Department of Electronics, Lighting Unit

LED lighting combined with solar panels in developing countries

Ater Amogpai

Aalto University

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LED lighting combined with solar panels in developing countries

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Abstract

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Abstract

The aim of the work was to find out the functionality of LED lighting combined with solar panels in developing countries and to find out the availability of solar energy in different geographical locations. Another aim of the work was to understand the advantages and disadvantages of photovoltaic systems and the optimum combination of PV systems for lighting.

Measurements of photovoltaic systems combined with LEDs and fluorescent lighting were conducted in an office building in Finland. Measurements in a one-room house in Sudan using LEDs and fluorescent and incandescent lamps were also conducted. The costs analysis comparing photovoltaics and diesel generators in Sudan are discussed. The results showed that in Finnish conditions photovoltaic systems may be combined with AC power sources and DC rectifiers. However, in Sudanese conditions, where solar radiation is available all the year round, photovoltaic systems can be used without inverters. LED lighting combined with solar panels was found to be suitable for lighting in developing countries. Photovoltaic systems have shown high potential for electricity generation in Sudan.

Keywords Lighting, LEDs, solar panels, developing countries

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Preface

This work was carried out in the Lighting Unit of the Department of Electronics, Aalto University School of Electrical Engineering. The work was conducted as a part of the HighLight – High Efficiency Solid State Lighting Enabled by New Technologies – project. This project is funded by the research group of the Aalto University Multidisciplinary Institute of Digitalisation and Energy (MIDE).

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Finally, I would like to express my warm thanks to my parents, my two brothers, my sister, and my fiancée for their love during my studies in Finland.

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Espoo, 2011

List of publications

I L. Halonen, E. Tetri, and A. Amogpai, “Needs and challenges for energy efficient lighting in developed and developing countries,” *Light & Engineering*, Vol. 17, No. 1, pp. 6-10, 2009.

II A. Amogpai, E. Tetri, and L. Halonen, “New lighting technologies in developing countries - case Sudan,” in *Proceedings of the 11th European Lighting Conference,* Istanbul, Turkey, 2009, pp. 235-242.

III A. Amogpai, J. Viitanen, M. Puolakka, and L. Halonen, “Solar panels combined with LED lighting - Case study from Finland,” in *Proceedings of the SB10 Sustainable Community - Building SMART Conference,* Espoo, Finland, 2010, pp. 801-811.

IV J. Viitanen, A. Amogpai, M. Puolakka, and L. Halonen, “Photovoltaic production possibilities and its utilization in office buildings in Finland,” *International Review of Civil Engineering (I.RE.C.E.)*, Vol.2, No.1, pp. 52-59, 2010.

V A. Amogpai, “Possibilities of new light sources and sustainable energy production in Sudan,” *Ingineria Illuminatului-Lighting Engineering*, Vol. 13, No. 1, 2011.

The author has played an active role in all the stages of the work reported in the publications. He was responsible for publications [I], [II], [III], and [V] as the main author. The work reported in [IV] was performed in cooperation with M.Sc Janne Viitanen.

List of abbreviations

AC	Alternating current
AEPC	Alternative Energy Promotion Centre
CFL	Compact fluorescent lamp
CO	Carbon monoxide
CO_2	Carbon dioxide
DC	Direct current
DLRLP	D. Light Rural Lighting Project
FL	Fluorescent lamp
IEA	International Energy Agency
IFC	International Finance Corporation
IL	Incandescent lamp
InGaN	Indium gallium nitride
LA	Lighting Africa
LED	Light-emitting diode
LRC	Lighting Research Centre
LUTW	Light Up The World
MOSFET	Metal-oxide-semiconductor field effect
NASA	National Aeronautics and Space Administration
NGO	Non-governmental organisation
NOx	Nitrogen oxide
Opt Ang	Optimum angle
OPV	Organic photovoltaic
PEAK	People’s Awareness – Khati
PV	Photovoltaic
PWM	Pulse width modulation
SOC	State-of-charge
SOx	Sulphur oxide
TERI	The Indian Energy and Resources Institute
YAG	Yttrium aluminium garnet

List of symbols

A_{req}	Solar panel area required (m^2)
A_{Fm}	Area of solar panel required (m^2) in Finland, based on measured data
A_L	Area of solar panel required (m^2) in the selected location
B_{bank}	Battery bank capacity (Ah)
C_i	Annual costs of the initial investment ($)
E_{daily}	Specific daily solar radiation ($kWh/m^2/day$)
E_m	Average illuminance (lx)
E_{min}	Lowest measured illuminance (lx)
E_{rad}	Daily solar radiation (kWh/day)
I	Initial costs ($)
i	Interest rate (%)
n	Number of years (service life of PV system installation)
R_f	Amount of radiation in Finland, NASA statistical data ($kWh/m^2/day$)
R_L	Amount of radiation in the selected location, NASA statistical data ($kWh/m^2/day$)
UGR	Unified glare rating, a measure of glare
W_p	Peak power (W)
η	Solar collection efficiency

Contents

1 Introduction

1.1 Background

The International Energy Agency (IEA) estimated in 2010 that 1.4 billion people (20% of the world population) are still without access to electricity [1]. For instance, 42% of the population currently (2011) living in South Asia is without access to electricity, while only 31% of Sub-Saharan African people have access to electricity. In these regions access to electricity is mostly concentrated in urban areas. For instance, the percentage of people with access to electricity in Sub-Saharan Africa is the lowest among the developing countries: around 60% in urban areas and only 14% in rural areas [1].

Programmes to electrify off-grid areas are ongoing in most developing countries [2]. However, the efforts to electrify rural areas face several obstacles, such as geographical remoteness, a scattered population, and the limited income of consumers. Thus, the extension of the electrical grid to such areas is characterised by high initial and maintenance costs. Despite of all these challenges, electricity may become a major strategic element in promoting the creation of local economic opportunities and helping to satisfy the basic needs of people [2].

People who live in rural areas in developing countries use firewood and kerosene lamps for lighting [3]. Kerosene lamps have a very low light output of around 4 to 10 lumens, compared to the 900 lumens of a 60 (W) incandescent lamp (IL) [3], [4]. Carbon monoxide (CO), sulphur oxide (SOx), nitrogen oxide (NOx), and carbon dioxide (CO_2) are gases emitted by firewood and kerosene lamps. These gases are detrimental to health and cause chronic respiratory problems [4]. Therefore, firewood and kerosene lamps need to be replaced by clean and efficient light sources such as light-emitting diodes (LEDs) [5], [6]. LED lighting combined with solar panels can offer a solution to provide clean and affordable lighting systems to 1.4 billion people in Asia, Africa, and Latin America [7], [8], [9], [10], [11]. Currently (2011), there are many ongoing projects in these regions combining LEDs with solar panels [10], [11]. These projects are usually run by international or local non-governmental organisations (NGOs) [10], [11].

LED lighting for developing countries was first introduced by the Light Up The World (LUTW) foundation in 2000 [10]. The first developing country to benefit from the service was Nepal. Since 2000, the LUTW foundation has illuminated with LEDs the homes of around 900,000 persons in more than 50 developing countries [10]. Currently (2011), the LUTW foundation is continuing its projects in Ghana, South Africa, Papua New Guinea, Tibet, India, Pakistan, Nepal, Sri Lanka, Afghanistan, Costa Rica, Ecuador, Mexico, Peru, the Dominican Republic, and the Philippines [10].

Lighting Africa (LA), a joint International Finance Corporation (IFC) and World Bank programme, has started providing LED lights for rural areas in Sub-Saharan Africa [11]. Its goal is to improve access to energy for about 585 million people in Sub-Saharan Africa. Currently (2011), the Lighting Research Centre (LRC) is testing LED-based off-grid lighting products for Sub-Saharan Africa [12]. The tests are designed to evaluate several performance and reliability criteria. The test results will be used to provide feedback to manufacturers and institutional buyers in Sub-Saharan Africa. In addition, these results may also help to form a basis of demand for lighting quality by Sub-Saharan African consumers [12]. Lighting Africa has started its approach in Kenya and Ghana and is currently (2011) extending its activities to provide LED lights to people in Tanzania, Ethiopia, Senegal, and Mali [11].

