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Economic and Affordability Analysis of Off-Grid Photovoltaic Systems in Sub-Saharan Africa

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Affidavit

I, **MICHAEL ROHRER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ECONOMIC AND AFFORDABILITY ANALYSIS OF OFF-GRID PHOTOVOLTAIC SYSTEMS IN SUB-SAHARAN AFRICA", 149 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

The focus of this master thesis is on the economic and affordability analysis of small off-grid photovoltaic systems in rural areas of Sub-Saharan Africa (SSA). In order to grasp the motivation and importance of modern energy services, this paper also gives an overview of the relevant context for electricity (e.g. political, social and economical situation in SSA) and reviews the literature of electricity access, consumption, production, affordablitlity and rural electrification in the region. Afterwards, the PV potential, the PV market and the PV technology applicable for small off-grid usage in SSA are discussed.

This sets the stage for an economic analysis of three exemplary PV systems. The PV systems analysed are a 5W picoPV, a 50W SHS, and a 100W SHS system. The economic analysis uses present value calculations (including reinvestment, O&M, Management costs and depreciation), calculations on monthly financing costs (assuming a 10% annual interest rate) and LCOE calculations (including a sensitivity analysis). Furthermore, the available household budget for electricity is estimated for 47 SSA countries using income quintile data (of 43 SSA countries), GDP per person data and an estimated household size (of 5 persons). The monthly financing costs together with the available household budget for electricity are then used to assess the affordability of the PV systems that have been examined.

The results in this paper indicate that a 5W picoPV system is competitive with the substitutes, kerosene, candles and batteries, in average SSA households. It is also affordable for 75% of the rural population in SSA (under good financing conditions e.g. monthly payments, 3 years financing period, 10% interest rate). Furthermore, it is shown that SHS systems can be more economical than diesel in remote areas with high irradiation, but have only limited affordability. Between 19% (100W with 10 financing period) and 29% (50W with 5 years financing period) of the rural population could afford such systems.

Acknowledgements

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List of Abbreviations/Acronyms

Ah	Ampere hour
CSP	Concentrating Solar Power
DC	Direct Current
DG	Director General
EPIA	European Photovoltaic Industry Association
ESCO	Energy service company
GDP	Gross Domestic Product
GIS	Geographic Information System
GNI	Gross National Income
GTZ	Gesellschaft für Technische Zusammenarbeit
ICT	Information and Communication Technology
IEA	International Energy Agency
IMF	International Monetary Fund
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
LCOE	Levilized Cost of Electricity Generation
MDG	Millennium Development Goals
MW	Megawatt
MWh	Megawatt hour
O&M	Operation and Maintenance
PPP	Purchasing Power Parity
PV	Photovoltaic
ROI	Return on Investment
SE4ALL	Sustainable Energy for All
SHS	Solar Home System
SLI battery	Start-Lighting-Ignition battery
SSA	Sub-Saharan Africa
UN	United Nations
UNIDO	United Nations Industrial Development Organization
USD	United States Dollar
W	Watt
Wh	Watt hour
WTP	Willingness to Pay
Wp	Watt Peak

1. Introduction

The UN started the initiative “Sustainable Energy for All” (SE4All) in 2012. One of the aims is to ensure univeral access to modern energy services by 2030, because for once, it is understood that providing energy access can contribute to sustainable development (DFID, 2002). It is also assumed that without access to modern affordable energy, it is impossible to achieve the Millenium Development Goals,e.g. reducing poverty by half by 2015. As K. Yumkella, Director General of UNIDO, (UN-Energy, 2011) wrote *“Energy is important, not as an end in itself, but rather as a means to tackle the major developmental challenges that exist in Africa today.”*

The first Global Tracking Report for Sustainable Energy for All defined electricity access as *"availability of an electricity connection at home or the use of electricity as the primary source for lighting"* (UN et al., 2013). Currently, worldwide, around 1.3 billion people lack access to electricity (IEA, 2011). Approximately 590 million of those people live in Sub-Saharan Africa (World Bank, 2010a) and about 84% of them live in rural areas (IEA, 2011). Thus, the paper at hand has the regional focus on rural areas in Sub-Saharan Africa and the focus on household electricity. Chapter 2.4 gives a more detailed overview of the electricity access situation, including the benefits of electricity and the appliances used with electricity in rural Sub-Saharan Africa.

Before going into the electricity access situation, this paper gives a short introduction into the political situation (chapter 2.1), the social context, e.g. the population distribution (chapter 2.2), and the economic situation (chapter 2.3) in the region. After all, according to DFID (2002), providing energy access should take the national and local context, such as the political, social, economic and technical situations, into account (DFID, 2002). So, in order to increase the energy access and improve consumption levels in Sub-Saharan African countries, it is necessary to understand what causes the current situation in the first place. However, as this paper tries to give an overview, a deep analysis on the national level is beyond the scope of this work.

The defintion of electricity access by SE4All does not yet take into account the adequacy, quality and quantity of service. In 2009, the average electricity consumption, or the quantity, in rural and urban Sub-Saharan Africa (without South Africa) was just 153 kWh per capita (Monari, 2011). The electricity consumption and demand will be discussed in chapter 2.5. The demand for electricity also highly depends on the affordability of electricity. As poverty is widespread and data on this topic is scarce, chapter 2.6 introduces ways to estimate spending on electricity, the willingness to pay for electricity and the affordability of electricity.

As actual consumption is a function of both demand and supply according to basic economic theory, the electricity supply situation in SSA will be discussed in chapter 2.7, including adequacy and the quality of electricity services. Summarizing the the state of supply, one has to say that most SSA countries are in a power crisis. Electricity generation capacity is lower in this region than in any other region in the world, capacity growth is stagnant, the average electricity price is double the price in other developing regions, and the supply is unreliable throughout the continent (The World Bank, 2011).

After discussing the current state of low electricity access and consumption and their causes, this paper explores the rural electrification situation in SSA, in chapter 2.8. First the motivation and the actual situation of rural electrification from the political perspective are considered. Next the paper goes into more detail of the technology options to provide electricity to rural areas, including a discussion on grid supply, diesel generators, renewable energies (with a focus on PV), and followed by a cost comparison of electricity generation technologies in SSA. The paper further reviews barriers to rural electrification in chapter 2.9.

A further aim of the “Sustainable Energy for All” initiative is to double the share of renewable energy in the global energy mix. This and the high technical potential for solar power in SSA are the reasons for the focus on photovoltaic energy technologies in this paper. The technical potential of PV in SSA is discussed in chapter 2.10.1, before reviewing the current market for PV technology in SSA in chapter 2.10.2.

The International Renewable Energy Agency (IRENA, 2011b) states that certain types of renewable energy can help to overcome the electricity access gap. IRENA also proposes that especially small-scale solutions deserve attention in the African context due to their easier implementation, their reduced transportation cost and their ability to work efficiently off-grid or as mini-grids (IRENA, 2011b). Thus, this paper, before going into the design of the analyzed systems, discusses the components of off-grid PV systems in chapter 2.10.4. Furthermore, the literature on the economic analysis on PV is shown in chapter 2.11, including typical costs found in terms of the system price (in €/Wp) and the levelized cost of electricity generation (LCOE) (in €/kWh), with the range of assumptions found on lifetime, discount rate, operation, maintenance cost, and management cost of these systems.

After reviewing the environment for PV in SSA and the basics of PV itself, the methodology used in this paper is described in a separate chapter (chapter 0), and the results and the discussion of the results are shown in chapter 4. First, the design of the three analyzed systems, one picoPV and two Solar Home Systems is discussed.

PicoPV systems are defined to have a capacity of 1-10W which is barely enough for 4 hours of lighting, mobile phone charging and listing to the radio. However, using this system as the main source of lighting and mobile phone charging provides economic benefits for households which have been previously without access to electricity. It would further count as having access to modern energy services according to the UN SE4All criteria. Additionally, the “Lighting Africa” initiative is also supporting the development of the markets of SSA countries for such products (The World Bank, 2011). One exemplary picoPV is analyzed in this paper, based on the IEA report Pico Solar PV Systems for Remote Homes, by Lysen (2013).

In addition to the 5W picoPV system, two SHS systems, one 50W and one 100W, are analyzed, based mostly upon the report by Carrasco (2013), analyzing 13.000 SHS systems in Morocco, which is the most recent detailed report on SHS systems in Africa. SHS systems are defined to have a capacity between 10W and 150W. In developing countries, these systems would be mainly feasible in areas with a long distance to the next population center, which increases diesel prices and that do not have the prospect of a grid connection in the near future. The benefits compared to a picoPV system are longer usage times and better lighting, which provides the possibility of watching television for a few hours a day and for charging small laptops or tablets.

After the system design in chapters 3.1 and 4.1, the energy output of the three systems is calculated separately in chapters 3.2 and 4.2. This energy output mainly depends on the irradiation, the efficiency of the panel and the battery, efficiency losses due to high temperature and panel degradation. The irradiation is assumed to be 4000 Wh/m²d, this low irradiation level for Africa was chosen to show the possibilities of the systems in a low irradiation environment. The total system efficiencies are set at 7% and 10.5% respectively. The panel degradation is assumed to be 0.5% per year; this reduces the energy output after 25 years lifetime by around 11%.

After the system design and the calculation of electricity output, the paper analyzes the economics of the chosen systems (in chapters 3.3 and 4.3) based on price data from Lysen (2013) and Carrasco (2013). The lifetimes are three years for the picoPV system and 25 years for the SHS with reinvestment for batteries (every five years) and for the charge controller and lamps (after 15 years). O&M and Management costs are both assumed to be 5% of the original investment cost, and the depreciation rate is assumed to be 10%.

Furthermore, different financing periods (with an interest rate of 10% per year) are assumed, as it is unfeasible to buy these systems over the counter with cash for most people in rural SSA. Thus, for a picoPV system with a regular lifetime of three years, two different financing periods, one year and three years, is assumed. For both SHS systems financing periods of one year and of 25 years are assumed, additionally calculations are a five year financing period for the 50W SHS system and a 10 year period for the 100W SHS system. With this input data, the present value of the systems is calculated first, before calculating the necessary monthly payments with different financing times. Afterwards, a LCOE analysis with a sensitivity analysis is performed.

This economic analysis is then used to first compare LCOE costs of the suggested systems with other generation technology and then to calculate how many people would be able to afford these systems under the set assumptions. Another input needed is the available household budget for electricity in SSA. This budget is calculated with income quintile data, GDP per person data for more or less all the SSA countries, assumed household sizes of 5 persons, and an assumed affordability threshold of 5%. This data is then compiled into the three different country income groups, Low Income, Low-Middle Income, and Upper-Middle Income countries. The methodology is described in detail in chapter 3.4 and the results are shown in chapter 4.4. One main outcome is similar to a market potential analysis for the three systems under different assumed financing periods. In other words, it shows how many people can afford a specific PV system with different loan or payment conditions.

The conclusion, in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, summarizes the results and discussion and gives an outlook of the relevance of this paper.

Environmental considerations, especially the climate impact, are not discussed in this paper because as the IEA (2012) wrote, achieving modern energy access for all in Sub-Saharan Africa does not magnify the challenges of climate change. Universal access by 2030 would only increase global energy demand by 1% and CO_2 emissions by 0.6%.(IEA, 2012)

1.1. Hypothesis & Research question

The research question is: What is the economic potential of small off-grid PV systems in Sub-Saharan Africa?

The primariy hypothesis of this paper is that off-grid photovoltaic technology can play an important role in rural electrification in Sub-Saharan Africa.

2. State of the art

2.1. Political situation in SSA

This chapter shortly defines the countries in SSA and introduces the political situation, the status of political rights and civil liberties, the number of conflicts and the current perception of corruption in the region.

Table 1: List of Sub-Saharan African Countries after (UN-STAT, 2012)

Sub Saharan Africa		
Eastern Africa	**Western Africa**	**Central Africa**
Burundi	Benin	Angola
Comoros	Burkina Faso	Cameroon
Djibouti	Cape Verde	Central African Republic
Eritrea	Côte d`Ivoire	Chad
Ethiopia	The Gambia	Democratic Republic of the Congo
Kenya	Ghana	
Madagascar	Guinea	Equatorial Guinea
Malawi	Guinea Bissau	Gabon
Mauritius	Liberia	Republic of the Congo
Mayotte	Mali	São Tomé and Principe
Mozambique	Mauritania	**Southern Africa**

Réunion	Niger	
Rwanda	Nigeria	Botswana
Seychelles	Saint Helena	Lesotho
Somalia	Senegal	Namibia
South Sudan	Sierra Leone	South Africa
Tanzania	Togo	Swaziland
Uganda		
Zambia	**Northern Africa**	
Zimbabwe	Sudan	

Politically, Sub-Saharan Africa consists of all African countries fully or partially located south of the Sahara, see in Table 1 (UN-STAT, 2012). Sub-Saharan Afican states are mostly *de jure* democracies (Wikipedia, 2011) and elections have become commonplace. In fact, since the late 1990s the number of elections has increased while at the same time the number of coups has declined sharply. Anywhere from 15 to 20 elections have been held each year since 2000. However, many elections are rigged and have been charades held by regimes in power. The amount of successful coups numbered approximatly 20 per decade in 1960-2000, but fell to just six in the 2000s. (EIU, 2013) However, Freedom House assessed that in 2011, more countries are authoritarian than democratic (Kangas and Lucas, 2011). Even though coups have become more rare, conflicts, failed governments, and human-rights abuses are still widespread (EIU, 2013).

Table 2: Political situation in Sub-Saharan Africa, (Kangas and Lucas, 2011) adapted from Freedom House, 2000-2011, ´Freedom in the World´

<table>
<tr><th>Remained democratic throughout the decade</th><th>Remained authoritarian throughout the decade</th><th>Switched from democratic to authoritarian</th><th>Switched from authoritarian to democratic</th></tr>
<tr><td rowspan="2">Benin
Botswana
Cape Verde
Ghana
Malawi
Mali
Mauritius
Namibia
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
South Africa</td><td rowspan="2">Angola
Burkina Faso
Cameroon
Chad
Congo (Republic)
Congo (DRC)
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia
Guinea
Mauritania
Rwanda
Somalia
Sudan
Swaziland
Togo
Uganda
Zimbabwe</td><td>Central African Republic
Djibouti
Guinea-Bissau
Madagascar
Mozambique
Niger
Nigeria

(225 million people, based on 2010 population)</td><td>Comoros
Lesotho
Tanzania
Zambia

(61 million people, based on 2010 population)</td></tr>
<tr><td colspan="2">Started and finished as authoritarian, with a period of democracy
Burundi, Kenya

Started and finished as democratic, with a period of authoritarianism
Liberia</td></tr>
</table>

Freedom House even ranked sub-Saharan Africa as the world's most politically volatile region, with coups, civil strife, and authoritarian crackdowns in some countries, but also major democratic breakthroughs in others (Freedom House, 2013a). In their World 2013 Freedom survey, they divided countries into three categories: Free, Partly Free, and Not Free. Sub Saharan Africa, according to their definition, had 11 Free, 19 Partly Free, and 20 Not Free countries in 2012 (Illustration 1). The definition for a Free country is "*one where there is broad scope for open political competition, a climate of respect for civil liberties, significant independent civic life, and independent media.*" A Partly Free country is defined by "*some restrictions on political rights and civil liberties, often in a context of corruption, weak rule of law, ethnic strife, or civil war.*" And Not Free countries are those "*where basic political rights are absent, and basic civil liberties are widely and systematically denied*" (Freedom House, 2013b).

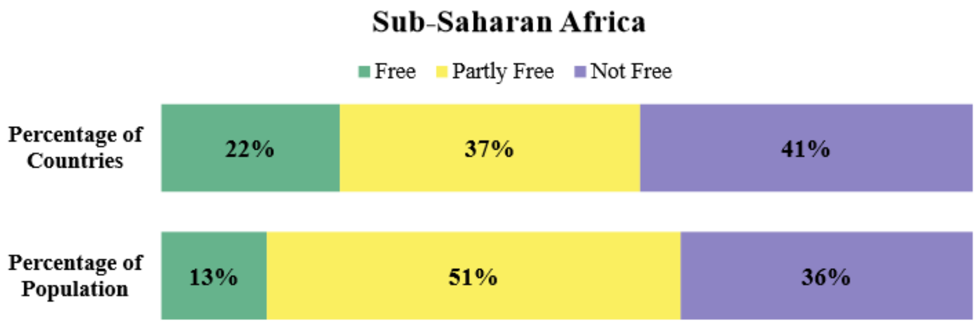

Illustration 1: Freedom in Sub-Saharan Africa, adapted from (Freedom House, 2013b)

However, the good news is that in Africa, in the 2000s, there were one-third fewer active armed conflicts (more than 25 battle deaths) than during the 1990s according to the Uppsala Armed Conflict Data Program (Themner and Wallensteen, 2012). Yet these conflict numbers do not show the full picture as they do not account for indirectly caused deaths such as, for example, deaths as a result of displacement.

Corruption is still seen as endemic in Sub-Saharan African countries. There are many different data sets capturing corruption in Africa, including, among others, Transparency International´s Corruption Perceptions Index, the Ibrahim Index of African Governance, or the World Governance Indicators (Jerven, 2013). In the Transparency International 2011 Corruption Perceptions Index, *a*ll but four countries in the region *(*Botswana, Cape Verde, Mauritius and Rwanda) came in on the lower half of the scale (Uwimana, 2011).

2.2. Population in SSA

Population data is a central factor in most conventional measures of development (Jerven, 2013). It is also relevant for electricity access, power consumption, and estimates for aggregated power demand, among others. However, population data for developing countries is often questionable. In theory, counting the population is straigthforward, in practice a range of discrete decisions are required. Furthermore, a population census is usually only undertaken once a decade, and survey aggregations act on the assumption that the census is representative (Jerven, 2013). In Sub-Saharan Africa, overestimation is a general problem in postcolonial censuses.

In 2010, according to the World Bank, the total population in Sub-Saharan Africa was 869.8 million. Nigeria had the largest population, 159.7 million, followed by Ethiopia with 87.1 million and DR of the Congo with 67.8 million. On the other end of the spectrum is the Seychelles with the smallest population at 0.04 million. (World Bank, 2013b)

In 2010, around 63 percent of the population (or 553 million people) in Sub-Saharan Africa lived in rural areas (World Bank, 2013b), despite accelerating urbanization (The World Bank, 2011). The range was from 14% in Gabon to 89% in Burundi. Africa's population density in 2000 ranged from 1-4 persons per km² to over 1000 persons per km² in cities. Illustration 2 gives a detailed overview over the population density, adapted according to CIESIN & CIAT (2013).

World average population growth rate has declined in the last 40 years (from 1970 - 2010) from 2% per year to 1.2 % per year. At the same time, the population growth rate in Sub-Saharan Africa remained more or less the same and has been slightly above 2.6% per year (UN, 2013b). In Sub-Saharan Africa, the population growth has contributed to the low rate of electricity access as it outpaced electrification rate (IIASA et al., 2013).

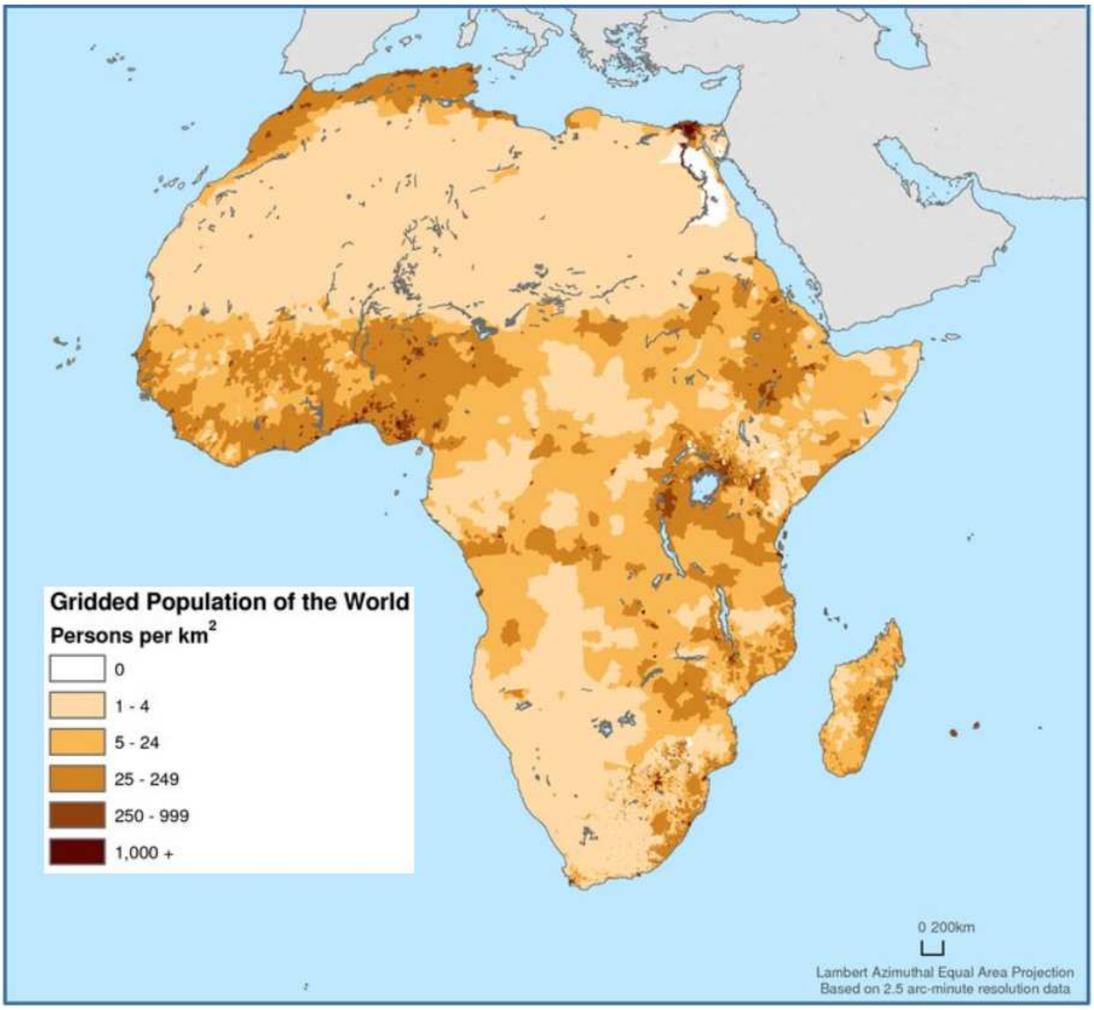

Illustration 2: Population density of Africa in 2000, adapted after (CIESIN and CIAT, 2013)

2.3. Economic situation SSA

"Statistics on African economies are widely known to be inaccurate. (...) Published data, both national and international, suffer from serious conceptual problems and measurement biases and errors" (Jerven, 2013).

This paper, nonetheless, depends on using a lot of the data provided by statistics on Africa, especially to access the affordability of the proposed PV systems. Thus, this chapter will first explain how national GDPs and GDPs per person are calculated and the limitations these calculations face. It will susbsequently describe equally a relevant measure of GNI with Purchasing Power Parity (PPP) per person before discussing poverty rates and inequallity indeces. Finally, the main metric used in this paper, income distribution per quintiles, will be presented.

Economies are divided in income group by the World Bank according to their GNI per capita. The groups in 2012 are: low income economies (LI), which have a GNI per capita of 1,035 USD or less; lower middle income economies (LMI), 1,036 USD - 4,085 USD; upper middle income (UMI), 4,086 USD - 12,615 USD; and high income (HI), 12,616 USD or more. (World Bank, 2013a) This division of economies will be used in later chapters.

2.3.1. Gross Domestic Product (GDP)

Most of the central development questions revolve around the gross domestic product (GDP). It is, together with the gross national income (GNI), the most widely used measure to size an economy. In theory, three distinct ways of aggregating GDP exist: the production method, the income method, and the expenditure method. In postcolonial Africa, the production method, which sums estimates of value-added per sector to provide the total value added (which is the GDP), has been favoured in official national income accounting. Even though the System of National Accounts recommends that all three methods should be calculated independently, in practice this is not often done in African countries. Thus, GDP statistics from African countries are best guesses of aggregate production (Jerven, 2013).

However, this is not the only problem with GDP calculations. Other basic questions determining the quality of GDP, are data availability at the statistical office, data accuracy, and how national accountants deal with missing data (Jerven, 2013). In other words, "*African development statistics have both validity and reliability problems"*[1] (Jerven, 2013). Another issue is the chosen base year, which is of fundamental importance for the calculation of GDP. The difference in base years explain some of the differences between data sources, which can be as high as 43% for GDP (Jerven, 2013).

Worldwide, there are three major sources of national income data for Africa: the World Development Indicators, the datasets of Angus Maddision, and the Penn World Tables. Each is based on national account data as prepared by national statistical agencies, with validity and reliabilty problems already included (as discussed in the paragraph above). On top, these three data sources differ in the modifications, the purchasing adjustments, and in the currencies they use. These sources disagree on most GDPs and on the ranking according to GDP of the

[1]Validity describes whether a measure is accurate. Reliability defines whether a measure is similarly accurate or inaccurate each time.

countries in SSA and in some cases, they do so with a large discrepancy (Jerven, 2013).

This paper uses GDP data from the World Development Indicators to calculate average GDP per person and GNI PPP per capita data, even though the data face the discussed limitations. As the total GDP per country is not as relevant for the calculations in this paper, only a short overview is provided; more detailed information can be found in

Table **4**.

The total GDP of Sub-Saharan Africa in the year 2010 was around 1,145 billion USD. Two countries, Sourth Africa and Nigeria, dominated the total, accounting for more than half of the GDP, with 363 billion USD and 228 billion USD respectively. The smallest economy in terms of GDP was São Tomé and Principe with 0,2 billion USD (World Bank, 2013b), the complete list can be seen in

Table **4**. On a side note, GDP growth rates in Sub-Saharan Africa surpassed the global average in the last 10 years (see Table 3), yet, the growth is unevenly distributed between and within countries. Before providing further details regarding this issue, the average GDP per person and the GNI PPP per person will be discussed.

Table 3: Real GDP Growth, Sub-Saharan Africa (IMF, 2013)

(Percent change)

	2004-08	2010	2011	2012	2013	2014
Sub-Saharan Africa (Total)[1]	**6.4**	**5.4**	**5.3**	**5.1**	**5.4**	**5.7**
Of which:						
Oil-exporting countries[1]	8.5	6.6	6.1	6.4	6.6	6.8
Middle-income countries[2]	5.0	4.0	4.7	3.3	3.6	4.0
Of which: South Africa	4.9	3.1	3.5	2.5	2.8	3.3
Low-income countries[2]	7.3	6.4	5.6	5.7	6.3	6.6
Fragile countries	2.5	4.2	2.4	7.0	6.8	6.5
Memo item:						
World	4.6	5.2	4.0	3.2	3.3	4.0

Source: IMF, World Economic Outlook database.
[1] Excluding South Sudan.
[2] Excluding fragile countries.

Table 4: Sub-Saharan population, GDP; GDP and GNI per capita in 2010 (except for DR Congo 2011, Djibouti 2009 und Somalia 1990) adapted from (World Bank, 2013b), Population below the International Poverty line and Gini Coefficient from (AfDB, 2013b)

	population in 2010	GDP for the year 2010	GNI per capita, PPP	GDP per capita	Population below the International poverty line (%)			Gini coefficient**	
Country	[mio pop]	[bnUSD]	[USD]	[USD]	year	<$1.25	< $2	year	Index
Angola	19,5	82,5	5150	4219	*2000*	54,3	70,2	*2000*	58,6
Benin	9,5	6,4	1560	678	*2003*	47,3	75,3	*2003*	38,6
Botswana	2,0	13,9	13610	7057	*1994*	31,2	49,4	*1994*	61
Burkina Faso	15,5	9,2	1260	593	*2009*	44,6	72,6	*2009*	39,8
Burundi	9,2	2,0	580	220	*2006*	81,3	93,5	*2006*	33,3
Cameroon	20,6	22,5	2240	1090	*2007*	9,6	30,4	*2007*	38,9
Cape Verde	0,5	1,7	3680	3407	*2002*	21	40,9	*2002*	50,5
Central African Rep	4,4	2,0	780	456	*2008*	62,8	80,1	*2008*	56,3
Chad	11,7	8,5	1360	729	*2003*	61,9	83,3	*2003*	39,8
Comoros	0,7	0,5	1090	795	*2004*	46,1	65	*2004*	64,3
Côte d´Ivoire	19,0	22,9	1790	1208	*2008*	23,8	46,3	*2008*	41,5
DR Congo	67,8	15,7*	n/a	232	*2006*	87,7	95,2	*2006*	44,4
Djibouti	0,9	1,0*	n/a	1167	*2000*	18,8	41,2	*2002*	40
Equatorial Guinea	0,7	12,3	21530	17616	…	…	…	…	…
Eritrea	5,7	2,1	540	369	…	…	…	…	…
Ethiopia	87,1	29,7	1030	341	*2005*	39	77,6	*2005*	29,8
Gabon	1,6	14,5	13050	9344	*2005*	4,8	19,6	*2005*	41,5
Gambia	1,7	1,0	1840	566	*2003*	33,6	55,9	*2003*	47,3
Ghana	24,3	32,3	1610	1331	*2006*	28,6	51,8	*2006*	42,8
Guinea	10,9	4,7	980	435	*2007*	43,3	69,6	*2007*	39,4
Guinea-Bissau	1,6	0,8	1200	526	*2002*	48,9	78	*2002*	35,5
Kenya	40,9	32,2	1640	787	*2005*	43,4	67,2	*2005*	47,7
Lesotho	2,0	2,2	2000	1097	*2003*	43,4	62,3	*2003*	52,5
Liberia	4,0	1,3	470	327	*2007*	83,8	94,9	*2007*	38,2
Madagascar	21,1	8,8	950	419	*2010*	81,3	92,6	*2010*	44,1
Malawi	15,0	5,4	840	360	*2004*	73,9	90,5	*2004*	39
Mali	14,0	9,4	1020	674	*2010*	50,4	78,7	*2010*	33
Mauritania	3,6	3,7	2390	1017	*2008*	23,4	47,7	*2008*	40,5
Mauritius	1,3	9,7	13770	7586	…	…	…	*2006*	38,9
Mozambique	24,0	9,3	900	387	*2008*	59,6	81,8	*2008*	45,7
Namibia	2,2	11,0	6160	5063	*2004*	31,9	51,1	*2004*	63,9
Niger	15,9	5,4	720	340	*2009*	43,6	75,2	*2008*	34,6
Nigeria	159,7	228,6	2160	1432	*2010*	68	84,5	*2010*	48,8
Republic of the Congo	4,1	12,0	3170	2921	*2005*	54,1	74,4	*2005*	47,3
Rwanda	10,8	5,6	1180	519	*2011*	63,2	82,4	*2011*	50,8
Senegal	13,0	12,9	1910	993	*2005*	33,5	60,4	*2005*	39,2
Seychelles	0,1	1,0	22720	10933	*2007*	0,3	1,8	*2007*	65,8
Sierra Leone	5,8	2,6	1050	448	*2003*	53,4	76,1	*2003*	42,5
Somalia	9,1	0,9*	n/a	98	…	…	…	…	…
South Africa	50,0	363,2	10310	7266	*2009*	13,8	31,3	*2009*	63,1
South Sudan	9,9	15,0	n/a	1506	…	…	…	…	…
Sudan	35,7	64,8	2050	1817	*2009*	19,8	44,1	*2009*	35,3
Swaziland	1,2	3,7	5570	3094	*2010*	40,6	60,4	*2010*	51,5
São Tomé and	0,2	0,2	1980	1129	*2001*	28,2	54,2	*2001*	50,8
Tanzania	45,0	22,9	1410	510	*2007*	67,9	87,9	*2007*	37,6
Togo	6,3	3,2	990	503	*2006*	38,7	69,3	*2006*	34,4
Uganda	34,0	17,2	1250	506	*2009*	38	64,7	*2009*	44,3
Zambia	13,2	16,2	1420	1225	*2006*	68,5	82,6	*2006*	54,6
Zimbabwe	13,1	7,4	n/a	568	*2004*	61,9	…	*2004*	50,1
Total SSA	869,8	1144,6		1316					

2.3.2. GDP per capita

Real GDP per capita is, in theory, measured by totalling the value of all value-added activities in an economy over one year (the GDP) and dividing that sum by the total population of a country during a given year. This product is then deflated by the consumer price index or another measure of price changes. In practice, this measure is prone to some inaccuracies. Most of the time, some economic activity is not accounted for, a population census is typically only undertaken once a decade, and the creation of price indices involves compromises, on, for example, the goods and services included in the index (Jerven, 2013).

Inconsistencies in the definitions of GDP and measurements of national income also create problems when comparing income (Jerven, 2013). According to Jerven (2013), income levels on a per capita basis can be subject to revisions by 50 to 100 percent. Since 2000, Sub-Saharan African countries achieved improved average income growth rates, largely due to primary commodity-driven growth. The average real per capita income is, nonetheless, still hardly higher than in 1970 (Sundaram and Schwank, 2011).

According to the World Bank (World Bank, 2013b), in 2010, the average GDP per capita in SSA was around 1,331 USD per person and year, this amounts to a little more than a 110 USD per month. Equatorial Guinea has the highest GDP per capita with 17,857 USD[2]; Somalia has the lowest with 97 USD per capita and year. Similarly dividing these numbers with 12 one gets the average income per month, ranging from 8 USD per month to 1,488 USD. However, it is important to note that these numbers do not yet account for unequal distribution of income within the population. This will be discussed in the next chapter.

For an international comparison of average income data, national currencies have to be converted into a common currency. Thus, average income per person is often presented as purchasing power parity (PPP) of GDP or GNI in USD. The PPP metric accounts for the fact that, for example, a dollar's worth of rupees will buy more of the majority of goods and services in India than it would buy in the US. Consequently, 1 USD converted at the PPP exchange rate into rupees should buy a similar quantity of goods and services in India as it does in the US. Measured at

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[2] Equatorial Guinea is the only High Income Country in SSA as classified by the World Bank, and is thus not included in the calculations and the discussion in this paper

PPP exchange rates, average incomes in developing countries can be three to four times higher than when measured at market exchange rates (Anand et al., 2009). GNI per capita data for Sub-Saharan Africa can be found in

Table **4**.

2.3.3. Poverty and Inequality

This chapter will first give an overview of the poverty and inequality situation, as poverty or limited income is the main barrier for the adoption of any infrastructure service in Africa. In general, poverty refers to the absolute levels of living and inequality refers to disparity in levels of living within a population such asthe income gap between rich people and poor people (Ravallion, 2003).

However, there is currently no commonly accepted international definition of poverty (2011), and there is still a debate on poverty and inequality (Ravallion, 2011). According to Jerome (2011) the only point of possible general agreement is that *"people who live in poverty must be in a state of deprivation; that is, a state in which their standard of living falls below [a] minimum acceptable standard"* (Ravallion, 2011).

The foundation for domestic and international efforts to fight poverty is based on empirical poverty data for specific countries (Ravallion, 2011). Consumption surveys and household income in the countries are the main source for these data. (Anand et al., 2009) These empirical data allowed research on poverty in the 1990s (Ravallion, 2011). While there is much debate on the causes of poverty and solutions to this problem, a premise of modern writing is the belief that poverty is something that can be explained by deeply rooted economic and social inequalities and by market or governmental failures. It is also believed that it can be greatly reduced and even eliminated with the right economic and social policies (Ravallion, 2011).

To measure and quantify poverty, poverty thresholds are defined. The original poverty threshold for international comparison was the World Bank PPP$1-a-day poverty line at 1985 prices (Anand et al., 2009), which was anchored to the national poverty lines in the poorest countries. Due to improved data, the World Bank now uses a 1.25 USD line at 2005 PPP for international comparisons of extreme poverty (Ravallion, 2010). National poverty lines differ greatly across the globe, from under 1 USD per person per day to over 40 USD, at 2005 purchasing power parity. Obviously, the national poverty lines vary systematically; countries with a higher mean income and consumption also have a higher poverty line (Ravallion, 2012). However, statistical foundations of poverty estimates in Africa remain wanting, due to irregular and often uncomparable poverty and inadequate price deflators (Chuhan-Pole et al., 2013).

The aforementioned MDGs propose to reduce the proportion of people living in extreme poverty by half from 1990 to 2015. In SSA, the prospect of meeting the Millennium Development Goals are bleak even though the proportion of people living in extreme poverty (1.25 USD poverty line) in SSA fell from 56.5 per cent in 1990 to 48.5 per cent in 2010, arround 20.25 percentage points short of the 2015 target. Moreover, in absolute numbers, more people are joining the ranks of extreme poverty in the region over time. Some 124 million additional people fell into extreme poverty from 1990 to 2010 (from 290 million people in 1990 to 408 million people in 2010) (UNECA et al., 2013).

The prevalence of poverty in the SSA countries, in the form of international poverty lines of 1.25 USD and 2 USD, can be seen in

Table **4**. The percentage of people living below 1.25 USD ranges from 0.3 % in the Seychelles to 87.7% in the DR of Congo. The range for the 2 USD line is from 1.8% in the Seychelles to 95.2% in the DR of Congo.

The difference between urban and rural poverty is particularly important in developing economies, because rural poverty tends to be more prevalent (Ravallion, 2011). Sometimes the number of people living in poverty is three times higher in rural areas than in urban (UNECA et al., 2013). The average, for all of SSA, is 2.75 times (after calculations using data from (AfDB, 2013b)).

On a side note, inequality in Sub-Saharan Africa also remains high, with Gini[3] coefficients arround 45 percent. (Chuhan-Pole et al., 2013). In general, income inequality lessens the poverty reducing effects of economic growth (Ravallion, 2007).

2.3.4. Income Distribution and Household Budget

African households survive on very limited household budgets (The World Bank, 2011). In 2008, Banerjee et al. evaluated data from the African Infrastructure Country Diagnostic analysis, which collected household surveys from the year 2000 to 2005. The results will be presented in this chapter and in chapter 2.6. Even though the data is outdated, it is the most recent regional analysis of income distribution and infrastructure affordability. Moreover, the income and budget distribution is important for understanding the ability of Sub-Saharan African households to afford infrastructure, which is discussed in chapter 2.6 (Banerjee et al., 2008).

The average African household (five persons) has a monthly budget below 180 USD[4], the range is from arround 60 USD in the poorest quintile to 340 USD in the richest quintile (Table 5). Consequently, even Africa's most affluent households have only a modest purchasing power in absolute terms. Across the 30 countries in SSA (including Morocco) covered in the study, household budgets in middle-income countries are about twice those in low-income countries.

Table 5: Monthly Household Budget, in 2002 USD (The World Bank, 2011) adapted from (Banerjee et al., 2008) based on AICD Expenditure Survey Database 2007

[3] The Gini coefficent is used to measure income or wealth inequallity. A Gini coeffient of zero indicates perfect equality, whereas a coefficient of 1 indicates maximal inequalty.
[4] All USD in this chapter are in 2002 USD PPP.

