year. The design of the attachment is described in Appendix F.

8 Data and assumptions for the calculations

The dimensioning and feasibility study of a solar power system is complex and varies between different locations and facilities. For the calculations, data, like climate data and technical specifications has been used, but some of the calculations require assumed values. The used data and the assumptions made for the calculations and dimensioning is presented in this chapter.

8.1 Reflectors

The calculations of how much attached reflectors could increase the generation from solar panels, led to a few assumptions. An assumption was that the reflections (η_{surf}) from the designed attachment will be the same as the reflection measured in the laboratory work, described in Chapter 7.3.1. It is also assumed that the reflection is the same for different incoming angles to the reflector. Though, the angle of the reflected radiation hitting the solar panel is considered in the calculations

In the case of designing the attachment, see Appendix F, an angle and a length of the reflectors had to be chosen. The angle was set to 65°. Different lengths can be chosen, but since the panels often are located at roofs, a stable construction is desired. For the internet café a length of 1.5 meter was chosen, based on the size of the panels. For the case with the school, the length was calculated in order to give the same reflections as for the attachment at the internet café. To calculate the width of the reflectors with Equation 20 in Appendix F, the solar height, that the reflections should be valid for, had to be chosen. From Appendix A and Appendix D it is graphically evaluated that about 85 % of the daily radiation occurs during 9.00 – 16.00. It was assumed to be enough if all the panels are covered by the reflections at this time. The height of the sun at 9.00 is about 30° above the horizon. At 8.00 and 17.00 the height of the sun is about 20°. From Appendix A and Appendix D it is graphically evaluated that about 97 % of the daily radiation occurs during 8.00 – 17.00.

In Chapter 4.1 it is described that a higher working temperature decreases the generation from solar panels. Ahmad and Hussein measured that the surface temperature increased with 10°, for a panel with one reflector (25). It is hard to estimate how much the surface temperature would increase with two reflectors, since it is dependent of many factors. For the calculations an increase of 15° is assumed. The results from the report of Nilsson that the efficiency will decrease with 0.4 %/° C has been used (22).

The cost of the reflector, including installation, was by (3) estimated to 35 SEK/m^2.

8.2 Dimensioning the solar power systems

Data from Meteonorm was used as climate data (16). The absorption efficiency ( ) with the estimated value of 0.974 is used from European Commission (13). The efficiencies used for the equipment in the systems are:

- PMW controller 72 %
- MPPT controller 96 %
- AGM batteries 80 %
- Flooded batteries 75 %

- Inverter 85 %

When a MPPT charge controller is used, all the generated power is assumed to bypass the batteries during periods of low generation, i.e. for the dimensioning of the energy storage. During normal operation it is assumed, for both cases, that 50 % of the energy goes through the batteries ( ), while 50 % supplies the loads with electricity directly. For a PMW controller all the energy is assumed to go through the batteries at all times, based on information from (28). The increased generation, in the case of used reflectors, is included in the system efficiency ( ), causing efficiency higher than 100 %.

In Chapter 5.1.4 it was described that a safety margin must be included when a charge controller is dimensioned. A safety margin for the current ( ) of 1.25 is recommended by Li, (38). The calculations of the increased radiation in the case of using reflectors were dependent of several estimations and reflectors lead to an increased temperature, which also increases the current. Based on this another safety margin of 1.5 for the reflectors ( ) was used.

For the sensitivity analyses, described in Chapter 5.2.3, a 20 % decreased insolation and a 20 % decreased battery capacity has been used.

8.2.1 Internet café

In case of a blackout the solar power system must cover the electricity demand for the laptops during one day. All the laptops are rarely used the whole day, nine hours is more likely according to (3). Nine hours usage means a consumption (of 1.35 kWh, which was used for the dimensioning. The consumption was assumed to be constantly 150 W. Since the power production from the existing panels varies with the weather, the present weather during the days of electricity blackout is affecting the size of the required battery bank. The minimal power production, presented in Appendix E, is valid for a few days per year. The likelihood for the blackout to occur at those days is rather low. Therefore the tenth lowest daily irradiation, that is assumed to occur during a year of data, was used. Figure 11 and Appendix E was used to estimate the tenth minimal generation (, for the six panels, to 500 Wh/day.

In Chapter 4.2.2 it is described that the life time of a lead-acid battery is highly decreased when the battery is discharged to low levels. A DOD of 50% is aimed for, since long lifetimes for the batteries are wanted, but a slightly higher DOD is accepted in the dimensioning.

8.2.2 School facility

If an autonomous energy system is used for the school facility the energy storage most supply the loads with power, during periods with low generation over the whole year. The energy storage is dimensioned after the minimal expected generation and the weekday consumption.

Appendix E shows how the minimal generation varies over the year, showing that the lowest values of April and July are 0.4 Wh per rated W_p, which was used for the *single-day scenario*. In Figure 11 it is seen that the irradiation changes from day to day so it is very unlikely that the values are this low during several days in a row. It is from Figure 11 and Appendix E estimated that the lowest average generation that is likely to happen during a *five-day scenario* gives a daily generation of 1.8 Wh per rated W_p.

It is assumed that the battery bank is fully charged at 18.00 the day before a period with low generation occurs. It is also assumed that the days after a period with low insolation, the panels generate enough power for the loads. A DOD for the battery bank of 80 % is accepted for the occasions with low generation.

8.3 Investment analysis

For the investment analysis the most important estimation is the interest rate and the future electricity price. The investment analysis was done with interest rates of 10 and 20 % and with an increased electricity price of 5 or 10 % per year. The expected solar panel lifetime of 25 years was used for the Net Present Value (NPV) calculations.

The expected lifetime of the equipment also affect the results of the investment analysis. The expected lifetime for the AGM battery is five years and for the flooded type two and a half year. A new charge controller is assumed to be required after 15 years, while the inverter is assumed to last 25 years. The development within this area is assumed to keep the price of those devices at a constant level, which means a lower cost for the future replacements, in the NPV calculation, because of the interest rate.

8.3.1 Internet café

The direct benefit for the internet café, of having a backup system, is the increased income during blackouts. The increased income is estimated to 830 SEK per month for all alternative backup systems. The income is assumed to increase with 5 % per year, due to inflation. Since a switch is connected and the system is flexible, it is assumed that all the generated power can be utilised to decreases the amount of electricity required from the grid.

The generation from the solar panels is assumed to decrease to 95% of the expected generation after five years and to 90 % after twelve years

The decreased generation from the solar panels in the future are not assumed to affect the increased income, since the battery capacity covers the most of the required energy. Though, the increased demand for electricity from the grid, when the generation from the panels is decreased, is included.

8.3.2 School

In case of a grid connection, for the school facility, the fans are assumed to consume 1000 kWh per year, which means a total consumption of 4 200 kWh per year.

The designed autonomous system will lead to reduced lighting and laptop charging during some periods. The electricity grid on the other hand will most likely lead to occasional power blackouts that will affect the whole facility. From a quality perspective, both options are regarded as similar and therefore the quality and performance is not included in the cost comparison.

The decreased generation from the solar panels in the future is neglected in the investment analysis for the school facility. The system is designed after the consumption, including an extra load, see Appendix H, and it is assumed that the consumption can be decreased, by energy efficiency methods, like more efficient laptops and lighting, with the same amount as the generation is decreased.

The monthly fee for the case of a grid connection was included in the electricity price.

9 Results from the laboratory work

In this chapter the results from the laboratory work, done in the thesis, are presented. First, the results of the measured $I_{SC,}$ from the panels at the internet café, are presented. The second part shows the result of tilting and cleaning the panels. The last part shows the results from the laboratory work with reflectors and the results from the calculation of the increased generation with reflectors.

9.1 Generated current from the panels

The results from the measurements of the generated current, from the solar panels at the internet café, are given for a day with sunny respective changing weather.

9.1.1 Power generation during clear weather

The measured generation from the six panels shows that the I_{SC} varies between 3.64 and 4.41 A, while the voltage differs from 17.83 to 18.67 V. Panel 1 and especially panel 2 generate a much higher I_{SC}. The V_{OC} is about the same for all panels, except panel 5 which has a lower V_{OC}.

The results from the measured I_{SC} every half an hour, during a clear day are shown in Appendix D. The results show that the I_{SC} is highly dependent of the solar angle, with high values when the solar angle is close to the normal line perpendicular to the panel. It is seen that the I_{SC} decreases and fluctuates at the time of 16.30, when a tree was shadowing parts of the panel.

9.1.2 Power generation during changing weather

The I_{SC} measurements during a day with changing weather shows that I_{SC} the can vary from 1 to 5 A in less than a minute. Figure 17 shows how the shadow changes when the current varies from 1 to 5 A. Since the current is directly dependent of the radiation it is also given that the insolation during one day of sunny weather is five times higher than during one day with cloudy weather.

9.2 Optimal installation and maintenance of the solar panels

The first part of this chapter shows how the power output varies for different installation angles. The results from the measurement of the generated power from dirty respective clean panels are presented in the second part.

9.2.1 Tilting the panels

The six existing solar panels at the internet café are installed on the 20° sloping roof. The expected power generation for a panel at this location compared to a panel with a horizontal attachment is presented in Appendix C. The result shows that the generation is more than 20 % lower for a tilted panel, during the months May to July. A change to a horizontal installation would increase the total yearly power production with 4 %. The most important is, though, that it would lead to a more constant electricity generation over the year, which is important for a facility with a similar consumption throughout the years.

9.2.2 Cleaning the panels

The result shows that water covering part of the panel, didn't affect the I_{SC} very much at all. And the water dried up very quick due to the hot surface of the panel. The result from cleaning all the panels shows that the generation increases with 5-10 % if the panels are cleaned one year after installation.

9.3 Attaching reflectors to solar panels

The laboratory work shows that a blank aluminum surface increase the I_{SC} (η_{surf}) with 63 %. The results of how the different angles of one reflector increase the generation are shown in **Fel! Hittar inte referenskälla.**.