1.2 Objectives of the work

The aim of the work was to find out the functionality of LED lighting combined with solar panels in developing countries and to find out the availability of solar energy in different geographical locations. Another aim of the work was to understand the advantages and disadvantages of photovoltaic (PV) systems and the optimum combination of PV systems for lighting. The work was conducted through electrical and lighting measurements and calculations in a Sudanese one-room house and in an office building in Finland. Another aim of the work was to examine the possibilities of new light sources and sustainable energy production in Sudan. This included comparisons of incandescent lamp and compact fluorescent lamps (CFL) with LED light sources and the utilisation of solar energy for electricity generation.

1.3 Research methods

The work presented in this thesis consisted of scientific and theoretical analysis studies. The scientific studies included two case studies, one in Finland and other one in Sudan.

The study done in Finland, solar panels combined with LED lighting was conducted using photovoltaic lighting system built around the light cube of the department of Electrical Engineering of the Aalto University. The system consisted of three 100 (Wp) solar panels, a 210 Ah/24 V battery unit, two LED luminaires, five 13 (Wp) solar panels, a battery charge controller, installation accessories and data logger unit. The system was implemented using only DC power. In the Sudan study, possibilities of new light sources and sustainable energy production were introduced in a one room house. In this study, lighting measurements were conducted both at night and daytime. Incandescent lamp, compact fluorescent lamp and LED lamp were used for measuring the illuminance levels in a one room house.

The solar panel area (A) and battery bank size required for different light sources were calculated. The annual costs for a PV system were also calculated. Based on these calculations the theoretical evaluation analysis in each measurement and study were carried out.

2 State of the art of power supply and lighting in developing countries

2.1 Electricity and photovoltaic (PV) systems in developing countries

Electric power was first supplied to people in the middle of the 19th century in the United Kingdom and quickly spread throughout Europe and America [2]. In the 20th century, electricity supply to people in developing countries became a high priority for their governments. However, the financial resources to build up and accelerate the spread of electricity services were limited. Thus, access to electricity has been uneven for the people of developing countries [2].

Solar energy is the most abundant energy resource on earth. Great potential for solar energy exists in many developing countries and can be utilised in decentralised PV power systems [13]. The region between latitudes 30° N and 30° S around the equator contains most of the developing countries of Asia, Africa and Latin America with the highest solar energy radiation in the world (Figure 1).

Today, PV technology is being widely promoted in developing countries. PV systems are often the only viable ones for applications such as lighting in rural areas [15]. Even when diesel generators do exist, PV systems frequently prove to be more reliable and more cost-effective in terms of total lifetime cost, when loads are small and operating and maintenance costs are significant [15].

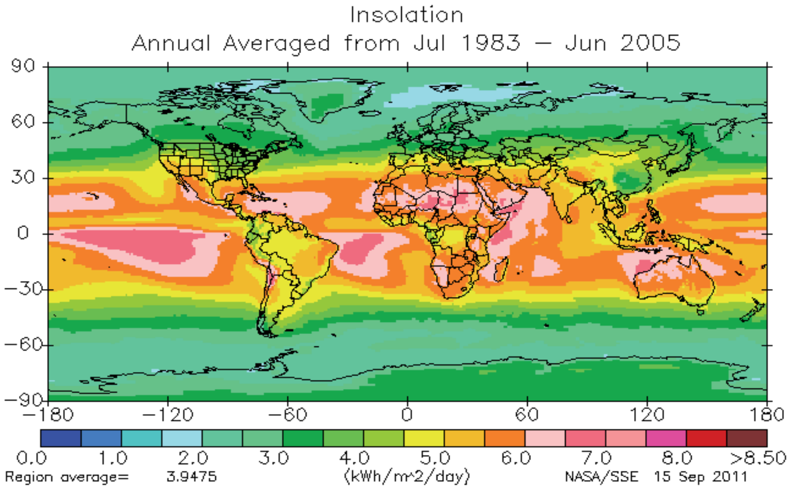

Figure 1 The world annual solar energy distribution between July 1983-June 2005 [14].

PV power means the direct generation of electricity from sunlight [16]. The PV effect was first recorded in the laboratory by the French scientist Edmund Becquerel in 1839. In 1954, Bell Telephone Laboratories made practical silicon PV cells that converted sunlight into electricity with an efficiency as high as 6%. Since 1958, PV cells have powered most U.S. satellites in space. On the other hand, PV systems gained attention for use in homes during the oil crisis of the 1970s. However, their high costs led scientists to explore and develop new solar cells for PV systems suitable for use in homes [16].

PV cells are made from semiconductors of crystalline and thin-film materials [17], [18]. These materials are divided into single-crystalline and multi-crystalline or amorphous thin-film materials [17], [18]. Crystalline materials are generally more efficient but thin-film materials cost less. Thin-film cells have poorer efficiency (11%) when compared to crystalline silicon cells (18%), although the research in this area is rapid and the future promises cost reductions and improvements in the efficiency of the cells [19]. Thin-film solar cells are flexible, which means that they can be coated on top of different surfaces. They also require less expensive materials so they can result in high-volume production of low-cost solar cells. The thin structure of these solar cells also means that the heat can be conducted away from the solar module more easily than in the thicker crystalline silicon solar cells [19]. Significant advances in the development of low-cost solar cells known as organic photovoltaic (OPV) cells are being developed for the reduction of the costs of PV systems [17].

Lead-acid batteries are widely used in PV systems. They usually operate at 10.5–13 V with a state-of-charge (SOC) of 80% in order to avoid overcharging [20]. A discharge controller used in PV system-powered lighting consists of a DC/DC converter that converts the floating battery voltage into a constant current. The DC/DC converter may also increase system costs and reduce system reliability as a result of the additional components [20]. To eliminate the DC/DC conversion loss (15%) of the battery discharge controller, the load (LED light) could be directly driven by the battery voltage using the pulse width modulation (PWM) technique with constant-power feedback control. The battery output current is switched on/off by a metal-oxide-semiconductor field effect transistor (MOSFET) through a PWM signal that is generated by a feedback control system to maintain an average current [20].

PV systems have low operating costs and high initial costs [18]. For instance, in Syria (Damascus), a PV system (3.6 kW) and a system based on a diesel generator (2.4 kW) were used to calculate the annual total costs [21]. The results showed that the annual total cost for the PV system was US $730/year, while the total cost for the diesel generator was US $802/year [21]. Thus, it is cheaper to use a PV system than a diesel generator for electricity generation. The initial costs of PV systems need to be reduced for them to become widely used in developing countries [18]. This can be done through establishing markets for PV systems at affordable prices. Financial models provided by governments, private sectors, local entrepreneurs, and international and local NGOs can help the growth of markets for PV systems [15].

PV systems can be compared with diesel generators to understand their costs and benefits [15]. However, the costs differ and depend on the local income of the area and country and thus they cannot be generalised. Such costs and a comparative approach help in selecting the optimum technological solution for power supply in developing countries [15], [22], [22]. To assure the high quality and low cost of the PV system, solar panels with flexible solar cells and a good battery charge controller are needed [23], [24]. Photovoltaic power systems can be used to supply medical refrigeration and solar home systems in these countries. Media and electronic equipments such as televisions, radios, and computers benefit from PV systems [13].

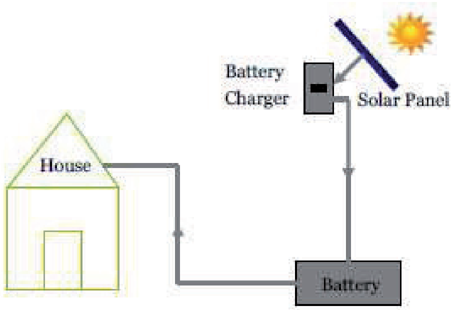

Figure 2 PV power system containing solar panels, battery charger, battery and wiring.

2.2 Lighting in developing countries

Firewood is a lighting method used by people who cannot afford kerosene or diesel lamps in developing countries. Firewood can be replaced by fuel-based lighting. However, both methods, fuel-based lighting and firewood, are inefficient ways to produce light [25]. Kerosene fuels cost about US $38 billion/year or US $77/household globally [26]. In developing countries, kerosene fuel costs families without electricity around US $100/year [27]. Electric lighting (incandescent lamps, fluorescent lamps, LEDs) is a more efficient method than fuel-based lighting and firewood to provide light in developing countries [28]. LEDs have great potential to replace incandescent and fluorescent lamps. Small size, ease of control, high luminous efficacy, and a long lifetime are the benefits behind the high potential of LEDs for general lighting. However, the cost is the main challenge to the use of LEDs [29].