	Income group					
	National	*Poorest quintile*	*Second quintile*	*Third quintile*	*Fourth quintile*	*Richest quintile*
Overall	177	59	97	128	169	340
Low-income countries	139	53	80	103	135	258
Middle-income countries	300	79	155	181	282	609

Another clear outcome from this study is that urban households possess approximately 100 USD per month more than rural households (Table 6). Household budgets range from about 50 USD per month in the first (poorest) income quintile to no more than 400 USD per month in the highest quintile, except for middle-income countries, where the people in the highest quintile have between 200 USD and 1,300 USD per month (Banerjee et al., 2008). The monthly budget of the first quintile ranges from 18 USD per household in Burundi to 102 USD in Senegal (160 USD in Morocco). The first quintile has a median household budget of around 50 USD, that of the richest is about 240 USD (Banerjee et al., 2008).

Furthermore, most African households spend more than half of their modest resources on food, with little remaining for other items, including infrastructure (The World Bank, 2011). In low-income countries, even the households in the highest quintile spend, on average, half of their monthly budget on food, whereas the other four quintiles all allocate about 60 percent of their budgets to food (Banerjee et al., 2008). In Middle-income countries, food expenditure amounts to approximately 50 percent among all quintiles.

Table 6: Detailed Monthly Household Budget and share of Food expenditure, (Banerjee et al., 2008)

	Total household budget (2002 US$)								Food expenditure as a share of total household budget (percent)							
	Nat'l	Rural	Urban	Q1	Q2	Q3	Q4	Q5	Nat'l	Rural	Urban	Q1	Q2	Q3	Q4	Q5
Overall	177	130	241	59	97	128	169	340	55	61	48	63	64	63	60	48
Low-income countries	139	109	208	53	80	103	135	258	59	64	50	67	68	66	64	52
Middle-income countries	300	199	350	79	155	181	282	609	45	54	42	51	55	52	50	38

2.4. Electricity access

Extending modern energy access in Sub-Saharan Africa is essential, yet it consitutes a major challenge in the region. This chapter will first discuss the benefits of electricity access for rural households, then define energy access, and finally give an overview of global and regional (Sub-Saharan African) electricity access.

2.4.1. Definition of Electricity access

Firstly, "there is no universally agreed-upon definition on energy access" (UN et al., 2013). As previously mentioned, SE4All defines electricity access in terms of availabilty of an electricity connection at home or the primary usage of electricity for lighting (UN et al., 2013). The IEA, however, defines modern energy access differently. It is defined as "*a household having reliable and affordable access to clean cooking facilities, a first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average.*" This definition further includes a specified minimum level of electricity consumption. In rural areas this consumption minimum for households would begin at 250 kWh per year (IEA, 2013).

The distinction between the two definitions is important, because following the SE4All definition, stand-alone PV systems (like SHS or PicoPV) can contribute to increasing electricity access. Under the IEA definition, this would only be possible for large SHS (>125W) under very good irradiation conditions involving huge costs. This paper will mainly consider the SE4All definition.

2.4.2. Usage and Benefits of Electricity access in rural households

Most researchers agree that the availability of electricity has the potential to improve the quality of life and increase economic activity (UNDP and World Bank, 2002). The basic purpose of electricity in rural households is to provide lighting, at higher quality and lower costs than alternatives like kerosene lamps (IEG and World Bank, 2008). The better quality of electric lighting is more adequate for reading or indoor work than kerosene lanterns or candles (Barnes, 2005). Thus, in 2011, the World Bank found that electricity provision increases literacy and primary school completion rates.

Despite these benefits most rural households in the developing world still depend on kerosene, candles, biomass, or batteries for their lighting needs. Obtaining these fuels can be a time-consuming task usually undertaken by women and children. Furthermore, fuel-based lighting is associated with indoor air pollution, soot, and burns (Adkins et al., 2010). Moreover, fuel-based lighting is usually more expensive than using electricity; sometimes rural households spend around 25% of their household budgets for lighting (Adkins et al., 2010).

Further social benefits of rural electrification can be increased access to televisions, radios and mobile phones (IPCC, 2012). The use of television, radio, and mobile phones usually result in improved access to news, information, and distance education opportunities (IPCC, 2012). Around half of electrified rural households have a television or a radio, (IEG and World Bank, 2008) and in 2012 around 475 million people had a mobile phone in Sub-Saharan Africa (Deloitte and GSMA, 2012), which is a higher number than people with electricity access in SSA. Aker and Mbiti (2010) wrote that research confirms that "*the reduction in communication costs associated with mobile phones has tangible economic benefits, improving agricultural and labor market efficiency and producer and consumer welfare in specific circumstances and countries.*"

2.4.3. Electricity appliances in rural households

According to Adkins et al. (2012), the main energy services utilized by households in rural Sub-Saharan Africa can be categorized into a) lighting, power for mobile phone recharging, and other information technologies (e.g. radio and television), b) cooking and heating, and c) agro-processing and/or pumping (see Table 7).

Table 7: Transition to renewable energy in rural off-grid areas (IPCC, 2012) and (REN21, 2010)

Rural Energy Service	Existing Off-Grid Rural Energy Sources	Examples of New and Renewable Energy Sources
Lighting and other small electric needs (homes, schools, street lighting, telecom, hand tools, vaccine storage)	Candles, kerosene, batteries, central battery recharging by carting batteries to grid	• Hydropower (pico-scale, micro-scale, small-scale) • Biogas from household-scale digester • Small-scale biomass gasifier with gas engine • Village-scale mini-grids and solar/wind hybrid systems • Solar home systems
Communications (televisions, radios, cell phones)	Dry cell batteries, central battery recharging by carting batteries to grid	• Hydropower (pico-scale, micro-scale, small-scale) • Biogas from household-scale digester • Small-scale biomass gasifier with gas engine • Village-scale mini-grids and solar/wind hybrid systems • Solar home systems
Cooking (homes, commercial stoves and ovens)	Burning wood, dung, or straw in open fire at about 15% efficiency	• Improved cooking stoves (fuel wood, crop wastes) with efficiencies above 25% • Biogas from household-scale digester • Solar cookers
Heating and cooling (crop drying and other agricultural processing, hot water)	Mostly open fire from wood, dung, and straw	• Improved heating stoves • Biogas from small- and medium-scale digesters • Solar crop dryers • Solar water heaters • Ice making for food preservation • Fans from small grid renewable system
Process motive power (small industry)	Diesel engines and generators	• Small electricity grid systems from microhydro, gasifiers, direct combustion, and large biodigesters
Water pumping (agriculture and drinking water)	Diesel pumps and generators	• Mechanical wind pumps • Solar PV pumps • Small electricity grid systems from microhydro, gasifiers, direct combustion, and large biodigesters.

The paper at hand only considers category a), as the main appliances for electricity in rural households are lighting, mobile phone charging, radio, and television. Electricity in rural areas is usually not used for cooking (IEG and World Bank, 2008). Fridges, fans, and irons can be used with a strong power source, e.g. with grid connection but not with small decentralised PV systems. Laptops or tablets could also be used by rural households in developing countries thanks to the continuous price reductions.

Lighting is the key demand for electricity in rural households of developing countries. Light is measured in lumens (or lux which is lumen per square meter); the higher the lumens of a lighting system the more light it produces. Likewise, the higher the lumen per watt (lm/W), the higher the efficency of the lighting system. Incandescent lamps have a low luminous efficiency of arround 10lm/W while fluorescent tubes are around 50 to 100 lm/W. CFL (compact fluorescent lights) have a range from 50 to 60 lm/W, and LEDs reach 70 to 120 lm/W. For developing countries, a minimum of 300 lumen per household is recommended. The electricity demand for lighting can be calculated on the basis of the number of lights, their power demand, and the number of hours they are used per day (Lysen, 2013).

Mobile phone charging is the second most important demand for rural homes in developing countries. Simple mobile phones have a typical battery capacity between 2.6 and 3.7 Wh, including a charging efficiency of 90%. Fully charging a simple mobile phone takes about 3 to 4 Wh. The charging of a smart phone typically doubles the electricity demand. Charging during the day is recommended as it circumvents the battery and reduces efficiency losses (Lysen, 2013).

A small radio takes around 0.5 Watt, or for two hours of listening per day, about 1 Wh. Running a small TV (e.g. a 7 inch LCD) requires less than 10 watts of power. Thus watching TV for three hours per evening would mean an electricity consumption of 30 Wh/day (Lysen, 2013). Small laptops have around 20 Watts, and small tablets around 10 Watts, and energy consumption by these ICTs depends on the hours of usage.

Refrigerators have a relatively high energy consumption, power consumption range from 0.6 - 4 kWh per day depending mostly on the size, efficiency, temperature setting, and the room temperature in which it is placed. Fans tend to consume quite a lot of energy; a 50 W fan running for 6 hours per day would consume approximately 0.3 kWh/ day. Irons need around 1kW, and therefore, if in use for half an hour per day, would use up to 0.5 kWh/ day (Lysen, 2013). All the appliances mentioned here are high efficient and usually not second hand.

In 2009, the GTZ estimated the unit costs of lighting from different sources, measured in kilolumenhours (klmh). They found that costs for candles and kerosene are the highest of all compared options. They established typical cost of 2 USD/klmh for candles, 0.1 – 1 USD/klmh for kerosene lamps, 0.1 – 4 USD/klmh for solar lanterns, 0.04 USD/klmh for solar home systems and 0.01 USD/klmh for conventional lighting via electricity. However, this study is not representative of current prices, in particular due to the fact that the cost of solar lanterns has decreased dramatically in the past few years.

2.4.4. Global status of Electricity access

According to the World Energy Outlook 2012 (IEA, 2012), in 2010, around 1.27 billion people worldwide, or 24% of the world population, lacked access to electricity, as seen in Table 8. Around half of those people lived in Sub-Saharan African countries. In 2010, the overall electrification rate in Sub-Saharan Africa was only 32%. In contrast, North Africa had an overall electrification rate of 99%, developing Asia a rate of 74% and OECD countries a rate of 99.5%. Although the overall access situation in Sub-Saharan Africa is already distressing, the conditions for the rural population are even worse. In rural areas of Sub-Saharan Africa only 13% of the population has access to electricity, compared to a global level of 68% (IEA, 2012).

Table 8: Electricity access in 2010 - Regional aggregates, (IEA, 2012)

Region	Population without electricity millions	Electrification rate %	Urban electrification rate %	Rural electrification rate %
Developing countries	**1 265**	**76,1**	**92,1**	**63,7**
Africa	590	43	72	24
North Africa	*1*	*99*	*100*	*99*
Sub-Saharan Africa	*589*	*32*	*64*	*13*
Developing Asia	628	83	96	74
China & East Asia	*157*	*92*	*98*	*88*
South Asia	*471*	*70*	*92*	*61*
Latin America	29	94	98	76
Middle East	18	91	99	75
Transition economies & OECD	**2**	**99,8**	**100,0**	**99,5**
World	**1 267**	**81,5**	**94,7**	**68,0**

2.4.5. Electricity access in Sub-Saharan Africa

Illustration 3 summarizes the Sub-Saharan African electricity access, in 2007, by geographic region (a) and by household budget quintile (b). The first obvious fact in the graph (a) is that energy access is significantly lower in rural areas both in low-income and in middle-income countries. The second fact is that the regional gap in electricity access in middle-income countries is much wider than in low-income countries. Thirdly, on a national level, middle-income countries do much better in providing electricity access. As the World Bank wrote in 2010, the challenge of providing electricity access is tougher in low-income countries where available resources and the numbers of consumers and taxpayers able to contribute to subsidies tend to be low (World Bank, 2010a).

Graph (b) shows that electricity coverage is unequally distributed in favor of more affluent households; this is even more prevalent in low income countries. The poorest 40 percent of households only have an overall electricity access rate of arround 10%, whereas it increases for the richest 20 percent of households to close to 80 percent. According to the World Bank (The World Bank, 2011), the inequality of access rates even increased in most SSA countries over time. This suggests that most new electricity connections have gone to richer households.

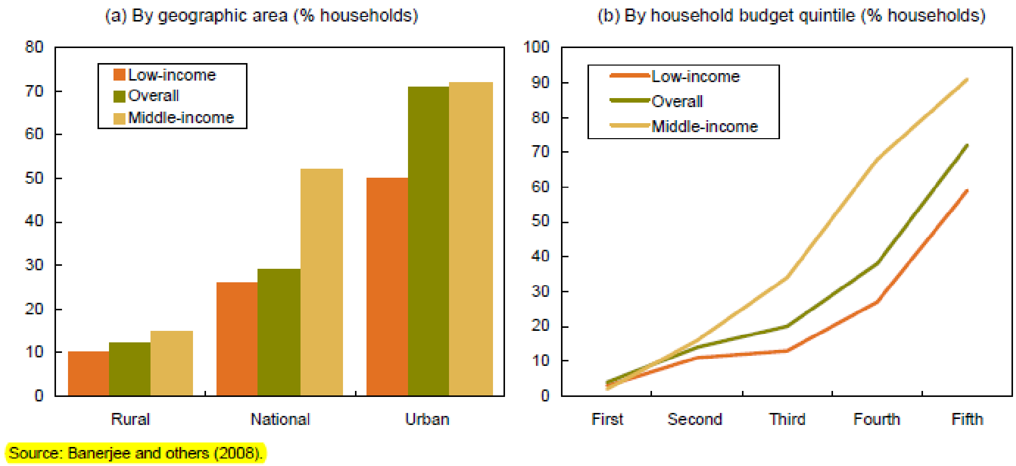

Illustration 3: Electricity service coverage in Sub-Saharan Africa, (IMF, 2008) adapted from Banerjee et al (2008)

As previously mentioned, access rates differ between low-income and middle-income countries in Sub-Saharan Africa. However, a closer look at the country level reveals high differences in the region, as seen in Illustration 4 and Illustration 5. In countries such as Chad, Liberia, and Burundi, more than 95 percent of people lack electricity access. At the same time, in Mauritius, less than 1 percent lack access. Morevoer, the rural electrification rate for at least 17 countries in Sub-Saharan Africa was below 5 percent in 2007 (UNDP, 2009). As the World Bank wrote in (2011), the high percentage of people living in rural areas poses a significant challenge in raising access rates (The World Bank, 2011).

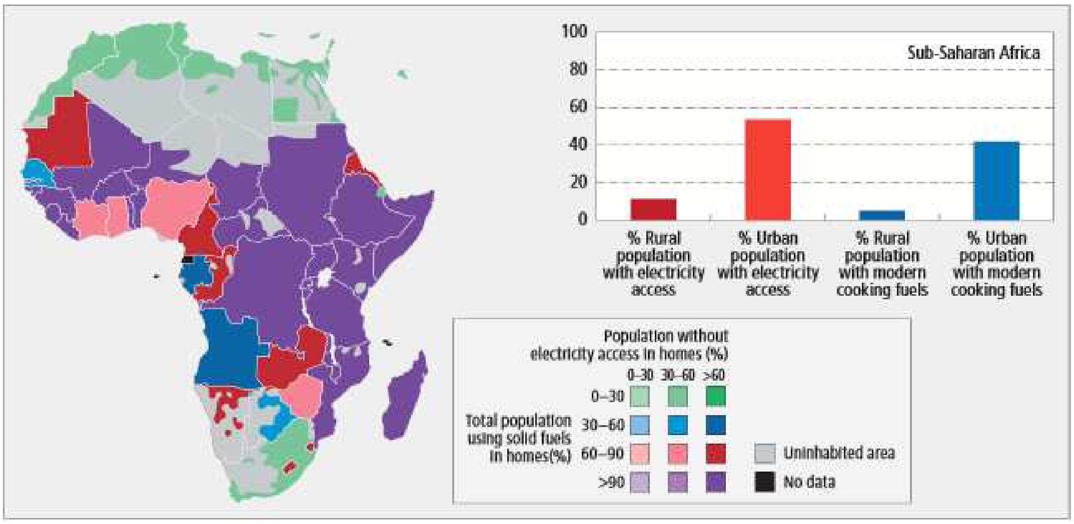

Illustration 4: Status of Energy Access in Africa (IIASA et al., 2013)

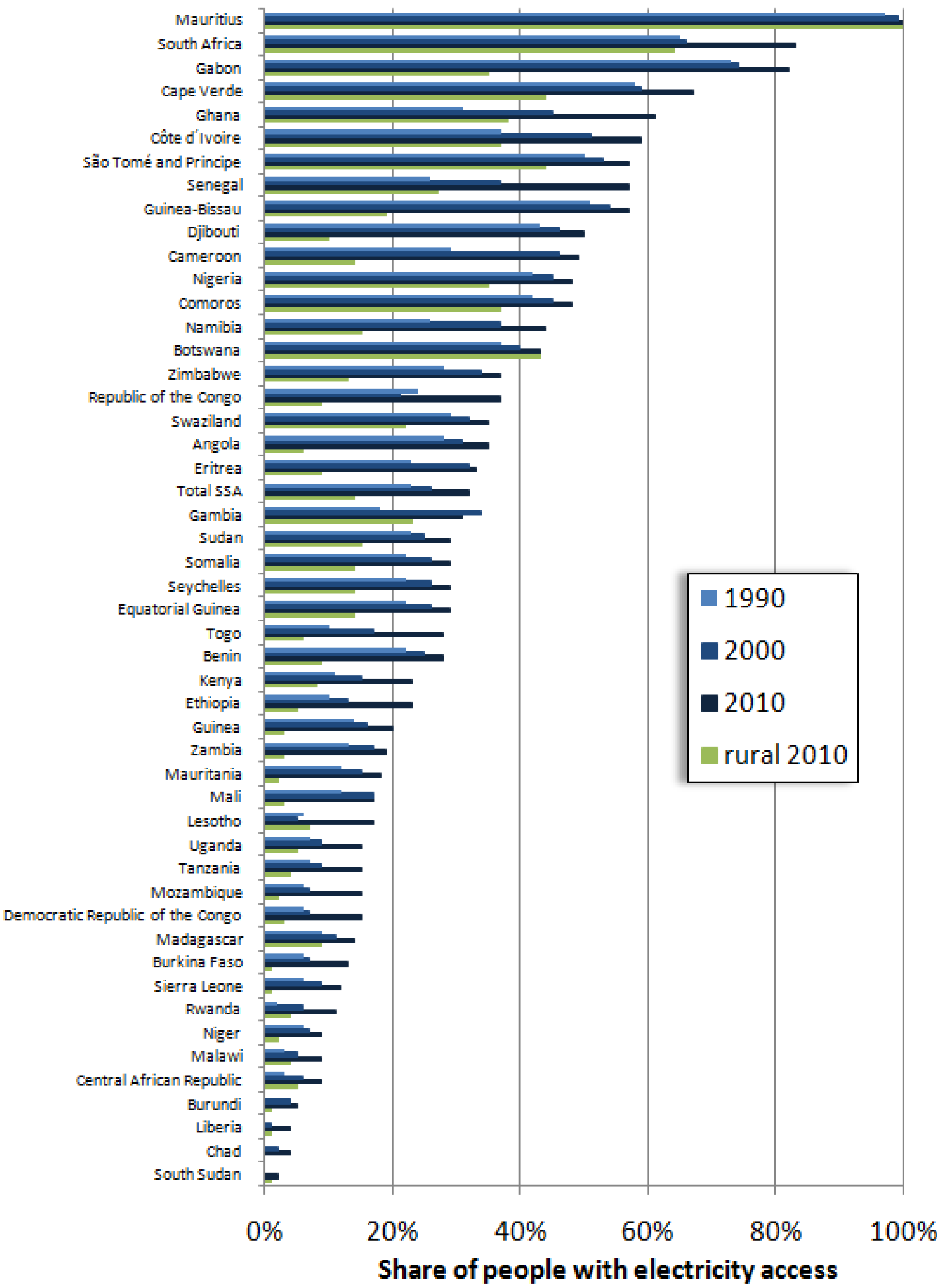

Illustration 5: Electricity access in Sub-Saharan Africa, 1990, 2000, 2010 and in rural areas 2010, own graph, data from (UN et al., 2013)

The rate of access expansion differs significantly across countries in SSA. In the more recent past, some countries managed to increase electricity access levels. Ghana, for example, has raised rural access from 5% to 40% from 1989 to 2011. In South Africa, rural access has risen from 12% in 1994, to 57% in 2011 due to democratization (IRENA, 2011b). A few other countries such as Cameroon, Côte d'Ivoire, and Senegal have also achieved some progress; close to half of their populations now have access to electricity. However, these are exceptions as most countries in SSA still lag far behind (The World Bank, 2011).

The factors that influence low electrification rates are manifold. Onyeji et. al (2012) analyzed the connection between energy access rates with other country specific factors for Sub-Saharan Africa via a regression analysis. They concluded that the share of poor people in the rural population, the gross domestic saving rates, the corruption level, the share of rural population, and the population density explain 90% of the variation in electricity access levels across emerging countries. However, "*correlation does not imply causation*" (Jerven, 2013). Nonetheless, these political, economic, and population related figures are discussed in previous chapters.

Future projections for universal access to electricity services in SSA under a business as usual scenario show that less than 45 percent of the countries will reach universal access to electricity in 50 years (Banerjee et al., 2008). This low projected rate of universal access is certainly influenced by the investment costs involved. Achieving universal energy access in SSA by 2030 would require an additional investment of 20 billion USD per year above the baseline investments according to (UNECA, 2011). The IEA (2012), estimates similar investment needs for universal access by 2030. They project total investment cost of 385 billion USD by 2030 for SSA. In comparison, the present total african power sector investment is around USD 50 billion per year, including operation and maintenance (UNECA, 2011).

National electrification rates that are currently available are likely to overestimate access to electricity due to inadequate quantity, quality, or reliability of electricity supply (UN et al., 2013) and underestimate it due to missing to include stand alone electricity generators (Welle-Strand et al., 2012). An existing proxy for supply problems is the average residential electricity consumption (UN et al., 2013) which will be discussed in the next chapter.

2.5. Electricity consumption and demand

Electricity access alone does not give a complete picture of electricity usage in Sub-Saharan Africa. Further parameters include the quantity of electricity provided to the end-user which is measured as electricity consumption, the adequacy of the electricity provided (the difference between actual electricity consumption and electricity demand), and the service quality (e.g. the frequency and duration of black-outs and brown-outs). Service quality will be discussed in chapter 2.7.

Worldwide, an average household consumes around 3,010 kWh of electricity annually, in 2010. However, average household electricity consumption differs significantly around the world; it varies from around 6,000 kWh in developed countries to about 1,000 kWh in underserved regions of developing countries (UN et al., 2013). In Sub-Saharan Africa, excluding South Africa, the average household electricity consumption was just 153 kWh per capita in 2009 (Monari, 2011), which is around 5% of the global average and only 2% of the average electricity consumed in developed countries. Furthermore, Sub-Saharan Africa, again excluding South Africa, is the only region in the world with falling electricity consumption per capita (The World Bank, 2011). Yet, as always, there are big differences in electricity consumption between the countries in the region, as seen in Illustration 6[5]. In SSA, 18 countries have an average electricity consumption per person below 100 kWh per year (Chad and Sierra Leone only have an average consumption of 10 kWh/year and person), 29 countries are below 200 kWh per year, and only 8 countries have an average consumption of above 1000 kWh per year. These figures, however, do not account for electricity access.

Measuring actual household electricity demand in Sub-Saharan Africa is complicated. Basic economic theory states that demand is a function of price and income[6], the lower the price and the higher the income, the higher is the demand for goods and services. Sub-Saharan African people, as discussed in the previous chapter, have, on average, the lowest income in the world and the highest percentage of people living in absolute poverty. The price for electricity in SSA ranges between 0.10 to 0.30 USD/kWh (Foster, 2008). This means that price levels are similar to or higher than developed countries. As a consequence, the current electricity demand level in SSA would be the lowest in the world. A sample of electricity prices can be found in chapter 2.7.

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[5]This graph shows total electricity consumption for 2009 (household consumption plus other consumption) from the African Development Bank online dataset (AfDB, 2013a), divided by the respective number of total population for 2010. Therefore, it is not an accurate measurement of household consumption put a simplification showing average urban and rural per capita consumption including electricity consumed outside households.

[6] Actual consumption, according to basic economic theory, is the point at which the demand curve meets the supply curve. So real consumption is both depending on supply and demand.

In general, electricity demand has three components, market demand which is related to economic growth and population growth (among others); suppressed demand formed by frequent blackouts and the ever-present power rationing; and social demand*,* which represents political targets for increased electricity access. In most low-income countries in SSA, electricity demand exceeds supply. In urban areas the coverage gap is as much about affordability as it is about supply (The World Bank, 2011).

For the household level, a simplified electricity demand can be derived from the definition of access to electricity by the IEA, which involves a specified minimum level of electricity consumption (which could also be termed household electricity demand). This consumption minimum for households is assumed to be 250 kWh per year in rural areas[7] (and 400 kWh per year for urban areas). This rural consumption level could, for example, provide electricity for a floor fan, a mobile phone, and two compact fluorescent light bulbs for around five hours per day (IEA, 2013). This considerably low consumption minimum can only be assumed to be achieved in 12 out of the 48 SSA countries as seen in Illustration 6 (not cosidering the higher minimum consumption in urban areas).

[7] This corespondes to 50 kWh per person and year, with the IEA definition of 5 persons per household (IEA, 2013).

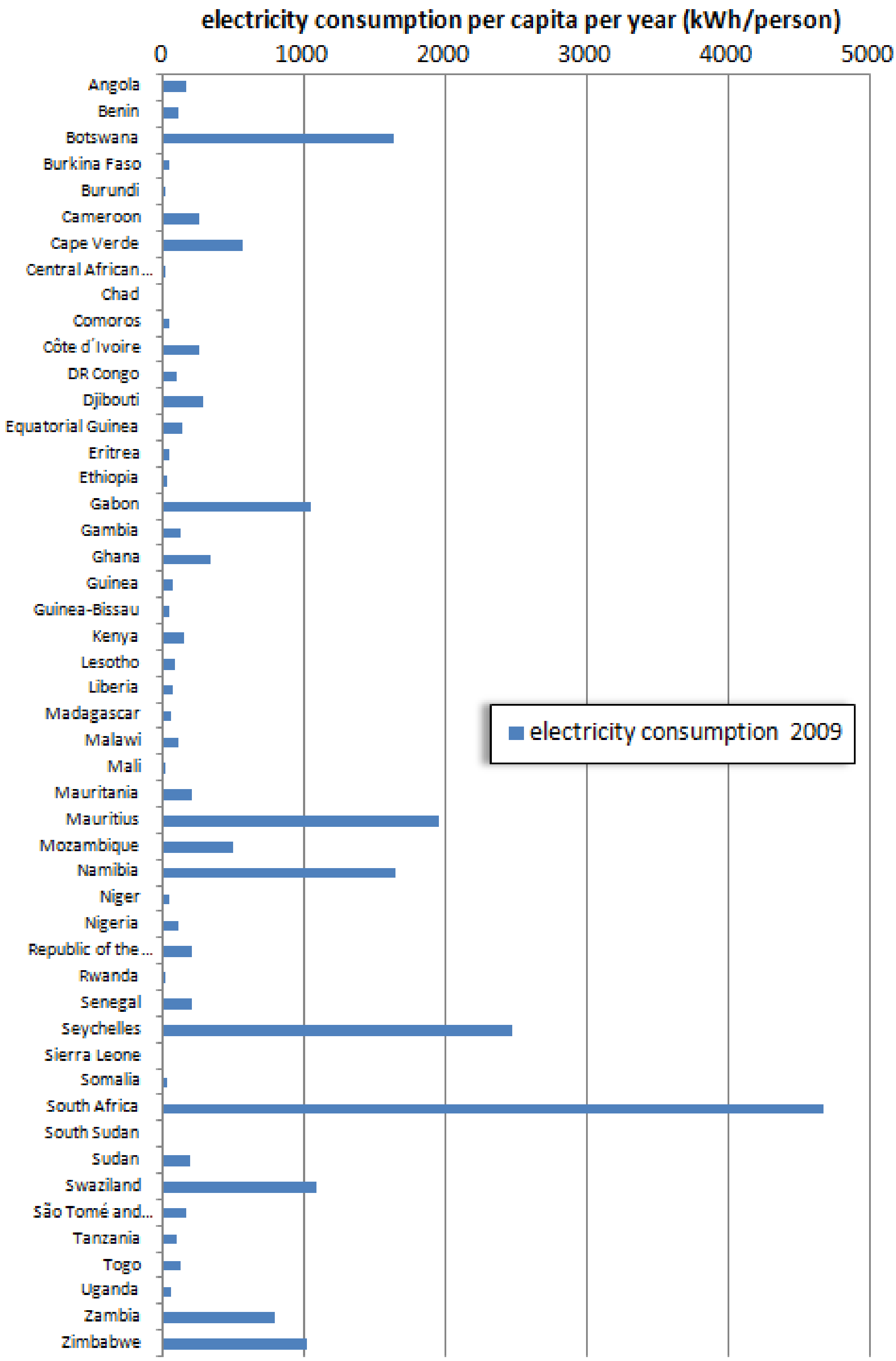


Illustration 6: Electricity consumption per capita in Sub-Saharan Africa, adapted after (AfDB, 2013a) source for total electricity consumption and (World Bank, 2013b) source for population data 2010,

2.6. Spending, willingness to pay, and affordability

Given the low household budgets in SSA, a key question is, whether or not households can afford modern infrastructure services like electricity access (The World Bank, 2011). While the technical potential in SSA countries for all energy is more than sufficient to meet the electricity demand, the ability and willingness to pay continue to be critical factors for both grid based services and off-grid service provisions (Deichmann et al., 2010). It is especially true because utilities will not invest in expanding supply before the demand for their services and the ability to pay are established (Banerjee et al., 2008).

The amount an average rural household in developing countries can pay for energy is typically between 5 and 10% of their income. Yet it is important to obtain country specific local data via market surveys to access the actual customer ability to pay. Rural customer willingness to accept electricity service is mostly based on their capacity to either pay the connection fee or the investment costs. Reducing or spreading out the connection fee or the investment cost are effective methods of gaining new customers. Additionally, allowing different levels of service or providing different capacity of the generation technology for different customer categories usually improves affordability for the poorer customers (The World Bank, 2008).

The following subchapters will first discuss actual spending on electricity services in SSA, then give an overview of the willingness to pay (WTP) for electricity and introduce concepts of affordability. Affordability of electricity is one of the key parameters analyzed in this paper.

2.6.1. Spending

The data presented by Banerjee et al. (2008) summarizes that households spend around 20 percent of their budgets on infrastructure services, mainly on power and transport. More specific, electricity absorbs 5–10 percent of the household budget in most countries (Banerjee et al., 2008).

Households with a higher budget also spend a growing share of their budget on infrastructure services. Infrastructure expenditure varies from less than 4 percent in the poorest quintile to more than 8 percent in the richest quintile (see Illustration 7). In terms of absolute costs, the difference in expenses for income groups is even more evident. The poorest households spend, on average, less than 2 USD[8] per month on all infrastructure services together while the richest households spend almost 40 USD per month (The World Bank, 2011).

The IMF (2013) asessed household survey data from nine African countries suggests that the richest 20 percent of households spend, on average, nearly 20 times more on fuel and electricity than the poorest 20 percent of households (IMF, 2013). The energy expenditure of the poorest 250 million Africans are, nontheless, estimated at 12 USD billion per year (Banerjee et al., 2008).

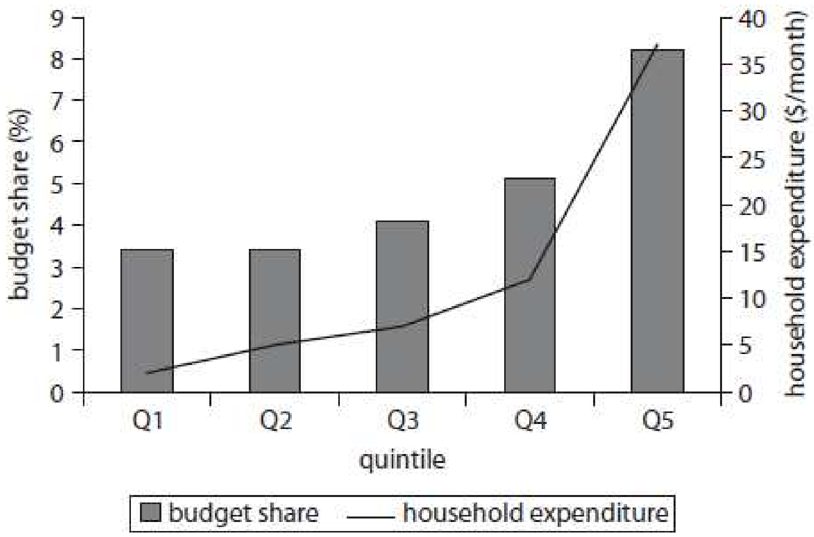


Illustration 7: Household budget and overall Infrastructure service expenditurein quintiles, (The World Bank, 2011)

Market studies linked with World Bank projects revealed that low-income rural households which are not connected to rural electricity grids usually pay 3 USD to 15 USD per month for energy, on candles, kerosene, disposable batteries, and battery charging, among others (The World Bank, 2008). More specifically, according to Anisuzzaman and Urmee in 2006, a World Bank study (2001) found that the average monthly spending of rural households in developing countries for kerosene lamps and lead acid batteries alone amounts to between $2.30 for low income families and to $17.60 for upper income. In a study on energy consumption in ten millennium villages in different Sub-Saharan African countries, Adkins et. al, found that, on average, 48 USD per year are spent for lighting and electricity. The

[8] All USD in this chapter are in 2002 USD PPP.

main energy sources for lighting are kerosene, accounting for approximately 26 USD, batteries amounting to 19 USD, and candles add up to 4 USD. (Adkins et al., 2012) In total Africa, consumers and small businesses spend around 17 billion USD a year on kerosene lamps and candles (OECD, 2009).

2.6.2. Willingness to pay

A World Bank study from 2008 showed that WTP for electricity is high, and often exceeds long-run marginal cost of supply in developing countries. They analyzed the willingness to pay for the two main domestic uses of electricity, lighting and television, for different developing countries[9]. In Mozambique (in 2003) the WTP for lighting was 4.87 USD per month and 5.07 USD per month for TV (IEG and World Bank, 2008). According to the World Bank in 2013 (Alleyne, 2013), evidence suggests household consumers were willing to pay more than the prevailing tariffs in SSA in 2010. For residential customers in SSA, the WTP would be around 0.498 USD/kWh (Alleyne, 2013). Sabah conducted a study on willingness to pay for electrification in Kenya via 400 household interviews. He found that responents are willing to pay more for grid electricity than for photovoltaic systems (Sabah, 2009).

As mentioned above, the upfront investment or connection costs are an obstacle to electrification in rural areas. World Bank surveys in Kenya have indicated that rural customers are willing to use financial programmes or take medium-term loans to spread the upfront cost and pay it back through their monthly bills over five or more years (Abdullah and Jeanty, 2011).

On a side note, the willingness to pay for picoPV lamps, obtained through Dutch auctions, reaches from 5 USD to 90 USD depending on the value class. However, country surveys also showed that the poorest people often lack the required cash to pay for the upfront cost, especially for the more expensive PicoPV systems, which range from 80 to 150 USD even though the lamps would pay off within a year, replacing conventional lighting solutions (GTZ, 2010).

2.6.3. Affordability

Affordability is usually measured by defining a threshold for infrastructure spending of the total household budget and assessing if people in different income quintiles

[9] Nowadays mobile phones can be as important as lighting for the population in SSA.

can afford an infrastructure service within this threshold. There is, however, no absolutely scientific basis for determining these affordability thresholds, yet they are based on results of willingness to pay surveys and actual household expenditure patterns (see chapter 2.6.1). Banerjee et. al (2008) use two different affordability thresholds for electricity, a 3% and a 5% threshold.

Banerjee et. al (2008) assume a subsistence consumption from 25 - 50 kWh per month and an electricity price range from 0.08 USD to 0.25 USD per kWh. The calculated lower bound monthly bill coincides at about 2 USD and the upper-bound montly bill at 12 USD. By looking at the household budget distribution and using a 3 percent threshold, they found that utility bills of the order of 6 USD per month for electricity are likely to be affordable for most households except in the poorest countries. Whereas utility bills of around 10 USD per month start to become too expensive for a large share of the population. Additionally, grid connection charges which are usually about 100-200 USD would be unaffordable for all but the wealthiest households.

A more detailed result of the share of average urban household budget required to purchase subsistence amounts of electricity by income quintiles can be found in Illustration 8.[10] It can be seen that the average household in the poorest quintile meets the 5 percent affordability threshold at around 4 USD per month, and that households in the richest quintile do not face any affordability constraints. In general, the study found that full cost recovery tariffs or an increase in consumption are unaffordable for about 60 percent of the African population. One limitation of the study was that the continental results cover great variations across individual countries. For example, almost all of the households from poorer countries may be in the poorest quintile for the whole of Africa, while at the same time, almost all of the more affluent countries households may be in the richest quintile for the whole of Africa (Banerjee et al., 2008).

[10] Banerjee et al. (2008) does not focus on rural household budget

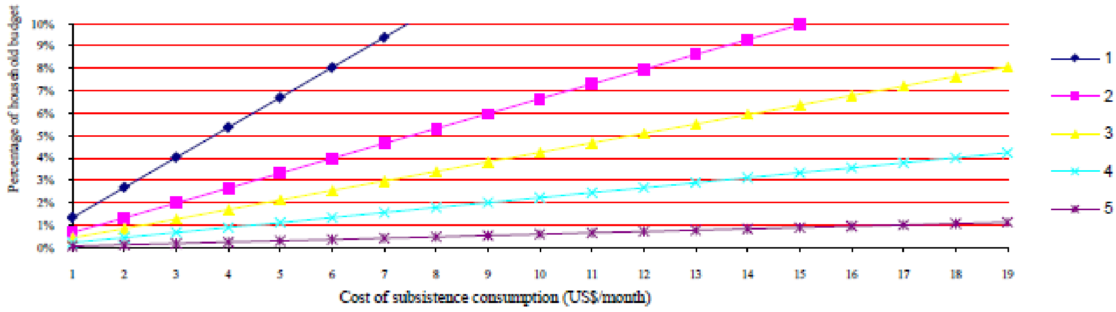


Illustration 8: Share of average urban household budget required for subsistence electricity, by income quintiles, in 2008 USD, from (Banerjee et al., 2008)

Another measure of affordability is nonpayment for infrastructure services. On average, a projected 40 percent of people with infrastructure service connection do not pay for it. Nonpayment rates vary from around 20 percent in the richest quintile to about 60 percent in the poorest quintile. The high nonpayment rate among the richest quintile suggests problems of payment culture (The World Bank, 2011). This method, however, is not further discussed and used in this paper.

2.7. Electricity production

The total power generation capacity of the 48 Sub-Saharan African countries (with a population of 869 million) amounted to only 63 GW in 2008, which is comparable to the generation capacity of Spain (with a population of 45 million). Furthermore, as much as one-fourth of the power plants in Sub-Saharan Africa were not in operating condition (IMF, 2008).