Table 3 Increase of SCC with reflector at different angles

Reflector angle (α)	Short-circuit current	Increase
No reflector	2.6	-
50°	2.7	4 %
60°	3.0	15 %
70°	3.4	31 %
80°	3.5	35 %

From Appendix F, it is given that a solar panel, with a width of 0.55 m, a reflector with a length of 1.5 m and an attachment angle of 65°, can fully absorb reflections from an incoming solar angle (S) down to -9°. This means that for angles from -9° to 9° reflections from the reflectors on both sides will cover the panels and increase the generation.

Equation 1 and Equation 2 gives the result of the increased radiation for different solar angles. The result is presented in **Fel! Hittar inte referenskälla.**.

Table 4 Increased generation for different solar angles

Solar angle (S)	Incoming angle (E) (Equation 1)	Reflection efficiency (η_r) (4)	Increased radiation (R) (Equation 2)
23.5°	16.5°	0.76	14 %
20°	20°	0.82	18 %
15°	25°	0.88	23 %

10°	30°	0.90	28 %
9°	31°	0.90	74 %
5°	35°	0.91	74 %
0°	40°	0.92	74 %
-5°	45°	0.93	74 %
-9°	49°	0.94	74 %

It can be seen in **Fel! Hittar inte referenskälla.** that the increased radiation is 74 % when the solar angle is within the tolerated angle of 9°. From a web based simulation tool it is shown that this is from 25th of February to the 12th of April and from the August 30th to October 17th, (18).

To be able to utilize the increased radiation from both reflectors throughout the year the installation must be tilted towards the solar path. If the installation is tilted 15° to the south the 15th of October until the 1st of March and 15° to the north the 10th of April until the 1st of September, the panels will be reflected from both reflectors throughout the year.

Since the panels with this tilting are aimed towards the sun, the direct radiation is also increased. From European Commission it is shown that the increased direct radiation due to the tilted panels is 5-11 %, (13). The total increased radiation, at solar noon, is thereby on average about 80 %, every month of the year.

To utilize the reflections for all panels, from 9.00 – 16.00, with a 1.5 meter long (L) reflector at an angle of 65° (α), based on Appendix F, Equation 20 gives that the reflector must be 2.4 meter wider on both sides, than the total width of all panels. The average increased generation over a full day, for all panels, is with Equation 3 calculated to about 76 %.

The surface temperature is assumed to increase with 15° C if reflectors are attached, see Chapter 8.1. This means a decreased efficiency for the solar cells of about 6 %. Which means that the increased output ( ) with attached reflectors is about 65 %.

The total size of each reflector should be 12 m x 1.5 m, which gives a total area of 36 m^2 for the both reflectors. This can be compared with the 4 m^2 that the panels cover, meaning that the reflectors are 9 times larger than the solar panels.

The total cost for the reflectors is about 1260 SEK, which can be compared with the cost of installing additional solar panels of 230 W, which costs about 2840 SEK.

10 Results of the cost and performance analysis

In this chapter, the results from the cost and performance analysis, of the alternative energy system for the two cases, are presented. First, the analysis of the backup energy system, for the internet café, is presented and then the analysis of the autonomous energy system, for the school facility, is presented.

10.1 Analysis and comparison of the backup energy systems

The expected system efficiency, annual generation, backup capacity and robustness of the alternative systems and the *Zero case*, suggested for the internet café, see Chapter 6.1.3, are presented in this chapter.

The efficiency of the alternative systems depends on the chosen devices, as well as the share of the energy that goes through the batteries. The efficiency of the devises is presented in 8.2. The system efficiency, calculated with Equation 9, includes the increased radiation from reflectors, why a value above 100 % is possible. The annual generation for the alternative systems is calculated with Equation 10 and is presented in Table 5.

Equation 11 was used to calculate how long time the laptops and the server can be used in case of a power blackout and low radiation, see Chapter 8.2.1. The results, presented in Table 5, show that the capacity is 8.4 – 9.5 hours with a DOD limited to 50 %. In reality a deeper DOD can be accepted a few times, why the nine hours backup capacity that was requested can be fulfilled for all the alternative systems.

The sensitivity analysis gives a value of the robustness for each alternative system. The robustness is valued by showing the Depth Of Discharge (DOD) that the battery bank will get, in case of a power blackout, if the laptops and server are used nine hours, during a day when the generation is 20 % lower than it was estimated to in the calculation of the energy storage capacity, see Chapter 8.2.1, and the battery capacity is reduced with 20 %. The results are shown in Table 5.

Table 5 System efficiency, expected annual generation, backup capacity and robustness for the alternative energy systems, suggested for the internet café.

	Zero case	*12V*	*24V*	*36V*	*36V Reflector*
System Efficiency	-	49 %	49 %	73 %	118 %
Annual generation (kWh)	0	330	330	500	800
Backup capacity (h)	0	8.4	8.4	9.5	8.8
DOD	-	71 %	71 %	63 %	78 %

The results in Table 5 show that the system efficiency varies a lot between the alternatives. This is because different charge controllers are used. A MPPT charge controller has a higher efficiency, thanks to an optimal operation point, see Chapter 4.2.3. It also have the advantage that the batteries can be bypassed, resulting in even higher system efficiency. The usage of reflectors means a higher radiation than the panels are rated with, why the system efficiency becomes higher than 100 %. The annual generation is directly depending of the system efficiency. The backup capacity is mainly dependent of the size of the battery bank. For the *12V*, the *24V* and the *36V Reflector* alternatives the chosen batteries has a slightly too low capacity, why the backup capacity gets lower than the requested nine hours if a 50% DOD is assumed. The calculation of the robustness shows that all the alternatives will manage to supply the server and the laptops with power for nine hours, even if both the generation and the battery capacity is decreased with 20 %.

10.2 Investment analysis for the internet café

The required investment cost and cost of maintenance has been compared with the benefits from the backup system, which is increased income due to availability and a reduced amount of electricity required from the national grid. The investment is analyzed by calculating the payoff time and the Net Present Value, for the 25 years expected lifetime. The results are shown in Table 6.

Table 6 Investment analysis for the alternative backup energy systems.

	Zero case	*12V*	*24V*	*36V*	*36V Reflector*
Investment cost (SEK)	0	5000	4200	5000	6800
Profit per month (SEK)	0	860	860	875	900
Payoff time	-	6 months	5 months	6 months	8 months
NPV with 10 % interest rate and 5 % increased el. price	0	144 700	146 600	144 500	145 000
NPV with 10 % interest rate and 10 % increased el. price	0	145 500	147 400	145 400	146 100
NPV with 20 % interest rate and 5 % increased el. Price	0	72 100	73 700	72 100	72 200
NPV with 20 % interest rate and 10 % increased el. price	0	72 500	74 100	72 500	72 800

The results show that the NPV of the alternative systems are very similar. This is because the assumed increased income was assumed to be the same for each alternative. The increased income is a far higher benefit than the reduced electricity consumption.

10.3 Analysis and comparison of the autonomous energy systems

The expected system efficiency, annual generation, backup capacity and robustness of the alternative autonomous systems, suggested for the school facility, are presented in this chapter.

For the two alternatives with reflectors attached, the generation will increase with about 65%, see Chapter **Fel! Hittar inte referenskälla.**, resulting in a system efficiency of 121 %. Equation 10 is used to calculate the expected annual generation.

The time when all the laptops will be supplied with power during the *five-day scenario* is used as measure of performance. These values are given by the Matlab calculation, see Appendix L. The results are presented in Table 7.

A sensitivity analysis was evaluated to see how robust the different alternatives are. The result of the reduced lighting, the DOD for the *single-day scenario* and the DOD for the *five-day scenario* is presented in Table 7.

Table 7 Comparison between the alternative autonomous systems.

	130 W panels, 22 pcs	130 W panels, 14 pcs with reflectors	230 W panels, 9 pcs with reflectors
System efficiency	73 %	121 %	121 %
Annual generation (kWh)	4 600	4 800	5 300
Laptop charge *five-day scenario*	8 h	8 h	18 h
Reduced lighting	36 %	28 %	9 %
DOD single-day scenario	84 %	83 %	82 %
DOD five-day scenario	126 %	115 %	84 %

The results for the *single-day scenario* show that the system can withstand a lower insolation. Since the system reduces the lighting and computer charge when the battery capacity gets low, the DOD at the end of the scenario is about the same for all alternatives.

The results for the *five-day scenario* with reduced insolation show that the batteries for the two systems with 130 W modules will be fully discharged. In reality the charge controller will cut the entire load when the batteries are almost fully discharged. From the Matlab calculations it is seen that this occurs the night between the forth and the fifth day of low generation.

10.4 Investment analysis for the school facility

The result from the investment analysis of the three alternative autonomous systems and the grid-connection is shown in Table 8. The payoff time is presented together with the Net Present Value, with different interest rates and future electricity price, for the 25 years expected lifetime.

Table 8 Investment analysis for the alternative autonomous energy systems and the grid-connection.

	Grid-connection	130 W panels, 22 pcs	130 W panels, 14 pcs with reflectors	230 W panels, 9 pcs with reflectors
Investment cost (SEK)	5 000	44 000	41 800	47 400
Payoff time	-	13.6 years	13.3 years	14.6 years
NPV with 10 % interest rate and 5 % increased el. price	- 71 700	- 56 800	- 54 800	- 60 600
NPV with 10 % interest rate and 10 % increased el. price	- 120 500	- 56 800	- 54 800	- 60 600
NPV with 20 % interest rate and 5 % increased el. Price	- 39 000	- 49 400	- 47 200	- 52 900
NPV with 20 % interest rate and 10 % increased el. price	- 54 100	- 49 400	- 47 200	- 52 900

11 Discussion and analysis

In this chapter the method used for dimensioning and results of the thesis is discussed. The discussion involves; climate data, solar power for electricity generation, method used for the dimensioning, economic results and the practical usage of solar power in Kenya

11.1 Solar power for electricity generation

One important result from the analysis of the solar power systems is the low system efficiency. For a system without charge controller or with a simple PMW controller system efficiencies of below 50 % is achieved. This is when it is assumed that all the available energy can be utilised. In an autonomous system with varying consumption and limited energy storage, a part of the generated energy must be consumed in a dump load.

In this thesis it has been shown that the usage of reflectors can increase the generation a lot, the same results have been shown in two other studies (25) and (24). However, reflectors are rarely seen in solar power systems. One reason can be that it is a complex attachment where the angles must be correct for the location. It is of great importance that the operator is well educated about the system and understands the importance of maintenance. If the attachment is not tilted correctly the reflectors will, instead of increasing the generation, shadow the panels.