The incandescent lamp (IL) was developed in the 19th century. A modern incandescent lamp has a luminous efficacy of around 10 to 20 (lm/W) [5], [6]. The fluorescent lamp, patented in 1938, achieves a significantly higher luminous efficacy of 50 to 100 lm/W [5], [6]. Incandescent and fluorescent lamps are commonly used light sources in buildings [30]. However, an incandescent lamp has been proved to be an inefficient light source. It only converts around 5 to 15% of the electricity into visible light, while a fluorescent lamp converts around 20 to 40% of the electricity into light [30]. Each fluorescent lamp contains an amount of toxic mercury which can be dangerous to human health [31]. Because incandescent lamps are inefficient and consume much energy, they are being removed from industrialised countries. For instance, the European Union (EU) has started removing incandescent lamps from markets since 2008 [32].

In the 1960s, the first red LED was made, with a very low efficacy of 0.1 lm/W. After that, LEDs went through a number of improvements in terms of luminous efficacy [5], [6]. However, LED applications were usually limited to signalling and electronic displays [5], [33]. LEDs suitable for general lighting were introduced after Shuji Nakamura from the Nichia Corporation developed the blue LED from the indium gallium nitride (InGaN) material [5]. By adding a layer of yellow phosphor on top of a blue LED, a white LED can be produced [5]. Hence, the first white LED based on blue monochromatic light and yttrium aluminium garnet (YAG) phosphor was developed in 1996 [5].

The luminous efficacy of white LEDs has increased from 5 lm/W in 1996 to 150 lm/W in 2010 [6]. Now (2011) the highest luminous efficacy announced by manufacturers is 231 lm/W in the laboratory [34]. LEDs are rapidly developing light sources in terms of luminous efficacy, and they have several advantages over conventional light sources. These advantages include high luminous efficacy, a long lifetime, and low power requirements. LEDs can reduce indoor air pollution and improve health conditions in developing countries. LEDs have been used successfully to bring these benefits to households in developing countries [7], [8], [9], [10], [11], [12].

LEDs combined with solar panels can offer a solution to provide clean and affordable light to people without electricity [35]. The adoption of solar-powered LEDs can minimise the use of biomass- and fuel-based lighting. Solar-powered lighting can reduce indoor air pollution from firewood and kerosene smoke and hence reduce health risks. The use of solar-powered LEDs significantly reduces power consumption, causes no environmental pollution by mercury, and reduces expenses on kerosene or diesel fuels. The greenhouse gases associated with kerosene-based lighting will also be minimised with solar-powered LED lighting systems in developing countries [36].

2.3 LEDs combined with solar panels - Case studies from India, Ghana, and Nepal

2.3.1 India

The LUTW foundation and local NGOs have worked together since 2001, using LEDs for lighting in rural areas of India. As a result many houses have been provided with LED lights. In the years 2001-2004, the LUTW foundation and other local NGOs lit up 280 houses with LED lights [37]. They used a diesel generator and the electrical grid as power sources. Power from the electrical grid is used to charge batteries used by solid-state lighting in a medical theatre and offices in the Bagdogra area [37]. The LUTW foundation replaced incandescent lamps with LEDs, while electrical grid breaks were reduced [38]. The Indian Energy and Resources Institute (TERI) is also distributing LED lanterns to many rural areas of India. Since 2008, TERI has lit up 30,000 houses in rural India with solar-powered LEDs [38]. There exist other projects in India working on solar-powered LEDs: THRIVE, Hyderabad-India [39], People's Environmental Awareness-Khati (PEAK) [40], and the D. Light Rural Lighting Project (DLRLP) [41]. The LED lighting systems used by these projects usually consist of a solar panel, LED lights, and a rechargeable battery.

2.3.2 Ghana

The LUTW foundation, Deng Ltd, Ghana, Solar4Ghana, and the Ghanaian Ministry of Education are all providing solar LED lanterns for rural areas of Ghana without electric lighting [42]. The LUTW foundation and Ghana's Deng Ltd have installed 7100 solar LEDs in the rural areas of Ghana. Deng Ltd has been supplying solar LEDs to rural areas of Ghana since 1998 [42]. Solar4Ghana, in collaboration with the German SOLUX e.V NGO, launched the One Child One Solar Light project in Accra in 2009 [43]. The project aims to provide and distribute solar SOLUX-LED-50 LED lanterns to schoolchildren without lighting. SOLUX-LED-50 consists of a solar panel, rechargeable battery, and LED lights [43]. Lighting Africa (LA) is also providing solar LED lanterns for Ghana [11]. Ghanaian rural evening adult literacy classes have been provided with 15,000 Glowstar solar lanterns. These Glowstar solar lanterns were delivered by Ministry of Education of Ghana. A Glowstar solar lantern consists of a compact fluorescent lamp (CFL), a solar panel, and a battery [44].

2.3.3 Nepal

The LUTW foundation first launched LED lighting projects in Nepalese rural areas in the year 2000 [45]. The power sources used were generators, Pico hydropower, 220 AC grid power, and centralised solar power. All these projects used white LEDs as the light source [46]. The portable white LED lamp has been promoted by the Nepalese local NGOs, e.g. the Centre for Renewable Energy, Bag Bazar, Kathmandu. The LED lighting system consists of an LED, a rechargeable battery, a solar panel, and a 3-V output socket for an AM/FM radio [46]. RIDS-Nepal, a local NGO, provided solar LEDs for Western Nepal in collaboration with LUTW. RIDS-Nepal used solar panels and Pico hydropower to power LED lighting systems [47]. The government-based project, the Alternative Energy Promotion Centre (AEPC), has provided subsidised solar LED lamps to rural Nepalese people

[48]. In the years 2006-2007, AEPC delivered 60,000 solar-powered LEDs in Western Nepal with a 95% subsidy. The LED lighting system consists of a solar panel, an LED light source, and a battery.

2.4 Conclusions

International and local NGOs are the main players in off-grid lighting projects in developing countries. This is due to the limited financial resources the governments in these countries can provide to fund off-grid lighting projects. The common power sources used to derive electricity for lighting in developing countries are electrical grids, diesel generators, batteries (car or dry batteries), and solar power. Usually, electrical grids are associated with frequent blackouts, while diesel generators involve high operating costs, among other problems. PV systems with free fuel, sunlight, can provide sustainable power sources. The initial costs of PV systems are high, but in long-term operation they provide low costs. A photovoltaic system consisting of a solar panel, battery, and control unit is a suitable solution for lighting in off-grid regions in developing countries. Pico hydropower is also used to derive electricity for lighting.

LEDs are common light sources used in the projects in India, Ghana and Nepal for lighting. CFLs are also used as light sources, while incandescent lamps have higher power requirements than LEDs and CFLs. The LUTW foundation, Lighting Africa (LA), and the Lighting Research Centre (LRC) are undertaking research into LED lighting for developing countries [10], [11], [12]. The LUTW foundation has been working on LED lighting for developing countries since 2000 [10]. Lighting Africa (LA) and LRC have started providing and testing LED lights for Sub-Saharan Africa [11], [12].

3 Photovoltaic DC lighting systems

3.1 Electric lighting and the use of photovoltaics in office buildings

Lighting is a major electricity consumer in office buildings. For instance, European office buildings consume 50% of the total electricity consumption for lighting [49]. Energy-efficient lighting solutions need to be considered when office lighting systems are being designed. Currently, the dominant lighting technology in office buildings is fluorescent lamps. LEDs are expected to become the most important lighting technology in office lighting. They have great potential to save energy and enhance the quality of lighting [49]. DC distribution systems combined with photovoltaic lighting in office buildings can achieve higher efficiency and higher reliability as a result of the need for electricity storage and by avoiding unnecessary conversion losses [50].

Visual comfort in offices depends on the illuminaces of vertical and horizontal surfaces and the amount of light distributed onto these surfaces. Illuminances on a working area must be sufficiently high and the amount of light has to be properly distributed on the working area. Uncomfortable glare from luminaires or through the windows is avoided. In the office lighting study of Linhart and Scartezzini [51] lighting was used as a complement to natural daylight. Ceiling-mounted fluorescent luminaires were used to light the working area. The average illuminance and power density of the working area were 350 lx and 3.9 W/m^2, respectively. The corresponding uniformity was around 0.9, with the UGR value measured at 15. The study showed that low power density is possible with proper artificial and daylight designs.