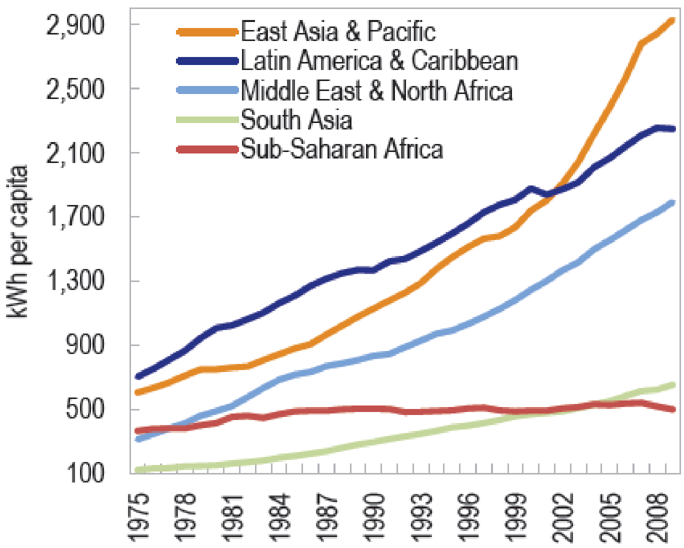
Table **9** shows the current total installed power capacity for each Sub-Saharan African country according to Werner et al. (2011). They approximate a capacity of

	Population in 2010	GDP for the year 2010	GDP per capita	Electricity consumption 2008	Total power plant capacity 2010	PV share in power plant capacity 2010
Country	[mio pop]	[bnUSD]	[USD]	[TWh]	[MW]	[%]
Angola	19,5	82,5	4219	3778	1112.0	0.27%
Benin	9,5	6,4	678	787	112.0	0.49%
Botswana	2,0	13,9	7057	3149	155.6	1.74%
Burkina Faso	15,5	9,2	593	744	275.1	0.65%
Burundi	9,2	2,0	220	183	40.9	0.46%
Cameroon	20,6	22,5	1090	5069	898.9	0.11%
Cape Verde	0,5	1,7	3407	278	81.8	9.66%
Central African	4,4	2,0	456	162	26.2	0.57%
Chad	11,7	8,5	729	93	187.0	0.29%
Comoros	0,7	0,5	795	51	14.2	1.13%
Côte d´Ivoire	19,0	22,9	1208	5162	n/a	n/a
DR of Congo	67,8	15,7*	232	6925	1469.8	0.07%
Djibouti	0,9	1,0*	1167	259	99.5	1.41%
Equatorial	0,7	12,3	17616	100	52.8	1.02%
Eritrea	5,7	2,1	369	271	144.0	0.28%
Ethiopia	87,1	29,7	341	3484	832.0	0.83%
Gabon	1,6	14,5	9344	1948	378.9	0.04%
Gambia	1,7	1,0	566	236	62.3	1.11%
Ghana	24,3	32,3	1331	8042	1951.7	0.04%
Guinea	10,9	4,7	435	819	381.1	0.31%
Guinea-Bissau	1,6	0,8	526	70	15.3	3.07%
Kenya	40,9	32,2	787	6887	1467.4	0.59%
Lesotho	2,0	2,2	1097	223	78.5	0.01%
Liberia	4,0	1,3	327	333	15.9	2.26%
Madagascar	21,1	8,8	419	1253	396.4	0.38%
Malawi	15,0	5,4	360	1782	310.9	0.12%
Mali	14,0	9,4	674	500	588.6	0.51%
Mauritania	3,6	3,7	1017	753	212.9	0.43%
Mauritius	1,3	9,7	7586	2580	810.2	0.16%
Mozambique	24,0	9,3	387	11570	2321.2	0.05%
Namibia	2,2	11,0	5063	4197	385.6	0.60%
Niger	15,9	5,4	340	658	135.9	0.59%
Nigeria	159,7	228,6	1432	20506	11101.1	0.10%
Rep. Congo	4,1	12,0	2921	786	189.0	0.90%
Rwanda	10,8	5,6	519	260	53.0	1.42%
Senegal	13,0	12,9	993	2225	719.4	0.65%
Seychelles	0,1	1,0	10933	235	140.7	0.04%
Sierra Leone	5,8	2,6	448	61	76.8	0.39%
Somalia	9,1	0,9*	98	326	15.6	0.51%
South Africa	50,0	363,2	7266	239744	44063.8	0.09%
South Sudan	9,9	15,0	1506		1586.3	0.13%
Sudan	35,7	64,8	1817	4497		
Swaziland	1,2	3,7	3094	1197	124.4	0.27%
São Tomé and	0,2	0,2	1129	34	n/a	n/a
Tanzania	45,0	22,9	510	4466	1186.0	0.24%
Togo	6,3	3,2	503	788	208.7	0.45%
Uganda	34,0	17,2	506	2031	640.5	0.77%
Zambia	13,2	16,2	1225	9619	1881.4	0.07%
Zimbabwe	13,1	7,4	568	12897	2005.8	0.15%
Total	869,8	1144,6	1316	372018,0	**79007.1**	**0.16%**

80 GW in Sub-Saharan Africa in 2010.

Electricity generation capacity growth has been mostly stagnant in the last three decades, with growth rates of just about half those in other developing regions (The World Bank, 2011). Moreover, per capita electricity generation in SSA during the same timeframe has not increased at all due to population growth, leaving the region to fall behind the rest of the world (Illustration 9) (IMF, 2013). The biggest exception in the region is South Africa, which has a total generation capacity of more than 40,000 MW with a population of 47 million people. Nigeria, the next biggest power producer, has arround 10,000 MW, even though it has a much larger population of around 140 million. Some countries have intermediate capacity, e.g. the Democratic Republic of Congo, Namibia, Zimbabwe, Zambia, Ghana, Kenya, and Côte d'Ivoire. In other countries, the capacity is much lower, as for example Mali, Burkina Faso, Rwanda, and Togo. However, not all of the installed generation capacity is operational (The World Bank, 2011; Werner et al., 2011).

Figure 4.1. Selected Regions: Electricity Production, 1975–2009



Sources: World Bank, *World Development Indicators*; and IMF staff estimates.

Illustration 9: Regional Electricity Production, 1975 - 2009, (IMF, 2013)

Table 9: Sub-Saharan population, GDP; GDP and GNI per capita in 2010 (except for DR Congo 2011, Djibouti 2009 und Somalia 1990) adapted from (World Bank, 2013b), Electricity consumption adapted from (AfDB, 2013a), Total installed Power Capacity and installed PV capacity adapted from (Werner et al., 2011)

	Population in 2010	GDP for the year 2010	GDP per capita	Electricity consumption 2008	Total power plant capacity 2010	PV share in power plant capacity 2010
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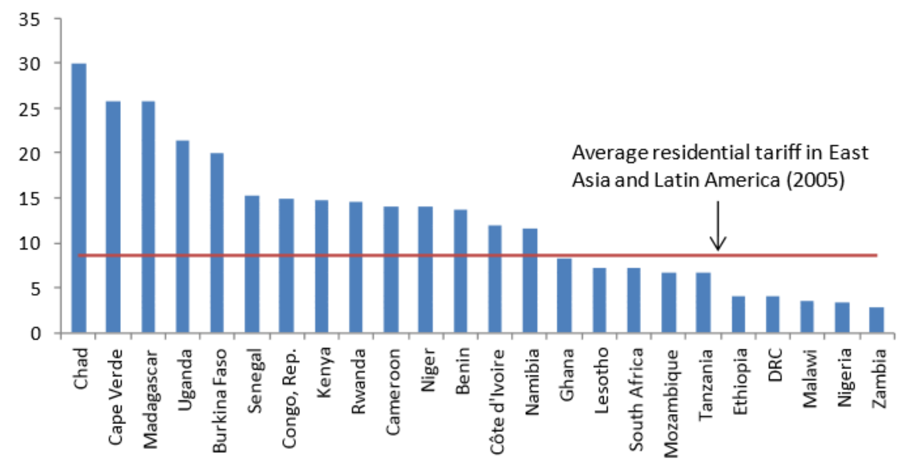
Zimbabwe	13,1	7,4	568	12897	2005.8	0.15%
Total	869,8	1144,6	1316	372018,0	**79007.1**	**0.16%**

In 2008, 21 of the 48 Sub-Saharan countries had national power systems smaller than 200 MW, which is the minimum efficient scale for electricity generation. As a consequence, the consumers in these countries pay a heavy penalty; operating costs can reach USD 0.30 per kWh compared to the USD 0.10 per kWh found in the continent's larger power systems (Foster, 2008).

In general, power in Sub-Saharan Africa is more expensive than in other world regions. There is, however, a huge variation of the electricity fees in Sub-Saharan African countries. Its fees span from some of the cheapest power in the world, at less than 0.05 USD/kWh in hydro power-based systems (and in South Africa based on cheap coal), to some of the most expensive electricity in the world, at over 0.30 USD/kWh in countries with diesel-based systems or landlocked and island locations, such as Chad and Madagascar (IMF, 2008). The residential sector power tariff for 24 SSA countries (latest year available from 2001-2008) is shown in Illustration 10. According to the World Bank (2011), the average power tariff in SSA is 0.12 USD per kWh, which is a lot higher than the tariff in other parts of the developing world, and roughly as high as in the OECD. However, as always, there are exceptions, as countries managed to maintain lower prices, such as in Angola, Malawi, South Africa, Zambia, and Zimbabwe (The World Bank, 2011). The average fees across countries today are high by international standards.



Source: AICD (2010); Briceno-Garmendia, and Shkaratan (2011); and IMF staff estimates
[1]Latest year available, 2001-2008.

Illustration 10: Residential Tariffs in SSA compared to other regions, (Alleyne, 2013)

Some countries even have tariffs which do not cover costs, (The World Bank, 2011) as power is often heavily subsidized in most SSA countries. On average, power tariffs only recover 87 percent of full costs in Africa. The resulting implicit service subsidies sum up to as much as 3.6 billion USD a year, or 0.56 percent of Africa's GDP. Tariff design could help subsidize electricity consumption for poor households. Yet, in reality, most of the subsidies typically benefit the wealthier. Data across a number of SSA countries show a very pro-rich distribution. This result is not surprising, as subsidies largely sidestep low-income households which do not even have access to electricity most of the time (The World Bank, 2011).

Moreover, in the Sub-Saharan Africa region, 30 of the 48 countries suffered from an acute power crisis in and before 2008 (IMF, 2008). "*The crisis is the result of many factors: strong economic growth, which has in turn led to the rapid increase in electricity consumption and urbanization; and poor planning for boosting generation and distribution capacity and maintaining infrastructure*" (OECD, 2009).

Electricity supply in SSA is typically unreliable. The World Bank enterprise surveys point out that most African enterprises experience frequent power outages (The World Bank, 2011). On average, African manufacturing enterprises report power outages of 56 days per year, which causes firms to lose 5–6 percent of their revenues. This, in turn, leads many firms to operate their own diesel generators, at costs of about 0.40 USD/kWh. In the informal sector, with firms often unable to afford backstop generation, power outages can cause a loss of revenues up to 20 percent (IMF, 2008).

As the IMF (2008) wrote, Sub-Saharan Africa faces major infrastructure challenges in the power sector, not only in rural but also in urban areas. The ACID in (2008) even found that "*Africa's largest infrastructure deficit is to be found in the power sector*." Escribano et al. (2008) estimate that infrastructure accounts for 30–60 percent of adverse impacts on firm productivity, well in front of factors like red tape and corruption in most sub-Saharan African countries (Escribano et al., 2010). The cost to the economies of Africa as a whole because of load shedding is estimated to be at 2.1% of GDP on average (OECD, 2009). Additionally, technical and nontechnical losses are, on average, very high (between 30 and 35 percent) (World Bank, 2010a).

In summary, the power sector in the region is in the midst of a serious crisis, characterized by poor development of energy resources, high costs, under-pricing, and large inefficiencies in performance. Under-pricing and regressive subsidies, in particular, have become serious obstacles in providing electricity to rural areas and the urban poor. As the World Bank wrote in (2010), it is essential to overcome the current power sector performance problems in Sub-Saharan Africa for an electrification effort to be sustainable. It is obvious that any effort to extend grid-access will not be sustainable if there is no advancement in addressing these sector-wide problems (World Bank, 2010a).

These infrastructure challenges occur despite (maybe also due to) liberalization efforts in SSA. As UN-Energy wrote in 2011, there was pressure for liberalization of electricity utilities from the World Bank and other international agencies (UN-Energy, 2011). Around 80% of SSA countries had implemented power reform laws by 2006, with the aim to bring in private participation, encourage efficiency, increasing energy access, and rationalize prices also due to this pressure (GNESD, 2006). However, Sub-Saharan African countries which have implemented this and other power sector reforms at a slower rate appear to have achieved better results in achieving their aims than those that have carried out reforms in a rush (UN-Energy, 2011). These liberalization reforms led to, among other things, a policy vacuum regarding the needs of poor people (GNESD, 2006). There are only a few African countries with comprehensive legislation linking liberalization of national utilities with increase of access rates in rural areas (UN-Energy, 2011). Furthermore, an important lesson learned from this situation is that government should be involved and committed to the reform process in the power sector, especially with regard to rural electrification. In South Africa, Zimbabwe and Ghana for example, government involvement and commitment has been significant, and it was only after achieving relatively high rural electrification levels that they began privatizing their power sector (UN-Energy, 2011), However, in some countries (such as Kenya and Uganda), liberalization led to a significant increase in tariff levels as well as stagnation in the electrification levels.

According to the African Development Bank, the power sector in Africa needs to install around 7,000 MW of new generation capacity each year in order to satisfy increasing demand and support economic growth (AfDB, 2010). In reality, the region witnessed considerable growth in investment flows for the region’s electricity sector from 1998 to 2008. In total, electricity generation increased by 70 per cent in the past 10 years (from 73 to 123 terawatt hours); this translates into an average annual growth rate of 6 per cent for the Sub-Saharan Africa region. Most of this growth, around 66 per cent, was due to renewable electricity generation, mainly in the form of hydro power (UNEP, 2012). Still, there is a large financing gap that will be very difficult to cover. While it is largely a matter of government priorities and, to some smaller extent, donor support, it is not probable that the necessary financing will be mobilized during the next two decades. Particularly low-income countries may decide that other more pressing social and infrastructure needs have priority (World Bank, 2010a).

2.8. Rural Electrification

The World Bank (2005) assessed that "*Rural electrification programs can face major obstacles. The low population densities in rural areas result in high capital and operating costs for electricity companies. Consumers are often poor and their electricity consumption low*" (Barnes, 2005).

The following chapter will give a short overview of some policy issues regarding rural electrification before going into more detail about the technological options to provide electricity in rural areas. The aim is to discuss policy considerations, effective institutional setup for the implementation of rural electrification programs, and the alternative electricity generation technologies for photovoltaic to rural electrification, as the economic analysis mainly depends on the cost comparison with its close substitutes grid access and diesel generation.

2.8.1. Rural Electrification - Policy

Governments' decisions for electrification are often based on country specific factors besides economic criteria, including, among others, equitable regional development. Often such decisions further involve trade-offs between equity and financial viability (World Bank, 2010a).

Up to this point, the allocation of generating capacity to urban areas is the priority of electricity supply utilities (UN-Energy, 2011). After all, supplying the dispersed rural population with electricity is expensive, often technically inefficient, and most of the time provides little return on investment (UN-Energy, 2011). However, access to electricity has been seen as the sine qua none of modernization. It still symbolizes progress and politicians pledge to provide electricity to communities in order to win elections (Wamukonya, 2007). Rural electrification is also often a preferred option to promote equity and economic development in poor countries (UNDP and World

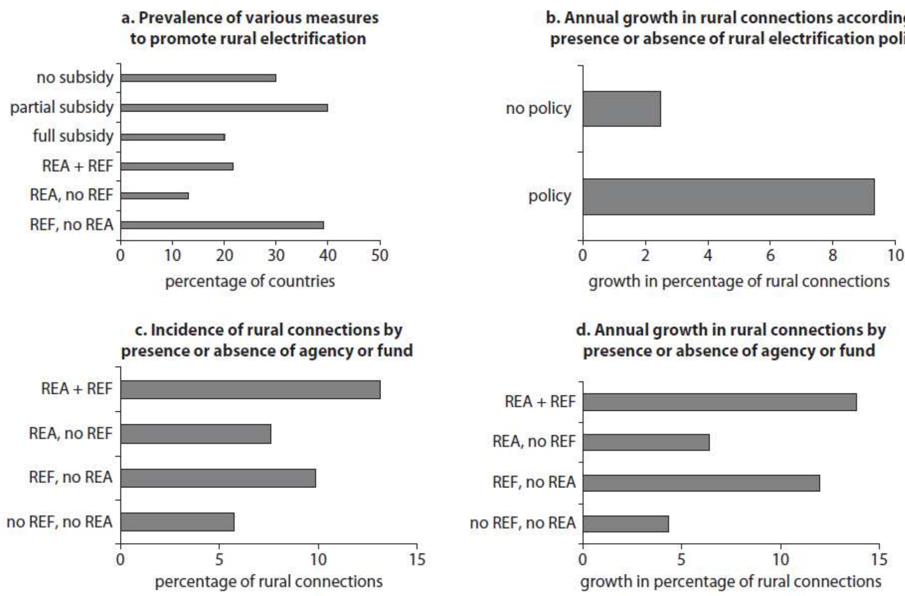
Bank, 2002). Further motivation for electrification is the promise of enhanced social development or improvement in quality of life (Wamukonya, 2007). However, the lack of large-scale productive uses remains a constraint for the financial viability of rural electrification especially for SHS (IEG and World Bank, 2008). Electrification of rural areas has non-the-less, often been justified on the basis that it results automatically in economic development. According to the World Bank (2008), rural electrification investments can generate satisfactory benefits to be practical from an economic standpoint (IEG and World Bank, 2008). Yet, nowadays it is generally acknowledged that electricity alone is not a catalyst for economic development even though it is necessary for it (Wamukonya, 2007).

The poor access situation, in rural as well as in urban areas, is often complicated by poorly performing utilities and regressive pricing policies subsidizing customers who can afford to pay cost-reflective tariffs. The consequence can be a perverse situation, in which higher-income consumers receive benefits they do not need, leaving fewer resources to expand access to the poor. Additionally, some subsidized rural electrification programs have drained the resources of state power companies, which reduced the quality of service and the overall performance. The result was widespread blackouts for all their customers. This also caused a reluctance of power companies to reach out and provide electricity access to the poor (Barnes, 2005).

The performance of rural electrification programs is both good and bad. The bad news is that in low income countries and in countries with high income inequality, the poor are often not able to afford electricity. Additionally, the wealthy among electrified households will be able to purchase more appliances, hence widening the gap between the rich and the poor. However, the good news is that for households which adopt electricity overall quality of life is enhanced, and to some extent the income gap between the middle income and wealthy households is lessened. Also, women and children benefit more from rural electrification than men (Barnes, 2005).

Responsible for urban and often rural electrification are mostly state owned national utilities. In the past decade, however, special-purpose agencies and funds for rural electrification have been the established. round half of the countries evaluated in the Africa Infrastructure Country Diagnostic (AICD) have rural electrification agencies (REAs), and more than two-thirds have rural electrification funds (REFs) (The World Bank, 2011). Most African countries have used loans extensively to electrify their populations and subsidies from the public sector have been quite helpful in facilitating electrification (Wamukonya, 2007). Most of the countries have either full or partial capital subsidies for rural electricity connections and also explicit planning criteria, e.g. population density, least cost, or economic or financial returns. Yet, in some cases, political pressures overrides these criteria (The World Bank, 2011).

To date, no sub-Saharan African country has managed to reach a significant majority of the rural population (UN-Energy, 2011). However, outstanding cases of success, clearly illustrate that it is possible to overcome these difficulties (World Bank, 2010a), as for example South Africa and Ghana (IMF, 2008). Greater progress, in terms of increased access rate, has been accomplished in those countries which have functioning electrification agencies and particularly in those with dedicated funds (Illustration 11). Additionally, countries with more people living in urban areas tend to have higher rural electrification levels, because of crosssubsidizing. Furthermore, analysis of electrification agencies in Africa has shown that centralized approaches, where a single utility is responsible forrural electrification, have been mostly more effective than decentralized approaches with several utilities or private companies (The World Bank, 2011).



Source: Eberhard and others 2008.
Note: REA = rural electrification agency; REF = rural electrification fund. Annual growth in new connections may seem high but comes off a low base; the overall percentage increase in households with access remains low.

Illustration 11: Rural Electrification rates, agencies and funds in SSA (The World Bank, 2011)

Côte d'Ivoire and Ghana are examples of countries which followed a centralized approach to rural electrification and made good progress with it. South Africa has also had considerable success by relying mainly on its national utility, Eskom, to carry out rural electrification. However, the World Bank (2011) also found, that decentralised rural electrification makes sense when smaller (private) initiatives focus mainly on minigrid or off-grid options complementing the efforts of the main utility in charge with extending grid access.

However, there is a fundamental difficulty in pushing for private business to provide rural electrification, while expecting social service to continue or be provided to the poor. Business needs to make a profit, which is not very likely to be gained from poor customers. Therefore, often the very people most in need of support; may be left behind by private companies.

In general, the World Bank (2010a) advices that local communities should be involved in the planning process of rural electrification programs. Involving local communities from the beginning can help improve the design, gain local support, mobilize contributions in cash or in kind, and increase local ownership.

2.8.2. Rural Electrification- Technology options

Governments´ decisions are seldom either grid or off-grid decisions, they depend on a country's income level and the stage of electricity infrastructure development (World Bank, 2010a). Extending rural electricity access is challenging no matter which technologies are used. These difficulties are associated with low population density and the isolation of the communities to be reached (World Bank, 2010a). As 80% of the population in Sub-Saharan Africa live on less than USD 2.50 per day, the choice of electricity source is mainly motivated by costs and affordability because even if electricity access is provided, it is not given that the population can afford it (UNEP, 2012).

All in all, governments usually prioritize grid extension programs (IRENA, 2012a).Grid extension is, after all, the cheapest way to increase access rates in areas close to the existing grid. In most Sub-Saharan African countries, between 80 to 95 percent of the unelectrified communities are targeted to get electricity supply through grid extension (World Bank, 2010a). Even though the low population density and the dispersed nature of the rural population means that grid extension is often not economical (IMF, 2008).

Off-grid technology options, mini-grids or individual systems, are suitable to supply populations living in areas far from the existing grid and areas with too low demand, to justify the cost of extending the grid (World Bank, 2010a). Additionally, off-grid solutions are an important step, causing a growth in demand and so improve the viability of grid connection for the future (IRENA, 2012a). Renewable energy sources are particularly suitable for small grids or off-grid solutions and have a great potential in many rural regions (UNEP, 2012). As REN21 wrote in (2011), off-grid renewable solutions are widely acknowledged to be a cheap and the most sustainable options for rural electrification in much of the developing world (REN21, 2011).

2.8.2.1. Grid supply

Most countries of Sub-Saharan Africa have the target to provide electricity access via grid connection to between 80 to 95 percent of the communities without electricity access (World Bank, 2010a). National governments have put the emphasis of electrification on grid electricity solutions, becausea high capacity and steady supply of electricity, can mostly only be provided by grid systems, which in turn is essential for most industrial activity (Welle-Strand et al., 2012), and extension of the distribution grid is regularly the cheapest way to widen electricity access. Such investments usually have lower costs per connection and are somewhat easy to implement. It is especially the case for all urban areas, where still 120 million people in Sub-Saharan Africa (IPCC, 2012), with no access to electricity presently live. Grid extension is often also for rural areas the least-cost solution (World Bank, 2010a). However, the per person costs of grid connections in rural areas can also be prohibitively expensive due to the low population density and the low average income levels in many developing regions (Welle-Strand et al., 2012). Thus, in many low-income countries electricity grids are often limited to areas with high population densities (Deichmann et al., 2010).

An important advantage of grid connection is, that with increased electricity consumption by the consumer levelized cost per kWh are reduced significantly (World Bank, 2010a). The estimated levelized marginal costs of grid supplied electricity lie between 0.16 and 0.50 USD per kWh for most areas. Yet, these costs rise steeply to more than 1 USD for the most remote demand areas in Sub-Saharan Africa (World Bank, 2010b).

Szabo et. al (2011) simulated a map of Sub-Saharan grid infrastructure, shown in Illustration 12, also simulating areas with a certain distance to the grid. They combined available grid data with the population density and city layers, and showed that populous cities were already connected to the grid. However, Illustration 12 clearly shows that certain rural areas are far away from any grid lines. The main source for this map of the electricity network infrastructure was the Africa Infrastructure Country Diagnostic (AICD) GIS database (JRC, 2013).

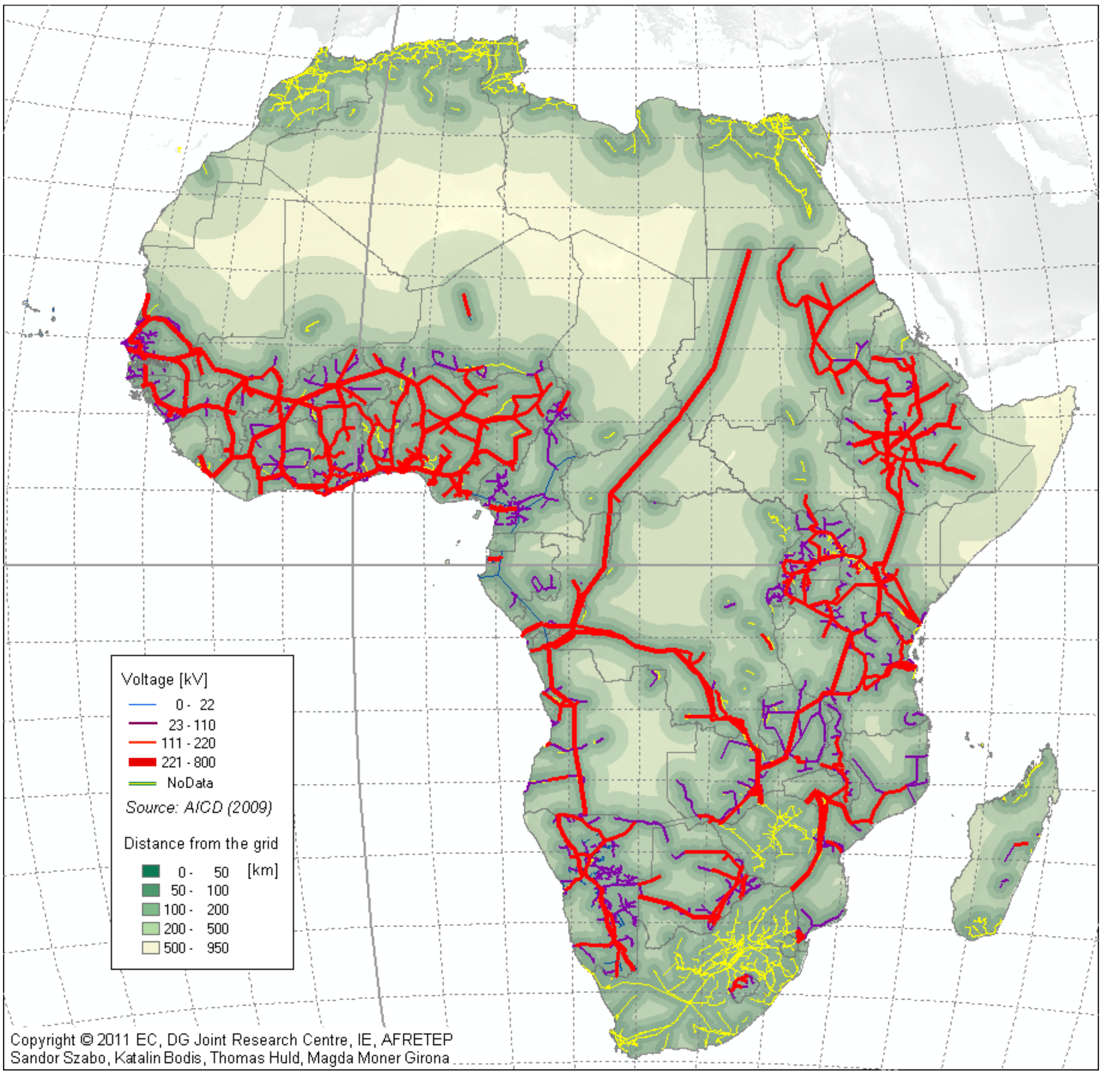


Illustration 12: Network infrastructure of Sub-Saharan African countries, (Szabó et al., 2011)

2.8.2.2. Off-Grid

Off-grid alternatives can supply electricity to buildings or to small areas through standalone systems or mini-grids. Diesel generators are the most commonly used off-grid option, however, they have non-negligible capital expenditures and reliable access to a diesel source is required. Another available option is the use of renewable energies or off-grid solar photovoltaic systems, yet, the cost of electricity generation per kWh is most of the time higher than either electricity supplied by the grid or diesel generators.

As costs are one of the most dominate factors in deciding which technology to deploy, Chaurey and Kandpal (2010) highlighted the importance of a standardized off-grid electrification approach based on the least cost for electrification. The price of fossil fuels plays an important role in determining the economic feasibility of renewable energy systems. These prices and anthropogenic climate change concern somewhat favor renewable energy over diesel generators in areas where access to the grid is not an option for years to come (Welle-Strand et al., 2012).

Yet, Deichmann et al. (2010) wrote that decentralized renewable energy will be the least cost option only for a minority of households in Africa, even after likely cost reductions during the next 20 years are considered. Decentralized renewables are most of the time only competitive in remote rural areas, while grid supply dominates denser areas. Their analysis, showed that decentralized renewable power cannot be the only solution to universal access in Sub-Saharan countries. However, decentralised renewable energy will likely play a main part in any significant expansion of electricity access.

Whichever off-grid solution is chosen, PV systems or diesel generators only offer little electricity for production activities. Though benefitial on the individual household level, the limited generating capacity results only to little overall economic growth (Welle-Strand et al., 2012).

2.8.2.3. Diesel

Diesel generators exist in many different sizes. Household level systems typically have only a size of a few kW (World Bank, 2010b). Additional to regular small-scale diesel units an estimated 700 MW of emergency diesel generators were operating in sub-Saharan Africa, before 2008 (IMF, 2008). The cost for diesel generated electricity mainly depends on the fuel consumption and fuel cost, as investment costs for generators are relatively low. The diesel price is influenced by crude oil world market prices, and national subsidy or tax schemes. The map and the GIS data in Illustration 13 show the retail prices of diesel (in EUR cents per liter) at the end of 2010 based on the GTZ data after JRC (2013. The prices show high variations because they are depending on national taxes and subsidies. National average diesel prices ranged between 10 eurocent (Libya) and 124 eurocent (Central African Republic) in 2010.

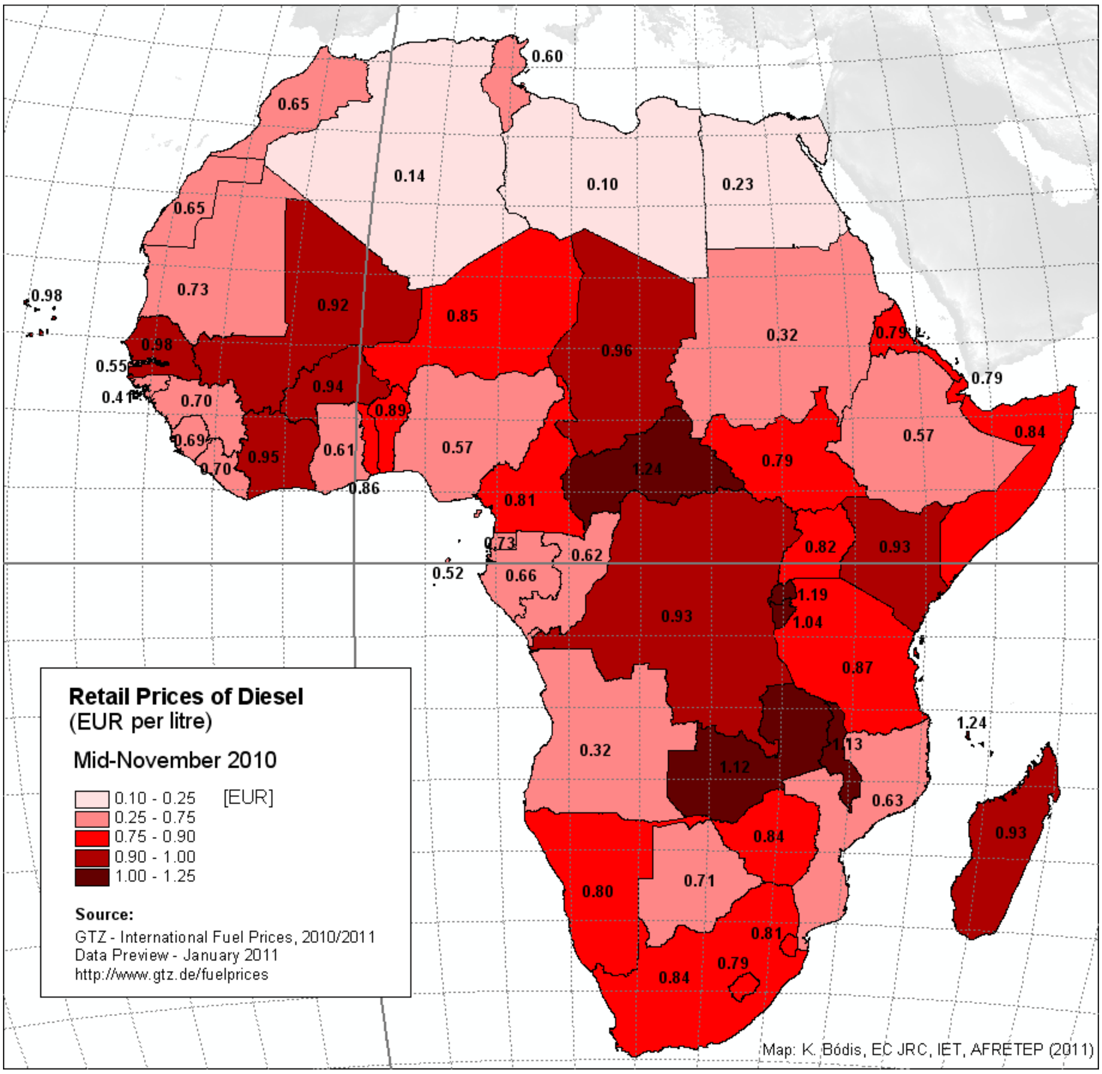


Illustration 13:Map of international Diesel prices, 2010, (JRC, 2013)

Additionally, the diesel price in rural areas highly depends on the distance to the closest major population center. The more remote the location is, the higher the diesel price. Szabo et. al further processed the database of international diesel prices for 2008 and 2010 in African countries to evaluate energy solutions in rural Africa and map electrification costs of distributed diesel generation versus grid extension and micro-gird solar generation, see in Illustration 14**.** They calculated final cost of diesel generated electricity, by a 4-15 kW diesel generator. The electricity price of this system consists of production cost, the labor cost, maintenance, amortization, and transport costs of the diesel. The electricity cost generated by diesel, thus range between 0.3 €/kWh (dark brown) and 2.4 €/kWh (light yellow) (Szabó et al., 2011). Which is a lot higher than the prices of grid electricity, which ranges from 0.05 USD/kWh to 0.30 USD/kWh, with a regional average of grid electricity prices of 0.12 USD/kWh.

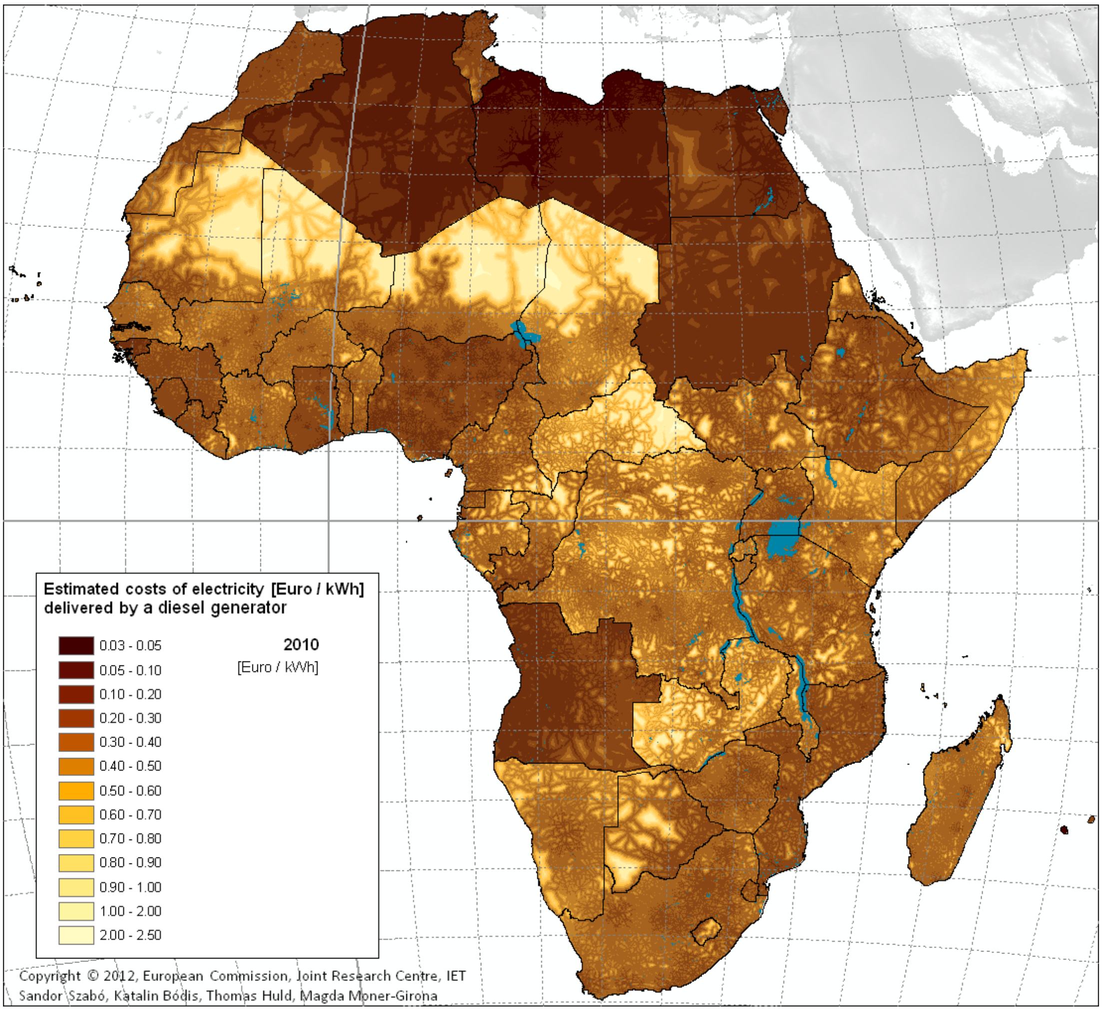


Illustration 14: Estimated costs of electricity [Euro/kWh] delivered by a Diesel generator in 2010, (Szabó et al., 2011)

2.8.2.4. Renewable Technologies

People without access to the grid but with access to finance, or private wealth, have often turned to diesel generators for their electricity in the past. In the last years the high price of oil and its price fluctuations however, has considerably increased the cost of keeping the generators running (UNEP, 2012). Additionally, on-grid supply becomes less economical, the lower the population density and the lower the electricity demand (Van Ruijven et al., 2012). These main reasons make renewable energy technologies a viable alternative for costly diesel generators or expensive grid expansion in some rural areas (UNEP, 2012).