The shadow effect can be a severe problem to solar power systems, especially when the panels are series connected, since all the panels in the series will be affected by the shadowing of one cell. The same holds for dirt covering the surface of the panels. If the panels instead are connected in parallel, it is important that panels with the same specific voltage are used. Otherwise the power output from the set of panels will be decreased.

The solar panels at the internet café were installed in November, at this time the optimal location were between 15° and 20° in a south direction. The roof is tilted 20° in a south south-west direction, therefore it the operator Okong’o thought it seemed like an optimal installation to place the panels with this angle. However this leads to reduced generation during other months. This highlights that it is important to consider the sun path over the whole year when solar panels are installed. It is also important to investigate if the consumption differs between the months, since if, for example, the consumption is high during one period of the year, the panels might preferably be placed at the optimal slope for those months to get a good result.

11.2 Radiation data

When an energy system based on solar power is dimensioned, accurate radiation data is required. Three databases have been investigated in this thesis, showing that data for the same location can differ a lot. In Chapter 9.1.2 it is shown that the power production is highly dependent on the weather, with much lower radiation during cloudy days. Figure 9 also shows that the solar radiation is much lower for cloudy weather, than for clear days. According to this it seems like the data from SWEREA (14) and European Commission (13) highly overestimates the solar radiation during cloudy days. Even if accurate data from one year is found, it is also important to consider climate change and normal climate variations from year to year.

11.3 Methods used for the dimensioning

During the design of the systems a constant consumption over the year was assumed. In reality this seldom is the case.

For the case of the internet café, it is assumed that all the generated power can be utilised, since a switch is installed and the facility has other loads, which together with the laptops are consuming more power than the maximal generation. This means a high demand on the operator to switch from grid power to solar power, when the generation is high and back to the grid power when the generation is low. So in reality generated energy might be lost, if the operator does not fulfil this task perfectly. For the internet café the increased income is the most important aspect, therefore an overestimation in the benefits from the reduced electricity bill was not assumed to affect the economic result to a large extent.

For the dimensioning of the battery capacity the tenth lowest radiation value is used, this means that for some of the years the blackout will occur during a day with lower radiation, the backup capacity will be lower. However, the result from the sensitivity analysis, see Chapter 10.1, shows that a reduced radiation only leads to a deeper DOD and that the laptops still can be used.

To compare an autonomous system based on solar power with a grid connection, an investment analysis and a performance analysis should be evaluated and weight with each other. To make a proper performance comparison, accurate data specified or each day is required. In that case an analysis can be done; of how many days the battery capacity will reach the level where the loads are disconnected by the charge controller. This result can be compared with the estimated amounts of blackouts that will occur in the grid. This gives a good comparison of how often the two types of systems will lead to lack of electricity supply. A price can be set on the blackout-time and it can be included in the investment analysis. Daily data is available from (14), but since it overestimates the minimal generation, the result would not have been accurate.

An eventual expansion of this thesis could include a more detailed performance-versus cost- analysis.

In this thesis it has been assumed that the performance is about the same for the autonomous system, with frequent reductions in lighting due to low insolation, and the grid connection, with occasional power blackouts affecting the whole facility. Because of this and since accurate data is not available, the performance was excluded from the investment analysis. Instead a separate cost analysis and performance analysis was evaluated.

For the case of the autonomous system the expected decreased generation from the solar panels was neglected. This leads to a lower supply to the loads in the future. It was instead assumed that more energy efficient equipment in the future is equal to this loss. The autonomous system with nine 230 W solar panels is quite hard to complement with an extra panel, since ten panels requires a new order of interconnection. This leads to other current and voltage levels from the set of panels, why the charge controller won’t suit for the system. An option is to change the whole system after 15 years, the end of the controller's technical life time. In the systems with 130 W panels, all panels are connected in parallel, why an extra panel might be installed in the future to cover the decreased generation from the existing panels. It should though be considered that the development of solar panels goes fast, why panels of the future might not be suitable to use with today's panels due to different voltage levels. Future work could include prospects of the energy system in the future.

11.4 Results from the economic study/analysis of the facilities

The result from the economic analysis shows that it should be attractive to use a solar power system as a backup system to increase the income. It is hard to compare the economic result with other studies, since the increased income is rather specific for this case. In 2010, Svensson & Suazo Farina reported that investing in solar power systems for small business in Tanzania, which can be compared with this case, can be a very feasible option, (42). If the internet café could invest 4 200 SEK on their existing solar power system, it could be operating and act as a backup system again. It would be a robust system, with a very low pay-off time with very good NPV results. It is important that the operator is well informed about the advantages of the system and how to control and maintain it. A saving account must also be started for future change of batteries etc. In developing countries investments with low pay-off time is often requested. In many cases lack of capital and opportunities to lend money is a big problem. The *24V* alternative has the lowest investment cost and payoff time and the highest NPV for all cases. The reliability and performance is slightly higher for the *36V* alternative.

In the case of the upcoming school facility, the results from this thesis have showed that, according to the NPV method, it is economically feasible to invest in an autonomous energy system, instead of using the national grid. This is true for all the assumed cases except for the case with an interest rate of 20 % and an increased electricity price of 5 %. This would be the case for many facilities in locations with similar or larger levels of solar radiation. The economic results are very good compared to other studies. In 2009, concluded that grid-connected solar panels are feasible if the electricity price is over 1.5 SEK/kWh (1). In their study the expected yearly insolation was set to 1 840 kWh/m^2, the inflation rate used was 3 % and the interest rate 4.5 %. The result from this thesis shows that the autonomous system is economic feasible for higher interest rate and a lower electricity price. The main difference is that the system in this thesis uses more recent and cheaper panels, the installation cost is lower and the insolation is higher. The electricity price is also assumed to increase more in the case in this thesis than in the study of Kornelakis and Koutroulis (1). The rather long payoff time can though be a drawback for investing in such an autonomous PV system.

For an autonomous system it is important that the consumption can be regulated and that it is rather constant throughout the year, to avoid expensive storage capacity.

The future electricity price is of great importance for the results of the feasibility study. With high development rate and decreasing oil reserves it is most likely that the electricity price will increase more than the assumed increase of 5 % per year.

In the NPV calculations, it was assumed that the spare parts, like batteries, will have the same price in the future. This leads to very low NPV for batteries that are required in a distant future, since the assumed interest rate is high. If the price of spare parts is assumed to increase as much as the interest rate, the feasibility of the autonomous energy systems would have been lower.

11.5 Using solar power systems for facilities in Kenya

Many small scale energy systems have been installed in Kenya, often by organizations. However lots of them are not operating at all or not operating in a satisfying way. During the field study of this thesis, many donated systems were seen that were not in operation. This is also a conclusion that Nieuwenhout et al. presented in their report (2). The problem is often the communication between the planner and the operator. The energy system must be adapted to the specific facility and it is important that the consumption is well defined. The operator or manager of the facility must have a good knowledge about how the system works. Another important part is the finance. In some cases, a renewable energy system at a facility is financed by someone else then the person that is operating the facility. If no finance is bound for maintenance, the system will most likely collapse within a few years. If the system is aimed to gain income for the facility, a part of the increased income must be saved for future maintenance of the system.

In the case of the internet café, the knowledge of the planner and installer was insufficient. The panels were connected directly to the laptops and no finance was bound for changing the batteries of the laptops, which quickly lost its capacity. It was not the operator of the facility’s idea to install the solar panels and there was none of the finances of the facility that were invested in the solar power. When the system did not work satisfying, they had neither finance nor knowledge to develop the system. Since this is the case for many facilities, it might be wise to develop the existing systems, with controllers, batteries and education in maintenance, instead of investing in new expensive systems in the country

It can be discussed if the installation of solar power systems, instead of using the national grid, leads to global reduction or increase of greenhouse gas emissions. The electricity generation for the national grid in Kenya is mainly based on renewable energy sources. However, the oil fired power plants has been on the margin in Kenya the recent years. High oil prices and an increased electricity usage will most likely lead to investments in alternative power sources, like hydro, wind and geothermal power. Hence it is questionable how much emissions an increased electricity usage leads to. A solar power system, which is decreasing (or in the case of the future school facility is avoiding an increase) the electricity usage from the grid, also means high energy consumption during the production of the panels and other devices. The solar panels are often produced in Germany or U.S., countries with a large share of coal power in the energy system. It is difficult to invest in a totally sustainable energy system in today’s society if the whole life cycle of every device is to be considered. However, investing in solar power at a school facility would enhance the students’ knowledge and interest in sustainability, which leads to a larger ecological profit than the system itself.

In Chapter 3.2, it is described that Nairobi gets among the lowest levels of solar insolation on a national level. This means that solar power is even more feasible in other parts of the country. The results from the investment analysis of the autonomous energy system for the school facility can be used for other facilities, with comparable energy consumption, in Kenya or in countries with similar, climate data, electricity price and interest rate. School facilities have a rather low energy demand during night-time, when the solar panels not are generating power, which leads to a low demand of short-term storage of energy. The energy demand is also rather constant over the year and few high consuming loads are used for school facilities, compared with i.e. small business where high power loads in forms of machines might be used.

12 Conclusions

The objective of this thesis was to design and present PV systems, in form of a backup energy system to an operating internet café and an autonomous energy system to an upcoming school facility. An investment analysis was used, in order to compare alternative systems and to show whether a solar PV system can be a feasible alternative to a grid-connection. The conclusions of the results in the thesis show that, if the facility is connected to a weak grid, an autonomous system can be a feasible supplement, in form of a backup energy system. If the backup system leads to enhanced business the investment is very cost-effective. For an upcoming facility an autonomous solar power system is a feasible option to the grid, if the electricity price is assumed to increase with the same rate as the assumed interest rate for the investment.