Efficiency in electricity generation and DC distribution systems is needed for lower losses and higher reliability. In office buildings, non-linear electronic loads, for example fluorescent lighting, LED lighting with electronic drivers, and varied-speed drivers all have losses resulting from conversion processes that involve AC/DC/AC. These conversion processes cause power quality problems such as reactive power consumption and low-frequency current harmonics [50]. Therefore, alternative electricity generation sources that reduce these losses are necessary. A photovoltaic power source can be directly connected to a DC distribution system or through a DC/DC converter. A non-linear electronic load such as lighting can be connected to a DC distribution system through a DC/AC converter [52]. DC distribution with solar PV for office lighting can lower the total costs and electricity consumption as a result of the absence of inverters [53], [54].

3.2 Office case study on photovoltaic DC lighting

The photovoltaic lighting system was built around the light cube of the Department of Electronics, Aalto University School of Electrical Engineering. The system was implemented using only DC power. The basic idea was to build an off-grid PV system that provides electricity to indoor LED luminaires and to see how well such an arrangement works under Finnish conditions. This off-grid PV system can be installed, for example, in summer cottages, third world country villages, research stations, or other places that are located outside an electrical grid. It is also possible to modify the system so that it can be utilised in office buildings or as a part of making the buildings zero-energy buildings [Publication III].

The system consisted of three 100 W_p (peak power) solar panels, a 210 Ah/24 V battery unit, two LED luminaires, five 13 W_p solar panels, a battery charge controller, installation accessories, and a data logger unit. The main panels used for electricity production were Naps Systems NR100G24 and the total effective area of these panels was 2.16 m^2, with a maximum power output of 300 W. The system voltage was 24 V. The main panels were facing south and tilted at a vertical angle of 48° [Publication III].

Figure 3 Main solar panels, 3 x Naps NR100G24.

Figure 4 Measurement panel, Naps 13009.

The original luminaires used 3 x 28 W TL5 lamps. Two of these lamps provided light upwards. The purpose of this demonstration was to gain better energy efficiency on the working area, so the upwards light capabilities of the luminaire were removed. After modification the luminaires had 1 x 28 W TL5 downwards light with a 3000 K colour temperature. In addition, two similar luminaires were converted to use LEDs as a light source. Each LED luminaire had 11 x 3 W (Citizen CL-L102-C3N-B) LEDs and 6 LED drivers (Innoline RCD-24-0.35). The colour temperature of the LEDs was 5250K. [Publication III]

Figure 5 Luminaires used: fluorescent (upper) and LED version (lower).

In the study an office with dimensions 2 m x 4 m x 2.5 m was used (Figure 6). The working area of this office was the enclosure of the table surface and the area around it. The illuminances of the working area and the whole area were measured for both LED and fluorescent lighting. The illuminance measurement spots are shown as the coloured area in Figure 7. For the fluorescent lighting the average illuminance was 420 lx for the working area and 377 lx for the whole area. The illuminance uniformity, minimum illuminance/average illuminance ($E_{\min}/E_m$) for fluorescent lighting was 0.8. The power density of the office room was 7.6 W/m^2 with fluorescent luminaires. For LEDs without dimming the average illuminance for the working area was 771 lx and it was 677 lx for the whole area. The illuminance uniformity for LED lighting was 0.75. The power density of the office was 9.5 W/m^2 for the luminous flux of the LED lighting without dimming. To minimise the power consumption, the LED luminaires were dimmed by 37.5% (39 W), 50% (29 W) and 62.5% (22 W). Full power was 74 W. The power density achieved with the dimming technique was 4.9 W/m^2, 3.6 W/m^2, and 2.7 W/m^2 respectively [Publication III]. The Unified Glare Rating (UGR) was 24.1 for the LED luminaire and 20.4 for the fluorescent luminaires, compared to the recommended UGR value of 19 for general office lighting [55]. UGR was measured using Nikon E8400 digital camera with fisheye lens from the east end of the office room at eye level of the sitting worker. UGR measurements and measurements in Figure 7 was measured in April 2010 in Finland.

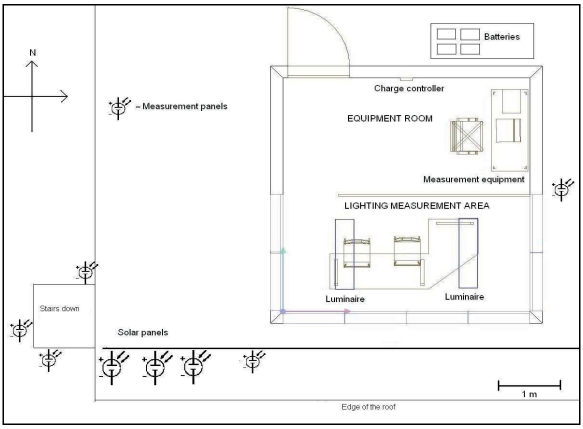

Figure 6 The layout of the demonstration system [Publication III].

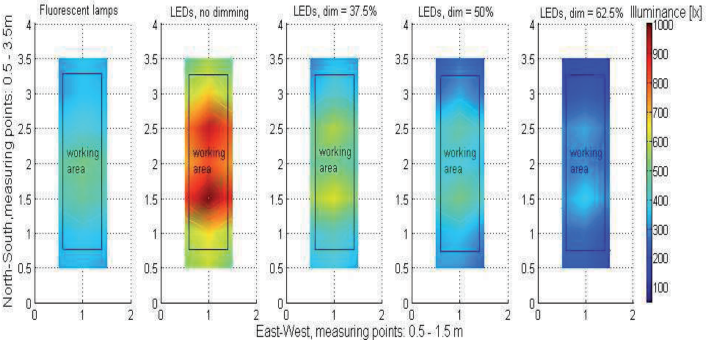

Figure 7 Effect of dimming on working area and surrounding area using LEDs and fluorescent lamps [Publication III].

3.3 Solar energy and solar panel area

The amount of solar radiation received depends on the installation position and angle of a solar panel, as well as on the geographical location of the installation. Two different locations were chosen to investigate the variation in solar energy. This was examined on the basis of solar radiation prediction and the solar panel area required to produce electricity for office lighting. The selected locations were Khartoum in Sudan (15.5°N, 32.5°E) and Espoo in Finland (60.11°N, 24.49°E) [Publication IV].

To receive the maximum amount of solar radiation, the optimum tilt angle (Opt Ang) is recommended for use [56]. Optimum tilt angles for Finland and Sudan were collected for the whole year using the NASA statistical database [57]. Thus, the radiations received with (Opt Ang) are presented in Figure 8 below. The fixed tilt angle for Finland, 45°, and 15° for Sudan were chosen to compare the solar radiation received because these angles are close to the annual optimums. The amount of radiation in these angles is shown in Figure 9. The monthly solar radiation (Table 1) is about 2% higher with monthly optimal tilt angles (Figure 8) when compared with annual fixed tilt angles (Figure 9).

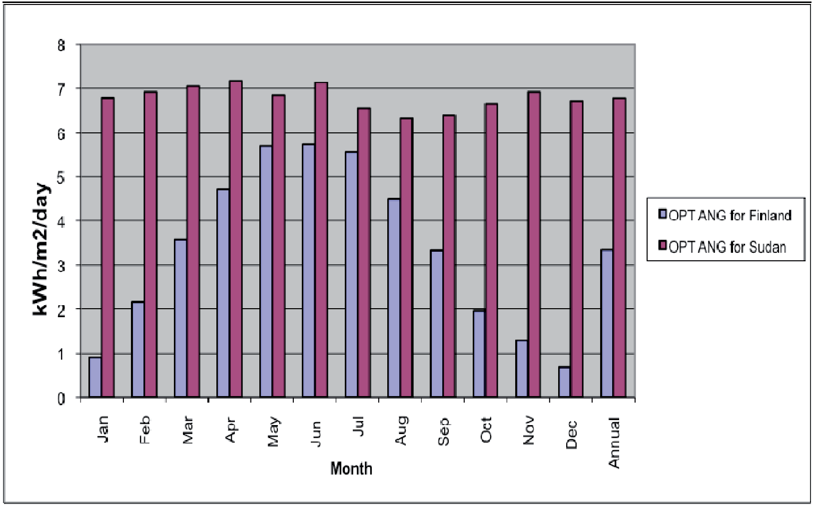

Figure 8 Solar radiation received in Finland (60.1°N, 24.5°E) and Sudan (15.5°N, 32.5°E) using the monthly optimal tilt angles (Opt Ang) [publication IV].