Until twenty years ago, grid extension, diesel-powered mini-grids, or mini-hydropower generators were, in most cases, the only electrification options available to rural communities. With the commercial maturation of different small-scale renewable energy-based technologies, from solar photovoltaic systems to small wind generators or micro hydropower, off-grid systems have emerged as a viable alternative to increase electricity access, especially in remote and dispersed communities or for households with low consumption levels. Additionally, most of these renewable off-grid technologies have the benefit of being independent of fuel and they do have lower health impacts and contribute less to global warming (World Bank, 2010a). Moreover, their costs are expected to decrease further (ESMAP, 2007). Global price for photovoltaic modules has decreased dramatically. Thus, with decreasing prices for photovoltaics and with rising fossil fuel prices, small-scale photovoltaics, as for example Solar Home Systems are an more and more attractive investment for individuals, companies or governments looking for electrification in rural areas. (UNEP, 2012) Furthermore in Sub-Saharan Africa, the sun shines throughout much of the year, yet, hydropower faces site constraints and hydrological variations, wind technologies are constrained by the availability of wind, and biomass technologies depend on the growing seasons (Van Ruijven et al., 2012).

For further information on renewable technologies in Africa not discussed here, e.g. biomass, pico and mini-hydro power and wind power, please refer to the JRC report (2011) “Renewable Energies in Africa” (Belward et al., 2011). This report assesses the renewable energy options for electricity production in rural areas in more detail.

2.8.2.5. PV

According to Bazilian et al., PV is a good economic alternative in remote or off-grid applications, especially to power electrical loads of up to hundreds kilowatts (Bazilian et al., 2013). PV technology can function virtually in any location and is therefore the only renewable technology that is not site-specific. Yet, there are geographic differences, such as solar radiation intensity and the number of days without sun irradiation (World Bank, 2008). As a study by Ruijven and al. (2012) showed solar PV off-grid or a wind/diesel microgrid are the most attractive options, in South Africa and Eastern Africa, when the demand is low, even when the investment cost for grid extension is also relatively low.

Chaurey and Kandpal (2010), wrote that PV systems are comparable with other systems for rural electrification on a life cycle cost basis. However, the competitiveness depends upon local costs of components and, therefore, varies across countries, making it difficult to generalize the competitiveness across regions.

PV systems increase their market share due to continuous cost reductions and the ability to produce electricity with no moving parts, no fuel requirements, no need for grid connection, no noise, and zero emissions. The modular nature of PV, which allows the generation of power from Watts to Mega-Watts, gives it a distinctive advantage over other technologies (World Bank, 2006).

PV systems for rural electrification can range from pico systems (<10 W), over Small House Systems (30-150 W), to micro-grid installations (>1kW) (World Bank, 2010a).

In a recent study, Szabo et al. (2011) evaluated the costs of running a mini-grid photovoltaic system (Illustration 15) versus diesel-powered generators and grid extension (see Illustration 16). This study took, amongst others, the different purchasing costs, diesel prices and geographical differences in solar radiation, into account. The conclusion was that in many rural areas the price per kWh generated by a solar PV system is equal or lower than the costs of running a diesel generator, see Illustration 16. After all, diesel generators have lower investment cost, but their operation costs have increased over recent years due to increasing fuel prices. At the same time, costs for renewable energies, especially PV, have decreased dramatically.

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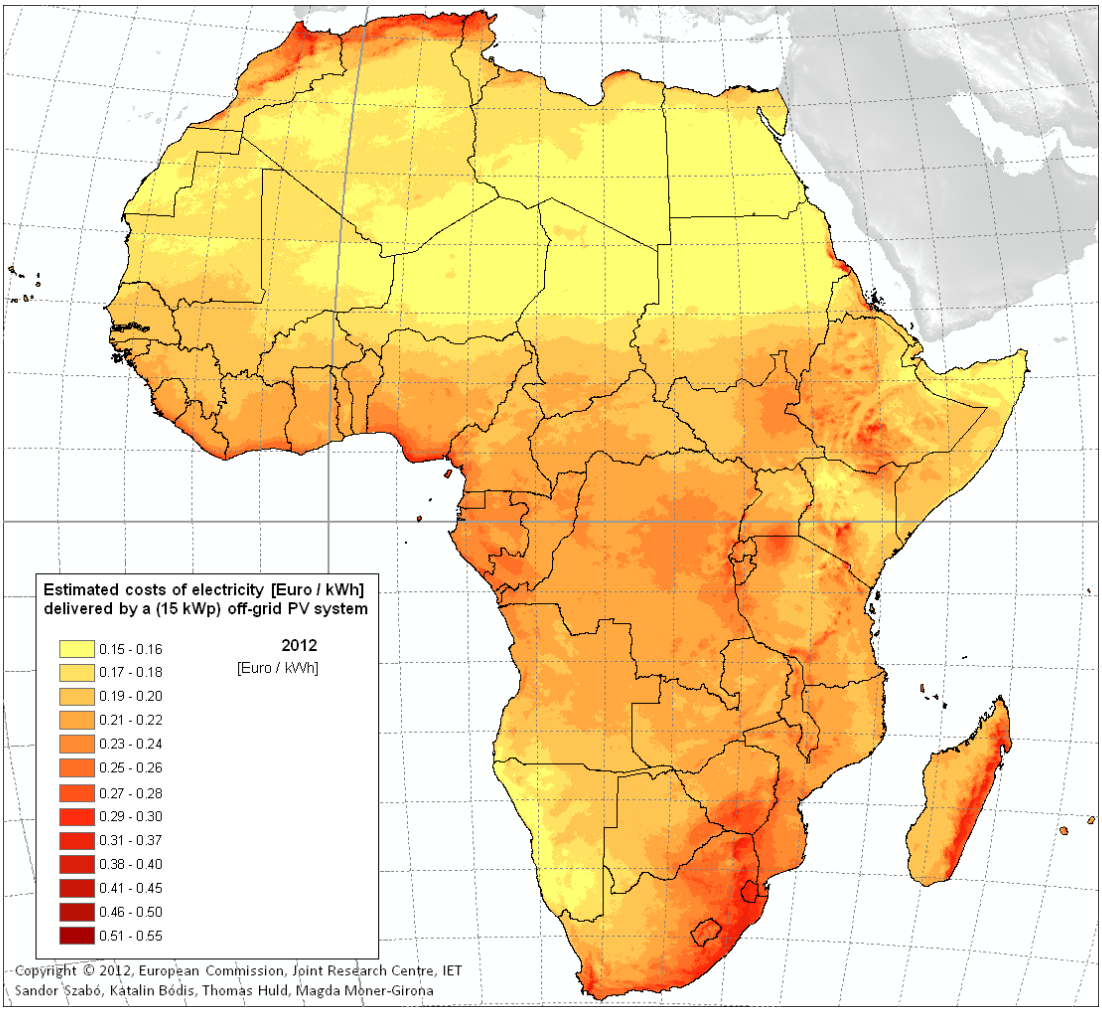


Illustration 15: Estimated costs of electricity [Euro/kWh] delivered by a 15 kWp off-grid PV system, (Szabó et al., 2011)

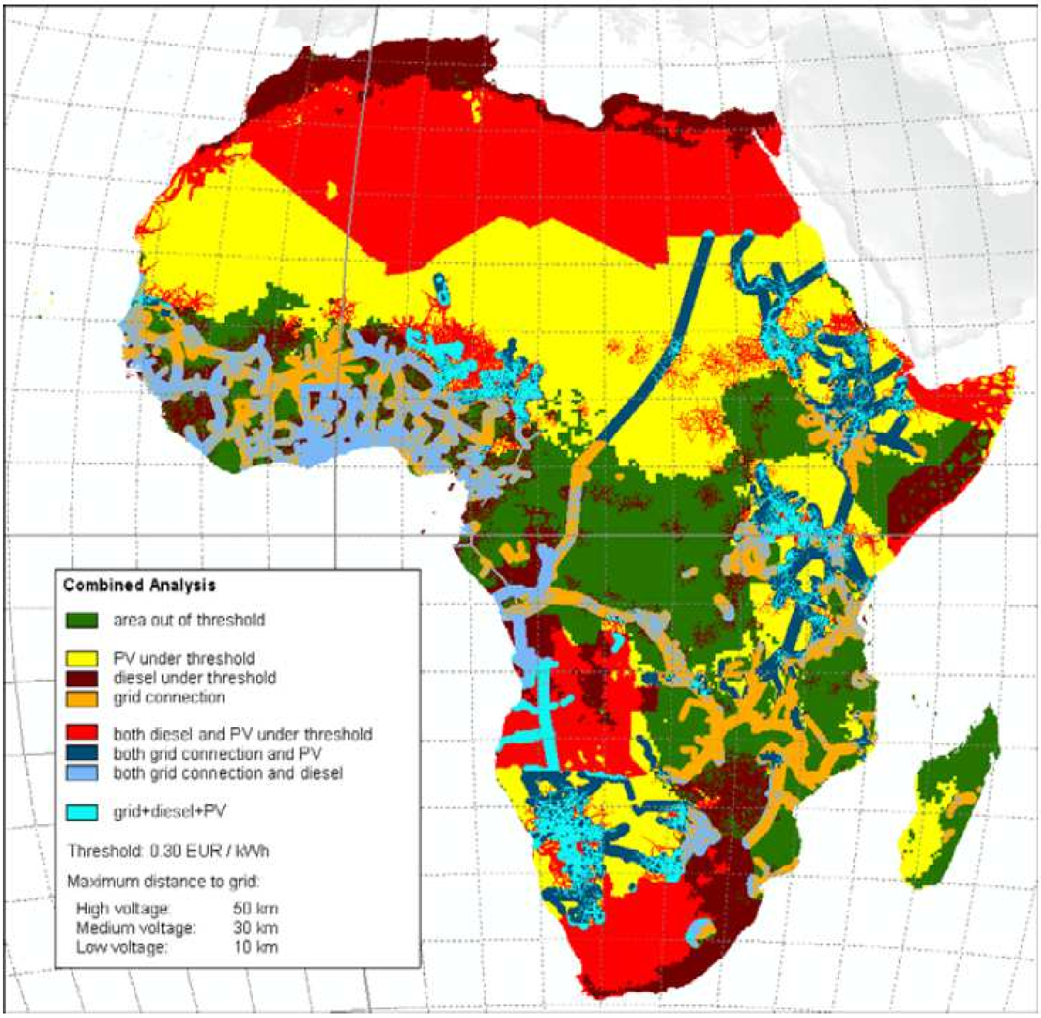


Illustration 16: Geographical distribution of technologies with electricity costs lower than 0.30 €/ kWh and conservative assumption on grid extension, (Szabó et al., 2011)

Trend pico systems

This paper includes the eoncomic and affordability analysis of a 5W picoPV system. Thus, here is its definition and other interesting facts.

The Alliance for Rural Electrification (2011) defines PicoPV system as a small SHS with a capacity of 1 to 10W, mostly used for lighting. Depending on the system, small information and communication applications, e.g. mobile phone charger or radio, can also be included. PicoPV systems are powered by a small solar panel and utilize a battery which often is integrated in the lamp itself. The panel can be either fixed on the system itself, e.g. solar lanterns, or mounted separately from it. In the second case, a part of the product does not have to be exposed to weather conditions (ARE, 2011).

PicoPV systems have the advantages of easy installation, user-friendliness, low investment costs, little required maintenance, a high degree of expandability and flexible use. A one lamp kit including solar module costs usually in the range of 50 EUR to 150 EUR. Other PicoPV systems can be cheaper for very small systems and solar lamps cost can be as low as 7 EUR. These prices are usually affordable for most of the rural people in developing countries. In fact, the majority of the PicoPV system market is currently running on cash payment (ARE, 2011). According to REN21 (2010), until 2009 around one million solar lanterns were sold.

The GIZ (2010) wrote that picoPV systems may allow “pre-electrification”, and that there are some good reasons to be optimistic regarding the potential of this emerging off-grid technology. First, Pico PV prices are decreasing fast. Second, Pico PV systems are over-the-counter products and not need specific knowledge for installation or O&M by the consumer. Therefore, the distribution has lower transaction costs than all other grid or off-grid alternatives. Third, it is argued that the welfare gain from electrification at household level are the highest after switching from flame-based lighting to efficient electric lights. And last, consumers do not fear that PicoPV lamps will prevent them from future grid roll-out, as they frequently do in the case of SHSs (GTZ, 2010).

Recent field studies by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), suggest that although there is progress, many of the solar lamp systems available on the market (in 2010) do not provide sufficient light to provide the level of lighting preferred by rural households or are not robust enough (REN21, 2011). However, the IEA wrote in 2013, that testing has improved the new generation of picoPV systems and that solar picoPV systems have experienced important developments in the last few years, combining the use of high efficient lights with refined charge controllers and efficient batteries (Lysen, 2013).

Solar Home Systems

Additionally to the 5W picoPV system, two SHS systems are analysed, one 50W and one 100W SHS system. Solar home systems are suitable when the expected consumption of households is very low and thus grid extension and mini-grids are not viable (World Bank, 2010a). This chapter gives an overview over the literature on SHS systems.

A typical SHS consists of a 10–150 Wp solar PV panel, a modified automobile battery or a low-maintenance deep cycle battery storing the solar energy collected in the daytime, and a charge controller for the overall energy management, cabling, some low wattage direct-current lamps, sometimes a charging station for mobile phones, and possible low wattage direct-current radio or TV (World Bank, 2010a). Significant advantage of classical SHS is that every appliance runs with DC loads, e.g. like DC energy saving lamps, DC radios, DC TV and DC fridges. Using DC appliances increases system efficiency, because there are no conversion losses (ARE, 2011). It is, indeed important to use energy efficient appliances in for these systems (Chaurey and Kandpal, 2010), as a SHS can only provide a small amount of electricity. For example, a 50W SHS operated with a 20 percent capacity factor would, with an average irradiation, only provide around 7 kWh of electricity per month (World Bank, 2010a). With energy efficient appliances and 7 kWh per month it is possible to operate four 7W compact fluorescent light bulbs and a black and white television (with 30W) (World Bank, 2010a).

By 2010, over 3 million solar PV home systems have been installed worldwide (REN21, 2010). Due to technological developments and improving learning rates, rapid cost reductions are being achieved for photovoltaic technologies. As a result, global annual capacity additions have been growing rapidly in the last years (IRENA, 2012a). For example Bangladesh which, in 2012, had more than 1 million (or 50MW) installed SHS (Grameen Shakti, 2013). The main factor holding back the widespread development of solar in Africa is its price and its load variability (IRENA, 2012a).

Small scale PV tends to be more expensive than other renewable energy technologies. Some past Africa specific studies Karekezi and Kithyoma (2002) and Wamukonya (2007) established that global economic and technological advancements in PV are not enough to justify deployment of SHS at the local level and that the costs of SHS remain quite high compared to conventional technologies for very low load levels (Chaurey and Kandpal, 2010). According to the World Bank (2010a), in 2005, the levelized cost of a 300W PV system was $0.56 per kWh. In contrast, a 300W wind turbine had costs of $0.30 per kWh, and a 300W pico hydro system 0.12 USD/kWh (World Bank, 2010a). Yet, with current prices ranging from 140 EUR to 1.600 EUR, many SHS are affordable for rural end-users and are sold without any subsidy (ARE, 2011).

In reality SHS systems, due to their relatively high investment costs are mostly only competitive when other renewables are not usable, a grid connection is uneconomic and diesel prices are high and when innovative service delivery models are applied (World Bank, 2010a). Solar PV, as rightfully criticized by Karekezi and Kithyoma (2002) is often unaffordable for the rural masses. Providing finance and spreading the initial high investment cost over a number of years, can help to make this system affordable for the rural population (UNEP, 2012). Additionally, arrangements must be made to ensure supply of spare parts and repair services (World Bank, 2010a).

Another disadvantage is, that the applications for SHS are more limited than other electricity generation systems, because the available load is smaller most of the time (Adkins et al., 2012). As the World Bank's Independent Evaluation Group (IEG and World Bank, 2008) points out, the benefits from SHS are usually smaller than from grid electricity. The reason is that the available capacity to consumers is usually smaller. Therefore, households with SHS have practically no electrical appliances, except for sometimes a television set, whereas a large part of grid-connected households have a range of appliances (World Bank, 2010a).

Yet, even though SHS provide only a limited amount of electricity, the service SHS provide can represent a clear improvement in the quality of life of beneficiaries. Though, the end target should be to reach service levels similar to a grid connection, thus SHS should be considered an initial transitory technology, with mini-grid or integration into the national grid as the aim. Nonetheless, SHS are likely to be a long-term transitory option for the rural populations in countries of Sub-Saharan Africa, which currently have very low access rates (World Bank, 2010a).

2.8.2.6. Comparison of Technologies

In 2007, the World Bank carried out a cost comparison of offgrid, mini-grid and grid electrification technologies, with data for the year 2005 (ESMAP, 2007). The conclusion was that the costs of providing electricity to grid-connected consumers is lower than costs of electricity provided by off-grid technologies. Yet, communities and households that are beyond a certain critical distance from the grid, the levelized cost per kWh of grid extension is greater than for off-grid supply, yet, SHS do not require a grid for transmission, distribution, and connection. On average, off-grid technologies have a LCOE between 0.11 USD/kWh to 0.60 USD/kWh. Mini-grids LCOE ranged from 0.05 USD/kWh to 0.50 USD/kWh, while the LCOE of grid connected power plants had a cost range of 0.04 USD/kWh to 0.15 USD/kWh, with the cost of grid usually adding another 0.05 USD/kWh to 0.10 USD/kWh to the total price.

Table 15 shows that the average cost of 50W SHS system of 0.62 USD/kWh exceeds the costs of typical centralised power generation technologies found in developing countries with low access rates, e.g. 0.05 USD/kWh for large hydro, 0.09 USD/kWh for a 5MW base-load diesel unit (diesel-based generation costs have risen considerably since 2005). However, the fact is that SHS are more widely applied than any other off-grid option, which suggests other off-grid technologies are not available or that they are inferior despite their apparent cost advantage (World Bank, 2010a).

Table 10: LCOE various technologies (World Bank, 2010a)

Table 5: Levelized Power Generating Costs for Various Technologies (2005)

Generating Type		Rated Output (kW)	Cost (U.S. cents/kWh)
Solar PV		0.05	62
		0.30	56
		25	51
		5,000	42
Wind		0.30	35
		100	20
		10,000	7
PV-wind hybrid		0.30	42
		100	31
Solar-thermal with storage		30,000	13
Geothermal Binary		200	16
Binary		20,000	7
Flash		50,000	4
Biomass Gasifier		100	9
		20,000	7
Municipal. Solid Waste/Landfill Gas		5,000	7
Biogas		60	7
Pico/Micro-hydro		0.30	15
		1	13
		100	11
Mini-hydro		5,000	7
Large Hydro		100,000	5
Diesel/Gasoline Generator		0.30	65
		1	51
		100	20
Base Load		5,000	9
Micro-turbines		150	32
Combustion Turbines			
Natural Gas		150,000	13
Oil		150,000	23
Combined Cycle	Natural Gas	300,000	6
	Oil	300,000	12
Coal Steam Sub Critical (with flue gas desulphurization and selective catalytic reduction)		300,000	4
Oil Steam		300,000	7

Source. ESMAP 2007b.
kW = kilowatts.

IRENA (2012a) in its report “Prospects for the African Power Sector” concluded that renewable options have most of the time a LCOE cost below those of diesel generated electricity but have higher costs that centralized coal- or gas-fired power plants, without considering fossil fuel price volatility.

Table 11 gives an overview over renewable electricity generation technologies in Africa regarding typical Investment costs and resulting electricity price, plus transmission and distribution costs where applicable. This excludes any subsidies or taxes and treats all electricity as being equally valuable (base load or peak load). It further accounts for grid connection, but not for the cost of grid integration (e.g. the backup or storage capacity need for variable renewable technologies). Furthermore, the cost of externalities is also excluded (IRENA, 2012a).

Large hydropower can have the lowest investment and production costs, followed by biomass co-combustion and onshore wind power. If grid connection, transmission and distribution are added, some decentralized solutions become competitive with grid-connected renewables. SHS would fall under the category Solar PV with battery, here Irena estimates investment costs to be 5-6 USD/W with an LCOE of 45-65 USD/kWh including the cost correction for dust and heat impacts on the performance, as well as the gradual degradation in the equipment over time.

However, Irena highlighted that one major advantage of decentralized technologies is, that these can be fully- or partly-funded by households or small communities. Which in turn may be a feasible option to extend access to power supply, especially in areas where utilities are constrained by a lack of capital (IRENA, 2012a).

Table 11: Typical LCOE of renewable power generation technologies in good African conditions, for the year 2010, adapted from IRENA, (IRENA, 2012a)

	Investment cost	Capacity factor	Fuel cost	Electricity price[1]	Transmission and distribution cost
	(USD/kW)		(USD/GJ)	(US cents/ kWh)	(US cents/kWh)
Solar PV grid connected (85%PR)	3,000-4,000	0.2		24-37	3-7
Solar PV no battery	3,500-4,500	0.2		30-47	
Solar PV with battery (2.4 kWh/kW)[2]	5,000-6,000	0.2		45-65	
CSP grid connected no storage (90% PR)	5,500[3]	0.3-0.4		35-47	3-7
CSP grid connected 8 hrs storage (90% PR)	8,500	0.5-0.7		31-43	3-7
Large hydropower (above 10 MW)	1,000-2,000	0.5		4.5-9	3-7
Small hydropower (0.1 to 10 MW)	2,000-4,000	0.5		9-18	1-2
Pico hydropower Below 0.1 MW	4,000-8,000	0.5		18-36	1
Onshore wind (2 MW)	1,750[4]	0.25-0.40		10-16	3-7
Onshore wind (0.2 MW)	3,000	0.2-0.25		27-34	3-7
Biomass (bagasse boiler)	2,500	0.5	0.5-3	12-15	3-7
Biomass co-combustion in coal-fired power plant	1,250	0.75	1-5	5-9	3-7
Geothermal (high quality resource)	5,000[5]	0.8		14	3-7

[1] *Assumes 15% annuity plus 5% O&M. Excludes inflation and taxes/subsidies.*

[2] *Given a 20% capacity factor, a 1 kW panel produces 1,740 kWh. If half of the electricity is stored, evenly divided over the days of the year, 2.4 kWh of daily storage is needed. If battery discharge is limited to 25%, 10 kWh of battery storage capacity is needed. For deep-cycling lead acid batteries this costs USD 1,500.*

[3] *This compares to the USD 6,000/kW cost for 100 MW Shams-1 plant in Abu Dhabi.*

[4] *This compares to the USD 3,750/kW for the 100 MW Cape Town wind park project in South Africa and USD 2,175/kW for the 300 MW Turkana wind park project in Kenya. This includes all project costs (AFD, 2011).*

[5] *This compares to the USD 7,000/kW cost for 185 MW Olkaria expansion project in Kenya (AFD, 2011).*

Source: IRENA, 2011b and IRENA analysis.

2.9. Barriers to rural electrification

Some developing countries in Sub-Saharan Africa have successfully increased electricity access in rural areas during the last two decades. However, most low-income countries have difficulties to provide electricity to rural areas. There are several reasons or barriers why closing the electricity access gap is tough (World Bank, 2010a).

2.9.1. Financial Risks

Most rural communities are characterized by low population density with a disproportionately high share of poor households. The low population density causes relatively high costs of electricity distribution shared by few people, causing high costs for each unit of electricity consumed. Thus, rural electricity systems have higher investment costs per consumer and per kWh of sales than urban systems. Building widespread central grid distribution systems to light rural households is expensive. Due to technical characteristics, rural systems also cause higher technical network losses and operating costs (World Bank, 2010a).

Furthermore, the biggest risk of rural electrification is that revenues earned will not be enough to cover the costs incurred (World Bank, 2010a). As often, the electricity prices simply fail to cover the costs (IMF, 2008). Unless a tariff is in place which recovers costs, utilities have no reason for grid extension in rural areas because providing rural electricity services is not financially viable. (World Bank, 2010a) Another big problem is non-payment for services and illegal connections, amounting to 52% of hidden costs attributable to collection losses for grid connections (OECD, 2009).

In 2005, the average operating costs for a diesel-based power generation system was 0.27 USD/kWh but average revenue was only 0.17 USD/kWh (OECD, 2009). The cross-country average electricity tariff in Sub-Saharan Africa is rather high at 0.13 USD/kWh, about twice as high as in other parts of the developing world. Yet the average revenue fails to cover the average operating costs of 0.27 USD/kWh, although during the last five years the average revenue in Sub-Saharan African countries has risen dramatically, from USD 0.08 to USD 0.17 per kWh (IMF, 2008).

These widespread insufficient tariffs are in place because many people are not able to afford the real costs of electricity in Sub-Saharan Africa. Banerjee et al (2008) estimated affordability problems of electricity in sub-Saharan African assuming modest consumption of 50 kWh/month. Cost recovery prices would amount to approximately 0.25 USD/kWh, a subsistence monthly bill would be USD 12. Only people living in a relatively small group of middle-income and better-off low-income countries could afford this (e.g. Cameroon, Cape Verde, Côte d'Ivoire, Republic of Congo, Senegal, and South Africa), however a large share of the population would not be able to afford cost recovery tariffs.

The World Bank wrote in (2010), that where costs of reaching distant communities surpasses a certain threshold, it becomes cheaper to use off-grid sources for supplying electricity, such as mini-grids served by mini-hydro plants or diesel units and solar-home systems (SHS). However, off-grid electrification also faces the low-demand and high cost challenges as grid extension in rural areas.

2.9.2. Exchange rate and Inflation Risk

Additionally, the investment required to increase rural electricity access often exceeds domestic sources of financing. It is therefore necessary to mobilize finance from sources abroad, and then the additional barriers of exchange rate risk and inflation becomes relevant. Most private investors use foreign currency loans but they earn their revenues in local currency. This causes an exchange rate risk if the local currency devalues, as investors would get less returns when they convert the local earnings to foreign currency (OECD, 2009).

Additionally, inflation makes it less attractive for foreign investors to lend money for energy projects. Inflation in Sub-Saharan Africa as of December 2011 was running at an average of 9,75 percent across the region, up from 7 percent a year earlier, this was mainly linked to the surge in global food and fuel prices (IMF, 2012). While this high inflation rate may be temporary, there is a risk that inflation continues to grow throughout the duration of an energy project (OECD, 2009).

2.9.3. Legal and institutional aspects

An effectively implemented rural electrification program needs technical and managerial capacity in place. Countries committed to extending electricity access initially, need a certain period to analyze the development of a strategy and the building of appropriate capacities. Often countries have to develop their own approach suitable to their social and political realities. This process may involve new or changed legislation, strengthening or creation of relevant institutions. Additionally, a careful planning, that defines the selection criteria for projects, creates technical standards and regulatory procedures customized to the nature of rural electrification, is needed. Many low-income countries have yet to complete this process (World Bank, 2010a).

Moreover, energy projects are often legally complex but in some countries of Sub-Saharan Africa, legal institutions and organizations are not able to handle such complexity. They often lack the experience with such work or have too few lawyers with professional training in energy contracts and laws. Law enforcement is also often quite weak. Utilities collect on average only 70% to 90% of billed revenues and distribution losses from illegal connections can reach 40% of total losses. Additionally, vandalism is often unpunished, because the police forces do not enforce any rules against it (OECD, 2009).

According to the IMF (2008), the perhaps most relevant institutional consideration is the governance of the national power utility. Poor governance can be seen in deficient performance as the inefficiency of Sub-Saharan African utilities generate substantial hidden costs in the range of 2% of national GDP. On average, 50 percent of the additional costs stem from collection losses and a further 30 percent from distribution losses. Improving utility performance can be often very profitable. Most utilities also benefit from sizable subsidies and tax breaks but are still not in a position to borrow at all.

The high costs of electricity in rural areas and the limited household's capacity to pay for the service make it challenging to attract investment in rural electrification. To do so would entail a system of tariffs and subsidies that guarantees sustainable cost recovery while at the same time minimizing price distortions. However, such a tariff and subsidies scheme is absent in many SSA countries. An additional problem in Sub-Saharan Africa is, that where residential subsidies are in place, these are often ill-designed and regressive, favoring the well-off, while failing to provide incentives for rural electrification programs (World Bank, 2010a).

2.9.4. Other reasons

An important barrier to rural electrification for the next several years in many Sub-Saharan Africa countries with low access rates is their inadequate power generation capacity to provide existing grid-connected demand, combined with the inability to import the missing electricity. A recent study suggests that more than 30 countries in Sub-Saharan Africa experience power generation shortages. As the World Bank states in the 2010: "*Angola, Gabon, Ghana, Kenya, Madagascar, Mauritania, Rwanda, Senegal, Sierra Leone, Tanzania, and Uganda have resorted to short-term leases of emergency generating capacity since 2004. Significant power outages have occurred in Benin, Burkina Faso, Cameroon, Cape Verde, the Democratic Republic of Congo, Ethiopia, Lesotho, Malawi, Mozambique, Namibia, Niger, Sudan,* *and Zambia."* They further assess that it is unrealistic to expect that these countries increase electricity access by means of rural grid extension to a high degree until the capacity constraints are removed. Off-grid electrification, on the other hand, is not affected by the constraints of the central generating capacity (World Bank, 2010a).

A further problem in expanding rural electrification in some Sub-Saharan African countries is the rapid growth of the rural population. This is the main reason explaining the *World Energy Outlook 2009* Reference Scenario, which foresees an increase by 110 million of the number of people without access to electricity in Sub-Saharan Africa during the next 20 years (World Bank, 2010a).

2.9.5. Specific Barriers and Challenges for SHS projects

Wamukonya (2007) summarized the barriers for PV penetration into four main categories (see Illustration 17). First, the financial barrier, which is mainly caused by the high up-front cost of the system. Posorski et. al (2003) further assessed, that SHS have a high costs of selling, including marketing, delivery and maintenance, in developing countries and recommended that these costs must be covered by the product margins (Posorski et al., 2003). Second challenge is the technological barrier, e.g. the required knowledge for the installation and maintenance. Chaurey and Kandpal (2010), for example, highlighted the unavailability of skilled technicians needed for the promotion and installation of the systems as a barrier in developing countries. Third barrier is the limited markets for PV in developing countries and fourth the challenge to guarantee the quality of PV systems.

Additional financial barriers in India, as Miller and Hope (2000) wrote, are that off-grid solar power projects face an aversion to rural credit, lack of market infrastructure and lack of support to entrepreneur. Furthermore Martinot et. al (2001) assessed that the credit risk is a serious concern for both financiers and dealers of PV systems and it was found that therefore credit sales of solar systems to be particularly challenging. Furthermore, they wrote that a viable business model, showing that profits are made in certain markets, is necessary to achieve private investment. Muntasser et al. (2000), on the other hand, emphasized the lack of investments and financing, high transaction costs, subsidies to fossil fuels and lack of awareness about PV systems at all levels as market barriers for PV in LDCs.

Barrier	Barrier removal strategies
Financial: high up-front capital costs high tariffs	Micro-credit facilities for end-users and dealers Loan schemes & revolving funds in conventional financing institutions Removal of taxes and levies Capital and tariff subsidies Fee-for-service delivery model
Technical support for installation and maintenance	Train locals as technicians within projects Train users on basic maintenance Disseminate user-friendly self explanatory manuals on operations and maintenance Shift responsibility to service deliverer (Service delivering agents in companies)
Limited markets	Large scale government sponsored projects Public-private partnerships to share costs Awareness raising targeting potential consumers Donor financed projects Policy including quotas for renewable energy technologies
Quality of technology	Labelling Standards Government programs selecting winners Regulation

Illustration 17: Key barriers to PV penetration and consequent barrier removal options, (Wamukonya, 2007)

The overview paper by, Chaurey and Kandpal (2010) on the "Assessment and evaluation of PV based decentralized rural electrification" adds some other challenges found in the PV literature. First, it is demanding to find the balance between market-pull and donor-push strategies for rural SHS dissemination. Market-pull strategies are based on desired products and system designs, assessment of willingness to pay, availability of financing, after sales service network. Donor-push strategies are driven by R&D support, simplified procedures and fiscal and financial incentives.

Second, the users' role in adoption of decentralized PV systems continues to be underestimated even though there are many studies showing the positive impacts of well-designed and delivered user awareness and training programs. Additionally to maximize the socio-economic benefits of PV systems, active participation in decision making process is required. (Chaurey and Kandpal, 2010) According to a study in Mexico referred to by Chambouleyron (1996), the user's attitude determines if the electrification program ends as a success or as a flop. The user must understand the characteristics of PV and must play a role in operating and maintaining the system. Yordi et al. (1996) further highlighted the importance of user training and stakeholder participation on the basis of experience in Africa.

2.10. Photovoltaic

This chapter will first highlight the technical potential for PV in Africa, then discuss the current market situation of PV in Sub-Saharan Africa and shortly mention the benefits of small decentralised PV systems. Last, the technical specifics and the costs of the main components for small off-grid PV systems are shown, e.g. the panel, the battery and the charge controller.

2.10.1. Potential for PV

Solar energy has the largest theoretical renewable potential in Africa, with a high solar irradiation available everywhere, except in the area of the equatorial rainforest, see Table 12. (IRENA, 2012a). The International Renewable Energy Agency (IRENA) assessed that the technical potential for photovoltaic (PV) in Africa could not only meet electricity demand, but even surpass it in 2050 (IRENA, 2012a). The most optimistic scenario by European Photovoltaic Industry Association and Greenpeace (2011) estimated that PV energy supply for Africa can reach between 15 GW and 62 GW by 2030 (EPIA and Greenpeace, 2011).

Table 12: Technical potential for power generation from renewables (uncertainty, typically +/-50%)(IRENA, 2012a)

	CSP	PV	Wind			Hydro	Biomass	Geothermal
			Total	CF 30%-40%	CF > 40%			
	(TWh)							
Central Africa	299	616	120	16	6	1,057	1,572	
Eastern Africa	1,758	2,195	1,443	309	166	578	642	88
Northern Africa	935	1,090	1,014	225	69	78	257	
Southern Africa	1,500	1,628	852	100	17	26	96	
Western Africa	227	1,038	394	17	1	105	64	
Total Africa	4,719	6,567	3,823	667	259	1,844	2,631	88

Most areas in Sub-Saharan Africa have average daily solar radiation of between 4000 Wh and 6,500 Wh per square meter and day. The map (Illustration 18) from the PVGIS database, which is based on solar radiation data from Helioclim-1, represents this yearly average of daily total global irradiation on a horizontal and/or optimally inclined surface in Africa. The data represents 20-years daily average irradiation values of the period 1985-2004 [Wh/m^2] with a spatial resolution of 15´ (~30 km at the equator) (Huld et al., 2005).

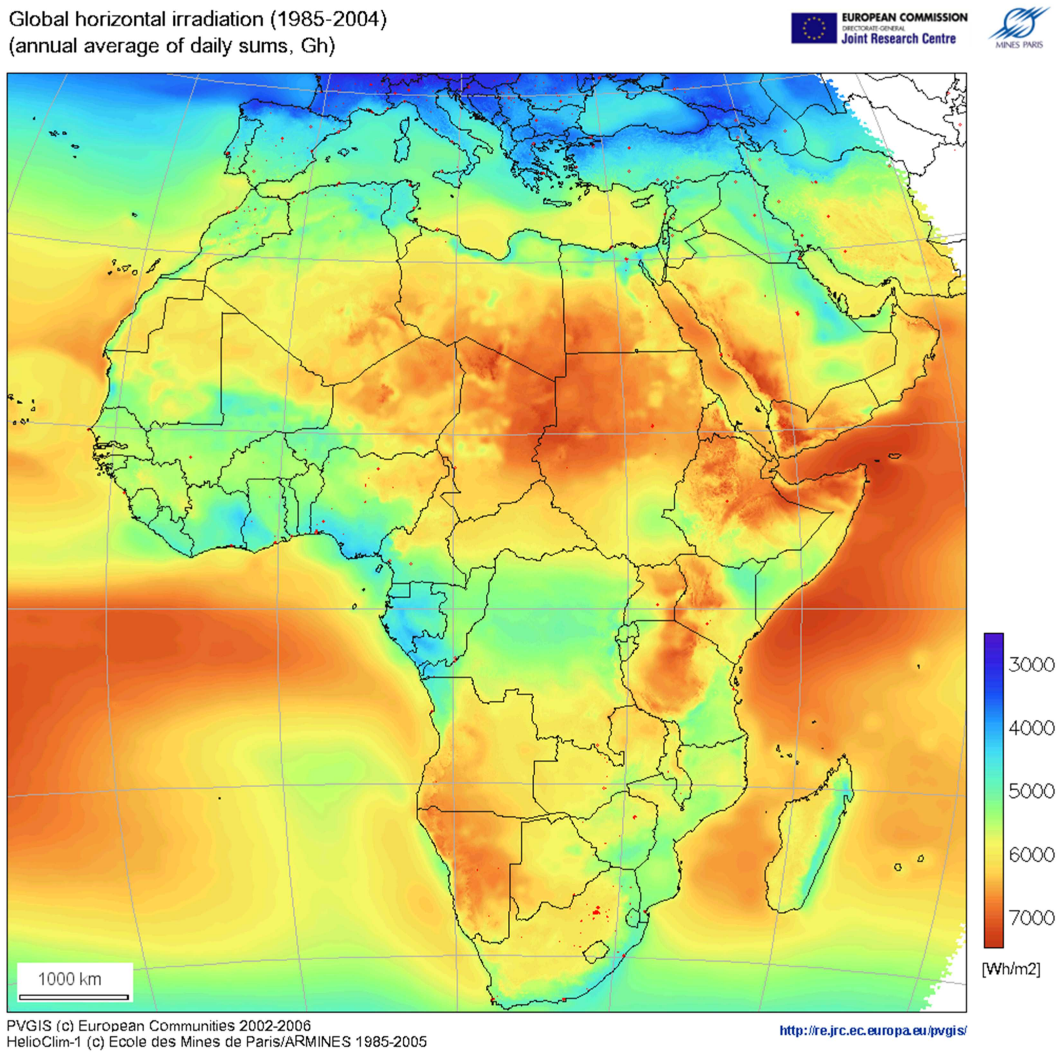


Illustration 18: Yearly average of daily total of global irradiation on a horizontal and/or optimally inclined surface, (Huld et al., 2005)

2.10.2. PV in Sub-Saharan Africa

In Sub-Saharan Africa policy support for PV remains limited. Often this is justified by high investment costs. However, PV can compete on an equal footing for off-grid generation e.g. battery storage or diesel generators. Thus, with the right policies and continued cost reductions, PV could play a very important role in Africa (IRENA, 2012a).

In many developing countries unfortunately statistics on the use of renewable energy are not being gathered systematically (REN21, 2011). EPIA and Greenpeace (2011) estimate that the total installed PV capacity in Africa (including North Africa) is in the order of 160 MW. However, a more comprehensible analysis was done by Werner et al. (2011), who indirectly calculated the cumulative installed

PV capacity for more than 190 countries. They used data from sources like EPIA, the IEA-PVPs and trade statistics from the International Trade Centre for their calculation. In this study they found, that the total cumulative installed PV capacity in Sub-Saharan Africa was around 126 MW at the end of 2010. They found that the growth rate was more 100 percent from 2009 to 2010. An excerpt of data, adapted with data from the World Bank (World Bank, 2013b), is given for Sub-Saharan African countries in

Table **13**. Additionally an overview map can be seen in Illustration 19.