Another objective was to investigate whether it is economic advisable to attach reflectors to solar panels to increase the power generation. The result from this thesis shows that the expected yearly generation is increased with 65 % if V-shaped reflectors are attached to a set of solar panel and the attachment is tilted four times a year, to follows the solar path. The required reflectors are nine times larger than the panels. The cost is estimated to less than 50 % of an alternative with additional panels instead of reflectors, why it is very feasible in a system with a high investment cost for solar panels. However, in a whole energy system the benefit of using reflectors is not that large. In the case of the school facility 2 200 SEK of the total 44 000 SEK investment, can be reduced if reflectors are used.

To get a robust backup energy system for the internet café, the existing solar panels must be complemented with a charge controller, a battery bank and a power inverter. The recommended system is the *24V* system, since it is the most economic alternative, with a payoff time of about 5 months.

The sensitivity analysis shows that the recommended backup system can withstand changed weather conditions, or reduced power generation, which only leads to a lower benefit from the reduction of the electricity bill. In this case, however, the main benefit of the backup system is the increased income, which is not affected by a slightly reduced generation.

An autonomous solar power system for the upcoming school facility, instead of a grid connection, is economically feasible if the interest rate is 10 % or if the interest rate is 20 % and the annual electricity price increase is 10 %. The autonomous systems presented in this thesis lead to reduced lighting and computer charge during some periods over the year. In comparison, a grid connected system in Kenya would lead to occasional power blackouts, affecting the whole facility.

The result from this thesis shows that a system with attached reflectors is preferable. The system with fourteen 130 W panels with attached reflectors is the most cost-effective option. The system with nine 230 W solar panels, dimensioned after the high weekday consumption, leads to a higher reliability and performance than the system with fourteen 130 W solar panels, dimensioned after the lower average consumption. The 230 W system costs 47 400 SEK compared with 41 800 SEK for the 130 W system. For this kind of facility a reduced lighting or a reduced laptop charging during short periods over the year is not considered as a major problem, why the least expensive system with 130 W panels is recommended.

The recommended set of panels are 14 pieces of the 130 W Micromorph Tandem Thin Film Solar Module. Reflectors are attached on both sides of the panels, see Figure 1. The attachment should be installed with an angle 1° north, but it should be tilted manually four times annually, to follow the solar path. A charge controller regulates the charging of six 100 Ah AGM batteries. An inverter is used to supply some of the loads with alternating current, while other loads are using the direct current generated by the solar panels. The total investment cost of the system is 41 800 SEK, which is less expensive than a grid-connection if the assumed interest rate is 10 % and the increased electricity price is at least 5 % or if the interest rate is 20 % and the electricity price is assumed to increase with 10 % or more.

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Appendix A – Global Horizontal Radiation

The global horizontal radiation (W/m^2) for Dagoretti in Nairobi, is presented in Figure 22 to Figure 33 below. Data between the hours 7-19 during the first five days of each month is used. The data was recorded at the year of 2000 (14).

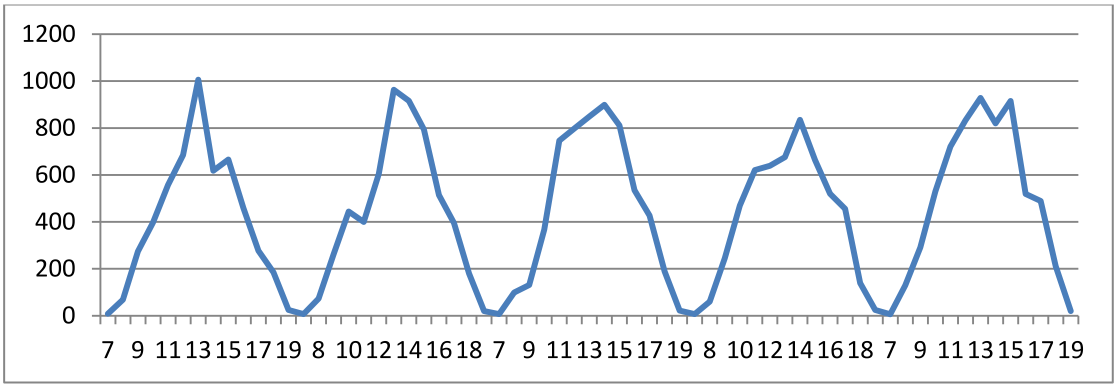

Figure 19   Global horizontal radiation (W/m^2), January 1st to 5th .

Day	1	2	3	4	5	Av. 1-5
Wh/(m^2)	5 225	5 573	5 880	5 356	6 413	5 689

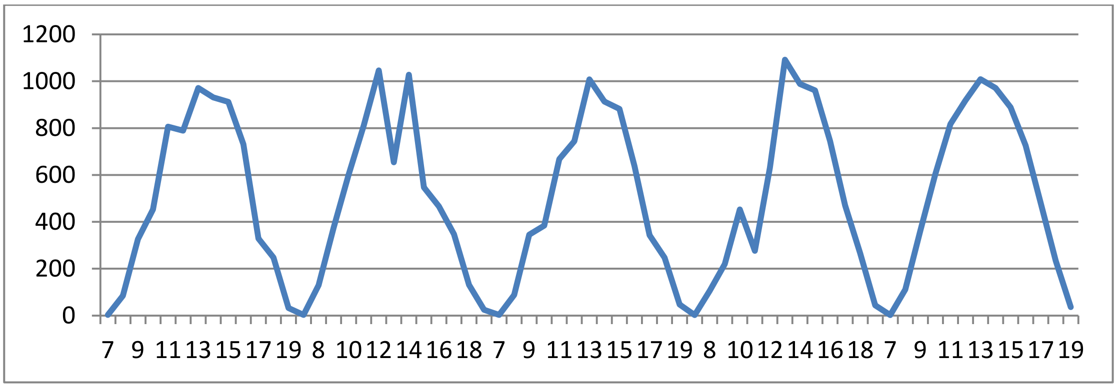

Figure 20   Global horizontal radiation (W/m2), February 1st to 5th 2000.

Day	1	2	3	4	5	Av. 1-5
Wh/(m^2)	6 616	6 165	6 310	6 254	7 160	6 501

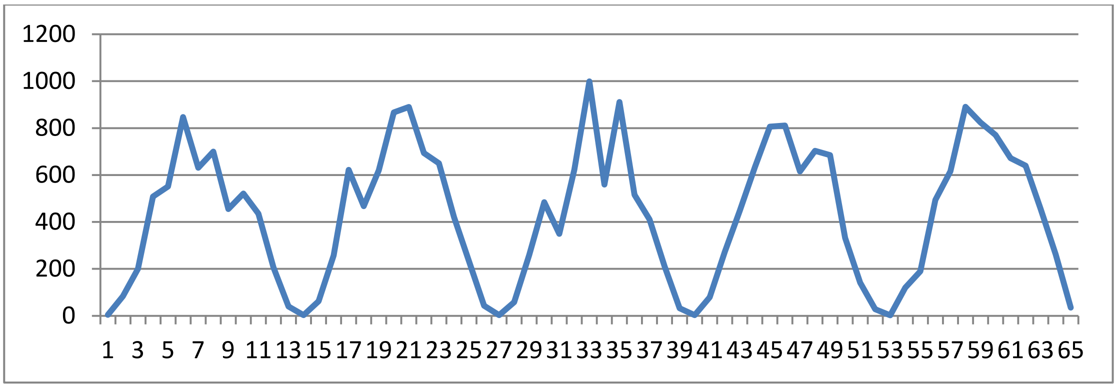

Figure 21 Global horizontal radiation (W/m2), March 1st to 5th.

Day	1	2	3	4	5	Av. 1-5
Wh/(m^2)	5 181	5 828	5 415	5 556	5 971	5 990

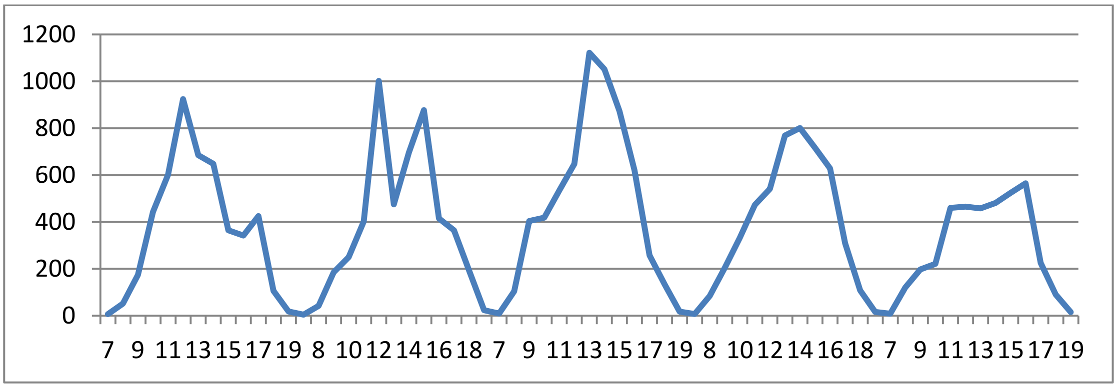

Figure 22 Global horizontal radiation (W/m2), April 1st to 5th.

Day	1	2	3	4	5	Av. 1-5
Wh/(m^2)	4 787	4 928	6 191	4 988	3 829	4 944

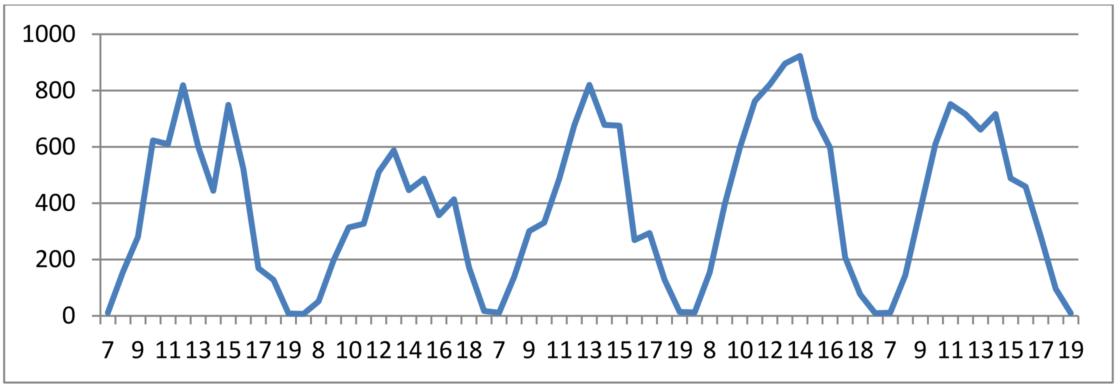

Figure 23 Global horizontal radiation (W/m2), May 1st to 5th.