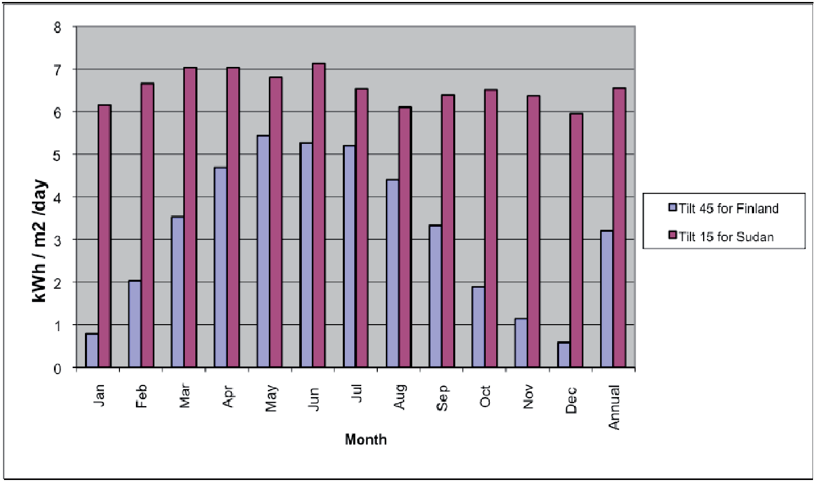

Figure 9 Solar radiation received in Finland (60.1°N, 24.5°E) and Sudan (15.5°N, 32.5°E) using the fixed annual optimal tilt angles [Publication IV].

Table 1 Solar radiation received, based on annual fixed tilt and monthly optimum angles in Finland and Sudan (kWh/m²/day) [57].

Month	Finland		Sudan	
	Tilt Ang 45	Opt Ang	Tilt Ang 15	Opt Ang
January	0.79	0.9	6.15	6.79
February	2.03	2.17	6.66	6.92
March	3.53	3.57	7.04	7.05
April	4.69	4.71	7.04	7.17
May	5.44	5.7	6.81	6.85
June	5.27	5.74	7.13	7.13
July	5.2	5.55	6.53	6.55
August	4.4	4.5	6.1	6.31
September	3.33	3.34	6.39	6.4
October	1.89	1.96	6.51	6.64
November	1.15	1.29	6.37	6.92
December	0.59	0.69	5.95	6.7
Annual	3.2	3.5	6.55	6.78

The data shown in Figure 9 were used to calculate examples of the solar panel area required to power office equipment in Finland and Sudan. The comparison was performed using the measurement data of the off-grid solar PV system installed in Aalto University, Finland [Publication III] and the information collected from the NASA Surface Meteorology Database [57]. This means that the solar panel area required to power up laptop and desktop computers was converted to match the conditions in Sudan on the basis of the statistical solar radiation data of the NASA Surface Meteorology Database using Equation 1:

$$A_L = A_{Fm} \cdot \frac{R_F}{R_L} \tag{1}$$

where:

A_L = Area of solar panel required in the selected location (Sudan)

A_{Fm} = Area of solar panel required in Finland, based on measured data

R_F = Amount of radiation in Finland, NASA statistical data [57]

R_L = Amount of radiation in the selected location, NASA statistical data [57]

It should be noted that these calculations were based on measurements done on December, February, April, June, and July during 2009-2010 in Finland, which was then scaled to the conditions in Sudan without actual measurement data from this location but using statistical data provided by the NASA Surface Meteorology Database. Annual changes in amounts of solar radiation can be significant, as can the impact of local weather variations etc., so the main purpose of these calculations was rather to point out the significance of installation location in PV system design than to provide accurate instructions concerning the size of the solar panel area [Publication IV].

These calculations were made for different months to show the effect of seasonal changes in the solar power levels in Sudan and Finland. These results are shown in Figure 10 and Table 2 below.

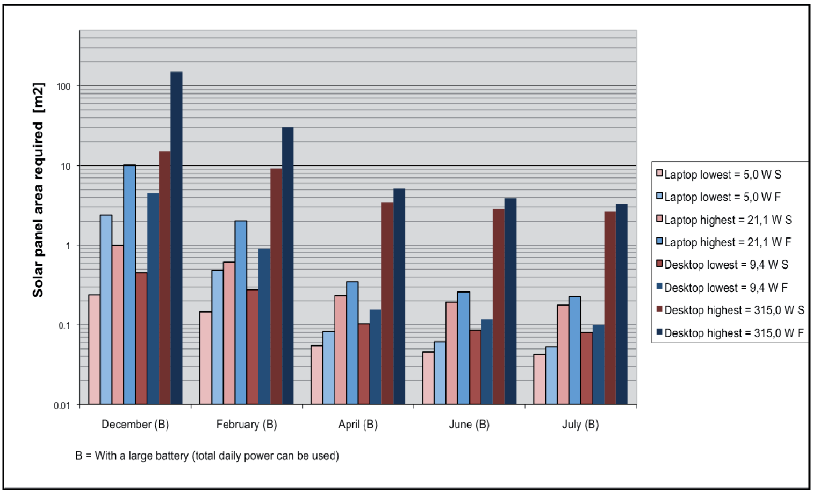

Figure 10 Solar panel area required to power office equipment for Finland (F) and Sudan (S) when using the annual optimum tilt angle throughout the year [Publication IV].

Table 2 Ratio of solar panel area required with the battery (B) [Publication IV].

Ratio	December (B)	February (B)	April (B)	June (B)	July (B)
Solar panel area Finland/Solar panel area Sudan	10.08	3.28	1.5	1.35	1.26

The closer the region is to the equator, the more solar radiation is received yearly and the smaller the required solar panel area. On the other hand, spring and summer are seasons that receive significant amounts of solar radiation in Espoo, whereas in Khartoum all seasons receive a large amount of solar radiation [Publication IV].

According to the calculations made when comparing solar panel areas in Sudan and Finland, the required solar panel area is 10 times greater during the winter in Finland when compared to Sudan. During the summer the radiation levels are more similar in these locations and the required solar panel area is only 1.3 times larger in Finland when compared to Sudan (Table 2).

3.4 Conclusions

When LED luminaires were dimmed by 50% the illuminance on the working area was about the same as with FLs (Figure 6). The measured UGR value was 20.4 for fluorescent luminaires and 24.1 for an LED luminaire. The UGR values were somewhat over the recommended UGR value of 19. The main reason for this was that in the LED luminaires the light came from a relatively small number of bright light points. Increasing the number of lower-power LEDs could diminish the problem. Better design of the LED luminaires or better integration of daylight lighting would most probably reduce the glare problems.

Photovoltaic energy production varies greatly according to the time of year, weather conditions, and the installation location. In Finnish conditions photovoltaics might be combined with other energy sources whenever possible. The use of photovoltaics combined with LEDs can result in energy savings, but they are still a relatively expensive choice today. Additionally, the efficiencies of photovoltaics and LEDs are still in a developing stage but they are expected to be better in the future with new technological innovations.

4 Electricity and lighting in Sudan

4.1 Electricity generation in Sudan

Sudan is the largest country in Africa, with an area of about 2.5 million square kilometres. The population is estimated to be 40 million. Sudan's climate is divided into tropical in the south and desert in the north. The northern parts of the country experience higher temperatures in summer, ranging from 25 °C to 41 °C, the winter season being quite cool in these regions. About 70% of the Sudanese population live in rural areas and have no access to electricity. Electricity is supplied through the national grid in Khartoum and central Sudan (Figure 11). More than 80% of the total electricity generation in Sudan is consumed in these regions. Off-grid towns use diesel generators to provide electricity, mainly for lighting. [Publication II]

The Roseires dam, approximately 500 km south-east of Khartoum, used to be the main hydropower plant and generates electricity with the capacity of 280 MW. This amount often drops to half as a result of poor water flows in late winter and early summer. The Merowe dam, built between 2003 and 2008, is located about 350 km north of Khartoum. The Merowe dam, with 10 units, compared to the Roseires dam, with 7 units, has a capacity of 1250 MW. [Publication II]

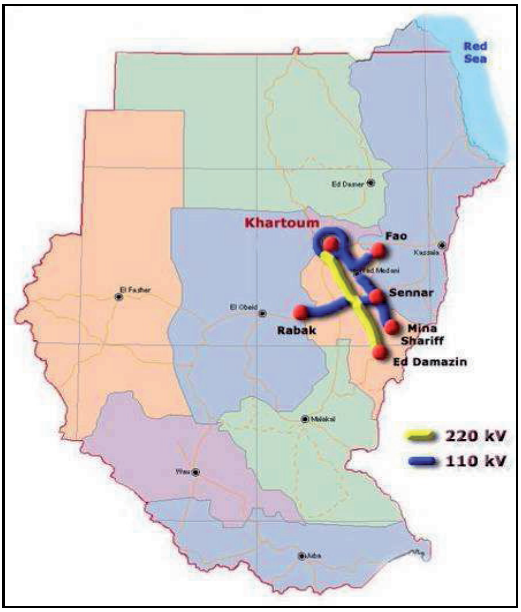

Figure 11 Sudanese national grid [58].