Table 13: Sub-Saharan Africa, cumulative installed PV capacity, adapted after (Werner et al., 2011) and (World Bank, 2013b)

Country	PV cumulative installed capacity (end 2010) [MW]	PV cumulative installed capacity (end 2009) [MWp]	growth rate in 2010 [%]	PV per capita by end of 2010 [Wp/capita]	PV per GDP [W/mUSD]
Angola	2,99	2,20	36%	0,157	0,037
Benin	0,55	0,16	244%	0,064	0,083
Botswana	2,70	0,11	2355%	1,350	0,181
Burkina Faso	1,80	2,00	0%	0,109	0,196
Burundi	0,19	0,15	27%	0,023	0,095
Cameroon	0,98	0,54	81%	0,050	0,044
Cape Verde	7,90	0,17	4547%	15,800	4,647
Central African Republic	0,15	0,14	7%	0,034	0,075
Chad	0,54	0,48	100%	0,048	0,064
Comoros	0,16	0,04	300%	0,229	0,320
Côte d´Ivoire	n/a	n/a	n/a	n/a	n/a
DR of the Congo	0,99	0,69	43%	0,015	n/a
Djibouti	1,40	0,21	100%	1,556	n/a
Equatorial Guinea	0,54	0,29	86%	0,771	0,043
Eritrea	0,41	0,34	21%	0,077	0,195
Ethiopia	6,90	6,70	3%	0,083	0,259
Gabon	0,17	0,15	13%	0,113	0,013
Gambia	0,69	0,67	200%	0,406	0,726
Ghana	0,84	0,55	53%	0,035	0,026
Guinea	1,20	0,74	62%	0,120	0,255
Guinea-Bissau	0,47	0,25	88%	0,313	0,588
Kenya	8,70	7,00	200%	0,215	0,270
Lesotho	0,01	0,01	0%	0,005	0,005
Liberia	0,36	0,10	260%	0,090	0,277
Madagascar	1,50	0,54	178%	0,072	0,170
Malawi	0,37	0,13	185%	0,025	0,069
Mali	3,00	2,30	300%	0,195	0,319
Mauritania	0,91	0,69	32%	0,260	0,246
Mauritius	1,30	0,32	306%	1,000	0,134
Mozambique	1,20	1,20	0%	0,051	0,130
Namibia	2,30	2,10	300%	1,000	0,207
Niger	0,80	0,42	90%	0,052	0,148
Nigeria	11,60	6,70	73%	0,073	0,051
Republic of the Congo	1,70	1,20	42%	0,425	0,142
Rwanda	0,75	0,56	34%	0,071	0,134
Senegal	4,70	4,90	400%	0,379	0,364
Seychelles	0,05	0,04	25%	0,500	0,050
Sierra Leone	0,30	0,15	100%	0,051	0,120
Somalia	0,08	0,08	0%	0,009	0,000
South Africa	39,50	12,00	229%	0,790	0,109
South Sudan Sudan	2,10	1,60	31%	0,048	0,026
Swaziland	0,34	0,07	386%	0,309	0,087
São Tomé and Principe	n/a	n/a	n/a	n/a	n/a
Tanzania	2,90	1,60	81%	0,065	0,127
Togo	0,93	0,19	389%	0,155	0,291
Uganda	4,90	1,10	345%	0,147	0,285
Zambia	1,30	0,85	53%	0,101	0,080
Zimbabwe	3,00	0,22	1264%	0,238	0,405
Total	**126,17**	**62,65**	**101%**	**0,147**	**0,111**

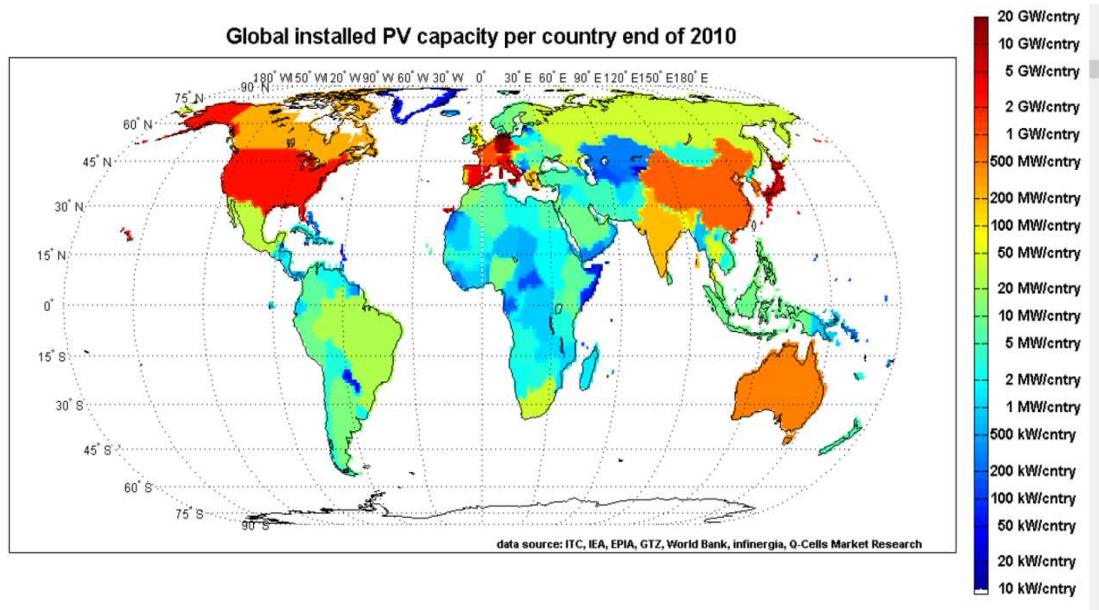


Illustration 19: Total installed PV capacity per country by end of 2010, (Werner et al., 2011)

Several rural electrification programs have been launched in African since the early 2000s. These involved large concessions of SHS, particularly in Western Africa, as for example Mali, Senegal, and Mauritania. (REN21, 2011) According to Nygaard (2009) there were more than 500,000 SHS in Africa, in 2008. These SHS were concentrated in a few countries which have engaged in specific SHS programs. Kenya has about 200,000 units, South Africa 150,000, Zimbabwe 85,000, and Uganda 20,000. Countries without specific support structures for SHS, such as Burkina Faso, have less than 3,000 units installed. (Nygaard, 2009) Africa has so far only one utility-scale PV plant (7.5 MW in Cape Verde). (EPIA and Greenpeace, 2011)

However, even though the installed capacity in Africa is currently low, the potential for growth is high, given that PV panels are a very good solution for the off-grid market. The use of PV for off-grid electrification, as for example SHS, will be where most growth can be expected (IRENA, 2012a). REN21 expects SHS market in Africa to take off either through fee-for-service programs or household-based schemes, e.g. micro-finance or cash (REN21, 2011).

2.10.3. Benefits of PV

The electricity services provided by small decentralized PV systems may be small in quantity, but their impact on socio-economic-cultural development for rural communities should be acknowledged (Chaurey and Kandpal, 2010). The IPCC

(2012) also assessed that "*Solar technologies can improve the economic opportunities and working conditions for poor rural populations*." However, the World Bank assessed that rural electrification does not drive industrial development, but that it can provide electricity for home businesses (IEG and World Bank, 2008).

Most decentralized PV systems experiences report the advantages of using electricity for daily requirements, especially improved illumination (Djamin et al., 2001; Ellegård et al., 2004), as PV lighting enables households to reduce adverse health effects of indoor smoke and heat from kerosene lanterns (Obeng et al., 2008). With the growth of the global communications network, mobile phone charging has also become an increasingly important need in developing countries. This has also contributed to the purchase of numerous solar PV systems, as some integrate mobile charging (REN21, 2011). Additionally, the increased access to televisions, radios and cellular telephones result in improved access to news, information and distance education opportunities (IPCC, 2012).

After all, household lighting and communication technologies require small amounts of power that can be covered by decentralized PV. Traditionally in rural areas, these needs were either covered by costly kerosene lamps, torches and candles or costly, inefficient, and unsustainable automotive batteries which are charged either on village generators or directly on the national grid (REN21, 2011).

2.10.4. PV Components

Photovoltaic systems use semiconductor-based materials, called solar cells, which convert solar energy directly into electricity when they are exposed to sunlight. Solar cells are assembled to solar modules and a group of solar modules connected together form a solar array. A SHS system typically consists of an array of solar cells, a charge controller, a battery and DC appliances. Additionally, support structure and cabling connecting the power system to either the load or the battery is needed (World Bank, 2006).

For off-grid systems, the energy output fundamentally depends on the installed capacity size of the PV system, the storage capacity of the battery and on the consumption patterns (Szabó et al., 2011). Standardized and integrated system design is more effective for the implementation of rural electrification projects. Furthermore, the possibility of selecting the needed components has a positive impact on system performance and user satisfaction. Reliable and easily replaceable components should be chosen and system configurations depending on user requirements can improve the acceptance of decentralized PV programs (Chaurey and Kandpal, 2010). Price information for PV systems in Sub-Saharan Africa is often difficult to compare, some include cost of installation, others only the hardware. Yet, generally the prevailing perception is, that the price of PV is decreasing (Nieuwenhout et al., 2000).

2.10.4.1. PV Module

The solar photovoltaic module is one of the main component of a SHS (World Bank, 2006). PV cell technologies can be classified based on the materials used in their manufacture. The main categories are: First-generation solar cells (crystalline or polycrystalline silicon), which are the most common solar cells in commercial use. The efficiency of these modules ranges from 13% to 19% (see Illustration 20). While it is already a mature technology, cost reductions are continuing through improvements in materials and manufacturing processes and through economies of scale. However, it is not clear whether further cost reductions will occur in a scale necessary to achieve full economic competitiveness in the wholesale power generation market, especially for areas with modest solar resources (IRENA, 2012b).

Photovoltaic modules of the second generation are thin-film solar cells, using amorphous silicon cells or compound semiconductors. Thin film PV can be utilized in flexible and lightweight structures and are therefore applicable for the integration into building components. These technologies can potentially provide lower cost electricity than first generation PV. However, this is not definite, as lower capital costs are offset to a certain extent by lower efficiencies. Additionally, the presently low c-Si module costs make the economics for thin-film solar cells even more challenging (IRENA, 2012b). Third-generation technologies are not yet commercialized at any scale (IRENA, 2012b) and are consequently not discussed here.

		1st Generation PV		2nd Generation PV		
Technology	Units	Single crystalline silicon (sc-Si)	Polycrystalline silicon (pc-Si)	Amorphous silicon (a-Si)	Copper Indium Gallium Diselenide (CIS/ CIGS)	Cadmium Telluride solar cells (CdTe)
Best research solar cell efficiency at AM1.5*	%	24.7		10.4 Single junction 13.2 Tandem	20.3	16.5
Confirmed solar cell efficiency at AM1.5	%	20-24	14-18	6-8	10-12	8-10
Commercial PV Module efficiency at AM1.5	%	15-19	13-15	5-8	7-11	8-11
Confirmed maximum PV Module efficiency	%	23	16	7.1/ 10.0	12.1	11.2
Current PV module cost	USD/W	< 1.4	< 1.4	~ 0.8	~ 0.9	~ 0.9
Market share in 2009	%	83	3	1	13	
Market share in 2010	%	87	2	2	9	
Maximum PV module output power	W		320	300	120	120
PV module size	m^2	2.0	1.4-2.5	1.4	0.6-1.0	0.72
Area needed per kW	m^2	7	8	15	10	11
State of commercialisation		Mature with large-scale production	Mature with large-scale production	Early deployment phase, medium-scale production	Early deployment phase, medium-scale production	Early deployment phase, small-scale production

Note: Standard Testing Conditions, temperature 25°C, light intensity 1000W/m², air mass 1.5.

Illustration 20: Overview and comparison of major PV technologies, (IRENA, 2012b)

According to the Universal Technical Standard for Solar Home Systems (1998), PV modules used for SHS should be first generation modules certified after the international standard IEC-61215 (Thermie, 1998).

No energy technology has changed more dramatically than photovoltaic, in terms of price and growth rates of installed capacity in the last years (Nemet, 2006). In the last five years, the PV industry has seen extraordinary decreases in global module prices (Bazilian et al., 2013). The most essential metric for the costs of PV is the module price in price-per-watt. The price per-watt metric has the advantage that it is simple and data is available, but has the disadvantages that the module costs cannot be automatically translated into full installed system costs. Furthermore, costs can be quoted as factory gate prices (manufacturers' underlying costs) versus wholesale costs or retail price (Bazilian et al., 2013).

PV module factory-gate prices have in the past decreased at a rate of 15 to 24% with a doubling of production capacity, this learning rate or experience curve can also be seen in Illustration **21**. Assuming a 3.00 USD/W average price in 2003, this experience curves would imply that prices should have fallen to 1.01 USD/W by early 2012. Yet, module prices momentarily increased to 3.88 USD/W in 2008 primarily due to silicon shortages, before falling, in some cases, below 2.00 USD/W by December 2009. Prices then decreased a further 14% in 2010. In April 2012, the factory gate price (without VAT) of PV modules from 'bankable' or "tier 1" manufacturers amounted to 0.85 USD/W for Chinese poly-crystalline silicon modules, or 1.01 USD/W for non-Chinese mono-crystalline silicon modules. Prices for thin film modules and module prices from less well-known suppliers were even cheaper (Bazilian et al., 2013).

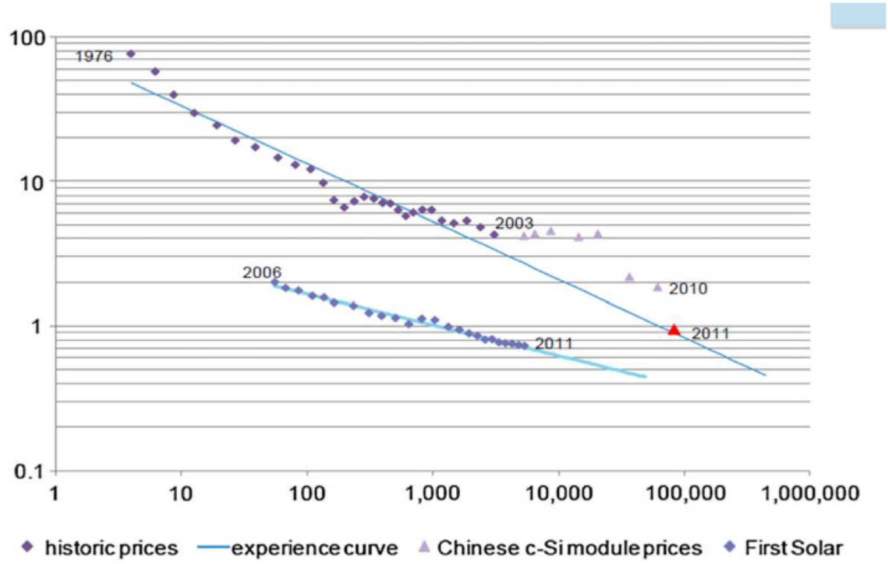


Illustration 21: PV module experience curve 1976-2011, (Bazilian et al., 2013)

The retail price in different countries depends on the PV-market in the respective country. Often distributors of these modules take a considerable margin, selling at the highest price the market can support (Bazilian et al., 2013). In 2012, the lowest retail price worldwide was 1,06 USD/Wp (for a multi-crystalline silicon module) from a German retailer (Solarbuzz, 2012c). Average retail module prices in Europe and the US from 2002 to March of 2012 are shown Illustration 22.

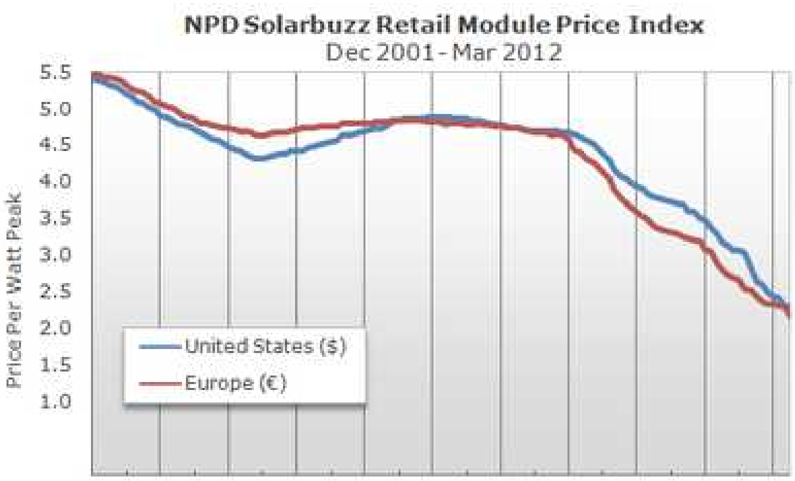


Illustration 22: Average retail module price index, (Solarbuzz, 2012c)

2.10.4.2. Battery

Experts commonly agree that one of the key weak link of the long-term operation of PV based energy systems is the system batteries. Batteries are not only important for system operation and performance, but also greatly affect the life cycle cost of a PV system, as the battery storage components constitute a significant part of both investment and operation and maintenance costs (Svoboda et al., 2007). Nieuwenhout et al. (2000) even said, that batteries are usually the most expensive part of a solar home system over the lifetime of the system. The lifetime of batteries varies significantly from project to project, from less than one year to more than eight years. Furthermore, batteries have a shorter life if they are operated for long periods without coming to a full charge condition. Another relevant parameter for the lifetime is the sizing of the battery, which in turn depends on the sizing of the PV module and battery maintenance (Nieuwenhout et al., 2000). Predicting the expected battery lifetime under operating conditions is essential for making credible estimates of the life cycle cost for the PV system (Svoboda et al., 2007).

Irena (2012a) recommends standard lead-acid batteries for small-scale systems. Lead-acid batteries are the oldest type of rechargeable battery, the most proven and most widely applied electricity storage technology. For SHS systems sometimes car or truckbatteries are used because they are a cheaper cost option, yet they are not designed for power generation technologies usage and have therefore a very short lifespan, as low as 50 (typical are 300 to 400 cycles) cycles. Deep-cycle leadacid batteries are an established alternative, with much longer lifespans if the discharge rate is kept low. For example, limiting the discharge to 20% of the capacity can allow the deep-cycle leadacid battery to last for 10 years. The trade-off is a higher initial cost, as 2.5 kWh of battery storage is required for every 500 Wh of electricity used from storage (IRENA, 2012a). Another alternative for SHS are modified SLIs sometimes named solar batteries. They increase the short lifetimes of automotive batteries by usually two modifications, thicker electrode plates and larger quantity of acid solution above the plates and allow up to 1,500 cycles (Thermie, 1998).

Whichever battery is chosen, according to the Universal Technical Standard for Solar Home Systems, following operating conditions must be avoided in order to maximize the lifetime of lead batteries:

- *"High voltages during charging (to prevent against corrosion and loss of water)*
- *Low voltages during discharge (corrosion)*
- *Deep discharge (sulphation, growth of dentrites)*
- *Extended periods without a fully charging (sulphation)*
- *High battery temperatures (all ageing processes are accelerated)*
- *Stratification of the electrolyte (sulphation)*
- *Very low charge currents (sulphation)"* (Thermie, 1998)

Moreover, battery design should always take the local conditions into account. Relevant are for example solar irradiation, PV module prices, battery prices, duties and taxes, components of local manufacturing and recycling infrastructure (Thermie, 1998).

Most battery failures in the past can be explained by poor charging conditions which can be solved by increased panel capacity. Batteries used for small home systems are usually oversized and panels are usually undersized (Nieuwenhout et al., 2000). Huacuz et al. found on that the battery capacity should be at least seven-and-a half times the daily load in Ah after accessing a sample of 555 batteries in Mexico [Huacuz et al, 1995].

Unlike solar modules, batteries are a mature technology used in high volume outside the PV industry. Thus, the prospect of major cost reductions over the medium term is limited. At the same time, a high weight-to-price ratio results in regional battery markets, because companies try to reduce transportation of batteries where possible (Solarbuzz, 2012a). Transport of batteries to rural areas is problematic (Huacuz et al., 1995).

Solarbuzz calculates the US/EU average global retail price index. In March 2012 this index for batteries most commonly used, ranged from 0.239 USD/Wh to 0.260 USD/Wh (Solarbuzz, 2012a).

2.10.4.3. Charge controller

The charge controller serves mainly to protect the battery against deep discharging and overcharging. It is further used to protect the load during extreme operating conditions, and to provide the user with operational information (Thermie, 1998).

Most of the SHS use charge controller which are based on voltage control, because they are the cheapest solution. Usually, charge controllers account only for about 5% of the initial investment cost of a SHS. However, the battery lifetime is directly linked to the quality of the charge controller, so the impact of the charge controller on the total long term cost of a SHS is quite high. Thus, good quality charge controllers should be used with a design lifetime of more than 10 years (Thermie, 1998).

Charge controller prices tend to change significantly less than solar module prices. The US price for a charge controller was about 5.92 USD/A in March 2012. The charge controller cost accounts for approximately 10% of the total installed cost of an off-grid solar system. Thus, charge controller prices are not as important as the solar module, battery, or installation costs for a SHS. Often charge controller manufactures serve only local markets unlike the PV manufactures (Solarbuzz, 2012b).

2.11. Economics of photovoltaic systems

Generally, costs for African energy projects tend to be higher than in other regions, due to the facts that most of the equipment must be imported, the payment of import fees and the higher internal transportation costs. Additionally, there are also often insufficient infrastructure and engineering and institutional capabilities. Yet, often costs can be reduced significantly when certain components can be constructed locally. For example, this is the case for batteries of SHS (IRENA, 2012a).

Renewables cost projections are complicated, the main issues are available data and the way of analysis. PV module costs depend heavily on improvements in technology and manufacturing, the prices decrease continuously by around 20% with a doubling of manufacturing capacity (learning rate). It is therefore vital that economic cost assumptions are based on the latest cost data available. For instance, solar photovoltaic module costs were almost twice as expensive as today's market price 12 months ago (IRENA, 2012a).

PV costs and prices are generally analysed using three related metrics, namely: the price-per-watt capital cost of PV modules (usually expressed in USD/Wp) sometimes also used for whole PV systems, the levelized cost of electricity generation (LCOE) (usually expressed as USD/kWh) and the notion of 'grid parity' (Bazilian et al., 2013). According to Bazilian et al. (2013): *"Each of these metrics can be calculated in a number of ways and depend on a wide range of assumptions that* *span technical, economic, commercial and policy considerations. Transparency is often lacking in published data and methodologies. Importantly, the usefulness of these three metrics varies dramatically according to audience and purpose."*

The next subchapters will give an overview of the costs or prices of Solar Home Systems in Sub-Saharan Africa. First, the price per watt peak, in the literature available, will be shown, second discussing the availabe levelized cost of electricity generation of Solar Home Systems in SSA. The concept of grid parity has no informative value for stand alone system, so it is neglected in the further discussion.

2.11.1. System Price USD/Wp

The price per watt metric is easily understandable and the data is often available, yet module costs in price per watt cannot be translated automatically into full installed systemcosts, even if often found in the literature. Different technologies have different causal relationships of average and peak daily yields. Furthermore, it is often unclear whether costs quoted are manufacturers´ costs or wholesale costs or retail price (Bazilian et al., 2013). Additionally, it is not clear if system prices include necessary reinvestments for batteries, charge controller and lighting. Moreover, this metric does not include O&M and Management costs, which depending on the distribution system can account for more than 50% of the system price, according to Carrasco (2013).

Price information for SHS in Sub-Saharan Africa is often difficult to compare, some include cost of installation others only hardware. Yet, the generally prevailing perception is that the price of SHS is decreasing (Nieuwenhout et al., 2000). From 1989 to 1999, reported retail prices for complete solar homes systems were in between of USD 10 to 22 per Wp. The table below show the system retail prices of SHS for Sub-Saharan Africa found in the literature. It must be mentioned that prices where it was possible to access the source literature are mostly more than 10 years old ((Nieuwenhout et al., 2001); (Karekezi and Kithyoma, 2002); (Moner-girona et al., 2006), additional SHS price estimates can be found at (Rosnes and Vennemo, 2009)**).** The few exceptions are SHS prices for Kenya in 2009 (Sabah, 2009), for Rwanda in 2012 (Disch and Bronckaers, 2012) and for Tanzania in 2011 (Ondraczek, 2011).

Table 14: Indicative System retail price, with sources, most SHS systems listed include PV panel, battery, lights, charge controller, installaion material and installation

Country	Year	system retail price [US$/Wp]	Source
Botswana	1997-1999	16	Nieuwenhout, 2001
Eritrea	???	13	Moner-Gironer, 2006
	<2001	12	Karekezi, 2002
Ethiopia	???	13-15	Moner-Gironer, 2006
Ghana	1998	14	Nieuwenhout, 2001
	2002	17	Nässen, 2002
Kenya	???	9,5-11	Moner-Gironer, 2006
	<2001	13	Karekezi, 2002
	2009	**13**	Sabah, 2009
Lesotho	<2001	20	Karekezi, 2002
Namibia	1997-1999	22	Nieuwenhout, 2001
Rwanda	**2012**	**9**	Disch & Bronckaers, 2012
Somalia	???	>16	Moner-Gironer, 2006
South Africa	1995-1996	10	Nieuwenhout, 2001
Sudan	???	12-13	Moner-Gironer, 2006
Swaziland	1997-1999	17	Nieuwenhout, 2001
Tanzania	???	14-17	Moner-Gironer, 2006
	2011	**10-16**	Ondraczek, 2011
Uganda	???	11-14	Moner-Gironer, 2006
	<2001	20	Karekezi, 2002
Zambia	<2001	24	Karekezi, 2002
Zimbabwe	<2001	17-18	Nieuwenhout, 2001
	<2001	18	Karekezi, 2002

The graph below shows SHS System retail prices, taking the most recent price and averaging price ranges. As it can be easily seen, the prices vary between 9 USD/Wp and 24 USD/Wp. These prices can only be used to get an overview over the price range currently seen in the literature. Unfortunately most of these prices are too old to be representative of SHS costs in the respective countries. PV module for example have decreased dramatically the last 10 years. Furthermore, the prices were calculted with different system components and different assumptions. A comparison of these prices was not performed for the paper at hand.

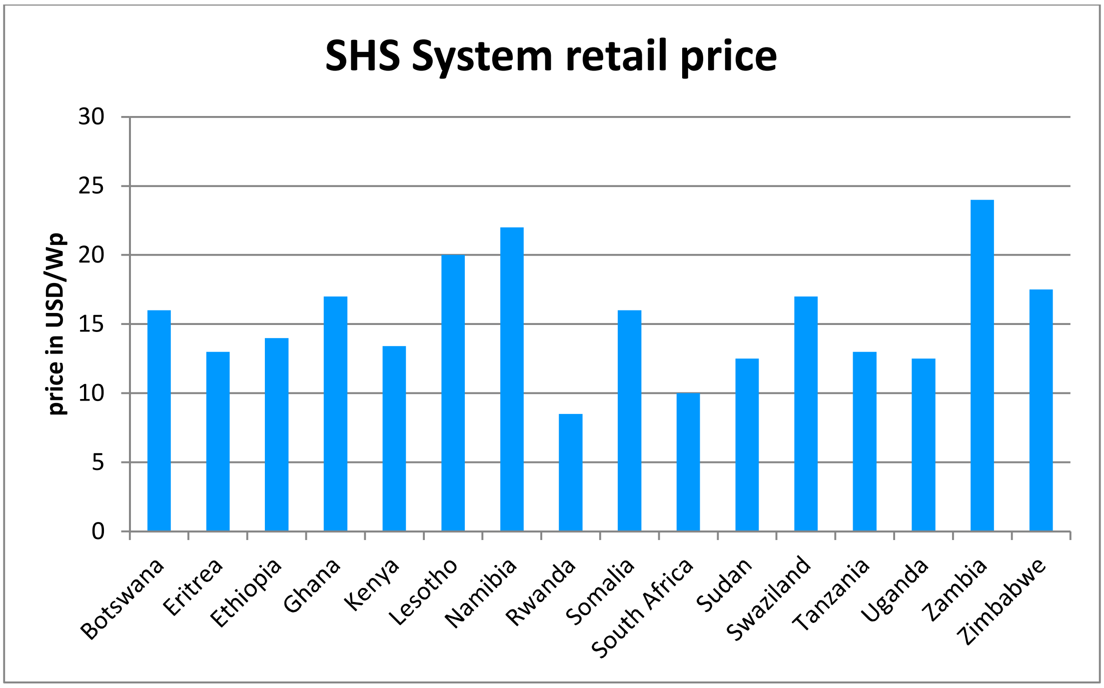


Illustration 23: Solar Home System retail prices in Sub-Saharan African countries, various sources for different years (Nieuwenhout et al., 2001); (Karekezi and Kithyoma, 2002); (Moner-girona et al., 2006)(Sabah, 2009), (Disch and Bronckaers, 2012)(Ondraczek, 2011)

2.11.2. LCOE

LCOE, or the levelized cost of electricity, is the most commonly and transparent used metric for the comparison of electricity costs from different generation technologies in modeling and policy discussions. After all, it is a useful tool for calculating the unit costs (USD/kWh) of different technologies over their whole project lifetime (IEA and OECD, 2010). Yet, there are also other indicators for economic feasibility like the ROI or IRR (Bazilian et al., 2013). Furthermore, more sophisticated methods exist for the comparison of electricity generation technologies but the LCOE metric remains as the most widely-used metric (Bazilian et al., 2013).

In 2007, the World Bank calculated the LCOEs for different electricity generation technologies in developing countries (see chapter 2.8.2.6). They estimated that a 50 watt SHS has a levelized cost of 0.62 USD/kWh in 2005, though they further projected that this LCOE will fall to around 0.51 USD/kWh by 2015 (ESMAP, 2007). The latest overview of PV LCOE estimation for Africa was done by IRENA (2012a), they estimateda LCOE range from 0.20 USD/kWh to 0.51 USD/kWh (more in chapter 2.8.2.6). A good overview of other studies dealing with the comparison of PV LCOE with other systems can be found in the paper by Chaurey and Kandpal (2010).

2.11.2.1. Calculation

The calculation of LCOE is based on the present value of the sum of discounted revenues and discounted costs divided by the electricity produced by the system in its lifetime. (IEA and OECD, 2010). LCOE calculation standards have been proposed for example by IEA (IEA and OECD, 2010). A closer discription of the calculation can be found in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, discussing the methodology of LCOE.

The method is deceptively simple, however LCOE calculations often lack a clear reporting of input parameters, assumptions and limits. This leads to irreproducible widely varying results (Bazilian et al., 2013). BNEF in 2011 identified the most influential factors for the levelized cost of PV as being *“capital costs, capacity factor, cost of equity, and cost of debt”* (Bazilian et al., 2013).

2.11.2.2. Variables and Assumptions

The literature states many variations of the underlying LCOE assumptions. Moreover, LCOE varies widely based on geography, regional costs and on the financial return requirements of investors. This prohibits robust single-point estimates (Bazilian et al., 2013). Thus sensitivities and explicit descriptions of input data and system boundaries are required (Bazilian et al., 2013). Important parameters include the capital cost for the PV system, the lifetime of its components, the long-term PV system performance, the discount rate, Operation and Maintenance, Management and Decommissioning. The PV systems capital cost in the more current literature ranges from 5.00 USD/W to 2.00 USD/W (Bazilian et al., 2013).

PV modules have often overlooked value. They can have a long lifetime at almost no operating costs and PV modules only have limited effiency losses are warranted between 20 and 25 years by manufacturers. The actual lifetime might be closer to 40 years for today’s crystalline technology (Zweibel, 2010). As already discussed in the chapter 2.10.4.2, battery lifetime depends on many factors and can range from around 3 years for SLI to approximatlly 10 years for optimally designed modified SLIs.

PV system performance is driven by factors including site specific solar insulation, system component technologies and specifications, the overall system design and installation and the maintenance (Bazilian et al., 2013). The module warranties often include an annual degradation rate of 1%, however actual PV modules appear to be degrading at 0.2–0.5% per year (Zweibel, 2010).

The discount rate applied in LCOE calculations reflects the return of investmentexcluding specific market or technology risks. Yet, excluding these risks creates a gap between the LCOE and real financial costs of an investor (IEA and OECD, 2010). There is still an unresolved debate about the interest rate that should be used for LCOE calculation for PV (Zweibel, 2010). The IEA usually uses two discount rates 5% and 10%, however these are mostly used for OECD countries. This discount rate depends on two important assumptions, first that it is stable and does not vary in the project lifetime and second that the electricity price is stable (IEA and OECD, 2010).

Operation and maintenance costs for off-grid solutions are quite high and often not sufficiently provided for in the long term (IRENA, 2012a). Notton et al. (1998) found that O&M cost in the literature vary between 1%, up to 10% of the hardware cost, but suggested 2% as a pragmatic assumption for LCOE analyses (Notton et al., 1998). However, Carrasco (2013) in evaluating the operational costs of 13,000 SHS in Morroco, calculated O&M cost of 9% annual of the equipment investment (for a 10 year project period) for the evaluated fee-for service operation. He further highlights that the initially wrongly assumed O&M costs lead to low established user fees which in turn contributed to a real total defict of the ESCO of around 3.4 million EURO over the whole project duration. In the same study Carrasco pointed out that the general management accounted for 18.5% of the total cost, also due to the fact that the ESCO structure was designed for 34,000 SHS system.

Solar panels in practice at the end of their operating lifetime are replaced, rather than decommissioned. The scrap value of the installation is estimated to account to 20% of the original capital investment (IEA and OECD, 2010). However, this paper neglects the decommissioning or scrap value in its LCOE analysis.

2.11.2.3. Capital Cost and Finance cost

Considerable overall cost reductions are foreseen which will make photovoltaics more competitive in the future. Table 15 provides an overview of the PV capital cost projections for the period 2010-2050 in Africa. The lower end of the price range assumes supportive policies in Africa and worldwide, whereas the upper end accounts for benefits from learning effects outside of Africa only. Costs may be higher than shown in Table 4 where high transportation costs for equipment occure, such as in landlocked countries (IRENA, 2012a).

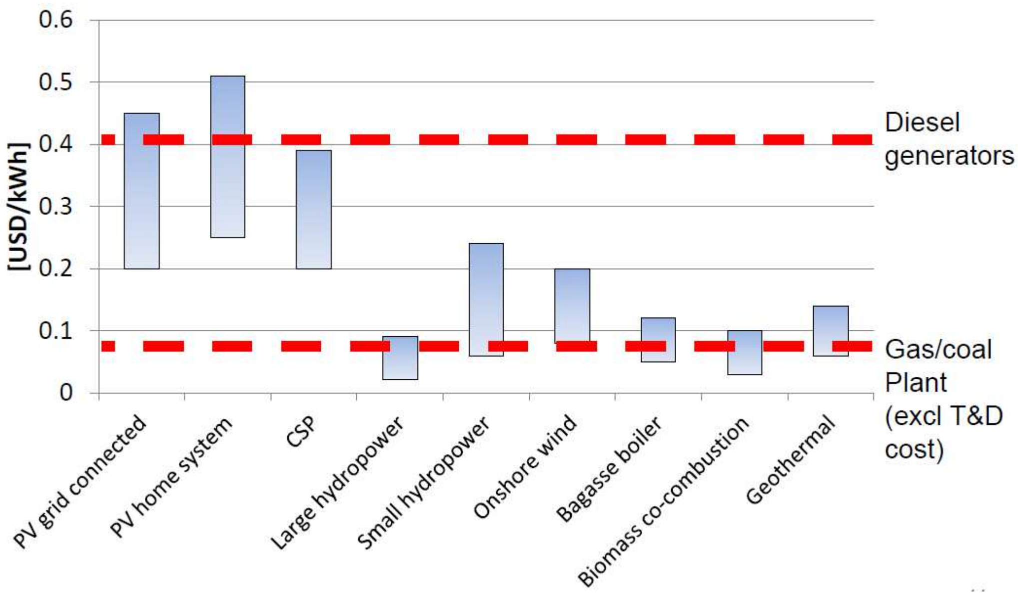
Table 15: Renewable capital cost-projections for Solar PV, adapted (IRENA, 2012a)

(USD/kWh)	2010	2015	2030	2050
Solar PV (utility-scale)	3,000-4,000	2,850-3,000	2,200-2,450	1,800-2,100
Solar PV (home system)	5,000-6,000	4,500-5,700	3,600-4,100	2,200-3,500

Note: Figures do not account for equipment transportation costs to remote locations in landlocked countries or for import tariffs.

Finance cost is a key factor, given that renewables are very capital intensive (IRENA, 2012a). Even if renewables are at a comparable LCOE levels with commercially proven technologies, differing risk profiles have a large impact on the feasibility of the project. The risk perception of a technology is directly related to the costs of capital and how and which projects are financed (Bazilian et al., 2013).

Fehler! Verweisquelle konnte nicht gefunden werden. shows LCOE costs for renewables including 10-20% cost of finance, however, LCOE may be significantly higher. Unconcessional loans and risk guarantees can reduce the cost of capital. Reducing the cost of capital is often critical for renewable energy projects in Africa to be the economically viable (IRENA, 2012a).



Graph 1: LCOE in Africa with a 10 – 20% cost of finance (IRENA, 2011a)

2.11.2.4. Limits of LCOE

Bazilian et al. (2013) concluded that *"LCOE metrics in the PV industry can be misleading and should therefore be applied with caution as they require careful interpretation and transparency".* Additionally, they wrote that the complexities of providing clear PV LCOE figures make it difficult to directly compare projects on a levelized cost basis. This is mainly due to significant discrepancies between the underlying characteristics and assumptions for the different power generating technologies and of markets they serve (Bazilian et al., 2013).

IRENA in (2011a) also stated, that a project comparison on LCOE basis is not always the right measure for economic evaluation and they further recommend that other economic valuation methods be explored (IRENA, 2011b).

2.11.3. Sensitivity Analysis LCOE

LCOE requires a wide set of assumptions and they further vary depending on geography and on the cost of capital and on the required financial return of investment. Thus, sensitivity analysis are normally required, yet rarely published (Bazilian et al., 2013). A sensitivity analysis for LCOE can show how changes of the uncertain input parameters would influence the total LCOE.

The International Energy Agency (2010) made a sensitivity analysis for the LCOE of PV in OECD countries and in the range of 2kW to 20MW. They showed that the LCOE of PV technology display a high sensitivity to variations in the load factor, followed by variations in construction costs, the lifetime and the discount rate. The methodology will be explained in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**.

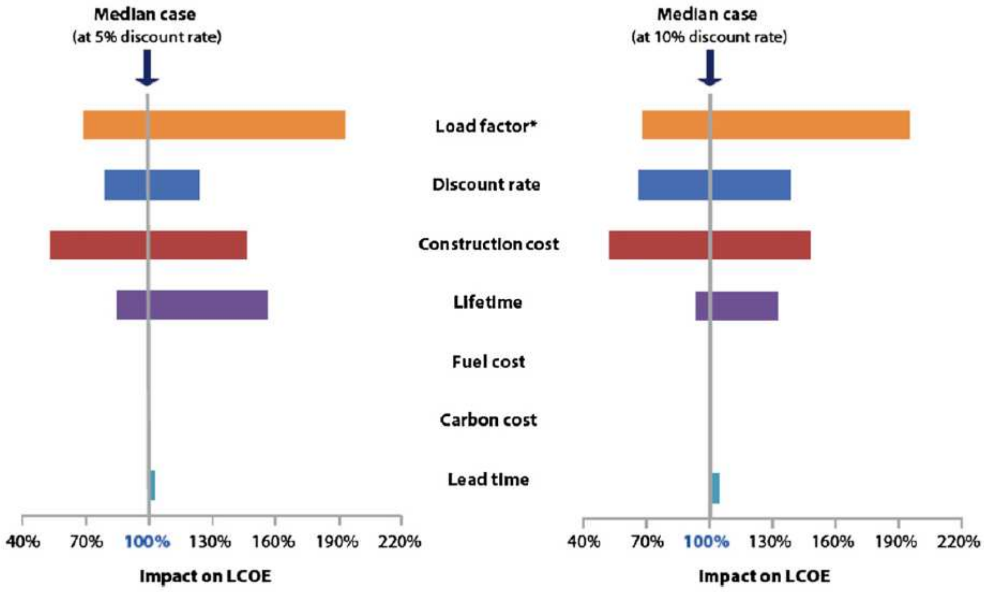


Fig. 5. Tornado graph PV LCOE ([41]).