Day	1	2	3	4	5	Av. 1-5
Wh/(m^2)	5 117	3 889	4 823	6 154	5 323	5 061

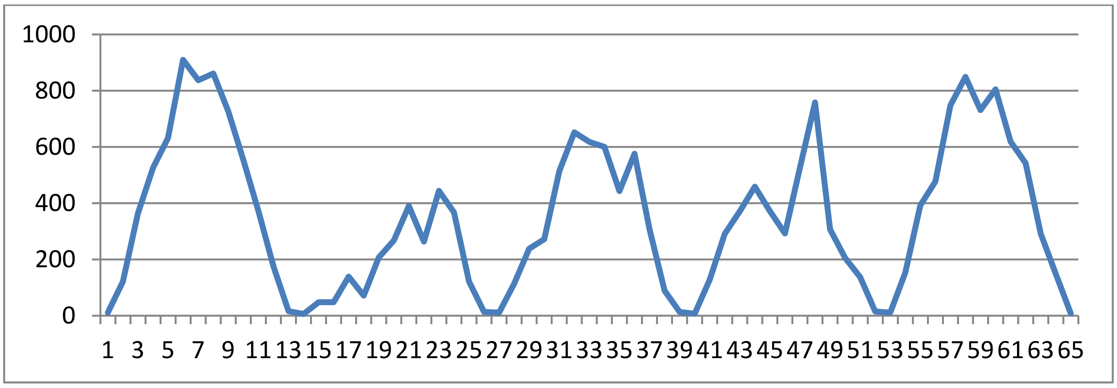

Figure 24 Global horizontal radiation (W/m2), June 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	6 103	2 384	4 447	3 869	5 776	4 516

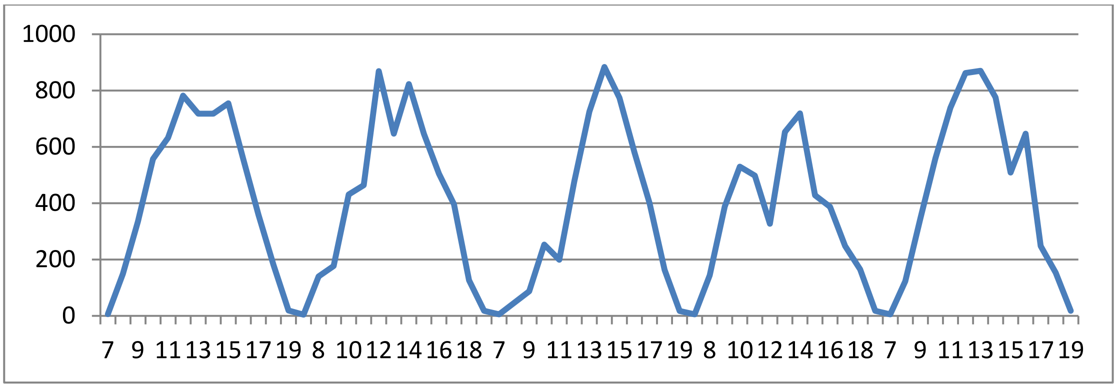

Figure 25 Global horizontal radiation (W/m2), July 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	5 766	5 246	4 611	4 510	5 854	5 197

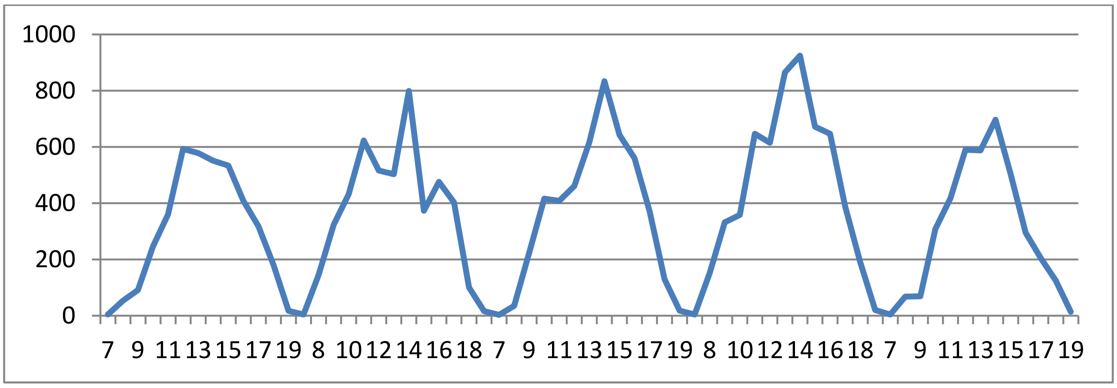

Figure 26 Global horizontal radiation (W/m2), August 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	3 934	4 713	4 720	5 817	3 884	4 613

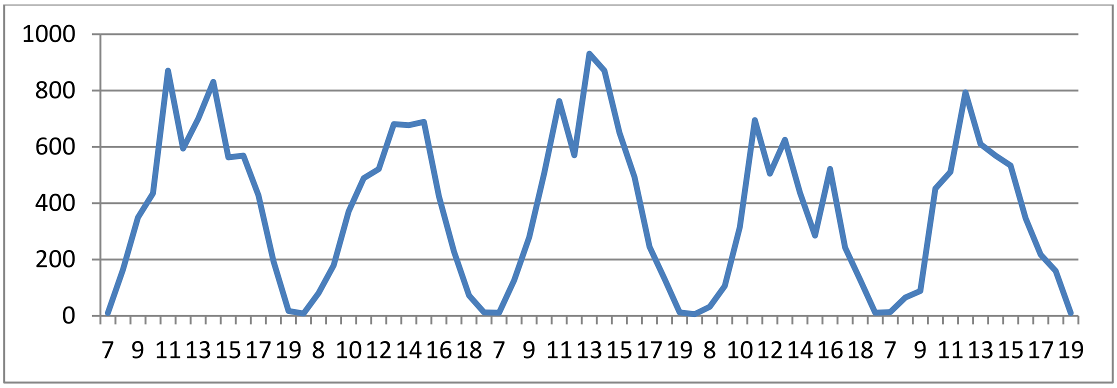

Figure 30 Global horizontal radiation (W/m2), September 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	5 724	4 432	5 589	3 909	4 368	4 804

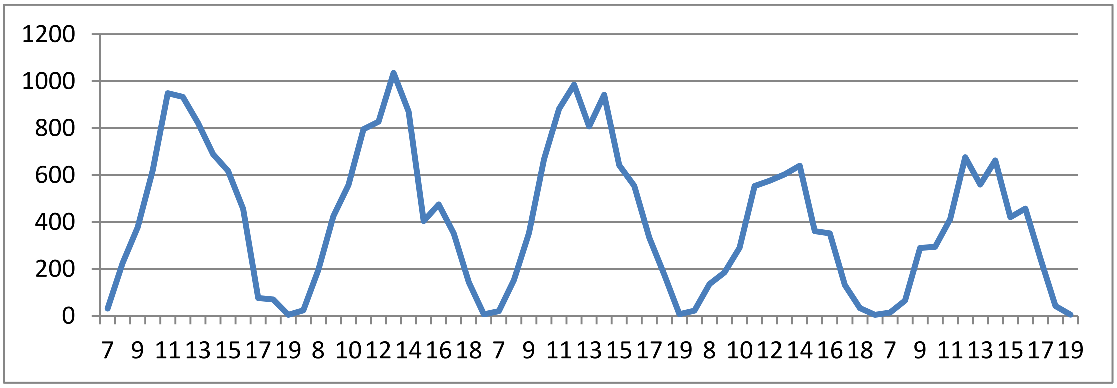

Figure 31 Global horizontal radiation (W/m2), October 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	5 869	6 107	6 519	3 884	4 139	5 304

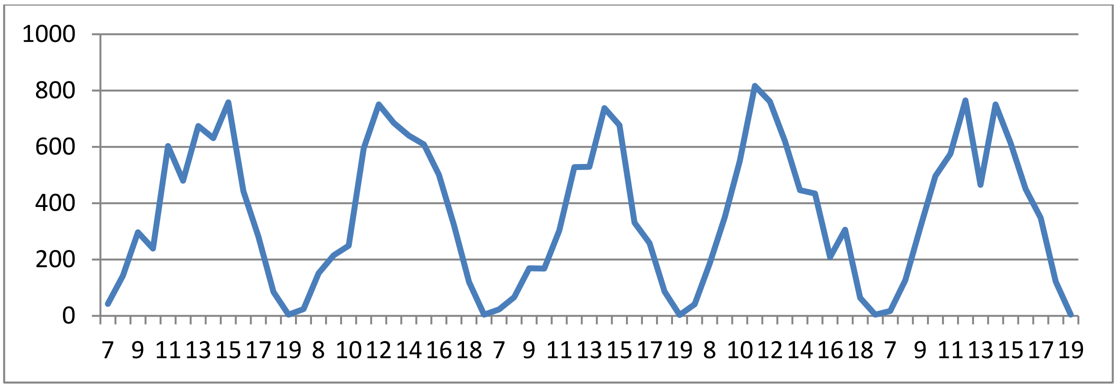

Figure 27 Global horizontal radiation (W/m2), November 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	4 679	4 866	3 879	4 787	5 047	4 652

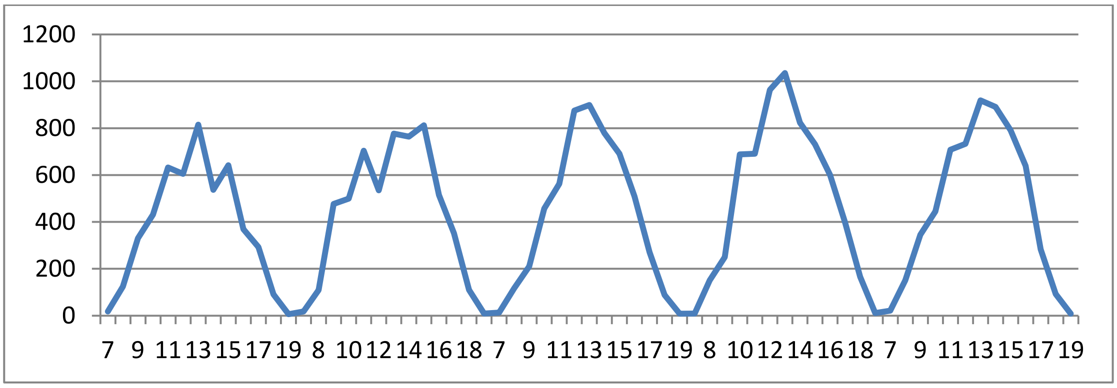

Figure 28 Global horizontal radiation (W/m2), December 1st to 5th.