4.2 Renewable energy sources in Sudan

Biomass, solar energy, wind power, and hydropower are the main renewable energy sources in Sudan. Biomass, petroleum products, and hydropower are the predominant energy sources at the moment in Sudan. The availability of sunlight in Sudan is in the range of 8.5 hours/day to 10.5 hours/day, with radiation on the horizontal surface in the range of 4.9-6.7 kWh/m^2 /day. The annual average wind velocity is about 5 m/s in most of the northern states and 2.5 m/s in the south of Sudan. The potential capacity of mini-hydropower plants in Sudan is estimated to be 5583 MW in the southern states. The western and central parts of the country have 4057 MW of mini-hydro potential. [Publication II]

4.3 Lighting in Sudan

4.3.1 Lighting in urban areas

Electric lighting is mainly concentrated in Khartoum, central Sudan, and in isolated towns. Most of these areas use electric lighting in homes, offices, schools, and hospitals. The most common light sources used in these buildings are incandescent lamps and fluorescent lamps. Incandescent lamps are cheap but less efficient than a fluorescent lamp. Daylight is widely used in residential, school, and office buildings during the daytime. The high cost of fluorescent lamps and the lack of efficient lighting products are the main barriers to their use in Khartoum and in isolated towns. The availability of efficient lighting products can help to provide efficient lighting systems in buildings in urban areas. [Publications I and II]

4.3.2 Lighting in rural areas

Firewood is a cheap source of energy for lighting in rural areas of Sudan. Other sources that are used for lighting in these areas include kerosene lamps, diesel lamps, and candles [Publication II]. Burning firewood, kerosene, diesel fuel, or candles for lighting produces smoke and causes indoor air pollution [13]. Indoor air pollution has negative impacts on human health and it is a cause of several diseases such as eye diseases, lung cancer, tuberculosis, and asthma [13]. LED lighting combined with renewable energy sources could reduce the use of firewood, kerosene fuel, diesel fuel, and candles for providing lighting in these areas [Publication I and II].

4.4 Case study in Soba Arradi area

4.4.1 Lighting measurements

Lighting measurements in the Soba area Arradi, in Khartoum, the capital of Sudan, were conducted using a one-room house (Figure 12). The dimensions of the room were 5 m × 4 m × 2.5 m, with two windows, each with dimensions 0.85 m × 1.05 m, and one door, with dimensions 1.85 m × 1.05 m. In the daytime there is no need for artificial lighting as enough light gets through the windows and the door [Publication V].

Figure 12 The one-room house where lighting measurements were conducted in Soba Arradi [Publication V].

The lighting measurements were conducted both at night and during the daytime. An incandescent lamp, CFL, and LED lamp were hung at a distance of 0.45 m from the ceiling and the measurements were conducted at a distance of 1.38 m from the lamp to the working area at night (Figure 13). The working area is a table with a height of 0.75 m from the ground. Illuminance values on the working area directly under the light source (centre of the room) and from three other measurement points were measured (Figure 13). It was not possible to perform long measurements for security reasons, since there was no advance permission to conduct such a study in the area. Such arrangements usually need time and advance permission from the authorities (security). The only available one-room house to conduct the measurements in was that in Figure 12. However, the room was full of objects and disorganised and only limited space was available for measurements (Figure 13). The measurements were conducted in one day in December, 2010: during the daytime from 1:00 pm to 2:00 pm and at night from 8:00 pm to 9:00 pm. The main objective of conducting these measurements was to point out the importance of using efficient lighting. This could be the first step to starting introducing lighting technology combined with photovoltaics in Sudan.

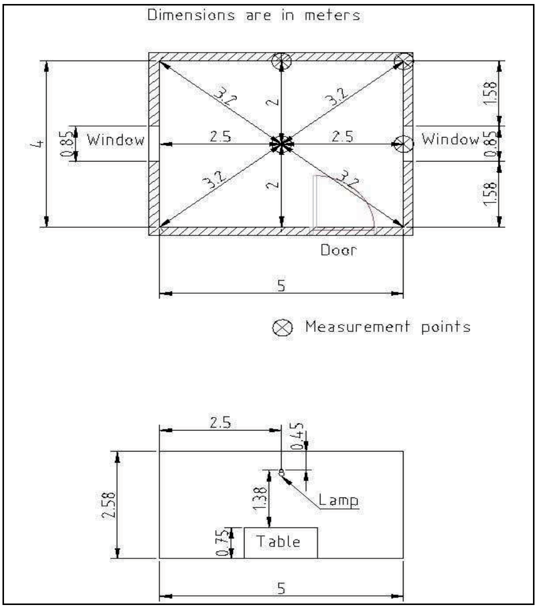

Figure 13 Dimensions of the room used for measurements [Publication V].

4.4.2 Results

The day-time measurements showed that the highest illuminance value was measured at the centre of the room (300 lx) and the lowest (75 lx) was measured at the distance of 3.2 m in the corner of the room. The illuminance value (280 lx) was almost as high at the distance of 2.5 m from the centre of the room, since this measuring point was close to the window (Table 3). These day-time measurements were conducted after the middle of the day (1:00 to 2:00 pm) with a clear sky. The night-time measurements/results showed that the LED provided the highest illuminance level in the centre of the room. The CFL provided the highest illuminance at distances of 2 m, 2.5 m, and 3.2 m, whereas the incandescent lamp and LED provided lower illuminances at the same distances (Table 3).

Figures 14, 15 and 16 show simulated lighting with CFL, LED lighting, and 60W incandescent lamp. The simulations are scaled so that the illuminance in the centre of the room is the same as the measured value. Without the scaling the illumination in the centre of the room was, for instance with 60 W incandescent lamp, 45 lx and the measured value was 19 lx. Because the electricity was supplied from diesel generator, the voltage was not constant. In addition there was voltage drop in the lines. Incandescent lamp is sensitive for the supply voltage. If the voltage is 200 V instead of 230 V, then the luminous flux is reduced to 60 %. LED lamp and CFL are less sensitive to the voltage, since they both contain rectifier.

Illuminance levels of 25 lx to 30 lx are necessary for normal reading or writing and illuminance levels of 5 lx to 15 lx for general lighting in rural houses [59], [8], [9]. These illuminance levels can also be used in households in Soba Arradi. However, the recommended illuminance levels for indoor lighting in developed countries range between 100 lx and 500 lx [55], [60], [61]. Unlike in developed countries, standards and guidelines for recommended lighting levels in houses are not yet in use in developing countries [8], [9].

Table 3 Illuminances during the day and at night [Publication V].

	Distance (m)			
Light source	Centre	2	2.5	3.5
	Illuminances (lx)			
Daytime light	300	190	280	75
IL (60 W)	28	9	4	2.5
CFL (18 W)	19	16	5	5.7
LED (8 W)	32	9	4	2

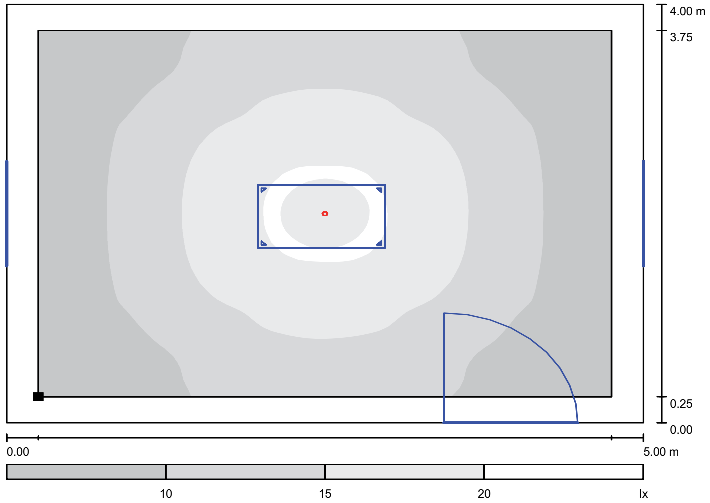

Figure 14 Simulated lighting with CFL.