Illustration 24 Tornado graph of PV LCOE, Load factor and LCOE are inversely related. A higher load factor results in a reduction of LCOE and a lower load factor results in an increase of LCOE (IEA and OECD, 2010).

3. Methodology

3.1. System design

Three different PV systems were designed, a 5W picoPV system, a 50W SHS system and a 100W SHS system. This chapter first describes the picoPV and SHS systems and its components, e.g. the PV panel size and efficiency, the battery capacity and efficiency, the charge controller and its setting. It also gives a conservative estimation (with an irradiation of 4000 Wh/m²d) on how much electricity each of these systems can provide per day before the possible appliances for each system and its running time per day are discussed.

The first system planned, after Lysen (2013), is a 5W picoPV system with a 50Wh lead acid battery and an assumed lifetime of 3 years. The PV panel is specified to be multi-crystalline silicium with a module efficiency of 10% and a size of 0,05m². The battery effiency is conservatively assumed to be 70%. The battery efficiency and the PV module efficiency add up to a system effiency of 7%. At a 4000Wh/m²d irradiation, this system has an electricity output of 14Wh/d or 5,11kWh/a. This is enough electricity to run LED lamps with a lumen output of 260 lm (e.g. a study lamp, a main lamp and a night lamp) for 5 hours, plus mobile phone charging every second day (4Wh for full-charge) and a small 0.5W radio for 2 hours.

The second system designed, after Carrasco (2013), is a 50W SHS system, with a 50W mono-crystalline silicon pv module with a size of 0,33m², a 15% module efficiency and a 25 year lifetime. The battery for this system is a 100 Ah (1200 Wh) modified SLI, C20 lead-acid battery with a lifetime of 5 years. The charge controller is a 10A series charge controller with PWM regulation but without MPPT function. The system effiency without the PV panel is 70% which total a system efficiency of 11%. At an irradiation of 4kWh/m²d, the energy output is 140Wh/d (or 51,1 kWh/a). With this energy output one can run 3 compact fluor-escent lamps (CFL) (2x7W and 1x11 W) for 4 hours, charge one mobile phone per day, listen to a 0.5W radio for 4h per day, watch television for 3h (with a small 10W TV) per day.

The third system also designed, after Carrasco (2013), is a 100W SHS system, with a 100W mono-crystalline silicon PV module with a size of 0,66m², a 15% module efficiency and a 25 year lifetime. The battery for this system is a 200 Ah (2400 Wh) modified SLI, C20 lead-acid battery with a lifetime of 5 years. The charge controller is a 20A series charge controlle with PWM regulation but without MPPT function. The system effiency is the same as for the 50SHS system, 11%. At an irradiation of 4kWh/m²d, the energy output is 280Wh/d (or 102.2 kWh/a). With this energy output it is possible to run 4 compact fluor-escent lamps (CFL) (3x7W and 1x11 W) for 4,5 hours, charge two mobile phone per day, listen to a 0.5W radio for 4h per day, watch telelvision for 4 hours (with a medium size 25W TV) per day and has some electricity (20Wh/d) left for other small ICT appliances like (a tablet, e.g. an iPad for a little less than 5hours).

3.2. Electricity generation

The electricity generation depends on the insolation, the PV panel size, PV module efficiency and the system efficiency. Usually, it is necessary to consider the local temperature, because with higher temperature the efficiency of the PV module is reduced. In this paper the temperature efficiency losses are assumed to be included in the system effiency. This is the reason why not 80% system effiency is assumed but only 70%.

$$P = I * \eta sys * A$$

P.........energy output $\left[\frac{kWh}{d}\right]$

I.......... insolation $\left[\frac{kWh}{m^2d}\right]$

ηsys.... system efficiency [%]

A ..... panel area $[m^2]$

To gain the necessary panel area for the calculation, a side calculation was performed. The area of the panel depends on the nominal peak power, which is the power rating given by manufacturers of the moduls, measured at Standard Test Conditions (STC)[11] and the module efficiency also measured at STC.

$$A = P_{pk}/\eta_{pv}$$

[11] Standard Test Conditions (STC) are 1000 W/m² solar irradiation, a modul temperature of 25°C and a solar spectrum corresponding to an air mass of 1.5 (JRC-PVGIS, 2013).

Ppk... peak power [$W_{el}/(W_{sol}/m^2)$]
ηpv.... effiency of pv module [%] = [W_{el} /W_{sol}]

For a calculating on electricity generation of PV over longer time periods, it is necessary to consider the degradation of PV panels. The calculations in this paper consider a 0.5% degradation (d) of the PV panel per year, which reduces the electricity output in year 25 by 11.3%. The electricity output figures in the chapter above are only applicable for the first year. Thus, the reduced electricity output means that the appliances can be used 10% less in the last system service year.

$$P_d = P_1(1-d)^1 + P_2(1-d)^2 + P_3(1-d)^3 + \cdots + P_n(1-d)^n$$

The electricity generation over the system lifetime is important for the LCOE calculation.

3.3. Economic feasibility calculation

This chapter will describe the calculation assumptions and the methodology for the economic and financial feasibilty of the designed systems. First, the simple investment and re-investment costs are discussed. Then, the assumption and calculation of O&M and Management costs are shown. Afterwards, the methodoloy for calculating the present value, with the assumed discount rate, is given. Later, the terms of the financing cost as well as the methodology to calculate monthly payments based on the financing cost is introduced. Last, the calculation methodology of the LCOE is given, before the methodology for the sensitivity analysis for the LCOE is shown.

3.3.1. Investment, Re-investment cost, O&M and Management cost

As with the system design the investment cost calculation is based on the reports of Lysen (2013) for the picoPV system and Carrasco (2013) for the two SHS systems.

The IEA report, on pico solar PV systems for remote homes by Lysen (2013), assessed different picoPV systems and their cost, they estimated that the average consumer costs for picoPV systems are around 23 USD per Wp for a 5Wp system, or 18,6 EURO[12] per Wp. This system cost already include high quality appliances and LEDs. The lifetime of these systems highly depends on the lifetime of the battery. With a Lead-acid battery with a depth of discharge of only 25% the lifetime is around 1200 cycles or 3 years. So, a reinvestment of the system would be necessary every 3 years.

Carrasco et. al (2013), in their report on the assessment of operational costs of a 13,000 SHS rural electrification program in Morocco, delivered concrete data on costs of SHS systems in Africa. However, this program bought their panels in the period of 2006 to 2008 with cost of 3.5 €/Wp (or 4.33 USD/Wp). As discussed, in chapter 2.10.4.1, in April 2012 factory gate prices of 0.8 USD/Wp were reached. As this does not include transport cost, profit margins and other costs, this paper asssumes a module price of 1.8 €/Wp (or 2.23 USD/Wp). The cost for batteries is assumed to be 1,51 €/Wp (or 1.87 USD/Wp) is directly taken from the Carrasco et. al paper. In the past, battery prices only decrease slowly and it is assumed that prices in SSA tend to be higher then in Marocco. It is further assumed that batteries have to be exchanged every 5 years, as the lifetime is usually only 5 years.

The charge controller and the lighting costs are also taken from Carrasco et. al (2013), however it is assumed that they cost more in SSA than in Morocco. Thus, the charge controller cost for the 50W SHS system are assumed to be 28€ (34,6 USD), (therefore they equal the cost for the 75W system of the Moroccean program) and the 100W SHS controller cost are higher by the factor 1,5 (42€, 52USD). The cost of the CFL are estimated with the same methodology at 43€ (or 53 USD) and 64,5 € (or 79,7 USD) respectively. Both charge controller and lighting have to be changed at least once during the system lifetime, as they only have a livetime of 15 years.

The installation costs for the SHS systems are assumed to be a little higher for the 50W SHS system (100€) then the costs described in Carrasco (~85€) and 1.5 times higher for the 100W system (150€) then for the 50W system.

The investment costs for the SHS are calculated by summing up the panel cost (cost per Wp times the Wp of the system), with the battery cost (cost per Wp times the Wp of the system), the charge controller cost, the lamps and the installation

[12] All calculations from Euro to Dollar or back use the average exchange rate from 2012, of 1,236 (IRS, 2013).

cost. Reinvestment cost for SHS are the cost of battery every 5 years and the cost of the charge controller and the lamps once after 15 years. In other words, the investment cost are the sum of the cost of the pv panel ($P_{pv} * cpv_{wp}$) plus the cost of the battery ($P_{pv} * \ cbat_{wp} = cbat$) plus the cost of the charge controller (c_{cc}) plus, the lamps (c_l) and the installation (c_{inst}).

$$I = P_{pv} * \left(cpv_{wp} + cbat_{wp}\right) + c_{cc} + c_l + c_{inst}$$

The before mentioned investment cost are the basis for the calculation of the O&M and the Management cost in the case of the SHS systems, not the picoPV. It is assumed that the picoPV system has no extra O&M and Management cost but that it is an over the counter sale without any support service during its livetime included. O&M costs for the two SHS is assumed to be 5% ($c_{o\&m}$) of investment cost per year and the Management cost is assumed to be 5% (c_{man}) of investment cost per year.

$$Z = I * (c_{o\&m} + c_{man})$$

3.3.2. Present value

The present value of the systems is calculated by discounting future costs to the present as for example the reinvesment cost or the operation cost. The assumed discount rate is 10% p.a. for all systems. The present value are the discounted yearly O&M and Management cost (Co), re-investment cost (RI) of the batteries every 5 years and reinvestment cost of the charge controller and the lamps after 15 years.

$$A_0 = I + RI + Co$$

$$RI = (cbat_5 q^{-5} + cbat_{10} q^{-10} + cbat_{15} q^{-15} + cbat_{20} q^{-20}) + (c_{cc} + c_l)_{15} q^{-15}$$

$$Co = Z_1 q^{-1} + Z_2 q^{-2} + \ Z_3 q^{-3} + \ Z_4 q^{-4} + \cdots + \ Z_{25} q^{-25}$$

3.3.3. Financing cost and monthly payments

Monthly payback payments are calculated to evaluate the costs per household per month. For this calculation, an assumption of the terms of interest is necessary for e.g. a loan that was used to finance the systems. The assumed cost of finance is 10% p.a.(p). To calculate the yearly payments (Z) the following equation is used:

$$F = \frac{A_0}{\beta_-}$$

Beta is used as the present value factor, and is calculated as follows:

$$\beta_- = \frac{(1+p)^n - 1}{p * (1+p)^n}$$

In total, eight different yearly payment costs (F) are calculated, two for the picoPV system (for a 1 and a 3 year payback period), 3 for the 50W SHS system (for a 1, a 5, and a 25 year payback period), and three for the 100W SHS (for a 1, a 10, and a 25 year payback period). These yearly payment costs are then divided by twelve to get the monthly payback cost (F_m).

$$F_m = \frac{F}{12}$$

3.3.4. Levelized cost of electricity generation (LCOE)

The levelized cost of electricity generation are used to compare energy sytem on the basis of the energy produced (kWh) over the system lifetime including the degradation of the system (calculated in chapter 3.2) and the depreciation of the energy produced (see below), according to IEA (2010).

$$P_n = P_1 \frac{(1-d)^1}{(1+q)^1} + P_2 \frac{(1-d)^2}{(1+q)^2} + P_3 \frac{(1-d)^3}{(1+q)^3} + \cdots + P_n \frac{(1-d)^n}{(1+q)^n}$$

LCOE are calculated by taking the present value of an energy system and devide it by the energy produced over the whole lifetime.

$$LCOE = \frac{A_0}{P_n}$$

LCOE costs are calculated for the 3 year picoPV system, for 25 years for the SHS systems.

3.3.5. Sensitivity Analysis

To quantify the impact of the replacement of parts of the system or of other parameters has on the levelized cost of electricity generation a sensitivity analysis is performed. The parameters were changed in 10% steps (from -50% to 50%) to see the changes in the total system performance. The following parameters are analysed: the PV panel cost, the battery cost, the battery lifetime, the discount rate, the O&M cost, the management cost and the irradiation.

3.4. Calculation of Affordability

The calculation of affordability of SHS for the population in Sub-Saharan Africa leans on the paper by Banerjee et. al (2008) which was discussed in chapters 2.3.4and 2.6. They used affordability thresholds to analyse which quintiles could theoretically afford certain electricity costs.

In this paper, more recent income quintile data, assessing allmost all SSA countries, from the World Bank (World Bank, 2013b) is used. When no country data for income distribution was available, estimates according to the population weighted average of the same country income group was projected and inserted. This was possible for all but the one High Income country, Equatorial Guinea. A further limitation is that it was not possible to assess the rural population separatly from the urban one, this is unfortunate especially because rural households in average over all income groups have only half (in LI countries) or four-seventh (in MI countries) of the urban household budget, according to Banerjee et. al (2008).

The method in more details is described below in calculation steps, which were all done in Excel.

1) First, different population data is presented. The total population data in SSA and the rural and urban population distribution data is gained from the World Bank (World Bank, 2013b), and rural electricity access rates are from UN Global Tracking Report for the year 2010 (UN, 2013a). From this data the amount of people with and without access are calculated. The number of people without access to electricity is then calculated for each country income group, LI, LMI and UMI. The country income groups are defined after (World Bank, 2013a).

2) Second, data for income share held by different quintiles was downloaded from the World Bank (The World Bank, 2013). This data was available for 44 countries of Sub-Saharan Africa, most of the data was for the years from 2001 to 2011, except for Botswana (1994) and Zimbabwe (1995). Even though this information is outdated, it was assumed to be still useful to

calculate the affordability of electricity services because the income distribution was deemed to be closer to reality as other estimates or projections.

3) The next step was to calculate the population weighted average of the quintile data according to country income group, for Low Income countries, Low-Middle Income countries and Upper-Middle Income countries, and for all countries in Sub-Saharan Africa. These averages were, among others, used to fill the gaps of missing income quintile data. The LI average was used for Eritrea, Somalia and South Sudan and the UMI average was used for Mauritius. For Equatorial Guinea, no projections were possible as it is the only High Income country in SSA. It was neglected in the further analysis, due to its different economic situation and its small population (0.7 million people). The formula used for the population weighted average was:

$$Q1_{LIav} = \frac{\sum(Q1_{CLI} * P_{LI})}{\sum P_{LI}}$$

The sum of all first quintile data multiplied with the respective country population divided by the sum of the population of all Low Income countries in Sub-Saharan Africa equals the average first quintile income for Low Income countries. The same methodology was used for all quintiles in Low Income countries and then also applied for Low-Middle Income countries and Upper-Middle Income countries and their income quintiles.

4) The fourth step was to calculate the income per household. The range of household size in SSA according to Banerjee et. al (2008) is from 4.03 persons in Ghana 2013 to 8.69 persons in Senegal 2005. However, in this paper household size is simplified and assumed to be 5 persons, according to the IEA (2013). The calculation uses GDP and population data to first calculate the GDP per person from the World Bank (2013a) and the quintile data compiled in step 2.

$$GDP_{pcC1} = GDP_{2010C1}/P_{2010C1}$$
$$HI_{C1Q1} = Q1_{C1} * GDP_{pcC1}$$

The GDP per capita (GDPpc) was calculated for each country by dividing the GDP for 2010 with the respective population in 2010. The household income for the first quintile was then calculated by multiplying the GDP per capita with the share of household income of quintile one in the respective country. The same method was repeated to calculate the household income of all five quintiles in all countries.

5) The fifth step was to calculate the population weighted average of the household income per quintile according to the country income group. The average household income of the first quintile in Low Income countries was calculated by summing up the household income of all Low Income quintile 1 data which was first multiplied by the respective population and then divided it by the total population of all Low Income countries. This was repeated for all quintiles for LI, LMI, UMI and SSA. (except for Equatorial Guinea)

$$HI_{LIQ1av} = \frac{\sum(HI_{CLIQ1} * P_{CLI})}{\sum P_{CLI}}$$

6) The next step was to calculation the household budget available for electricity investment. The affordability threshold used was 5% of household income. This means that 5 % of the monthly household budget can be spent for electricity. For this calculation, the average income of each quintile and each country was multiplied by 5%. For example, find below the formula for quintile one in a sample country:

$$HI_{elecQ1} = HI_{C1Q1} * 5\%$$

7) The seventh step was to calculate population weighted average of household budget available for electricity, in LI, LMI, UMI und SSA. This calculation is again performed by dividing the sum of all household income available in quintile one in Low Income countries, which is first multiplied with the population in the respective countries, with the total population of all Low Income countries.

$$Q1_{LIav} = \frac{\sum(HI_{elecLIQ1} * P_{LI})}{\sum P_{LI}}$$

8) The seventh step was to illustrate the different household budgets available per quintile and country income group in graphs.

9) At the 8th step, the different average information, average quintile share, average household income and average household budget available for electricity, per quintile and country income group is illustrated graphically.

10) At last, the monthly payments for the 3 different systems with the different payment periods (methodology described in chapter 3.3.3) are included in the affordability calculation. The aim was to estimate the number of people without access who are able to afford the different PV system with different payment conditions. Thus, first the rural population who still has no access to electricity is calculated. Then the percentage of people in the different countries who are able to afford a certain monthly payment is approximated by calculating the percentage of households which can still afford certain monthly system costs. This percentage is afterwards multiplied with the number of rural population without access to electricity. This is also graphically displayed.

11) The same process than in step number 10 are repeated with an adapted monthly household budget of rural households. This adaptation is done by calculating a rural correction factor for Low Income countries and a correction factor for Low Middle Income countries (which is also used for Upper Middle Income countries). This correction is deemed to be necessary due to the fact, that rural households in average earn considerably less than urban household. The correction factors are calculated based on average rural and urban household budgets in Low Income and Low Middle Income countries of Banerjee et. al (2008), presented in chapter 2.3.4 by dividing the average national household budget with the average rural budget. The resulting rural correction factors for household budget and household budget for electricity is 0.784 for Low Income countries and 0.663 for Middle Income countries.

4. Results and Discussion

4.1. System design

Three different PV systems were designed, a 5W picoPV system, a 50W SHS system and a 100W SHS system. This chapter describes the picoPV and SHS systems and its components after showing the appliances that can be used with each system.

The main appliances, as shown in Table 16, are lighting, mobile phone charging, radio, television and other Information and Communication Technologies (ICTs) e.g. a laptop or tablet. The first system is designed with high efficient lighting using LEDs, the two other systems use a different number of CFL. The full charging of a mobile phone needs 3-4Wh for simple devices. Efficient radios only need 0.5 Wh per hour of listing. The electricity consumption of television depends on the capacity it needs which in turn depends on the size. Other ICTs are included because prices for small laptops can be below 250$ and tablet prices can be as low as 40$ and thus, might be affordable for certain households.

Table 16: Appliances for the designed Systems

		Pico PV	SHS	SHS
Light		LED	CFL	CFL
	lm	260	1250	1600
	W	2.6	25	32
	h/d	4	4	4
	Wh/d	10,4	100	128
Mobile phone	Wh/d	2	4	8
Radio	Wh/d	1	2	2
TV	W	0	10	25
	h/d	0	3	4
	Wh/d	0	30	100
other ICT	Wh/d			40
total energy demand	Wh/d	13,4	136	278

The following table (Table 17) gives an overview of the PV system design, from the panel to the battery to the total system. First, the capacity of the panel is given in Wp, then the used technology is described, before the efficiency, the area and, the lifetime is shown. The type of battery, with the efficiency, the capacity and its lifetime is displayed later. Last, the calculated system efficiency is given.

Table 17: PV system design and specificiations

System		picoPV	SHS	SHS
PV panel				
Capacity	Wp	5	50	100
Technology		multi-crystalline	mono-crystalline	mono-crystalline
Efficiency of PV module	%	10%	15%	
Panel area	m²	0.05	0.33	0.67
Lifetime	a	3	25	
Battery				
Type of battery		lead acid	modified SLI, C20 lead acid	
			100 Ah	200 Ah
Efficiency of battery	%	70%	70%	
Capacity	Wh/Wp	10	20	
	Wh	50	1000	2000
Lifetime of battery	a	3	5	
System				
System efficiency	%	7%	11%	
Lifetime		3	25	

The first system planned, after Lysen (2013), is a 5W picoPV system with a 50Wh lead acid battery and an assumed lifetime of 3 years. The PV panel is specified to be multi-crystalline silicium with a module efficiency of 10% and a size of 0.05m². The total system efficiency is assumed to be 7%. At a 4000Wh/m²d irradiation, this system has an electricity output of 14Wh/d or 5,11kWh/a. This is enough electricity to run LED lamps with a lumen output of 260 lm (e.g. a study lamp, a main lamp and a night lamp) for 5 hours, to charge a mobile phone every second day (4Wh for full-charge) and to use a small 0.5W radio for 2 hours.

The second system designed, after Carrasco (2013), is a 50W SHS system, with a 50W mono-crystalline silicon PV module with a size of 0.33m², a 15% module efficiency and a 25-year lifetime. The battery for this system is a 100 Ah (1200 Wh) modified SLI, C20 lead-acid battery with a lifetime of five years. The charge controller is a 10A series charge controller with a PWM regulation but without MPPT function. The system efficiency without the PV panel is 70% which makes a total system efficiency of 11%. At an irradiation of 4kWh/m²d, the energy output is 140Wh/d (or 51.1 kWh/a) in the first year. With this energy output, one can run three compact fluorescent lamps (CFL) (2x7W and 1x11 W) for four hours, charge one mobile phone per day, listen to a 0.5W radio for 4h per day and watch telelvision for 3h (with a small 10W TV) per day.

The third system also designed, after Carrasco (2013), is a 100W SHS system, with a 100W mono-crystalline silicon PV module with a size of 0.66m², a 15% module efficiency and a 25-year lifetime. The battery for this system is a 200 Ah (2400 Wh) modified SLI, C20 lead-acid battery with a lifetime of five years. The charge controller is a 20A series charge controller with a PWM regulation but without MPPT function. The system efficiency is the same as for the 50SHS system, 11%. At an irradiation of 4kWh/m²d, the energy output is 280Wh/d (or 102.2 kWh/a). With this energy output it is possible to run 4 compact fluorescent lamps (CFL) (3x7W and 1x11 W) for 4.5 hours, to charge two mobile phones per day, to listen to a 0.5W radio for 4h per day, to watch a television for four hours (with a medium size 25W TV) per day and to have some electricity (40Wh/d) left for other small ICT appliances like (a small laptop (20W) or a small tablet (~10W)).

4.2. Electricity generation

The electricity generation of the three different systems, are calculated by using the methodology descripted in chapter 3.2. The irradation used (4 kWh/m²d) is rather low for Africa, where the irradation in many areas reaches above 7 kWh/m²d. Yet, this low irradiation is used to show the possible usage under unfavorable conditions. In many areas with higher irradiation, number of applications or the usage time of the appliances could be thus a lot higher.

The electricity generation for the first year with an irradiation of 4000 Wh/m²d without any degradation and depreciation is shown in Table 18. The 5W picoPV system would generate 14Wh/dof electricity, the 50W SHS 140Wh/d and the 100W SHS 280 Wh/d. This is enough energy for the, , described usage (see chapter 4.1).

Table 18: Energy output first year

System		picoPV	SHS	SHS
Capacity	Wp	5	50	100
Irradiation	kWh/m²d	4	4	4
	kWh/m²m	122	122	122
	kWh/m²a	1460	1460	1460
Energy output	kWh/d	0.014	0.14	0.28
	kWh/m	0.4	4.3	8.5
	kWh/a	5.11	51.1	102.2

The electricity generation over a 25-year period, including the 0.5% p.a. degradation of the PV panel,is displayed in Illustration **25**. The picoPV system is also viewed for 25 years, which would mean repurchasing the picoPV system every three years, in order to compare the energy output under given assumptions over the same periode. In total, over the 25 years, the 5W picoPV system would generate 126 kWh, the 50W SHS system 1198 kWh and the 100W SHS system 2395 kWh.

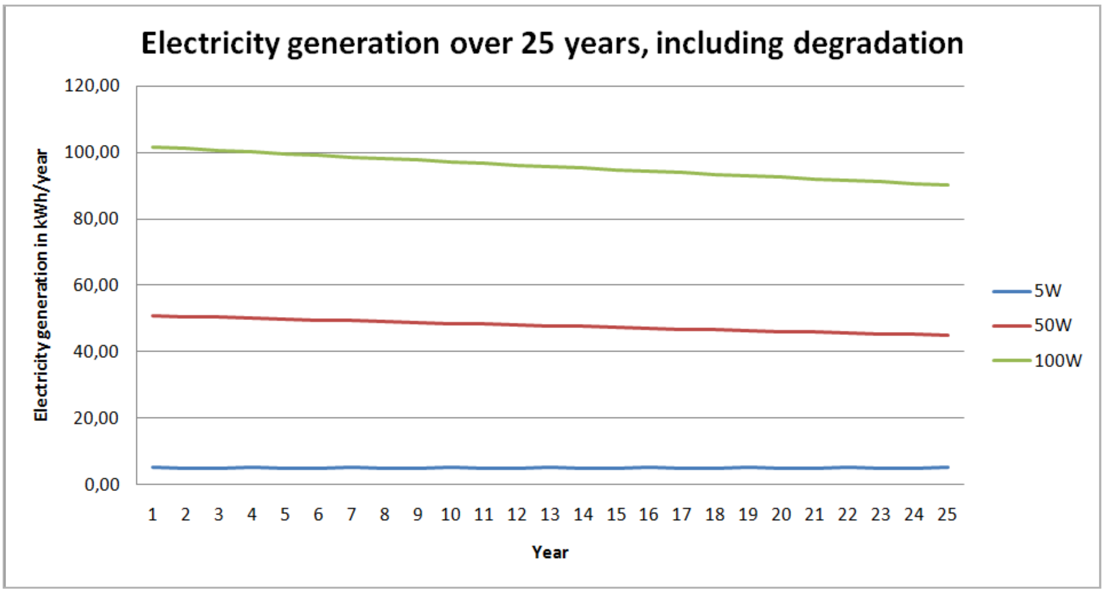


Illustration 25: Electricity generation over 25 years, including 0.5 % p.a. degradation

The energy production including a 10% discount factor to the calculation of electricity generation over the lifetime, necessary for the LCOE calculation, is given below in Illustration 26. Discounting the electricity generation in LCOE calculations is used to consider the fact that the electricity in the next year has not the same value as the electricity in the present year. With the discount factor included, the picoPV system produces in total 46 kWh over 25 year, the 50W system produces 445 kWh and the 100W system 890 kWh

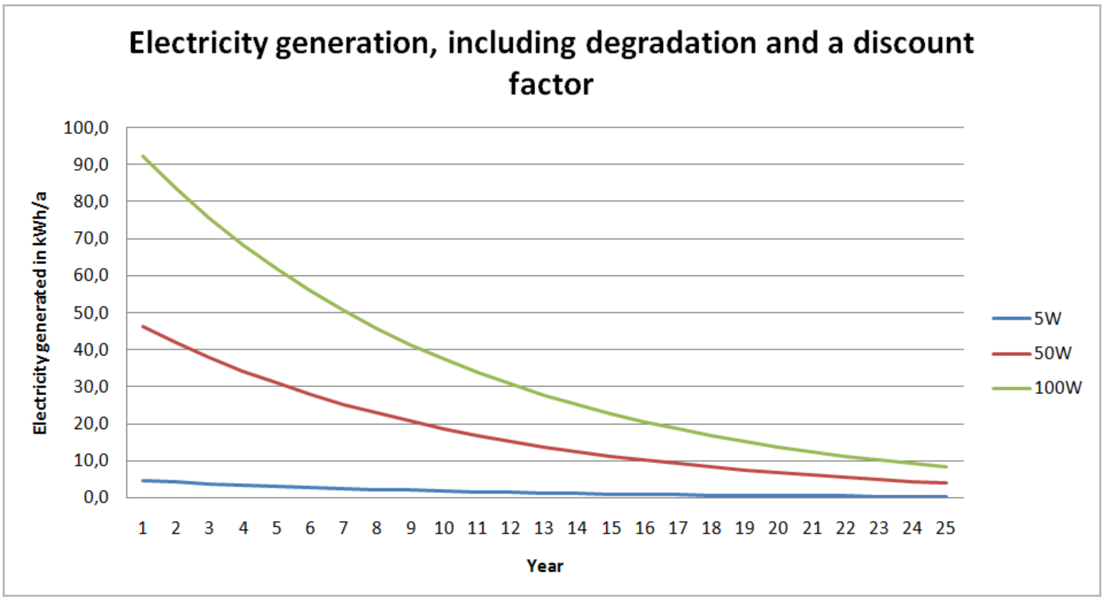


Illustration 26: Electricity generation, including 0.5% p.a. PV panel degradation and a 10% discount factor

4.3. Economic feasibility calculation

The system costs, or system component costs, as already described in chapter 3.3, are based on the reports of Lysen (2013) for the picoPV system and Carrasco (2013) for the two SHS systems. The methodology to calculate the investment cost and the present value over different lifetimes is also explained in chapter 3.3.

Below, in Table **19**: System cost and Investment costsTable 19, the system costs and the initial investment costsare shown. The picoPV investment cost amounts to 93.0 EUR, whereas the 50WSHS system amounts to 336.5 EUR and the 100W SHS system to 586.5 EUR.

Table 19: System cost and Investment costs

System		picoPV	SHS	SHS
Capacity	Wp	5	50	100
System cost	€/Wp	18.6		
Module	€/Wp		1.8	1.8
Battery	€/Wp		1.51	1.51
Charge controller	€		28	42
Lighting	€		43	64,5
Installation	€		100	150
Investment cost	**€**	**93.0**	**336.5**	**587.5**

The present value, calculated with a 10% discount factor, reinvestment costs and cost for O&M and Management are 93.0 EUR for the picoPV system, calculated for a 3 year period without any O&M and Management cost. The underlying assumption is that the picoPV system is an over the counter sale, payed by cash or by an external loan without any maintenance or management included over the three-year lifetime. For the SHS systems, reinvestments are necessary for batteries every five years and for the charge controller and the lamps after 15 years. Additionally, these systems are assumed to need O&M and Management of about 5% of the investment cost each. Thus, the present value calcuted over a 25 year lifetime and depreciated by 10% per year is 753 EUR for the 50W system and 1335 EUR for the 100W SHS system. A discounted distribution of the costs of these two systems over the 25 year lifetime can be found in Illustration 27.

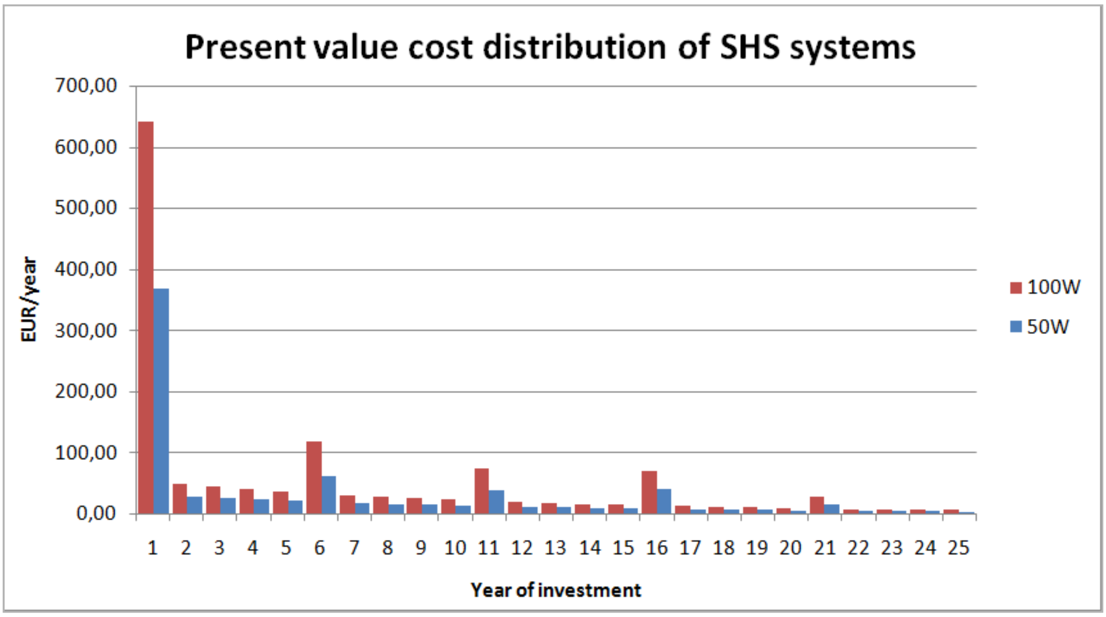


Illustration 27: Present value cost distributino of SHS systems

A typical cost distribution over the main categories Material, Installation and O&M and Management over the 25-year lifetime for the 50W SHS system is displayed in Illustration 28. It can be seen that the materials account for most of the cost, with the battery costs amounting to 23%, the PV panel to 12%, the lamps to 7%, and the charge controller to 4% of the total system cost. Installation and O&M together sum up to 34% of the system and Management to 20%. Thus, without including these costs in the economic calculation, the system costs would be 54% lower. Not including O&M and Management costs often happens in the literature on SHS systems, with the result that projects are based on wrong assumptions and thus do not meet initial economic targets.

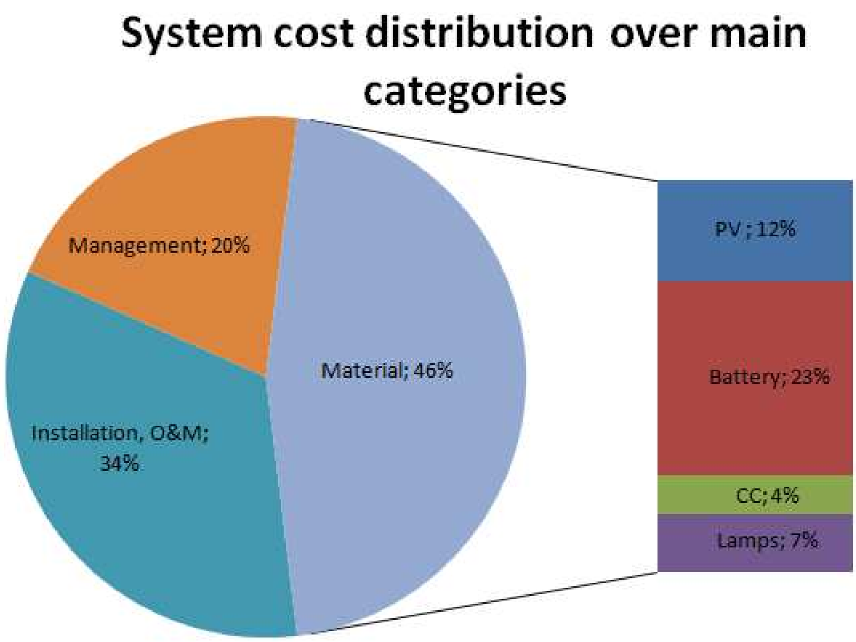


Illustration 28: System cost distribution over main categories for the 50W SHS over 25 years, with a 10% discount factor

To compare PV system costs, the literature often uses the metric USD/Wp, as discussed in chapter 2.11.1. The designed SHS systems have USD/Wp costs of 18.6 and 16.5, as can be seen in Table 20. This calculated result is in the upper half of the in the literature found system prices for SSA.

Table 20: System cost of the assessed P'V systems in USD/Wp

		5W picoPV	50W SHS	100W SHS
Lifetime	a	3	25	25
System cost (Investment cost for picoPV, present value for SHS)	€	93.0	753.1	1335.4
	€/Wp	18.61	15.06	13.35
	$/Wp	23.00	18.62	16.51

4.3.1. Financing cost and monthly payments

Monthly payback payments are calculated to evaluate the costs per household per month for each system under different assumed payback periods. The assumed cost of finance is 10% per annum.

In total, eight different yearly payment costs are calculated, two for the picoPV system (for a 1 and a 3 year payback period), three for the 50W SHS system (for a 1, a 5, and a 25-year payback period), and three for the 100W SHS (for a 1, a 10, and a 25-year payback period). These yearly payment costs are then recalculated to obtain monthly payback costs, first in EURO then in USD.

Table 21: Monthly payback cost with different financing periods in EURO and USD, with an exchange rate of 1,236 USD/EUR

		5W picoPV	50W SHS	100W SHS
Payback time	**a**	**1**	**1**	**1**
Investment cost	€	93.04	336.50	587.50
Yearly payback	€/a	102.34	370.15	646.25
Monthly payback	€/m	8.53	30.85	53.85
	$/m	**10.54**	**38.13**	**66.57**
Payback time	**a**	**3**	**5**	**10**
Present value	€	93.04	464.06	1033.73
Yearly payback	€/a	37.41	122.42	168.23
Monthly payback	€/m	3.12	10.20	14.02
	$/m	**3.85**	**12.61**	**17.33**
Payback time	**a**		**25**	**25**
Present value	€		753.11	1335.38
Yearly payback	€/a		82.97	147.12
Monthly payback	€/m		6.91	12.26
	$/m		**8.55**	**15.15**

The lowest monthly payback cost would be for a 5W picoPV system for three years at 3.85 USD per month, and the highest for the 100W SHS system financed in one year, with monthly costs of 66.6 USD. Thus, the smaller the system and the longer the financing period, the less are the monthly cost (only at low to medium interest rates). This can be also seen in

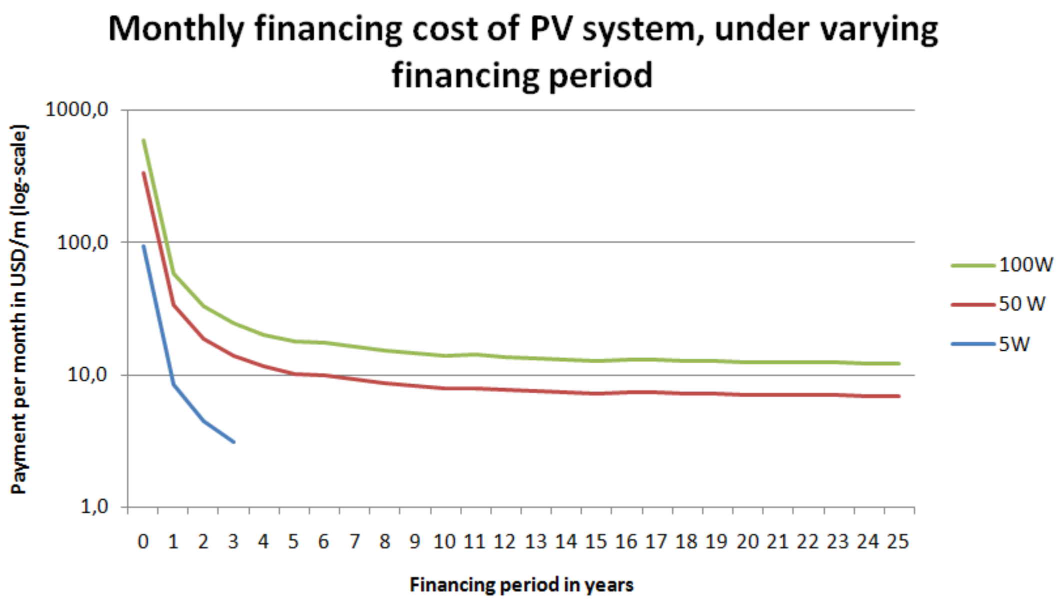


Illustration **29**, which depicts the monthly financing cost of the PV systems under varying financing periods (in a logarithmic scale). It can be further seen that from the year 10 onwards monthly paybacks only reduce marginally for the two SHS systems.