Day	1	2	3	4	5	1-5
Wh/(m^2)	4 893	5 680	5 480	6 516	6 026	5 719

Appendix B – Minimum daily insolation for Nairobi

Table 9 shows the minimal expected daily insolation for Nairobi, which was graphically evaluated from (16).

Table 9 Minimum insolation [Wh/(m^2 day)] (16).

Month	Minimal insolation Wh/(m^2 day)
January	1900
February	1700
March	1700
April	400
May	700
June	800
July	400
August	1200
September	1200
October	1600
November	1400
December	1400

Appendix C – Power production for a horizontal respective a tilted solar panel

The variation in power generation between a horizontal and a 20° tilted solar panel, in a south south-west direction, is shown in Table 10. The values comes from a web-based design tool from (13).

Table 10 Estimated daily power production (Wh) for a horizontal and a south south-west 20° tilted solar panel with a rated power of 1 kWp in Nairobi (13).

Month	Wh/day 20° south south-west location	Wh/ day horizontal location	Horizontal/tilted
January	5480	5040	0,92
February	5540	5350	0,97
March	4920	5120	1,04
April	4010	4500	1,12
May	3350	4010	1,20
June	2850	3510	1,23
July	2660	3190	1,20
August	2990	3380	1,13
September	4110	4390	1,07
October	4600	4580	1,00
November	4650	4360	0,94
December	5290	4800	0,91
Year	4200	4350	1,04

Appendix D – Current and voltage generated by the solar panels at the internet café during one day

The measured I_{SC} and V_{OC} generated by the panels at the internet café is presented in Table 11 The short-circuit current during one day

Table 11 The short-circuit current during one day.

Time	SCC of panel 1 (Amps)	OCV of panel 1 (V)	SCC of panel 6 (Amps)	OCV of panel 6 (V)
09.00	2.38	N.A	2.28	N.A
09.30	2.98	N.A	2.84	N.A
10.00	3.54	N.A	3.29	N.A
10.30	3.88	N.A	3.64	18.88
11.00	4.36	18.48	4.18	18.46
11.30	4.63	18.46	4.44	18.37
12.00	4.87	18.18	4.70	18.34
12.30	4.85	18.44	4.68	18.37
13.00	4.81	18.52	4.65	18.39
13.30	4.80	18.46	4.64	18.35
14.00	4.63	18.54	4.50	18.47
14.30	4.45	18.63	4.32	18.45
15.00	4.15	18.58	4.04	18.63
15.30	3.71	18.82	3.67	18.76
16.00	3.33	18.70	3.30	18.62
16.30	1.39 - 2.49	19.08	1.03 – 2.34	19.06
17.00	0.68	18.22	0.69	18.28
17.30	0.49	16.5 - 16.9	0.43	17.4
18.00	0.23	14.7	0.23	16.3

Appendix E – Expected daily power production at the internet café

The expected daily power generation from the six solar panels at the internet café was calculated with Equation 6. The result is presented in Table 12.

Table 12 Expected minimal and average power production (Wh/day) from the six solar panels at the internet cafe with a horizontal attachment.

Month	Minimal production	Average production
January	670	2 260
February	600	2 320
March	600	2 230
April	140	1 850
May	250	1 630
June	280	1 510
July	140	1 340
August	420	1 400
September	420	1 870
October	560	1 968
November	490	1 850
December	490	2 120
Year		1 860

Appendix F – Design of an attachment of reflectors

As described in Chapter 4.1.4, there are different ways to attach the reflectors. In the case of the internet café it is possible to tilt the panels and the reflectors but it must be a stable and reliable construction. The chosen attachment was a V-shaped, with one reflector at each side of the panel, see Figure 34. The movement of the sun is from east to west so the panels with the reflectors must be placed in an east to west direction so that the reflectors never shadow the panels.

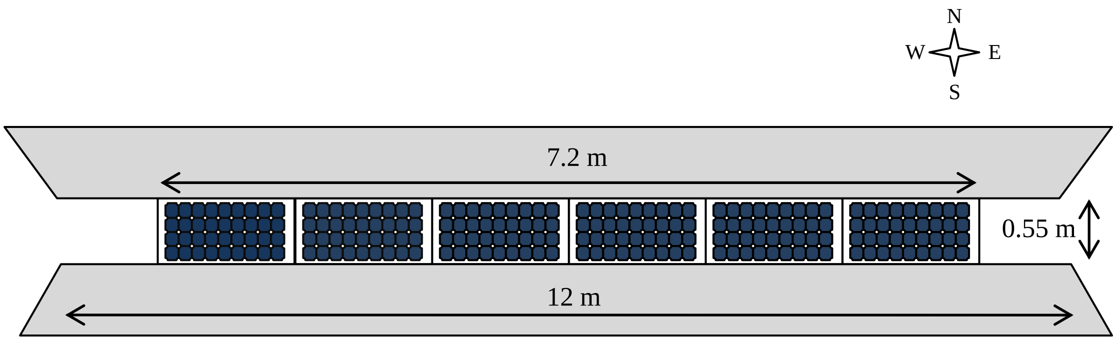

Figure 34   Proposed attachments of reflectors for the solar panels at the internet café.

In Chapter 3.2.2, the solar position for Nairobi is described. Since Nairobi is located 1° south of the equator an angle of 1° towards north is optimal for the solar panel. This angle is referred as the *base angle*. The suns location at solar noon varies with 47° over the year. **Fel! Hittar inte referenskälla.** shows that a large angle (α) is preferred to get a large increase in the generation. A larger angle though means that a longer reflector is required since the whole panel must be covered with the reflected radiation to gain from it. For the internet café a reflector with a length of 1.5 meter was chosen. A too large angle, for a fixed attachment, also means that the reflector will act as a shadow, during some months, when the solar height differs from the *base angle*. For a fixed attachment the largest possible angle is due to the solar path: 90 - 23.5 = 66.5°. For simplicity α = 65° are used in the calculations. This also gives a tolerance for the attachment of the reflector. The fixed attachment is presented in Figure 1 in Chapter 2.

The suns position varies over the year, the length and the angle of the reflector decides for which months the reflection will cover the whole panels. A calculation was done to see which span of the solar angle the designed reflector can operate in.

Geometrical theory gives Equation 15 – 19.

(15)

(16)

(17)

(18)

(19)

The equations above are valid at solar noon. To get advantage of the reflectors the reflected solar radiation must cover the whole panel, otherwise shadow effects will occur. The reflectors must therefore be wider (than the solar panels, see Figure 34. The length and angle of the reflectors as well as the solar height (*h*) decides how wide the reflectors should be. Equation 20 was geometrically developed to calculate how much wider the reflectors must be, than the set of panels.

(20)

For the case of the school facility the panels are wider (b_2). This means that a larger reflector (L_2) is required to give the same yield as for the internet café. The required size is calculated by Equation 21

(21)

Appendix G – Dimensioning a backup energy system for the internet café

Four alternative backup energy systems, *12V, 24V, 36V* and *36V Reflectors,* for the internet café are dimensioned.

Expected power generation

To calculate the expected power generation from a solar panel, with data of the insolation per area, the efficiency was calculated. With Equation 5 it is calculated that the six solar panels at the internet café has an efficiency ( ) of 9.1 %. The total peak power is 360 W.

Solar data for the calculation of the minimal expected production was taken from (16) see Appendix B. Data from (13) has been used when mean values for expected power production is done.

Equation 6 is combined with data from Table 1 and Appendix B to calculate the minimal and average expected power production for the six solar panels if they are placed at a horizontal location. Appendix E shows the results for each month. The results show that the minimal generation can be as low as 140 - 300 Wh/day during the months of April – July. The rest of the year the minimal generation is about 500 Wh/day. The mean value is in the range of 1.3 – 2.3 kWh/day.

Dimensioning the required energy storage capacity

A backup energy system based on solar power requires energy storage. As described in Chapter 4.2, the deep cycle lead-acid batteries are the most common storage technology for small PV systems. The internet café facility has the possibility to place the batteries in a ventilated space, which is required for the wet types.

The batteries available at Kenital Solar are 12 V deep-cycle lead-acid batteries. The flooded batteries are available with the capacities 45, 70 or 100 Ah. The specified capacity is for a 20 hours discharge rate. There are also sealed AGM batteries available with rated capacity of 100 Ah and 200 Ah, with a ten hours discharge rate. The capacity with 20 hours discharge rate is though 111 respective 226 Ah for this type of battery. For the 100 Ah batteries the price is 1 080 SEK for the flooded and 1 580 SEK for the AGM type. The 70 Ah flooded battery costs 830 SEK and has a rated capacity of 64 Ah during at 10 hours discharge. The advantages with the AGM battery are that the expected life length is about the double and the efficiency is higher.

The required energy storage capacity for the internet café is given by Equation 7. The efficiency of a PMW charge controller is 72 %, resulting in a required capacity, for the *12V* and *24V* systems, of 217 Ah for a 12 V battery. If a MPPT charge controller, with 96 % efficiency is used, the required capacity gets 185 Ah. If reflectors are connected to the panels, like in the *36V Reflectors* alternative, the required storage capacity gets 133 Ah. The discharge rate is ten hours. Two 100 Ah AGM batteries are used for the three alternatives without reflectors, resulting in a slightly too low capacity for the *12V* and *24V* systems. Two 70 Ah flooded batteries are used in the *36V Reflectors* alternative, also resulting in a slightly too low capacity since the rated capacity is 64 Ah with a ten hours discharge.