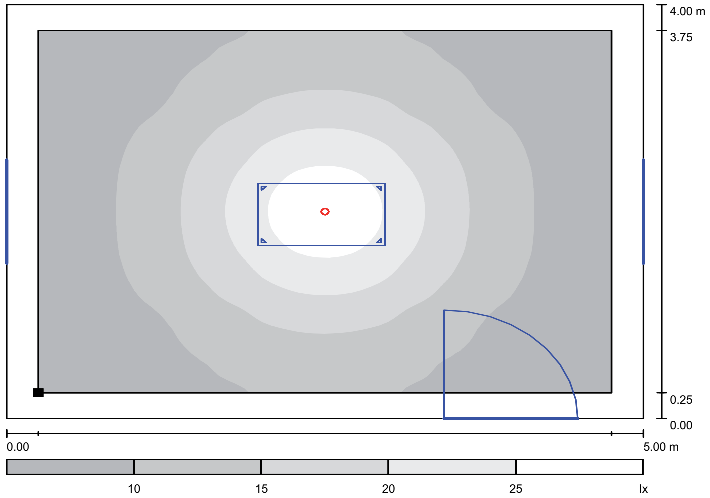

Figure 15 Simulated lighting with 1LED lighting.

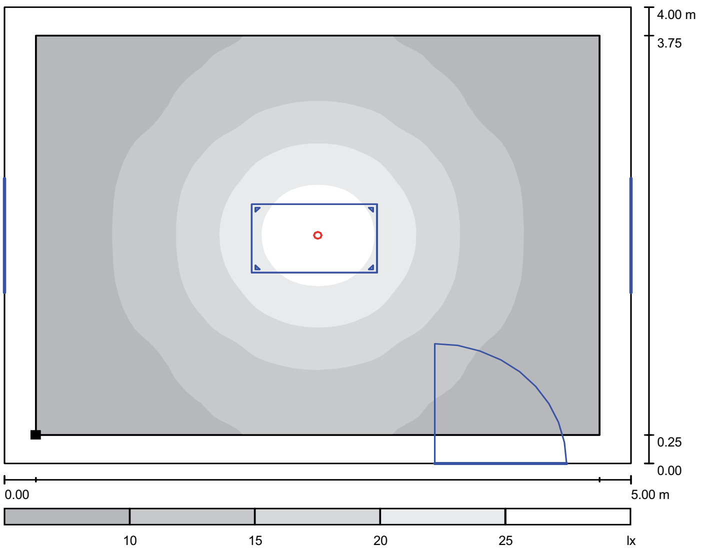

Figure 16 Simulated lighting with 60W incandescent lamp.

4.4.3 Replacement of diesel generators by PV systems

A study of the replacement of a diesel generator by a PV system was conducted in the Soba Arradi area in Khartoum (15.5°N, 32.5°E). The largest amount of solar energy can be produced by using the annual optimum tilt angle. The fixed tilt angle of 15° was chosen to maximise the solar radiation received, because this angle is close to the annual optimum (Figure 17).

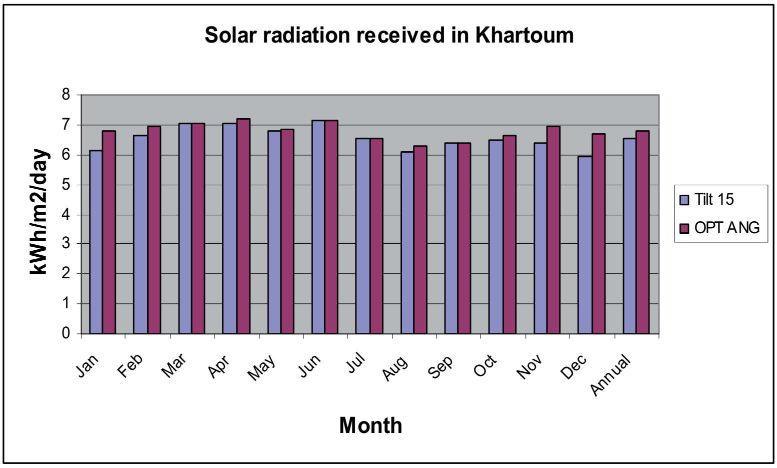

Figure 17 Solar radiation received in Khartoum (15.5°N, 32.5°E) based on optimal tilt and annual angles [57].

The solar panel area required for different light sources can be calculated on the basis of the data gathered from NASA statistical data (Figure 17). The size of the PV panel and battery bank required was determined with the assumption that the conversion efficiency of a solar cell is 10% [62]. Equations (2) and (3) were used to calculate the solar panel area and battery bank size required [63], [64]. The solar panel area required A can be calculated with:

$$A_{req} = \frac{1.5 E_{daily}}{\eta E_{rad}} \tag{2}$$

where:

A_{req} = Solar panel area required (m^2)

E_{daily} = Daily energy consumed (kWh/day)

E_{rad} = Daily solar radiation (kWh/m^2/day)

η = Solar cell conversion efficiency (10%).

The required battery bank size can be calculated with:

$$B_{bank} = \frac{5 \times 1.5 E_{daily}}{V} \tag{3}$$

where:

B_{bank} = Battery bank capacity (Ah)

V = The voltage value (12V)

The daily energy consumption was multiplied by a factor of 1.5 to account for system inefficiencies, which include wiring and interconnection losses, as well as the inefficiency of battery charging and discharging cycles. The factor 5 accounts for the battery capacity that can provide power continuously without recharging for five days [63].

To ensure the optimum of the PV system design, the minimum solar radiation received in Khartoum (6 kWh/m^2/day) was used (Figure 13). The calculation gives an approximate idea how large a solar panel area and corresponding battery bank size is required for lighting devices in the Soba Arradi area, where sunlight is available throughout the year (Figure 17). The calculation (Table 4) showed that the largest solar panel area and battery bank required were achieved when incandescent lamps were used and with an LED light source, the smallest solar panel area and battery bank required were achieved. This means that the greater the amount of energy and power consumed, the larger the solar panel area and battery bank required.

Table 4 Energy consumed in 50 houses using different light sources four hours/day.

Light source	Lamp power (W)	Total power (50 homes) (W)	Energy consumed daily (Wh)	Solar panel area required (m^2)	Battery bank (Ah)
IL	60	3000	12 000	30	7500
CFL	18	900	3600	9	2250
LED	8	400	1600	4	1000

4.4.4 Electricity and lighting costs

Diesel generators operate as electricity suppliers to houses. Usually, these generators are owned and run by individuals. They can be shop owners or even end users themselves living in Soba Arradi. For the following cost calculation, a diesel generator with the following specifications was chosen:

Power: 9.9 kW (Maximum)
Operating time per day: 4 hours
Supplies power to: 50 homes
Length of wires to homes: 500-800 m
Initial cost: US $480

A generator consumes 300 litres of diesel fuel per month, which costs US $120/month, and oil which costs US $20/month. Hence, the total monthly cost of the generator operating for four hours per day is US $140. The cost of electricity for one lamp in the Soba Arradi area is US $5/month for an incandescent lamp or CFL. Therefore, the operating cost for a lamp is US $60/year, while the operating cost for a diesel generator is US $1680/year. The energy consumed by a lamp does not affect the price charged for it. This means that energy is wasted just through clear inefficiency and this suggests that saving energy is the most effective way to improve the security of the electrical energy supply. Thus, it could be beneficial for the owner of a generator and residents to replace their incandescent lamps by CFLs, but at subsidised prices. However, no subsidy policy to purchase energy-efficient light sources and solar panels is in use in Sudan as yet [Publication V].

The cost of electricity in Soba Arradi does not include the purchase price of a lamp; only the electrical energy delivered from the diesel generator to light up the lamp is charged for. In the Soba Arradi area, the purchase prices for an incandescent lamp and CFL are US $0.8 and US $5.2 respectively. The replacement of incandescent lamps by CFLs is economically viable and benign in terms of energy saving for Soba Arradi residents. LEDs are energy-saving and can provide a cost-effective solution but they are not currently in use in this area [Publication V].