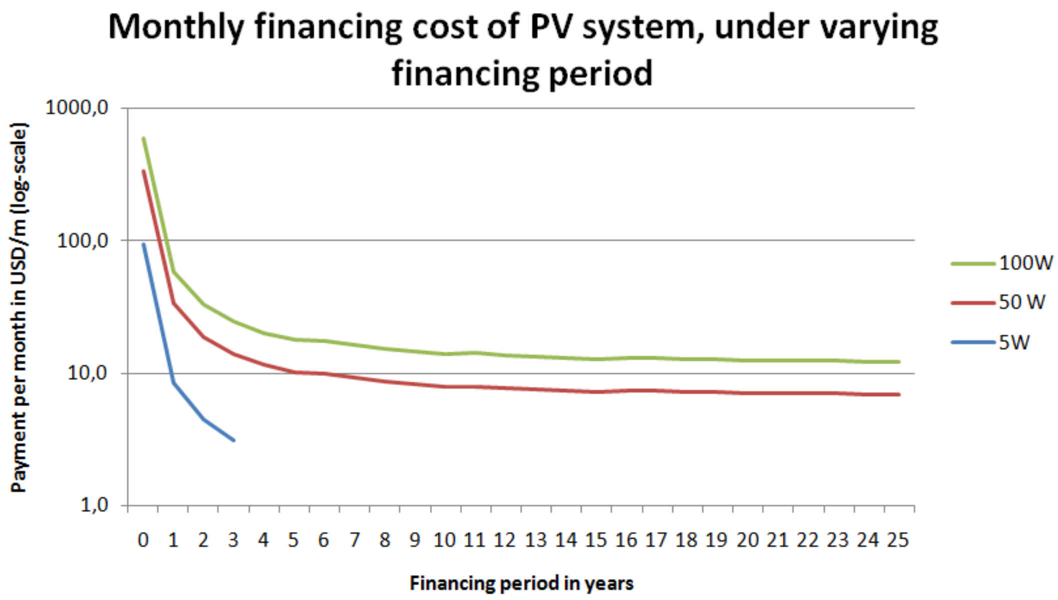


Illustration 29: Monthly financing cost of PV system under varying financing period, in USD, 0 on the x-axis is meant to show payments in cash, terms of finance are assumed to be 10% per year, and discount factor is also assumed to be 10%.

4.3.2. Cost of Electricity Generation (LCOE)

For the picoPV system the LCOEs and the investment costs are calculated for 3 years. For the SHS systems the present value costs for and the respective depreciated electricity generation are calculated for 25 years. The resulting LCOE costs are 9.14 USD/kWh for the picoPV system, 2.09 USD/kWh for the 50W PV system and 1.86 USD/kWh for the 100 W SHS system.

Table 22: Calculated LCOEs

		5W picoPV	50W SHS	100W SHS
Lifetime	a	3	25	25
Investment cost/present value	€	93.0	753	1335
Energy generation in the viewed lifetime	kWh	12.6	444.8	889.6
LCOE	€/kWh	7.39	1.69	1.50
	$/kWh	**9.14**	**2.09**	**1.86**

Thus, the calculated LCOE costs for the systems are higher than the ones found in the literature for the same system. Yet, the LCOEs for the three PV systems are calculated with a fixed irradiation of 4000 Wh/m²d, which is on the lower end of the irradiation levels found in SSA, thus regions with higher irradiation would have lower LCOE costs. Non-the-less, even with this low irradiation level assumed, there are still many regions in which the SHS systems would be cheaper than the diesel generated power, as can be seen in chapter 2.8.2.3, in Illustration 14, all areas with diesel generation costs higher than 1.5 EURO/kWh.

The picoPV system should not be compared to other electricity generation technologies with this methodology. It is mostly a substitute for kerosene or candle lighting and for mobile phone charging, but not for diesel generators. Adkins et. al, found that on average 48 USD per year are spent for lighting and electricity in Sub-Saharan African, see chapter 2.6.1. Thus, the system would break even after approximately two years, or would have a lower electricity and lighting cost per month if the costs are equally spread over the whole lifetime.

The difference in LCOE of SHS of this paper with the literature, especially with the 50W SHS system, which is the most often compared capacity of SHS, is most probably due to the different included costs and the methodology applied. If only material costs are included in the calculation, the LCOE would be 54% lower (see Illustration 28). It is also possible that sometimes only investment costs are considered and no reinvestment costs, then the LCOE would also be lower. Additionally, considering a higher irradiation reduces the LCOE. Not using the depreciation costs also changes the outcome. The next chapter shows the sensitivity analysis for the 50W SHS systems to see the influence of different input parameters on the system costs.

4.3.3. Sensitivity Analysis

The sensitivity analysis, see Illustration 30, shows how the system cost changes if individual inputs vary. The most influent parameter is the irradiation; then comes the discount rate and the battery lifetime. With the materials, the cost of the battery have a higher influence than the PV, the O&M and Management cost (the last two are the same). With an irradiation of 6kWh, which is 50% more than the basis, the LCOE would be reduced by 50%. With a depreciation of 5%, instead of 10%, the LCOE cost would be 38% higher, and with a discount rate of 15%, the LCOE cost would be

20% lower. With a 2.5 year battery lifetime, which is a 50% reduction to the 5 year lifetime basically assumed, the system costs would increase by around 15%, however with a 7.5 year lifetime, the system cost would only decrease by 4%. Changing the material costs of the system result in a linear change in the LCOE cost. With a 50% battery cost increase having a 15% influence on the LCOE cost, a 50% PV panel cost change having a 12% influence, and O&M and Management cost change of 50% influencing the costs of the system by 8% each. The sensitivity analysis for the 100W SHS system does only vary to a small degree compared to the 50W SHS, and is thus not extra displayed.

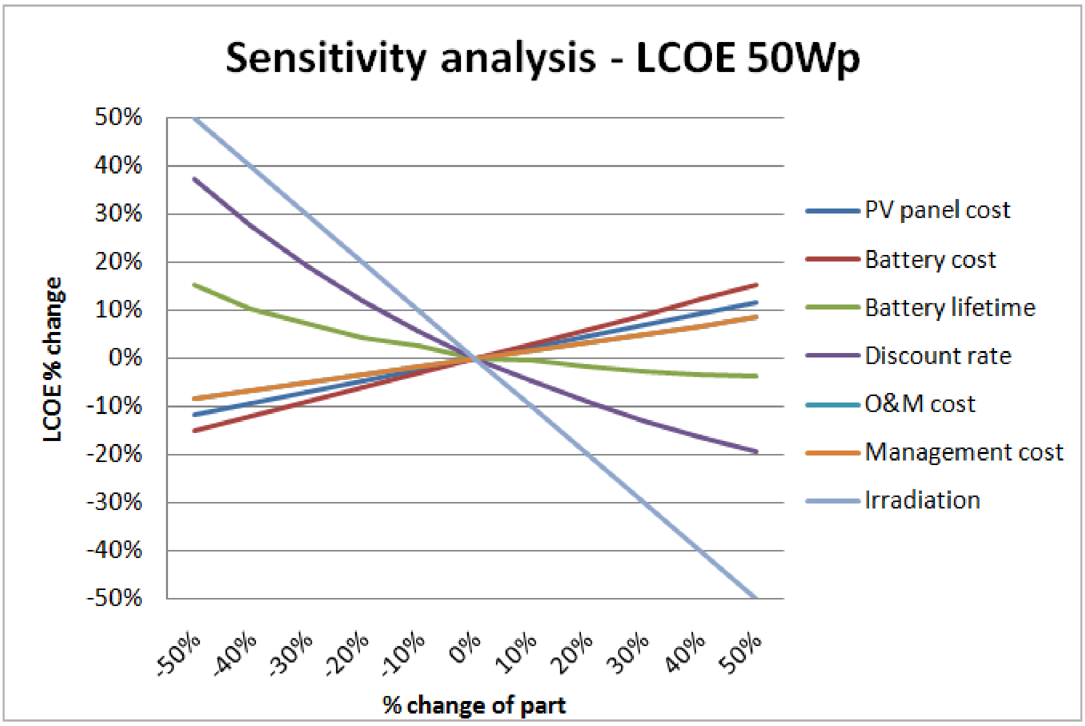


Illustration 30: Sensititivity analysis for the 50W SHS system

4.4. Calculation of Affordability

This chapter first illustrates some population numbers, e.g. number of people living in urban and rural areas, with and without electricity, and amount of people living without electricity per country income group. Second, the result on availabe budget of the country income groups is presented. Third, the available budget for electricity for each country in its respective country income group is showed. Fourth,the average budget available for electricity per country income group is presented and discussed. Fifth, the monthly financing costs, which were calculated in the previous chapter, are included into the discussion on the available budget. Sixth, the number of people who can afford the three different PV systems under various financing periods is calculated and the results are discussed. Finally, the same process is performed with a correction factor for the average rural income.

4.4.1. Population

Illustration 31 shows, in row one the total population of Sub-Saharan Africa, which amounted to 870 million people in 2010. Row two illustrates the number of people living in rural areas, 553 million people, and in urban areas, 316 million people, in SSA in 2010. Afterwards, row three, presents the number of people with access to electricity in rural areas, which counts 76 million people (or 14% of the rural population) and the number of people without access to electricity in rural areas of SSA, which are 477 million people. Of these 477 million people without access to electricity, 346 million live in Low Income countries, 114 million in Low Middle Income countries and 16.3 million in Upper Middle countries, which represents respectively 93%, 78% and 60% of the rural population of these countries.

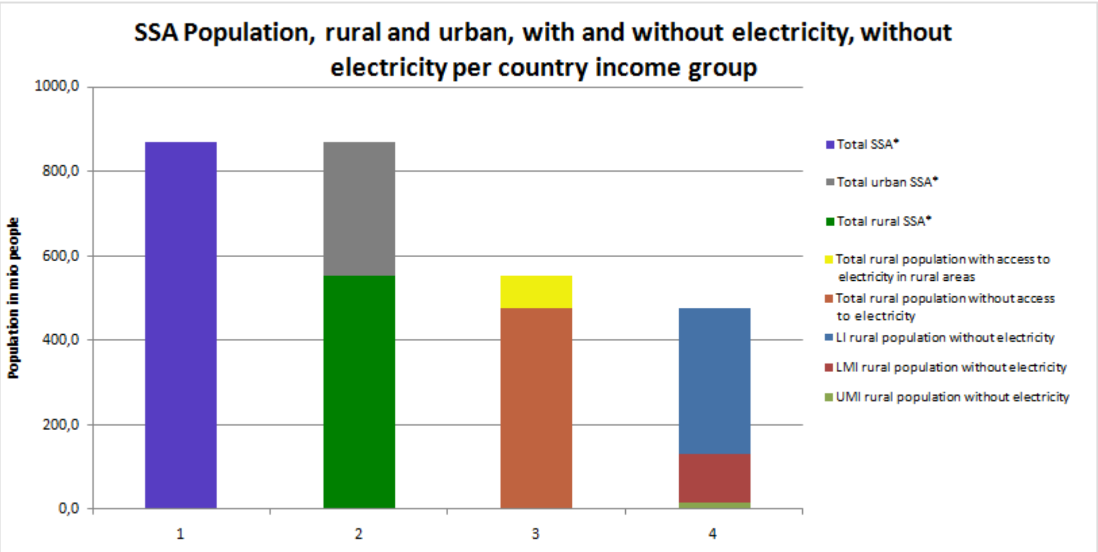


Illustration 31: Sub-Saharan Africa Population, rural and urban distribution, population with and without electricity, and the number of people without electricity per country income group in 2010; data for total, urban and rural population from (World Bank, 2013b), rural access to electricity from UN Global Tracking Report (UN, 2013a) and country income groups defined after (World Bank, 2013a)

4.4.2. Household budget

The average household budget per country income group and quintile, for an assumed average household size of 5 persons, is displayed in Illustration 32 (averages are population weighted averages). In Low Income countries, an average household in the first quintile has a budget of 60 USD, in the fifth quintile around 465, per month (for 5 persons), which corresponds to 0.40 USD and 3.1 USD per person and day. In Middle Income countries, the average household has a budget of between 174 USD and 1393 USD per month, again viewed with average quintile data. The average household income in Upper Middle Income countries is between 444 USD and 8652 USD, per month.

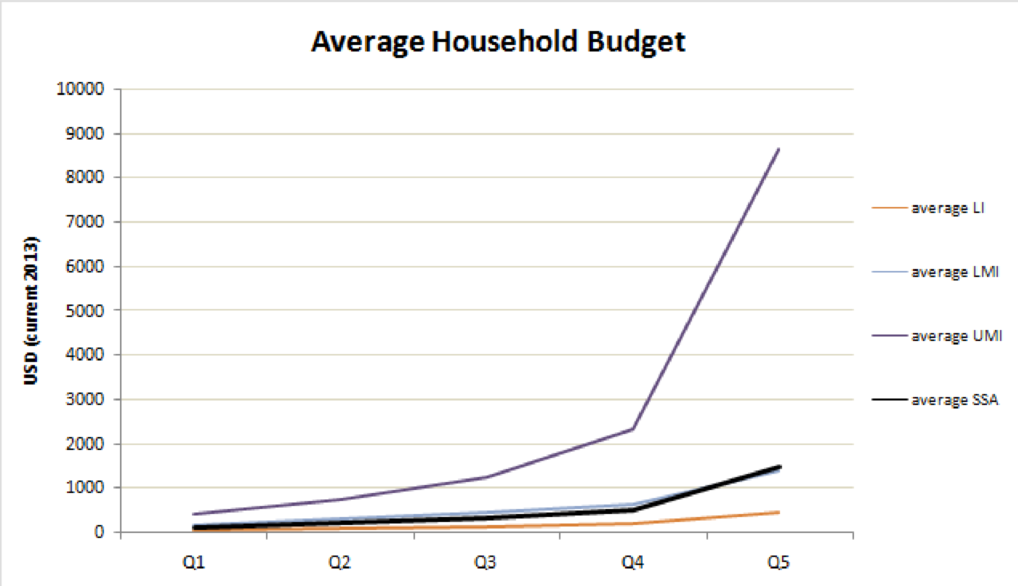


Illustration 32: Average Household Budget per month, per country income group and income quintiles in SSA, data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

There are however a few limitations for this household budget calculation, which carry through most of the following results. First, the income data is calculated with the most recent available country income quintile data, yet, in case of two countries the latest available data set were from before 2000. Additionally, income quintile data for four countries have been estimated according the population weighted average of the country income groups. Furthermore, the country quintile data was only available for the whole country, without distinquishing urban and rural areas. This is problematic because people in urban areas tend to earn significantly more money than people in rural areas. This limitation in data quality is, in a later stage of this paper, offset by including a rural correction factor calculated after Banerjee et. al (2008) average national and rural household data. Furthermore, the assumption of a fixed household size results in a reduced explanatory power, as usually household size decreases with income level and average household sizes per country vary from 4.3 to 9.8 persons, according to Banerjee et al. 2008. All these limitations reduce the calculations in chapter 4.4.4 to estimations.

4.4.3. Available budget for electricity

The available budget for electricity per country income group and quintiles, assuming that 5% of the household budget is spend for electricity, is shown in Illustration 33 to Illustration 36. First, the countries in the three different income groups, namely Low Income, Low Middle Income and Upper Middle Income ,are illustrated seperatly. Then, the average budget for electricity per country income group is shown. The country with the lowest average income per quintile is Somalia, the highest Seychelles.

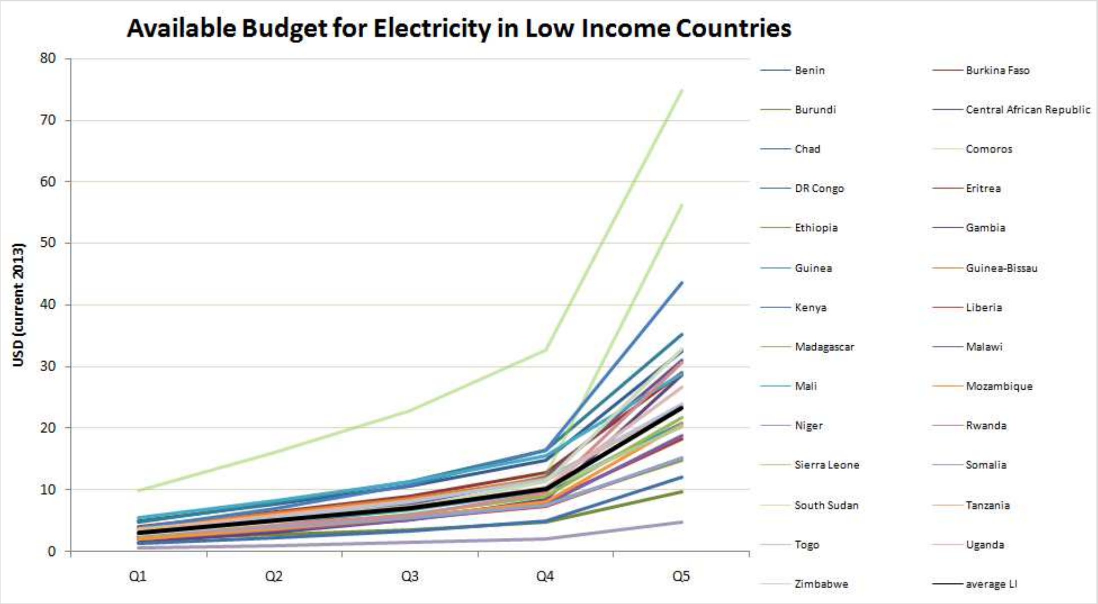


Illustration 33: Available Budget for Electricity in Low Income Countries in SSA per month, data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

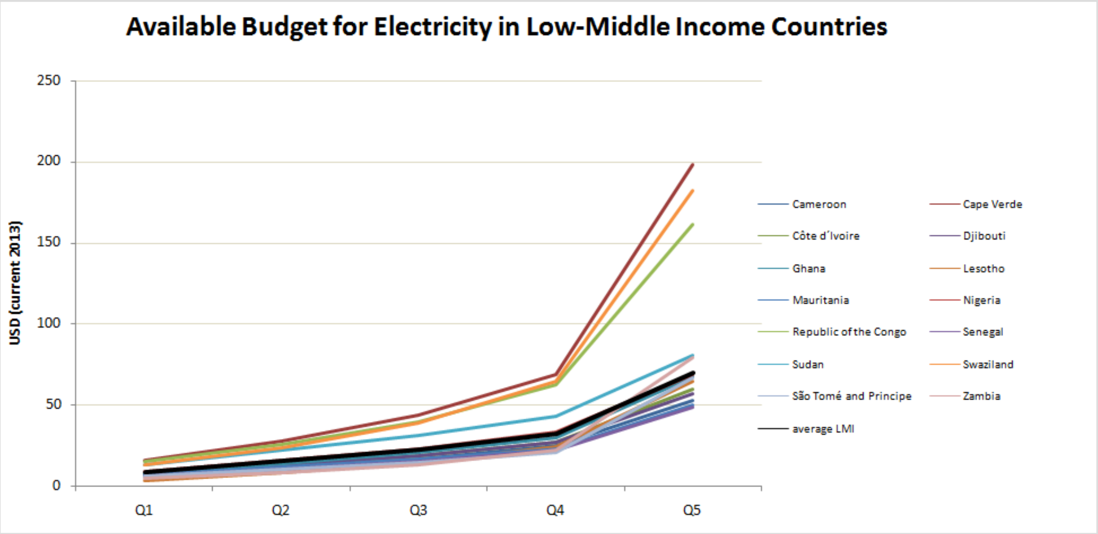


Illustration 34: Available Budget for Electricity in Low Middle Income countries in SSA per month, data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and

country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

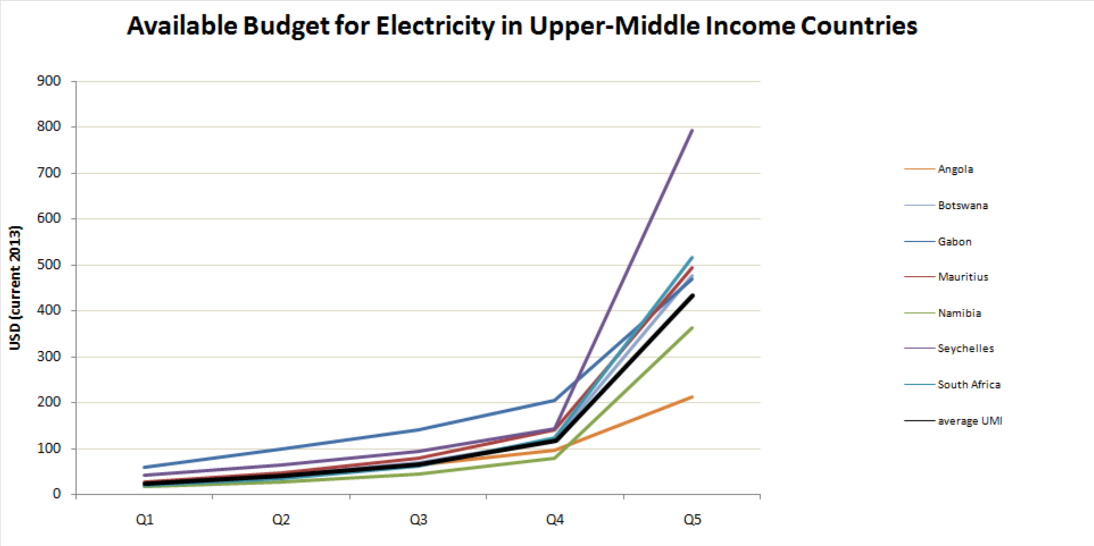


Illustration 35 Available Budget for Electricity in Upper Middle Incom countries in SSA per month, data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

The population weighted average of the quintile distribution per country income group is shown in Illustration 36 and Table 23. It can be seen that on average quintile 1, 2, 3 and 4 of the Low Income countries and quintile 1 of Low Middle Income countries, have less then 10 USD per month available for electricity. Furthermore, adding to the before mentioned quintiles, quintile Q5 of LI, Q2 and 3 of LMI and Q1 of UMI shows how many households could afford electricity prices below 21 USD.

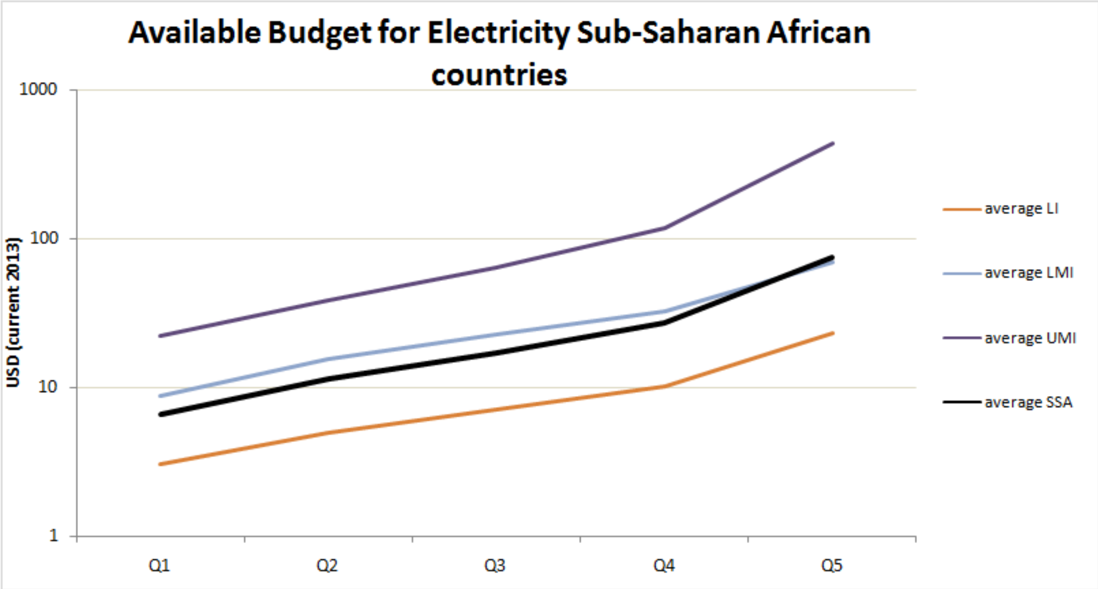


Illustration 36: Available Budget for Electricity average of country income groups in SSA per month, in log scale, data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

Table 23: Population weighted average household budget for electricity per month, per income quintile and country income group in SSA, in USD; data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

	Q1	Q2	Q3	Q4	Q5
average LI	3	5	7	10	23
average LMI	9	15	22	33	70
average UMI	22	38	64	117	433
average SSA	7	11	17	27	75

A graphical illustration of available electricity budget per month and monthly financing cost of different systems is displayed in Illustration **37**. The areas above the PV system costs per month are the quintiles which on average can afford a given system. It can be clearly seen that the lowest quintile in Low Income countries in average cannot afford any of the PV systems with their monthly available budget for electricity. However, all the rest on average can at least afford the picoPV system with over the three-year financing period. The 50W SHS system with a 25 year could be affordable, on average, for all but the lower four quintiles of LI countries and the poorest quintile in LMI countries. The 100W system would only be affordable for the population of the UMI countries and the upper three quinitles of LMI countries, in average.

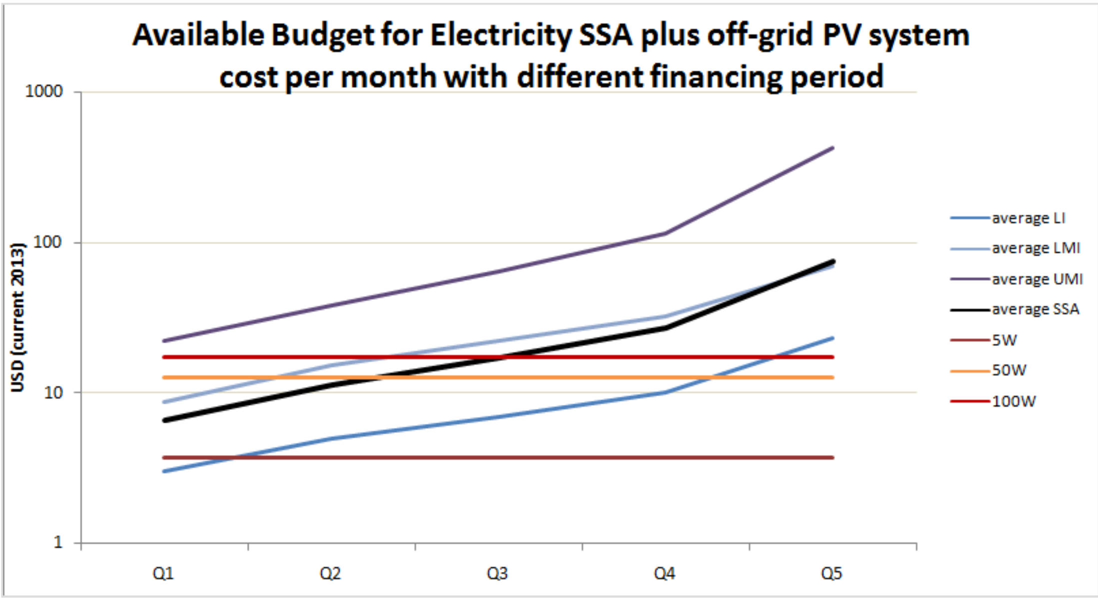


Illustration 37: Available Budget for Electricity per month, average of country income groups and three different monthly PV financing costs in SSA, in log scale, data for quintile distribution from (The World Bank, 2013), GDP per person from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

In this analysis, mentioning that all the quintile numbers are averages is necessary because this causes a further limitation, additional to the before mentioned, data quality, the rural data gap and the average household size. This paper does not calculate the actual number of people who can afford a given system with quintile data, as quintile data are averages of 20% of the population in the assessed country, country income group or region. For example, on average over the whole Sub-Saharan Africa, all people could afford electricity of around 7 USD per month. However, the Table 23 also shows that Q1, 2 and 3 of Low Income countries would not be able to afford this 7 USD. Average quintile data in this paper, thus, does not give any information of the actual percentage or number of people who are able to afford a given PV system. Especially if the average of a quintile is close to the monthly packback sum, it is probable that 50% of this quintile or 10% of the total population cannot afford it. It is even possible that more cannot afford it if the income distribution is not linear in the quintile but for example exponential. This is another reason why the calculated number of people who are able to afford a given system are just estimations.

4.4.4. Affordability of off-grid PV systems in rural areas

The results of the estimation of the number of people in SSA who are able to afford the PV systems with the above calculated monthly financing costs are shown in this chapter. At first, the estimation is based on nationwide quintile information. In the next step, a correction factor is introduced, and a new estimation is calculated.

Before going to the PV systems, it is interesting to analyse the number of people with a certain household budget for electricity. This is shown in Illustration 38, which illustrates the number of people with a certain average available household budget for electricity. This calculation is again based data for quintile distribution from (The World Bank, 2013), GDP per person from the World Bank (2013a) and country income groups defined after (World Bank, 2013a) with an assumed average household size of 5 persons. It is logical that with zero cost for electricity all households would be able to afford it and that the higher the cost the less people would be able to afford electricity. Yet, the distribution is interesting. Almost all the people without electricity access in SSA could afford electricity for 2 USD per month. If electricity would cost more, especially the number of people living in Low Income countries would decrease dramatically, from 346 million at 0 USD, to 256 at 5 USD and 108 million at 10 USD. In Lower Middle Income countries, the number of people unable to afford electricity decreases less from 114 million at 0 USD to 94 million at 10 USD and 66.8 million at 20 USD. In Upper Middle Income countries, the number of people able to afford electricity diminishes only marginally at first, from the 16.3 million people, 16.1 million could still afford electricity of 20 USD per month, 13 million at 30 USD and11.5 million at 40 USD.

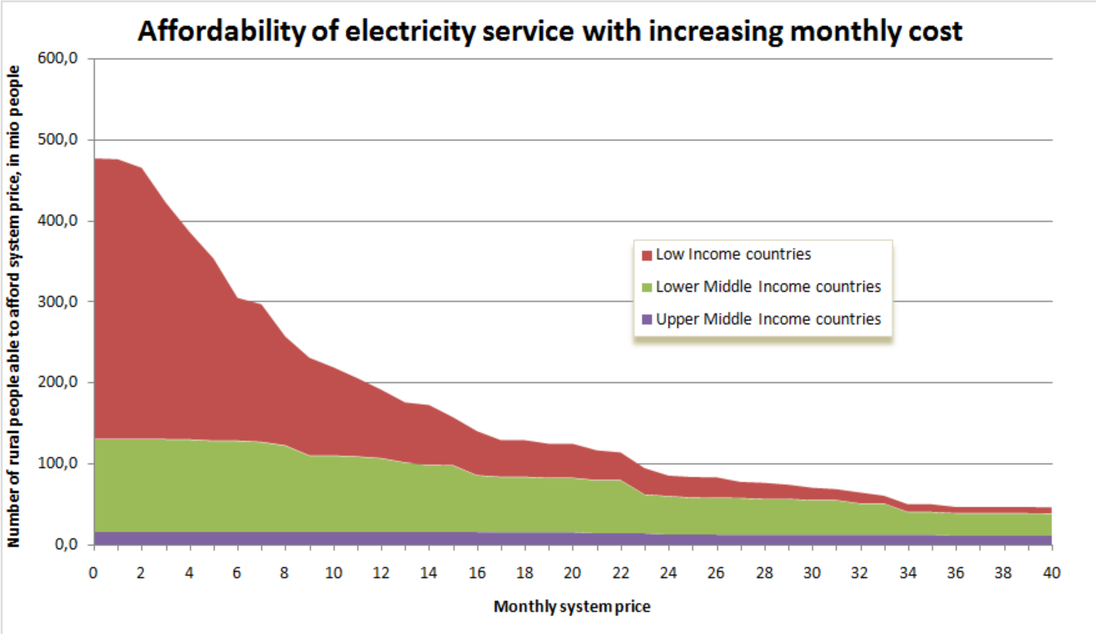


Illustration 38: Affordability of electricity service with increasing monthy cost for people without electricity access in 2010 in SSA, data for quintile distribution from (The World Bank, 2013), GDP per person and population from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

Illustration 39 shows the estimated number of people without electricity access in rural areas of SSA able to afford the analysed PV system with the above mentioned financing periods and costs. Nearly 400 million people in SSA could afford the 5W picoPV system with a price of 3.7 USD per month. Reducing the financing period to 1 year would result in monthly financing costs of about 10 USD, which would only be affordable to arround 220 million people. The 50W SHS system would be affordable to 240 million people for a 25-year financing period, to180 million for a 5-year period and only 45 million with a 1-year financing period. The number of people able to afford the 100W SHS system is again depending on the financing period, from 160 million people for 25 years, 130 million for 10 years and 31 million for a 1-year financing period.

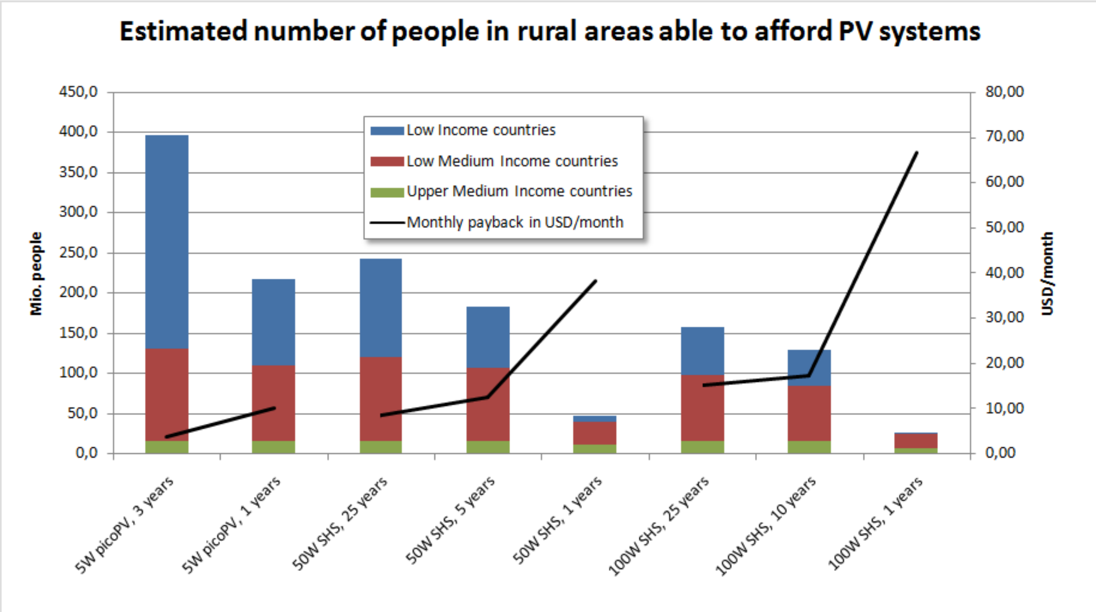


Illustration 39: Estimated number of people in rural areas able to afford PV systems in SSA, data for quintile distribution from (The World Bank, 2013), GDP per person and population from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

Recalculating the estimation on the number of people able to afford certain electricity prices or PV systems with a correction factor becomes necessary, due to the reduced income in rural areas compared to national average incomes. It is assumed that the income distribution between the quintiles stays the same but that the level is lower, by a calculated factor. For Low Income Countries, the factor is 0.78, which means that the rural population on average earns only 78% of the national average. For Middle Income countries, this factor is even more unfavorable at 0.66. Both factors are calculated after data provided by Banerjee et al. (2008).

Illustration 40 shows the recalculated estimations for the affordability of electricity services. The initial drop in number of people able to afford electricity is a lot sharper for LIs. In Low Income countries at first, with 0 costs, again all people would be able to afford electricity, at 5 USD only 174 million people and at 10 USD only 77 million people would be able to afford this service. In LMIs, the number of people able to afford electricity also decreases more continuously and to a deeper level, from 114 million people at 0 costs to 82 million at 10 USD and 42 million at 20 USD. For people in UMI, the estimated number reduces even more. It goesfrom 16.3 million at zero cost to 12.9 million at 20 USD, 9.6 million at 30 USD and 9.6 million at 40 USD.

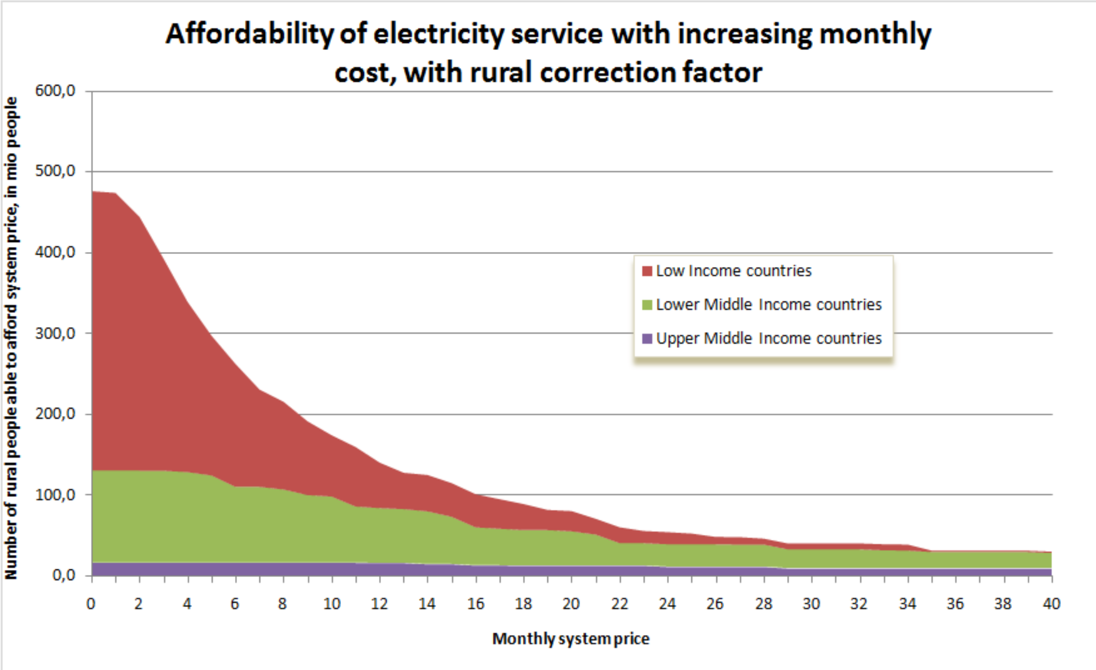


Illustration 40: Affordability of electricity service with increasing monthy cost for people without electricity access including a correction factor for reduced rural income in 2010 in SSA, data for quintile distribution from (The World Bank, 2013), GDP per person and population from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

The correction factor naturally also impacts the estimated number of people who are able to afford the PV systems, see Illustration 41. For most of the system examples, the number of people who can afford it would decrease by around 50 million in comparison to the analysis above.