The charge controller

To prevent the batteries form overcharging or deep discharge a charge controller is also required. Kenital Solar offers charge controller of sizes up to 45 A. All their controllers operate with PMW shunt, which means the system voltage must be the same for the whole chain. In Chapter 4.2.3 it was described that this type of charge regulator operates at a too low voltage level, which means a reduced generation with about 24 %. The overall efficiency for the charge controllers from Kenital is then about 72 %. Other charge controllers with MPPT can operate with a high input voltage from the panels and use a low output voltage for the batteries. One type of MPPT charge controller is the *Morningstar Sunsaver MPPT Charge Controller* (42). This charge controller is compatible with three panels connected in series, which means a maximal current of 11.2 Amps. The controller is rated for 15 Amps. The efficiency is dependent of the power level but an average value of 96 % is valid.

The charge controller must be capable of handling the generated currents from the set of solar panels. Equation 8 is used to calculate the rated current. The required capacity and a suitable controller for the different alternatives is presented in Table 13

Table 13 Charge controller for the alternative systems (28) & (43)

	12V	*24V*	*36V*	*36V Reflector*
Type of controller	PMW	PMW	MPPT	MPPT
Rated current (A)	33.8	16.9	11.3	29.4
Suitable controller	*KS45*	*Time K20*	*Morningstar Sunsaver MPPT*	*Tristar MPPT-45*
Efficiency	0.72	0.72	0.96	0.96
Cost (SEK)	1 540	750	1 530	2 530

The power inverter

To be able to use the DC current from the batteries to charge the computers and to supply the server with power, the power must be delivered with a valid current and voltage level. A safe system uses a power inverter to transform the DC voltage to AC current at 230 V. Then the laptops and the server can be powered via their regular power supplies.

The power inverter is dimensioned after the power it is meant to supply the system with. The *12V* alternative requires a 12VDC/220VAC inverter, while the other alternatives require a 24VDC/220VAC. The consumers are the laptops and the server, consuming 150 W. If a 300 W inverter is used the operation point will be at 50 % of its rated power, which is point where the inverter is the most efficient. The market price for a 300 W modified sine wave inverter is 300 SEK. If the reflectors are attached a 500 W inverter is preferred to be able to utilise all the solar power at sunny days. The market price is 330 SEK.

Appendix H – Expected daily power consumption for the school facility

The power consuming equipments are:

- Lightning for all building
- 15 computers á 25 W used eight hours every day
- Radio and loudspeaker equipment, used one hour regular weekdays
- Charging of 100 mobile phones per day
- Additional future equipment (i.e. a small fridge) 20 W all year around
- Fans operating in case of additional power

The lightning demand is fulfilled with LED technology. By own estimations the lightning in for the classrooms and kitchen will consume 1W/m^2 and the sanitary house and the dormitories will consume 0.5W/m^2. From the demand defined in Chapter 6.2.1, the expected consumption for the lighting is defined in Table 14.

Table 14   Estimated electricity consumption for lightning.

Building	Weekdays 9 - 17 (kWh/day)	Weekdays 17 - 9 (kWh/day)	Weekends 9 - 17 (kWh/day)	Weekends 17 - 9 (kWh/day)
Classrooms	4	0.40	0.80	0.40
Kitchen	0	0.12	0	0.12
Sanitary	0.08	0.16	0.08	0.16
Dormitories	0	0.8	0	0.8
Whole facility	4.08	1.48	0.88	1.48
50 % power	2.04	0.74	0.44	0.74

Fifteen laptops consuming 25 W each are used 9.00 – 17.00 every day. The total consumption is 3 kWh per day for the computers.

A stereo device consumes varying amount of electricity relative to the level of sound. A devise that consumes an average of 150 W and a peak power of 300 W is estimated to be suited for the purpose. Stereo devices in this size have a standby consumption of about 3W which is consumed 24 hours every day. This gives a consumption of 0.17 kWh during daytime on weekdays. During weekends the standby consumption is 0.02 kWh daytime. During night-time the consumption is 0.05 kWh every day.

The energy required to charge the battery of a mobile phone differs a bit between the brands of the phone. An estimation that is valid for the most common brands is that 4 Wh is required for a full charge. This gives a daily consumption of 0.4 kWh for the phone charging. Half of the charging was assumed to be during daytime.

A installation of additional power consumers used 24 hours a day should be included. The average consumption is 20 W, which gives a daily consumption of 0.16 kWh and 0.32 for daytime respectively night-time. The peak power is estimated to 100 W, The above mentioned consumers are considered as the primary load.

Fans can be installed in the facility. The fans are only supposed to operate when there is excess power which is not required for the other consumers or to charge the battery bank. The fans are considered as the secondary load.

The summary of the equipment shows that the consumption is 7.61 kWh during daytime weekdays and 2.05 kWh for night-time. The consumption on weekends is 4.26 kWh during daytime and 2.05 kWh night-time .The average consumption is 8.70 kWh per day. The yearly consumption is about 3 200 kWh.

Appendix I – Dimensioning alternative autonomous solar energy systems for the upcoming school facility

The dimensioning of autonomous solar energy systems includes finding suitable equipment. Equipment can be found from local companies or at the international market.

The required power generation

For the power generation, cheap panels are requested in order to get a cost-effective system. One of the cheapest panels per peak watt (W_P) is the 130 W Micromorph Tandem Thin Film Solar Module, with a cost of 1 300 SEK (44). The size of the module is 1 410 times 1 110 mm, which gives a panel efficiency (η_P) of 8.3 %. The specified VOC is 146.6 V. An alternative is the more efficient poly-crystalline 230 W solar module with a specified VOC of 37 V and SCC of 8.2 A, costing 2840 SEK. The size of this panel is 1 640 times 990 mm and the η_P is 14.2 % (44).

The results of Appendix E are used to calculate the expected power production for the 130 W with and without reflectors and for the 230 W Solar Modules with reflectors. Appendix J shows the results for each month. For the 130 W panel without reflectors the average daily generation varies from 500 in July to 860 in February with an average over the year of 690 Wh per day. For the 130 W panel with reflectors, the average daily generation varies from 820 in July to 1 420 in February with an average over the year of 1 140 Wh. The 230 W panel generates 1 440 Wh per day in July, 2 510 Wh in February, and an average over the year of 2 010 Wh.

The power producing solar panels must cover the electricity demand during every month. The system is designed for the daily generation during the month of July, which holds the lowest values of radiation. This means that during the other months the generation will be higher than the consumption. The energy losses in the charge regulation, the battery bank and the inverter are about 4, 20 and 15 % respectively. It is estimated that 50 % of the electricity will bypass the battery bank. The lighting, the mobile charge and the fans does not require a power inverter. The total energy loss for the system is thereby 20 %. The average daily generation in July gets 400 Wh for the 130 W module without reflector, 656 Wh for the 130 W module with reflector and 1 150 Wh for the 230 W module with reflector. The consumption during weekdays, 9 660 Wh, is used for the case with 230 W Solar Modules with reflectors. This means that nine modules are required. For the case with thin film 130 W modules the weekly average daily consumption, 8 700 Wh, is used. This means that 22 pieces of the 130 W thin film modules are required if no reflectors are used. If reflectors are attached 14 panels are enough.

The shipping to Mombasa port is about 1 500 SEK for all alternatives (45). The transport from Mombasa is estimated to 500 SEK (3).

The reflectors

The reflectors are attached as showed in Figure 34, but since the size of the 130 W and the 230 W panels are different from the ones at the internet café, a new sizing must be evaluated. The 230 W panel is 1.8 times wider than the 60 W panel, resulting in a desired 2.7 m reflector on each side. Equation 21 was used to calculate the required extension to 4.3 meters on each side. This results in a reflector size of 23.4 times 2.7 meter if nine panels are used and a size of 21.7 times 2.7 meter if eight panels are used. The 130 W panel is 2 times wider than the 60 W panel, which means a 3 m length for the reflectors. The extension is 4.7 meters, which gives a size of 30.6 times 3 meters for 15 panels. If 14 panels are used the size gets 29.1 times 3 meters The total cost was estimated to 5 000 SEK if eight or nine 230 W modules are used. If the 130 W modules are used the estimated cost was 7 500 SEK (3).

The required energy storage

During periods of low generation, the battery bank is bypassed resulting in a system efficiency of 89 %. The expected generation for the *single-day scenario* with very low generation and the *five-day scenario* with low generation is presented in Table 15.

Table 15 Expected daily power generation, for the different alternatives, during periods of low solar radiation.

Scenario	130 W panels, 22 pcs	130 W panels, 14 pcs with reflectors	230 W panels, 9 pcs with reflectors
Single day (kWh/day)	1.02	1.07	1.22
Five days (kWh/day)	4.58	4.81	5.47

The required storage capacities for the alternative systems for the single-day scenario was calculated in Matlab, see Appendix K, and are shown in Table 16. This capacity was used in another Matlab calculation, see Appendix L. The results showed that the capacity required for the *single-day scenario* was, for all of the alternatives, large enough for the *five-day scenario*. The DOD for the batteries at 09.00 the day after the five days is shown in Table 16.

Table 16 Required storage capacities (Ah) for the different alternatives.

Scenario	130 W panels, 22 pcs	130 W panels, 14 pcs with reflectors	230 W panels, 9 pcs with reflectors
Single day	687 Ah	684 Ah	674 Ah
Five days	73 %	61 %	54 %

The result shows that the required capacity and the DOD differ just a little between the alternatives. This is the result of a regulating system. When the two low-power alternatives with the 130 W panels were simulated, both the lighting and the laptop charge were reduced, from the first day until the end of the five-day period. When the high-power generating, nine pieces of 230 W modules were simulated the laptops were fully charged during about two and a half hour every day of this period.

When batteries were to be chosen, a capacity of 674 - 687 Ah was required. The discharge rate is varying during the 32 hours it is discharged in the *single-day scenario*. If the 100 Ah AGM batteries from Kenital Solar are to be used, six of this battery has a total capacity of 666 Ah at a 20 hour discharge rate (29). Since the discharge rate is longer than 20 hours it was assumed that this capacity is sufficient for all the sets of modules. The total cost for six batteries is 9 500 SEK (28).