4.4.5 Cost analysis of the PV system

For an economic evaluation of a lighting solution system, a cost analysis was carried out for the PV system, assuming a useful life of 15 years for a solar panel and two years for the life of a battery bank. This cost analysis includes initial and variable costs. Initial costs are costs for the lighting or PV system design, lighting equipment, wiring and control devices, and the labour for the installation of the system. Usually, only the installation costs are taken into account and people are not aware of the variable costs [Publication V].

PV modules can be purchased for about US $5/W and flooded acid batteries can be purchased for around US $1/Ah [63]. On the basis of these purchase prices, an estimation can be made; the only issue is the degree of precision to which we perform the estimation [63]. To design a PV system based on the parameter specifications in Table 5, CFLs are considered because they are currently in use in the Soba Arradi area. The subtotal cost of the PV system for CFLs is US $4500 for a solar panel and US $2250 for a battery (Table 5). To account for the costs of the mounting structure, wire, fuses, and switches, the subtotal costs were multiplied by 1.2 [63]. Therefore, the estimated cost of the PV system is US $5400 for a solar panel and US $2700 for a battery. Such a PV system could be reliable and environmentally friendly and has the potential to contribute to the development of sustainable electricity generation. In long-term operation, a PV system can perform and maintain the quality of electricity generated at a lower cost. The system could be a cost-effective solution in areas where there is no electrical grid, such as Soba Arradi.

Table 5 Estimated size and cost of PV system for 50 houses [Publication V].

Light source	Parameter size		Estimated initial cost	
	Solar panel	Battery bank	Solar panel	Battery bank
	(W)	(Ah)	(US $)	(US $)
IL	3000	7500	15 000	7500
CFL	900	2250	4500	2250
LED	400	1000	2000	1000

The energy costs of the lighting or PV system installation during its whole life cycle are often the largest part of the entire costs. The initial cost of the PV system is given in Table 5 for both a solar panel and battery bank. The annual cost for a PV system can hence be calculated from Equation 4 [65] as follows:

$$C_i = I \times \frac{i(1+i)^n}{(1+i)^n - 1} = \text{US \$486/year for solar panel} \qquad (4)$$

C_i = US $1458/year for battery bank

Total annual cost = 486 +1458 = 1944 US $1944

where:

C_i = Annual costs of the initial investment

I = Initial costs (US $4500 for solar panel, US $2700 for battery)

i = Interest rate (i = p/100, where p is interest rate as a percentage, 4%)

n = Number of years (service life for a solar panel is 15 years and for a battery it is two years).

The calculation of the costs showed that the annual cost of the initial investment (US $1944/year) for a PV system is higher than the annual costs of the initial investment in a diesel generator (US $43.2). In other words, the initial costs for a diesel generator (US $480) are much lower than the initial costs for a PV system (US $1944), but the variable costs (operating costs) for a diesel generator (US $1680) are much higher than the variable costs of a PV system (US $60). Therefore, the total costs for the PV system are US $2004/year and for a diesel generator they are US $1723.2/year. If they use solar panels combined with CFL, the 50 houses in Soba Arradi can pay US $3000/year. For the Soba Arradi area, the PV system proved to be the higher-cost choice if the service life of a solar panel is 15 years and the service life of a battery life is only two years. However, if the service life of a solar panel is 30 years and the service life of a battery is 10 years, the total cost of the PV system is US $705/year. This is when the battery discharges 20% of its full capacity. Therefore, the choice between the higher and lower cost of the PV system depends on the service life of the solar panel and battery. The longer the service life, the lower the cost. The PV system might be more suitable for electricity generation than a diesel generator in the Soba Arradi area when used for a longer period.

The use of solar panels instead of diesel generators would eliminate the running costs of diesel fuels each year in the Soba Arradi area. However, the initial cost of solar panels and batteries, respectively, are the obstacles to

Soba Arradi residents using a PV system. They lack funding for the greater initial investment related to the PV system. Perhaps the lack of experience of PV systems is another obstacle to their use instead of diesel generators in the Soba Arradi area.

4.5 Conclusions

Energy savings can be achieved by replacing incandescent lamps by CFLs in the Soba Arradi area. More energy savings can be achieved by using LEDs, but they are not currently available on the Sudanese market. However, the purchase prices of CFLs are higher than those of incandescent lamps. Diesel generators are an expensive choice for electricity generation in the Soba Arradi area. PV systems can offer an effective solution; however, their high initial costs are the main obstacles to their use. The initial costs of a diesel generator are much lower compared to the initial cost of the PV system, but its operating costs are higher. PV systems might be more suitable for electricity generation than diesel generators in the Soba Arradi area. However, diesel generators will still be in use while residents gradually switch to PV systems when their incomes increase and the government provides subsidies and incentives to buy energy-efficient products.

In Sudan, public awareness of solar energy technology is very low; thus it is first necessary to give information about the benefits this technology can offer. In order for PV systems to become widely used, they should be available at affordable prices.

The use of solar panels combined with energy-efficient light sources in Sudan is very low. Subsidy policies may help to accelerate and spread the use of energy-efficient light sources combined with photovoltaics. Cost-effective lighting and power solutions in Soba Arradi and similar areas in Sudan could be improved by replacing diesel generators by solar panels combined with energy-efficient light sources, such as CFLs and LEDs.

Sudan is rich in water resources that could be used to establish new hydropower plants across the country to increase the current electricity generation capacity. Solar and wind energy can help to provide electricity to off-grid areas of Sudan. Extension of the national electricity grid to isolated towns could reduce the use of diesel-powered generators for electricity generation in these areas.

5 Discussion and conclusions

The region between latitudes 30° N and 30° S above and below the equator contains most of the developing countries of Asia including India and Nepal, Africa including Ghana and Sudan and Latin America with the highest solar radiation in the world. India with latitude 28 ° N, Nepal 27° N, Ghana 5° N and Sudan 15° N have annual solar energy distributions of around 5-6 kWh/m^2/day, 5-6 kWh/m^2/day, 6-7 kWh/m^2/day and 6-7 kWh/m^2/day respectively. The annual variation outside latitudes 30° N and 30° S is high for instance in Finland the ratio between solar radiation on December and May is 0.78/5.44 is 15%. Therefore, it is not practical to use solar panels all year round without connected to grid. If the solar panels are used without inverters, then the solar area are to be designed according to the lowest solar radiation in the year.

The use of diesel generators for electricity generation in the Soba Arradi area in Sudan is an expensive choice. PV systems can also be used for electricity generation in the Soba Arradi area but their initial costs are the main obstacles to their use. The initial costs for a diesel generator are much lower compared to the initial cost for the PV system, but its operating costs are higher. Diesel generators will still be in use while residents gradually switch to PV systems when their incomes increase and the government provides subsidies and incentives to buy energy-efficient products. In order for PV systems to become widely used in Sudan, their benefits and more knowledge should be known first and they have to be available at affordable prices.

About 1.4 billion people who are now living without electricity use firewood and kerosene lamps as their light sources [2]. It is very unfortunate that some people still cannot even afford kerosene or diesel lamps for lighting. Among these people firewood is the only method to light up their houses. The lighting systems can be improved by first shifting to kerosene or diesel lamps or directly to LED lighting. The benefits that LED lighting can offer are, for instance, reducing indoor air pollution and the use of kerosene fuels. The greenhouse gases associated with kerosene lighting will be minimised with solar-powered LED lighting systems.

The governments in developing countries may encourage research into renewable energy sources and illumination engineering through educational and government institutions. Local enterprises cooperating with international solar energy and the LED industry can be encouraged to provide LEDs and solar energy products at affordable prices.

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About 1.4-1.5 billion people in the world are without access to electricity, most of them living in developing countries. The work presented in this Thesis discusses the benefits and costs of replacing diesel generators with solar photovoltaic systems in electricity generation. Electricity enables the replacement of kerosene lamps, diesel lamps, firewood, and agricultural residues with more efficient light sources like compact fluorescent lamps and LEDs for lighting in developing countries. Measurements of solar photovoltaic systems combined with LEDs and fluorescent lamps were conducted in an office building in Finland. In addition, measurements were conducted in a one-room house in Sudan using LEDs, compact fluorescent and incandescent lamps for lighting. The results indicate that there is high potential for energy savings in using solar panels combined with LEDs and other efficient light sources in developing countries.

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