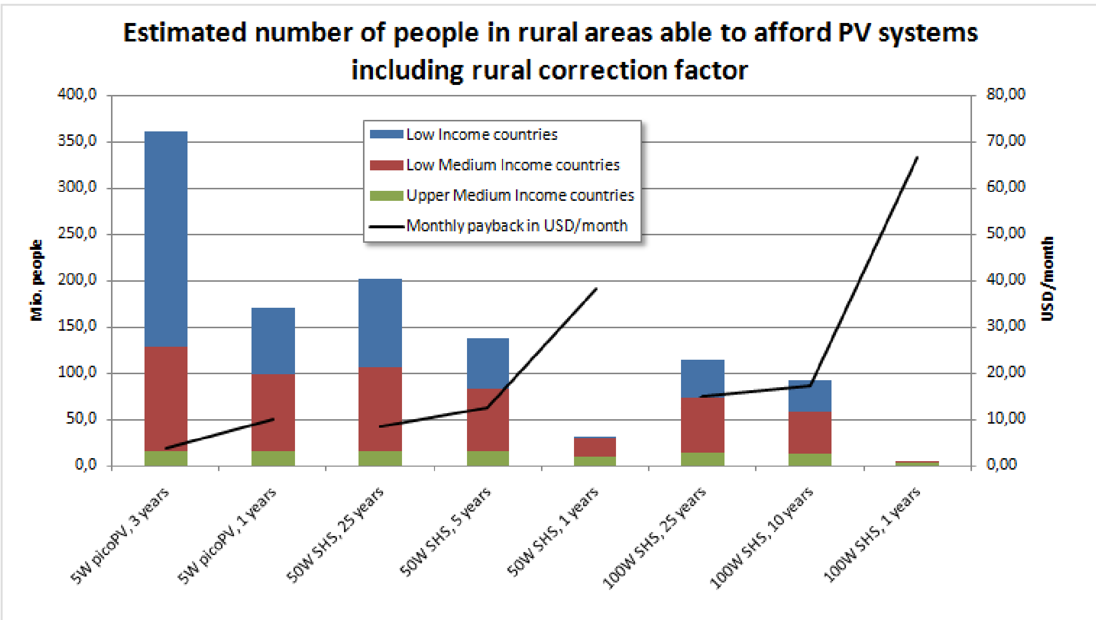


Illustration 41: Estimated number of people in rural areas able to afford PV systems in SSA, including a rural correction factor, data for quintile distribution from (The World Bank, 2013), GDP per person and

population from (World Bank, 2013b) and country income groups defined after (World Bank, 2013a), assumed average household size of 5 persons

5. Discussion

The hypothesis of this paper is that, off-grid photovoltaic technology can play an important role in rural electrification in Sub-Saharan Africa. To access the role small off-grid PV can play, first a comparison with other electricity generation technologies was performed, in order to be able to estimate the market potential of different PV technologies based on financing cost and affordability. The three systems evaluated are a 5W picoPV, a 50W SHS and a 100W SHS system.

The financing cost were calculated with present value costs which in turn are based on assumed system costs and installation cost, 5% O&M and Management cost and 10% discount rate and financing cost with different lifetimes and financing periods. These assumptions are estabilished according to recent literature and own estimations in the case of financing cost. The investment cost (system plus installation costs), amount to 89.4 EUR, 336.5 EUR and 587.5 EURO, respectively. The present value cost for a lifetime of 3 years (picoPV) and 25 years (SHS), including reinvestment, O&M and Management in the case of the SHS systems, are arround 89.4 EURO, 753 EURO and 1335 EURO for the three systems. In the often used USD/Wp metric the systems costs are 22.11 USD/Wp (5W picoPV), 18.62 USD/Wp (50W SHS) and 16.51 USD/Wp (100W SHS). These costs are on the upper end of the PV system prices found in the literature (see **Fehler! Verweisquelle konnte nicht gefunden werden.**), yet, as already discussed these prices in the literature are most of the time not reproducable, are usually outdated for SSA countries and often do not include reinvestment, O&M and Management costs. Furthermore, as Carrasco (2013) already highlighted, often rural electrification programs for SHS become unprofitable by underestimating O&M and Management costs. Thus, the calculated system prices are deemed to be a good basis for the further calculation of LCOE and monthly financing costs and estimation on affordability of these systems in SSA.

To access the costs of these systems compared to the main subsitute for electricity generation in rural off-grid areas, diesel, a LCOE calculation, including a sensitivity analysis was performed. The results of this calcuation are 7.11 EURO/kWh for the picoPV system, 1.69 EURO/kWh for the 50W SHS and 1.50 EURO/kWh for the 100W SHS (8.78 USD/kWh, 2.09 USD/kWh and 1.86 USD/kWh respectively). The SHS systems are in some areas cheaper than diesel (see map in Illustration 14). However, these areas are mostly in deserts or in very remote areas both with mostly very low population density (compare map in Illustration 14 with map in Illustration

2). The low population density reduces the possible consumer size and increases the cost of the distribution systems. This would suggest that SHS are mostly uncompetitive in SSA, yet, this paper due to its very broad regional scope (47 countries) and set irradiation level assumes that PV system cost and LCOE are the same for the whole region. In reality PV system costs or prices depend on many factors, the impact of some of those were analysed in the sensitivity analysis (e.g. irradiation, discount rate, battery lifetime, prices of PV panel and battery, and cost of O&M and Management).[13] The LCOE calcualtion for example uses an irradiation level on the lower end found in SSA. A 4000 Wh/m²d average irradiation was taken for the calculation, in SSA however, the average irradiation on an optimally inclined surface ranges from 3,500 to 7000 Wh/m²d (see Illustration 18). The sensitivity analysis clearly shows, that in areas with a 75% higher irradiation (7000 Wh/m²d) the LCOE would 75% lower, e.g. in the case of the 50W SHS LCOE costs would only be 0.375 EURO/kWh and thus be more competitive in many areas than previously mentioned. To truly assess the competitivness of off-grid PV systems with diesel generated electricity a spatial analysis, similar to the analysis of Szabo et al. (2012) should be performed (see Illustration 16). However, this was beyond the scope of this paper.

PicoPV system, on the other hand, shouldn´t be compared to diesel as it is no subsitute, but to the costs of kerosene and candles for lighting and batteries for lighting and mobile phone charging. Adkins et al. (2012) found in ten different millenium development villages in SSA that households spend in average arround 48 USD per year for lighting and electricity (Adkins et al., 2012). The assessed 5W picoPV system costs 89.4 EURO (or 111 USD) and has a minimum lifetime of 3 years. Thus, a picoPV system, with reasonable terms of finance, would be more economical than the alternatives and would also provide higher quality lighting, with less health impacts. In case of a 3 year financing period with a 10% per anno interest rate (without depreciation) the total costs amount to 133 USD, which is still cheaper than buying the alternatives (candles, kerosene, batteries) for 3 years.

Taking a closer look at the financing cost with 10% interest rate and varible financing periode, monthly costs for the picoPV system are 3 - 8.2 EURO (3.7 to 10.13 USD) with a 3 year and a one year financing period. For the 50W SHS system

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[13] Other factors indirectly impacting the costs are excluded in this paper (e.g. the market size, number of retailers, subsidies, taxes and import tariffs).

the financing cost are 6.91 EURO, 10.20 EURO and 30.85 EURO (8.55, 12.61 and 38.1 USD) for a 25 year, 5 year and 1 year financing period. The 100W SHS system with financing periods of 25 years, 10 years and 1 year have monthly financing costs of 12.26 EURO, 14.02 EURO and 53.85 EURO (15.15, 17.33 and 66.57 USD).

To see if these costs can be payed by the rural population in SSA, the affordability was estimated using income quinitle information of 43 countries (with calculated esitmations for 4 further countries), data on GDP per person, assuming a household size of 5 persons. The affordability again highly depends on the financing period, as the longer the financing period the lower the cost (at a low to medium interest rate). Factoring in lower incomes in rural areas 5W picoPV systems would be affordable for around 170 million (1 year financing period) to 360 million people (3 years financing period). Which are 36% and 76% of the rural population without access to electricity in SSA. For the 50W SHS system the number of people able to afford it are 200 million or 42% with a 25 year financing period, 138 million or 29% at 5 years and 31 million people or 7% at 1 year financing period. The 100W SHS is affordable for 115 million (or 24%) at 25 years, for 92 million (or 19%) at 10 years and 11 million (or 2%) at a one year financing period. This shows that even the cheapest system assessed, the 5W picoPV system, would only be affordable for 76% (without any subsidies) of the rural population without access to electricity.

6. Limitations

"Poor numbers fundamentally shape what we know about development in sub-Saharan Africa, which in turn shapes how decisions are made." (Jerven, 2013) This paper uses data provided by the World Bank, by the African Development Bank, by the International Energy Agency and by a number of other researchers. This data is mostly based on national statistics, thus often depends on data availability and often uses adjustments, revisions and estimates. This reduces the explanatory power of most of the presented outcomes in this paper.

There are also some limitations concerning the assumptions used and the calculations themself. SHS prices in the literature are most of the time not reproducable, are usually outdated for SSA countries and often do not include reinvestment, O&M and Management costs. Thus assuming costs based on recent literature and assuming these costs are the same in each country, is a necessary simplification, which however only allows to calculate an estimation of the number of people who are able to afford certain PV systems. Furthermore, the household budget calculation limitations are, outdated income data of SSA, no seperate income data for rural areas in SSA (which was tried to offset by including rural factors) and the assumption of a fixed household size. Additionally the affordability estimations are based on income quinitile information, which display income averages in 20% steps, and thus do not for example tell the income of the lowest 1%. It was further assumed that the 14% of the rural population with access to electricity are evenly split between the quintiles, which as can be seen in Annex II is not correct. Thus the calculated number of people who are able to afford a given system are just estimations.

7. Summary and Conclusion

Recently, universal access to modern energy services got more important on the international agenda, especially through the international targets for universal access to modern energy services. Sub-Saharan Africa lacks far behind other regions on this topic of providing energy access, especially in rural areas. This paper thus estimated the number of people who are able to afford different PV systems under different financing periods, to see the contribution PV can play for providing electricity access in rural areas.

Summarizing, the choice of technology for providing universal access to modern services in rural areas mainly depends on the cost of the different system applicable, as poverty is widespread. The assessed 5W picoPV system is competitive with the substitutes, kerosene, candles and batteries, in average households. It further is under good financing conditions (monthly payments, 3 years financing period, 10% interest rate) affordable for 75% of the rural population of SSA. SHS systems can be more economical than diesel in remote areas with high irradiation, but have only limited affordability, between 2 and 29% of the rural population without access to electricity, at reasonable financing periods, 1 to 10 years. Thus, the often in literature mentioned importance of modern financing or operation services, like fee for service, hire and lease or microcredit models can only be reaffirmed.

The results of this paper show that even the cheapest system assessed the 5W picoPV system, would only be affordable for 76% of the rural population without access to electricity, without any subsidies. Thus, if the target is a 100% electricity access rate, which means that electricity is the main source of lighting (see UN defintion), either cheaper systems have to be deployed or systems have to be subsidiesed in Low Income countries or specificially for low income households. The more expensive SHS systems are not affordable for most people in SSA even with very long financing periods and higher subsidies would therefore be necessary for universal access through this system. Moreover, SHS mostly also do not allow the electricity consumption on a level recommended by the IEA. Yet, as discussed before, SHS can be competitive and cheaper than diesel generation in remote areas with high irradiation.[14] Thus, SHS can be an important transition technology bridging the time until grid or micro-grid connection can be established.

[14] On a LCOE basis SHS would most of the time be more expansive than micro-grid PV systems, as larger systems have lower specific costs.

8. Bibliography

Abdullah S., and Jeanty P. W. (2011): Willingness to pay for renewable energy: Evidence from a contingent valuation survey in Kenya. Elsevier Ltd. Renewable and Sustainable Energy Reviews 15(6), 2974–2983. DOI: 10.1016/j.rser.2011.03.016.

Adkins E., Eapen S., Kaluwile F., Nair G., and Modi V. (2010): Off-grid energy services for the poor: Introducing LED lighting in the Millennium Villages Project in Malawi. Elsevier. Energy Policy 38(2), 1087–1097. DOI: 10.1016/j.enpol.2009.10.061.

Adkins E., Oppelstrup K., and Modi V. (2012): Rural household energy consumption in the millennium villages in Sub-Saharan Africa. International Energy Initiative. Energy for Sustainable Development 16(3), 249–259. DOI: 10.1016/j.esd.2012.04.003.

AfDB (2013a): Access to Services. African Economic Outlook- Statistical Annex. [Online] http://www.africaneconomicoutlook.org/en/data-statistics/table-15-access-to-services/ - accessed: July 1, 2013.

AfDB (2013b): Poverty and Income Distribution Indicators. African Development Bank - African Economic Outlook. [Online] http://www.africaneconomicoutlook.org/en/data-statistics/table-14-poverty-and-income-distribution-indicators/ - accessed: July 17, 2013.

Alleyne T. (2013): Energy Subsidy Reform in Sub-Saharan Africa: Experiences and Lessons., pp.119.

Anand S., Segal P., and Stiglitz J. E. (2009): Introduction: Debates on the Measurement of Global Poverty. (May), pp.35.

Anisuzzaman M., and Urmee T. P. (2006): Financing Mechanisms of Solar Home Systems for Rural Electrification in Developing Countries., pp.4.

ARE (2011): Rural Electrification with Renewable Energy - Technologies, quality standards and business models., Alliance for Rural Electrification, pp.56.

Banerjee S., Wodon Q., Diallo A., Pushak T., Uddin E., Tsimpo C., and Foster V. (2008): Access, affordability, and alternatives: Modern infrastructure services in Africa. (27740), pp.143.

Barnes D. (2005): Meeting the Challenge of Rural Electrification in Developing Nations: The Experience of Successful Programs. (March), pp.362.

Bazilian M., Onyeji I., Liebreich M., MacGill I., Chase J., Shah J., Gielen D., Arent D., Landfear D., and Zhengrong S. (2013): Re-considering the economics of photovoltaic power. Elsevier Ltd. Renewable Energy 53, 329–338. DOI: 10.1016/j.renene.2012.11.029.

Belward A., Bisselink B., Bódis K., Brink A., Dallemand J., Roo A. De, Huld T., Kayitakire F., Mayaux P., Ossenbrink H., Pinedo I., Sint H., Thielen J., Szabó S., Tromboni U., Willemen L., and Monforti E. F. (2011): Renewable energies in Africa. Luxembourg., pp.62. DOI: 10.2788/1881.

Carrasco L. M., Narvarte L., and Lorenzo E. (2013): Operational costs of A 13,000 solar home systems rural electrification programme. Elsevier. Renewable and Sustainable Energy Reviews 20, 1–7. DOI: 10.1016/j.rser.2012.11.073.

Chambouleyron I. (1996): Photovoltaics in the developing world. Energy 21(5), 385–394. DOI: 10.1016/0360-5442(95)00118-2.

Chaurey A., and Kandpal T. C. (2010): Assessment and evaluation of PV based decentralized rural electrification: An overview. Elsevier Ltd. Renewable and Sustainable Energy Reviews 14(8), 2266–2278. DOI: 10.1016/j.rser.2010.04.005.

Chuhan-Pole P., Christiaensen L., Angwafo M., Buitano M., Dennis A., Korman V., Sanoh A., and Ye X. (2013): Africa´s Pulse - An analysis of issues shaping Africa´s economic future. 7(April), pp.28.

CIESIN, and CIAT (2013): Africa: Population Density, 2000. Gridded Population of the World. [Online] http://sedac.ciesin.columbia.edu/downloads/maps/gpw-v3/gpw-v3-population-density/africadens.jpg - accessed: July 15, 2013.

Deichmann U., Meisner C., Murray S., and Wheeler D. (2010): The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa. (January), pp.69.

Deloitte, and GSMA (2012): Sub-Saharan Africa Mobile Observatory 2012. (November), pp.91.

DFID (2002): Energy for the Poor., Department for International Development, pp.32.

Disch D., and Bronckaers J. (2012): An analysis of the off-grid lighting market in Rwanda: sales, distribution and marketing. London, United Kingdom. (July), pp.46.

Djamin M., Salim Dasuki A., Yusak Lubis A., and Alyuswar F. (2001): Application of photovoltaic systems for increasing villagers' income. Renewable Energy 22(1-3), 263–267. DOI: 10.1016/S0960-1481(00)00023-9.

EIU (2013): Democracy Index 2012 Democracy at a standstill., Economist Intelligence Unit, pp.45.

Ellegård A., Arvidson A., Nordström M., Kalumiana O. S., and Mwanza C. (2004): Rural people pay for solar: experiences from the Zambia PV-ESCO project. Renewable Energy 29(8), 1251–1263. DOI: 10.1016/j.renene.2003.11.019.

EPIA and Greenpeace (2011): Solar generation 6 - Solar photovoltaic electricity empowering the world. European Photovoltaic Industry Association and Greenpeace, Brussels, Belgium and Amsterdam, Netherlands., pp.100.

Escribano A., Guasch J. L., and Pena J. (2010): Assessing the Impact of Infrastructure Quality on Firm Productivity in Africa - Cross-Country Comparisons Based on Investment Climate Surveys from 1999 to 2005. (January), pp.117.

ESMAP (2007): Technical and Economic Assessment of Off-grid , Mini-grid and Grid Electrification Technologies. (December), Energy Sector Management Assistance Program, The World Bank, pp.100.

Foster V. (2008): Overhauling the Engine of Growth: Infrastructure in Africa. (September), pp.26.

Freedom House (2013a): Freedom in the World 2013. Freedom in the World. [Online] http://www.freedomhouse.org/report/freedom-world/freedom-world-2013 - accessed: July 7, 2013.

Freedom House (2013b): Freedom in the World 2013: Democratic breakthroughs in the balance., pp.17.

Grameen Shakti (2013): Solar Home System. Homepage. [Online] http://www.gshakti.org/index.php?option=com_content&view=article&id=58&Itemid=62

GTZ (2009): Solar Lanterns Test : Solar lanterns test: Shades of light., Gesellschaft für Technische Zusammenarbeit, Eschborn, pp.14.

GTZ (2010): What difference can a PicoPV system make? Gesellschaft für Technische Zusammenarbeit, Eschborn, pp.28.

Huacuz J., Flores R., Agredano J., and Munguia G. (1995): Field performance of lead-acid batteries in photovoltaic rural electrification kits. Solar Energy 55(4), 13.

Huld T., Šúri M., Dunlop E., Albuisson M., and Wald L. (2005): Integration of HelioClim-1 database into PVGIS to estimate solar electricity potential in Africa. Proceedings from 20th European Photovoltaic Solar Energy Conference and Exhibition, 6-10 June 2005. Barcelona, Spain. [Online] http://re.jrc.ec.europa.eu/pvgis/

IEA (2012): World Energy Outlook 2012. OECD/IEA 2012 (Ed.). International Energy Agency , Paris, France. ISBN: 9789264180840.

IEA (2013): Defining and modelling energy access World Energy Outlook. International Energy Agency. [Online] http://www.worldenergyoutlook.org/resources/energydevelopment/definingandmodellingenergyaccess/ - accessed: June 17, 2013.

IEA (2011): World Energy Outlook - Energy for all - Financing access for the poor. International Energy Agency (October), pp.52.

IEA and OECD - (2010): Projected Costs of Generating Electricity. International Energy Agency and Organisation for Economic Cooperation and Development, Paris, France., pp.218.

IEG (2008): The welfare impact of Rural Electrification: A Reassessment of the Costs and Benefits., Independent Evaluation Group from the World Bank, pp.178. ISBN: 9780821373675.

IIASA, UNIDO, and GEF (2013): Access to Modern Energy Assessment and Outlook for Developing and Emerging Regions, International Institute for Applied Systems Analysis, United Nation Industrial Development Organisation, Global Environmental Facility (Ed.)., pp.60. ISBN: 9781107005198.

IMF (2008): Regional Economic Outlook Sub-Saharan Africa., International Monetary Fund, pp.145. ISBN: 9781589067110.

IMF (2012): Regional Economic Outlook Sub-Saharan Africa - Sutstaining Growth amid Global Uncertainty., International Monetary Fund, pp.137. ISBN: 9781616352493.

IMF (2013): Regional Economic Outlook - Sub-Saharan Africa - Building Momentum in a Multi-Speed World., International Monetary Fund, pp.117. ISBN: 9781484365151.

IPCC (2012): Renewable Energy Sources and Climate Change Mitigation - Special Report., Intergovernmental Panel on Climate Change, pp.1088. ISBN: 9781107607101.

IRENA (2011a): Presentation: Renewable Energy - Power Sector Costing Study., International Renewable Energy Agency, pp.34.

IRENA (2011b): Scenarios and Strategies for Africa., International Renewable Energy Agency, pp.36.

IRENA (2012a): Prospects for the African Power Sector - Scenarios and strategies for Africa project., International Renewable Energy Agency, pp.60.

IRENA (2012b): Renewable energy technologies: cost analysis series: Solar Photovoltaics. International Renewable Energy Agency, Abu Dhabi, United Arab Emirates. 1(4), pp.52.

IRS (2013): Yearly Average Currency Exchange Rates. Internal Revenue Service United States of America, homepage. [Online] http://www.irs.gov/Individuals/International-Taxpayers/Yearly-Average-Currency-Exchange-Rates - accessed: July 26, 2013.

Jerome A. (2011): Infrastructure, Economic Growth and Poverty Reduction in Africa, Nigeria Governors Form Secretariat, Abuja, Nigeria

Jerven M. (2013): Poor Numbers - How We Are Misled by African Development Statistics and What to Do about it. Cornell University Press, Ithaca and London.

JRC (2013): African Renewable Energy Technology Platform. AFRETEP. Joint Research Center European Commission, [Online] http://www.euei.net/wg/african-renewable-energy-technology-platform-afretep - accessed: April 26, 2013.

JRC-PVGIS (2013): Photovoltaic Geographical Information System - Interactive Map: Europe PV Estimation - help. - Joint Research Center European Commission - PVGIS Project European Union. [Online] http://re.jrc.ec.europa.eu/pvgis/apps4/PVcalchelp_en.html - accessed: May 5, 2013.

Kangas A., and Lucas B. (2011): Helpdesk Research Report: Political Trends in Sub-Saharan Africa. GSDRC - Governance and Social Development Resource Centre., pp.1–9.

Karekezi S., and Kithyoma W. (2002): Renewable energy strategies for rural Africa: is a PV-led renewable energy strategy the right approach for providing modern energy to the rural poor of sub-Saharan Africa? Energy Policy 30(11-12), 1071–1086. DOI: 10.1016/S0301-4215(02)00059-9.

Lysen E. (2013): Pico Solar PV Systems for Remote Homes Pico Solar PV Systems for Remote., pp.35. ISBN: 9783906042091.

Martinot E., Cabraal A., and Mathur S. (2001): World Bank / GEF solar home system projects: experiences and lessons learned 1993 – 2000 1. Renewable and Sustainable Energy Revies 5, 39–57. ISBN: 1202473016.

Miller D., and Hope C. (2000): Learning to lend for off-grid solar power: policy lessons from World Bank loans to India , Indonesia , and Sri Lanka. Energy Policy 28(28), 87–105.

Monari L. (2011): Financing Access at the World Bank, IEA Workshop on Financing Energy Access for the Poor, May 13, 2011 – Paris

Moner-girona M., Ghanadan R., and Kammen D. M. (2006): Decreasing PV costs in Africa: Opportunities for Rural Electrification using solar PV in Sub-Saharan Africa. Refocus (February), 40–45.

Muntasser M., Bara M., Quadri H., EL-Tarabelsi R., and La-azebi I. (2000): Photovoltaic marketing in developing countries. Applied Energy 65(1-4), 67–72. DOI: 10.1016/S0306-2619(99)00094-X.

Nemet G. F. (2006): Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34(17), 3218–3232. DOI: 10.1016/j.enpol.2005.06.020.

Nieuwenhout F. D., Dijk A. Van, Dijk V. A. Van, Hirsch D., Lasschuit P., and Roekel G. Van (2000): MONITORING AND EVALUATION OF Experiences with applications of solar PV for households in developing countries Acknowledgement / Preface. (September), pp.157.

Nieuwenhout F. D. J., Van Dijk A., Lasschuit P. E., Van Roekel G., Van Dijk V. a. P., Hirsch D., Arriaza H., Hankins M., Sharma B. D., and Wade H. (2001): Experience with solar home systems in developing countries: a review. Progress in Photovoltaics: Research and Applications 9(6), 455–474. DOI: 10.1002/pip.392.

Notton G., Muselli M., and Poggi P. (1998): Costing of a stand-alone photovoltaic system. Energy 23(4), 289–308. DOI: 10.1016/S0360-5442(97)00092-3.

Nygaard I. (2009): The compatibility of rural electrification and promotion of low-carbon technologies in developing countries - the case of Solar PV for Sub-Saharan Africa. European Review of Energy Markets 3(2), 1–34.

Obeng G., Akuffo F., Braimanh I., Evers H., and Mensah E. (2008): Impact of solar photovoltaic lighting on indoor air smoke in off-grid rural Ghana. Energy for Sustainable Development XII(1), 55–61.

OECD (2009): Increasing Private Investment in African Countries, Organisation for Economic Cooperation and Development, pp.19.

Ondraczek J. (2011): The Sun Rises in the East (of Africa): A Comparison of the Development and Status of the Solar Energy Markets in Kenya and Tanzania. Hamburg, Germany., pp.64.

Onyeji I., Bazilian M., and Nussbaumer P. (2012): Contextualizing electricity access in sub-Saharan Africa. International Energy Initiative. Energy for Sustainable Development 16(4), 520–527. DOI: 10.1016/j.esd.2012.08.007.

Posorski R., Bussmann M., and Menke C. (2003): Does the use of Solar Home Systems (SHS) contribute to climate protection? Renewable Energy 28, 1061–1080.

Ravallion M. (2003): The Debate on Globalization , Poverty and Inequality : Why Measurement Matters. International Affairs 79(4), 739–753.

Ravallion M. (2010): World Bank's $1.25/day poverty measure- countering the latest criticisms. Research at the World Bank. [Online] http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/0,,conte ntMDK:22510787~pagePK:64165401~piPK:64165026~theSitePK:469382,00.html - accessed: July 11, 2013.

Ravallion M. (2011): The Two Poverty Enlightenments - Historical Insights from Digitized Books Spanning. (January), pp.52.

Ravallion M. (2012): Poverty Lines Across the World. In: Oxford Handbook of the Economics of Poverty, p. 849.

REN21 (2010): Renewables 2010 - Global Status Report. Renewable Energy Policy Network for the 21st Century , Paris, France., pp.80.

REN21 (2011): Renewables 2011 - Global Status Report., Renewable Energy Policy Network for the 21st Century, pp.116.

Rosnes O., and Vennemo H. (2009): Powering Up: Costing Power Infrastructure Spending Needs in Sub-Saharan Africa. 5(March), pp.179.

Van Ruijven B. J., Schers J., and Van Vuuren D. P. (2012): Model-based scenarios for rural electrification in developing countries. Elsevier Ltd. Energy 38(1), 386–397. DOI: 10.1016/j.energy.2011.11.037.

Sabah S. M. A. (2009): Willingness to pay for renewable energy options in developing countries: the case of Kenya. University of Bath. pp.337.

Solarbuzz (2012a): Battery Prices. Battery Prices. [Online] http://www.solarbuzz.com/facts-and-figures/retail-price-environment/battery-prices

Solarbuzz (2012b): Charge Controller Prices. Charge Controller Prices. [Online] http://www.solarbuzz.com/facts-and-figures/retail-price-environment/charge-controller-prices

Solarbuzz (2012c): Module Pricing. Module Pricing. [Online] http://www.solarbuzz.com/facts-and-figures/retail-price-environment/module-prices

Sundaram J. K., and Schwank O. (2011): Globalization and development in sub-Saharan Africa. 24(102), pp.44.

Svoboda V., Wenzl H., Kaiser R., Jossen A., Baring-Gould I., Manwell J., Lundsager P., Bindner H., Cronin T., Nørgård P., Ruddell A., Perujo A., Douglas K., Rodrigues C., Joyce A., Tselepis S., Van der Borg N., Nieuwenhout F., Wilmot N., Mattera F., and Sauer D. U. (2007): Operating conditions of batteries in off-grid renewable energy systems. Solar Energy 81(11), 1409–1425. DOI: 10.1016/j.solener.2006.12.009.

Szabó S., Bódis K., Huld T., and Moner-Girona M. (2011): Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension. Environmental Research Letters 6(3), 034002. DOI: 10.1088/1748-9326/6/3/034002.

The World Bank (2008): Issue note - REToolkit: A Resource for Renewable Energy Development., pp.174. [Online] http://siteresources.worldbank.org/INTRENENERGYTK/Resources/REToolkit_issues_note.pdf, Washington, U.S.

The World Bank (2011): Africa´s Power Infrastructure - Investment, Integration, Efficiency., pp.352. Washington, U.S.

The World Bank (2013): Income share held by quintiles. Data. [Online] http://data.worldbank.org/topic/poverty - accessed: July 15, 2013. Washington, U.S.

Themner L., and Wallensteen P. (2012): Armed Conflicts, 1946-2011. Journal of Peace Research 49(4), 565–575. DOI: 10.1177/0022343312452421.

Thermie B. S. 995-96 (1998): Universal Technical Standard for Solar Home Systems., pp.61.

UN (2013a): Global Tracking Framework - Data Annex., United Nations, pp.29.

UN (2013b): World Population Prospects: The 2012 Revision. United Nations, Depeartment of Economic and Social Affairs, Population Division..

UN, ESMAP, and IEA (2013): Global Tracking Framework - Sustainable Energy for All., United Nations, Energy Sector Managment Assistance Program, and International Energy Agency pp.261.

UNDP (2009): The energy access situation in developing countries: A Review Focusing on the Least Developed Countries and Sub-Saharan Africa., United Nations Development Program , pp.142.

UNDP and ESMAP (2002): Rural Electrification and Development in the Philippines : Measuring the Social and Economic Benefits. (May), United Nations Development

Program, and Energy Sector Assistance Managment Program - the World Bank, pp.169.

UNECA, AU, and UNDP (2013): Executive Sumary: MDG Report 2013 - Assessing Progress in Africa toward the Millennium Deelopment Goals., United Nation Economic Commission for Africa, African Union and United Nations Development Program, pp.25.

UN-Energy (2011): Energy for Sustainable Development: Policy Options for Africa. New York., pp.116.

UNEP (2012): Financing renewable energy in developing countries - Drivers and barriers for private finance in sub-Saharan Africa. (February), United Nations Environmental Program , pp.56.

UN-STAT - U (2012): Composition of Macro Geographical Regions. UN Nations Statistics Division. nited Nations Statistics Devision. [Online] http://unstats.un.org/unsd/methods/m49/m49regin.htm - accessed: July 6, 2013.

Uwimana C. (2011): Corruption Perceptions Index 2011: A call to action. Blog. [Online] http://blog.transparency.org/2011/11/30/corruption-perceptions-index-2011-a-call-to-action/ - accessed: July 7, 2013.

Wamukonya N. (2007): Solar home system electrification as a viable technology option for Africa's development. Energy Policy 35(1), 6–14. DOI: 10.1016/j.enpol.2005.08.019.

Welle-Strand A., Ball G., Hval M. V., and Vlaicu M. (2012): Electrifying solutions: Can power sector aid boost economic growth and development? International Energy Initiative. Energy for Sustainable Development 16(1), 26–34. DOI: 10.1016/j.esd.2011.11.001.

Werner C., Gerlach A., Adelmann P., and Breyer C. (2011): Global cumulative installed photovoltaic capacity and respective international trade flows. 26th European Photovoltaic Solar Energy Conference, Hamburg, Germany. pp. 5–9.

Wikipedia (2011): Forms of government. online. [Online] http://en.wikipedia.org/wiki/File:Forms_of_government.svg - accessed: July 6, 2013.

World Bank (2006): Technical and Economic Assessment of Off-Grid , Mini-Grid and Grid Electrification Technologies Annexes. Washington, D.c., U.S.A. (September), pp.155.

World Bank (2008): Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices. (November), pp.32.

World Bank (2010a): Addressing the Electricity Access Gap. (June), pp.98.

World Bank (2010b): The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa. (January), pp.69.

World Bank (2013a): Country classification. Methodology. [Online] http://data.worldbank.org/about/country-classifications - accessed: July 15, 2013.

World Bank (2013b): Data Sub-Saharan Africa. Homepage2. [Online] http://data.worldbank.org/region/sub-saharan-africa - accessed: July 15, 2013.

Yordi B., Gillett W., Edwards H., Blaesser G., and Gerhold V. (1996): THE COMMISSION OF THE EUROPEAN COMMUNITIES' (EC) DEMONSTRATION AND THERMIE PROGRAMMES FOR PHOTOVOLTAIC (PV) APPLICATIONS. Solar Energy 59(96), 59–66.

Zweibel K. (2010): Should solar photovoltaics be deployed sooner because of long operating life at low, predictable cost? Elsevier. Energy Policy 38(11), 7519–7530. DOI: 10.1016/j.enpol.2010.07.040.

9. List of illustrations

10. List of tables

11. Annex

11.1. Annex I

Table 24: International standards for small standalone PV systems and components, (ARE, 2011)

Components	International Standards and Explanation
Panels	IEC 61215 Ed. 2.0: Crystalline silicon terrestrial photovoltaic modules - Design qualification and type approval. IEC 61646 Ed. 1.0:Thin-film terrestrial photovoltaic modules - Design qualification and type approval.
Charge Controllers	IEC 62509 Ed.1: Performance and functioning of photovoltaic battery charge controllers IEC 62109: Safety of power converters for use in photovoltaic power systems. Part 1: General requirements, Part 3: Controllers IEC 62093 Ed. 1.0: BOS components - Environmental reliability testing - Design qualification and type approval. IEC CISPR 11:1990, Limits and methods of measurement of electromagnetic disturbance characteristics of industrial, scientific and medical (ISM) radio-frequency equipment. IEC 61000-4:1995, Electromagnetic compatibility (EMC). Part 4:Testing and measurement techniques, Sections 2-5. PV GAP, PVRS6A "Charge controllers for photovoltaic stand-alone systems with a nominal voltage below 50V" accepted for use in the IECEE PV scheme.
Inverters	IEC 61683 Ed. 2.0: Photovoltaic systems - Power conditioners - Procedure for measuring efficiency IEC 62109 Safety of power converters for use in photovoltaic power systems. Part 1: General requirements. Part 2: Particular requirements for inverters. IEC 62093 Ed. 1.0: BOS components - Environmental reliability testing - Design qualification and type approval. IEC CISPR 11:1990, Limits and methods of measurement of electromagnetic disturbance characteristics of industrial, scientific and medical (ISM) radio-frequency equipment. IEC 61000-4:1995, Electromagnetic compatibility (EMC). Part 4:Testing and measurement techniques, Sections 2-5. PV GAP, PVRS 8A "Inverters for photovoltaic stand-alone systems."
Energy-efficient lights	IEC 60969 Ed 2: Self ballasted lamps for general lighting purposes - Performance Requirements. IEC 61347-1: 2007, Lamp control gear. Part 1: General and safety requirements. IEC 61347-2: Lamp control gear. Part 3: Particular requirements for AC-supplied electronic ballasts for fluorescent lamps, Part 4: Particular requirements for DC-supplied electronic ballasts for general lighting. PV GAP, PVRS7A "Lighting systems with fluorescent lamps for photovoltaic stand-alone systems with a nominal voltage below 24 V."
BOS components and minor equipments	IEC 60669-1: Switches for household and similar fixed-electrical installations. Part 1: General requirements. IEC 60227-1-4: Polyvinyl chloride insulated cables of rated voltage up to and including 450V/750 V-Parts 1-4: General requirements

11.2. Annex II

Table 25: Access to electricity in selected SSA countries, source (Banerjee et al., 2008)

Table A1.2.5 Electricity

Percentage population	By time period (national)			By location		By expenditure quintile				
	Early 1990s	Late 1990s	Early 2000s	Rural	Urban	1st	2nd	3rd	4th	5th
By country										
Benin	—	14	22	6	51	0	1	3	24	82
Burkina Faso	6	6	10	1	54	0	0	1	2	57
C. African Rep	5	—	—	1	11	0	0	0	1	25
Cameroon	31	42	46	16	77	1	14	37	78	98
Chad	—	3	4	0	20	0	0	0	0	21
Comoros	—	30	—	21	54	0	7	17	48	84
Congo, Rep.	—	—	35	16	51	5	14	20	47	88
Cote d'Ivoire	39	50	—	27	90	4	19	41	87	100
Ethiopia	—	11	12	2	86	0	0	1	3	56
Gabon	—	75	—	31	91	17	69	93	98	99
Ghana	28	39	44	21	77	8	39	28	57	90
Guinea	—	17	21	3	63	0	0	4	18	83
Kenya	9	12	13	4	51	0	0	1	7	57
Lesotho	—	—	6	1	28	0	0	0	1	27
Madagascar	9	11	19	10	52	0	0	1	11	82
Malawi	4	6	7	2	34	0	1	0	3	34
Mali	—	8	13	3	41	1	3	2	5	54
Mauritania	—	—	23	3	51	0	2	5	29	81
Mozambique	—	10	11	1	30	0	0	1	4	51
Namibia	20	32	—	10	75	1	1	6	51	100
Niger	6	8	—	0	41	0	0	0	4	36
Nigeria	26	45	51	35	84	10	37	40	78	91
Rwanda	2	7	5	1	27	0	0	1	1	25
Senegal	25	32	46	19	82	4	12	46	76	94
South Africa	—	63	—	36	86	10	36	74	98	100
Tanzania	6	7	11	2	39	0	0	0	3	50
Togo	—	15	—	2	44	0	0	2	10	62
Uganda	7	—	8	3	47	0	0	2	2	38
Zambia	23	20	20	3	50	0	0	0	15	84
Zimbabwe	23	34	—	7	90	0	12	12	50	97
Congo, Dem. Rep.	—	—	—	—	—	—	—	—	—	—
Sudan	—	—	—	—	—	—	—	—	—	—
By income group										
Low income	17	24	27	11	69	3	12	15	32	68
Middle income	59	55	53	27	81	7	28	59	86	97
By urbanization										
Low	8	8	11	3	56	0	0	1	4	52
Medium	24	30	28	3	48	0	1	2	11	60
High	37	47	51	30	83	8	32	45	79	94
By subregion										
East	17	24	27	2	60	0	0	1	3	53
West	25	37	43	20	78	6	23	27	55	80
South	36	37	35	13	66	4	14	28	42	77
Central	25	28	29	8	66	1	11	20	47	76
Overall	23	28	31	12	71	4	14	20	38	72

Source: AICD DHS/MICS Database, 2007.

Note: Location and expenditure quintile data is for the latest available year. Shaded 'Trends in Access' figures are based on Method 3 (Annex A1.1.5).