Charge regulation

In order to find a suitable charge regulator the expected current had to be defined for the alternatives. The different sets of panels can be connected in different ways in order to regulate the current and the voltage from the modules. If nine 230 W panels are installed they can be series connected in groups of three and then parallel connected. As described previously, the V_{OC} for the 130 W modules are rather high, why they are preferred to be connected in parallel, in a system this size. The current, with safety margin included, and the voltage from the different alternative sets are shown in Table 17. For each alternative system, suitable charge controllers and the price of them are also presented in Table 17.

Table 17 Current and voltage from possible sets of modules (44), (43), (46).

	130 W panels, 22 pcs	130 W panels, 14 pcs with reflectors	230 W panels, 9 pcs with reflectors
Current (A)	33	58	80
Voltage (V)	147	147	111
Controller	*Tristar MPPT-45*	*Tristar MPPT-60*	*OutBack FlexMax 80*
Cost (SEK)	2 500	3 200	4 000

Both *Tristar MPPT* controllers are rated at a maximal V_{OC} of 150 V (43). For the two alternative systems they were chosen for, the rated V_{OC} of the panels is close to the rated maximal V_{OC} for this controller. It can therefore be questionable if it can be used for those alternatives. Appendix D shows that the existing panels at the internet café generated a lower V_{OC} than the specified value. In Chapter 4.1 it is described that an increased operating solar cell temperature causes a decreased V_{OC}. The measurement of the internet café, the attached reflectors and the warm climate in Nairobi, was considered when it was assumed that the V_{OC} won't ever reach 150 V. The controller could therefore be used for the alternatives with an V_{OC} level close to 150 V.

Power inverter

The computers, the stereo and the additional future equipment need alternating current. The maximal power consumption if all those devices are used at the same time the required power is 775 W. A more usual state is when only the computers are used, which gives a power of 375 W. An 800 W modified sine wave inverter was assumed to be well suited for this facility. The market price in Nairobi is about 430 SEK for this device (28).

Appendix J – Expected daily power production for a 130 W and a 230 W solar panel with or without reflectors

The daily power generation that the alternative sets of panels are expected to supply, is calculated with Equation 6. The result for one 130 W panel without reflector, one 130 W with reflector and one 230 W panel with reflector is presented in Table 18.

Table 18 Expected power production (Wh/day) for one 130W with and without reflectors and one 230 W solar panel with reflectors. The panels are installed in a horizontal attachment.

Month	130 W	130 W with reflectors	230 W with reflectors
January	840	1 380	2 450
February	860	1 420	2 510
March	820	1 360	2 410
April	680	1 130	2 000
May	610	1 000	1 760
June	560	920	1 630
July	500	820	1 440
August	520	860	1 520
September	680	1 130	2 000
October	730	1 200	2 130
November	680	1 130	2 000
December	780	1 290	2 290
Year	690	1 140	2 010

Appendix K – MATLAB code for iteration of required battery capacity in case of a single day with very low generation

The required battery capacity for the autonomous energy systems at the school facility was calculated with Matlab. The code, which has been changed for each alternative is presented below.

```
clear all

% Define parameters
% Electricity consumption (W)
% Daytime
L_d=951.25;
% Daytime 50 % lights
L_d50l=696.25;
% Daytime 50 % lights and only 5 laptops
L_d50l5c=446.25;
% Night-time
L_n=128.125;
% Night-time 50 % lights
L_n50l=81.875;
% Time vector from 18.00 to 09.00, 39 hours later
Time=linspace(0,39,391);
% Important times are defined
T_9a=Time(151);
T_17=Time(231);
T_9b=Time(391);

% Define the generation for the different modules
% E_8_230W=1150;
% E_9_230W=1290;
% E_14_130W=1130;
% E_15_130W=1210;
E=1210;

% Define a large starting capacity (Wh)
C=20000;
C_20=C*0.2;
% Set the ending capacity to the starting capacity
C_end=C

% A while loop will run until the ending capacity is 20 % of the
required
% capacity
while C_end>C_20
    % The capacity is decreased step by step
     C=C-1
C_70=C*0.7;
C_60=C*0.6;
C_20=C*0.2;

% The capacity at 09.00 is the starting capacity minus the night load
C_Time9=C-L_n*Time(151)

% The time that the capacity reaches 70%. It is assumed that
```

```
% 1/3 of the generated energy is added to the capacity this period
T_c70=T_9a+(C_Time9+(E/3)-C_70)/L_d
% The time that the capacity reaches 60%.
% 1/3 of the generated energy occurs this period
T_c60=T_c70 +(C_70+(E/3)-C_60)/L_d50l
% The capacity at 17.00. It is assumed that
% 1/3 of the generated energy occurs this period
C_Time17=C_70+(E/3)-L_d50l5c*(T_17-T_c70)

% The ending capacity
C_end=C_Time17-L_n50l*(T_9b-T_17)

end
 % The capacity in Ah for a 12 V system.
C_Ah=C/12
```

Appendix L – MATLAB code used to check if the capacity is enough even for five days with low generation

With Matlab it was checked if the required battery capacity, calculated in Appendix K, for the autonomous energy systems at the school facility, was sufficient for *five-day scenario*. The code, which has been changed for each alternative is presented below.

```
clear all

% Define parameters
% Electricity consumption (W)
% Daytime
L_d=951.25;
% Daytime 50 % lights
L_d50l=696.25;
% Daytime 50 % lights and only 5 laptops
L_d50l5c=446.25;
% Night-time
L_n=128.125;
% Night-time 50 % lights
L_n50l=81.875;
% Time vector from 18.00 day 1 to 09.00 day 6, 135 hours later
Time=linspace(0,135,1351);
% Important times are defined
T_9mon=Time(151);
T_17mon=Time(231);
T_9tue=Time(391);
T_17tue=Time(471);
T_9wed=Time(631);
T_17wed=Time(711);
T_9thu=Time(871);
T_17thu=Time(951);
T_9fri=Time(1111);
T_17fri=Time(1191);
T_9sat=Time(1351);
% Define the generation for the different modules
% E_8_230W=4910;
% E_9_230W=5530;
% E_14_130W=4860;
% E_15_130W=5210;
E=5210;

% Define the capacity (Wh) found from the calculation in Appendix K
C=8100;
C_75=C*0.75;
C_70=C*0.7;
C_65=C*0.65;
C_60=C*0.6;
C_20=C*0.2;

% The capacity is calcuated for important times
% Monday
C_Time9mon=(C-L_n*T_9mon)
T_c70mon=T_9mon+(C_Time9mon+(E/2)-C_70)/L_d
T_c60mon=T_c70mon +(C_70+(E/2)-C_60)/L_d50l
```

```
C_Time17mon=(C_60-L_d5015c*(T_17mon-T_c60mon))

% Tuesday
C_Time9tue=(C_Time17mon-L_n50l*(T_9tue-T_17mon))
C_Time17tue=(C_Time9tue+E-L_d5015c*(T_17tue-T_9tue))
if (C_Time17tue/C)>0.65
    T_c60tue=T_9tue +(C_Time9tue+(E/2)-C_60)/L_d5015c
    C_Time17tue=(C_60-L_d5015c*(T_17mon-T_c60mon))
end


% Wednesday
C_Time9wed=(C_Time17tue-L_n50l*(T_9wed-T_17tue))
C_Time17wed=(C_Time9wed+E-L_d5015c*(T_17wed-T_9wed))
if (C_Time17wed/C)>0.65
    T_c60wed=(T_9wed +(C_Time9wed+(E/2)-C_65)/L_d5015c)
    C_Time17wed=(C_65+(E/2)-L_d50l*(T_17wed-T_c60wed))
end

% Thursday
C_Time9thu=(C_Time17wed-L_n50l*(T_9thu-T_17wed))
C_Time17thu=(C_Time9thu+E-L_d5015c*(T_17thu-T_9thu))
if (C_Time17thu/C)>0.65
    T_c60thu=(T_9thu +(C_Time9thu+(E/2)-C_65)/L_d5015c)
    C_Time17thu=(C_65+(E/2)-L_d50l*(T_17thu-T_c60thu))
end

% Friday
C_Time9fri=(C_Time17thu-L_n50l*(T_9fri-T_17thu))
C_Time17fri=(C_Time9fri+E-L_d5015c*(T_17fri-T_9fri))
if (C_Time17fri/C)>0.65
    T_c60fri=(T_9fri +(C_Time9fri+(E/2)-C_65)/L_d5015c)
    C_Time17fri=(C_65+(E/2)-L_d50l*(T_17fri-T_c60fri))
end
%Saturday
C_Time9sat=(C_Time17fri-L_n50l*(T_9sat-T_17fri))

% Depth of discharge (DOD) at the end of the period
DOD=1-C_Time9sat/C
```

Appendix M – MATLAB code used for NPV calculations

To calculate the NPV for the internet café and the school facility, Matlab calculations was used. The code, presented below, was modified to suit the specific alternative and the specific case.

```
% Input
E=linspace(1,25,25)
I=linspace(1,25,25)
P=linspace(1,25,25)
% Interest rate 10 or 20 %
R=0.2
% Annual generation (kwh)
a= 500
A=
[a,a,a,a,a,a*0,95,a*0,95,a*0,95,a*0,95,a*0,95,a*0,95,a*0,90,a*0,90,a*
0,90,a*0,90,a*0,90,a*0,90,a*0,90,a*0,90,a*0,90,a*0,90,a*0,90,a*0,90,a
*0,90,a*0,90,]
% Investment cost per year for the specific alternative
C = [4200,0, 0, 0, 0 , 3167, 0, 0, 0, 0 , 3167, 0, 0, 0, 0 , 3917, 0,
0, 0, 0 , 3167, 0, 0, 0,0]
i=1
while i<=25

% Electricity cost with 5 or 10 % increase per year
E(i)=1 * 1.1^i * A(i)

% Increased Income per year
I(i) = 12*800 * 1.05^i

% The electricity is for free in the solar power systems so it is
included
% as an income.
P(i)=I(i)+E(i) - C(i)
NPV(i)=P(i)/((1+R)^(i-1))
i=i+1;
end
npv=sum(NPV)
% The sum of all years gives the value of today.
```