The Electricity Economics of Solar Powered Electricity Generation for Augmenting Grid Electricity Supply and Rural Electrification

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ABSTRACT

This study aims to assess the economic feasibility of introducing solar photovoltaic (PV) facilities in capital constrained African countries. This is carried out in the context of the falling prices and costs of the solar PV technology. The economic analyses are done comparing solar PV technology with the low-carbon fossil fuel technologies such as combined cycle (CC), and diesel power plants in terms of their economic net present values (ENPV) and environmental impacts. The economic analyses are carried for both on-grid and off-grid applications of solar PV technology.

The feasibility of off-grid solar PV systems in sub-Saharan Africa (SSA) is analysed focusing on five major issues: cost-effectiveness, affordability, financing, environmental impact, and poverty alleviation. Solar PV power systems are found to be an extremely costly source of electricity for the rural poor in SSA. It is estimated that it will take at least 16.8 years for solar PV systems to become competitive with conventional small diesel generators. Moreover, the cost of reducing CO_2 emissions through solar PV electrification is far in excess of the estimated marginal economic cost of CO_2.

In this context, investing in thermal plants powered by heavy fuel oil (HFO) would be two times as effective in reducing GHG as the same value of investment in solar PV plants. The results show that ENPV is negative for solar PV plant, whereas it is a large positive value for the thermal plants. Even if solar investment costs fall as anticipated, in such a situation without subsidies it will take 9 to 28 years of continuous decline before solar generation technology will become cost-effective for many electric utilities in Africa.

Given the current costs of solar PV plants and the falling prices of solar PV systems, it is not advisable for such electric utilities in Africa to invest in this technology (unless subsidized from abroad) until the solar PV plants become competitive with thermal plants. If unsubsidized, it is the relatively poor consumers of Africa who will pay for these inefficient technological choices.

Keywords: Solar PV, Electricity Generation, Africa, Greenhouse Gas Mitigation, Cost-Benefit Analysis.

ÖZ

Bu çalışmanın amacı güneş enerjisi ile çalışan elektrik panellerinin bütçe kısıtı olan Afrika ülkeleri icin fizibilitesini ortaya çıkarmaktır. Analiz gerçekleştirilirken son dönemlerdeki güneş panellerinin maliyet ve fiyatlarının düşüşü dikkate alınmıştır. Ekonomik analiz gerçekleştirilirken güneş panelleri teknolojisi ile düşük karbon salınımlı fosil yakıt teknolojili kombine edilmiş enerji modeli ile, dizel güç panelleri net mevcut değer ve çevresel etki bağlamında karşılaştırılmıştır. Ekonomik analiz aynı zamanda güneş panallerinin hem kapalı hem de açık şebeke uygulamaları için yapılmıştır.

Kapalı güneş panelleri şebekelerinin fizibilitesi Sahra altı Afrika ülkelerinde beş önemli sorun dikkate alınarak gerçekleştirilmiştir: maliyet etkinligi, ödenebilirlik, finansman, çevresel etki ve fakirliğin giderilmesi.. Analiz sonucunda kırsal kesim Sahra altı Afrika'sı için güneş panelleri son derece maliyetli bulunmuştur. Çalışma bulgulari en azından 16.8 yıllık bir sürecin, güneş panellerinin geleneksel küçük dizel jeneratorler ile rekabetçi hale gelebilmesi için geçmesi gerektiğine işaret etmektedir. Dahası, karbondioksit emisyonlarini güneş panelleri aracılığı ile düşürmenin maliyetinin, emisyonların marjinal ekonomik maliyetinden daha yüksek olduğunu analiz sonuçları ortaya koymaktadır.

Bu bağlamda, seragazlarını azaltmak maksatlı yatırımı ağır yakıt kullanan termal ünitelere gercekleştirmenin maliyeti, güneş panellerine yönelik yatırımın maliyetinin yarısı kadardır. Ampirik bulgular net mevcut değerin güneş panelleri için negatif, termal üniteler içinse pozitif olduğunu vurgulamaktadır. Günes panellerinin

maliyetlerinin düşmesi beklenmektedir. Bu durumun gerçekleşmesi durumunda bile panellerin elektrik üretiminde rekabetçi bir yapıya ulasması için 9 ila 28 yıllık bir sürece ihtiyaç duyulmaktadır.

Güneş panellerinin güncel maliyetleri altında ve fiyatlarindaki süre gelen ucuzlamaya rağmen hala bu teknolojiler Afrika için tavsiye edilememektedir. Güneş panelleri ancak dışarıdan subvansiye edilirlerse Afrika için doğru bir tercih olabilir. Eğer dışarıdan subvansiyonlar gercekleşmezse Afrika için güneş panellerinin yüklenmesi maliyetli ve ekonomik açidan yanlış tercihler olacaktır.

Anahtar kelimeler: Güneş Panelleri, Elektrik Üretimi, Afrika, Seragazı Antlaşmaları, Maliyet-Fayda Analizleri.

To My Family

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LIST OF ABBREVIATIONS

CC	Combined Cycle
CDM	Clean Development Mechanism
CO_2	Carbon Dioxide
EIRR	Economic Internal Rate of Return
ENPV	Economic Net Present Value
ESCO	Energy Service Company
GHG	Greenhouse Gas Emissions
IRR	Internal Rate of Return
kWh	Kilowatt hour
MW	Megawatt
MWh	Megawatt hour
MW_p	Megawatt peak
NPV	Net Present Value
PR	Performance ratio
PV	Photovoltaic
SHS	Solar Home System
SSA	sub-Saharan Africa
W_p	Watt peak

Chapter 1

INTRODUCTION

Worries about climate change, high oil prices and government subsidies have increased the popularity of electricity generation from solar, wind and other renewable sources over the past decade. As a consequence, governments and international development organisations have supported renewable energy projects worldwide. Many of these projects are in low-income African countries where the electrification coverage is low and their power generation systems are small. The African continent has an overall electrification rate of only 41.8%, with 585.2 million people not having any access to electricity. Except for the five North African countries (Algeria, Egypt, Libya, Morocco and Tunisia) and Mauritius, the rest of the countries in Africa have very low electrification rates (IEA, 2011).

According to the World Bank (2014) some 25 countries in sub-Saharan Africa (SSA) are facing a power crisis today. Insufficient generation capacity, low capacity utilization and availability factor, inadequate maintenance, insufficient acquisition of spare parts, severe electrical power outages, and high transmission and distribution losses are among the most common problems faced by many power utilities in Africa (Eberhard et al., 2008; Eberhard et al., 2011; Eberhard and Shkaratan, 2012; IMF, 2013; Iwayemi, 2002; Karakezi and Kimani, 2002; Mkhwanazi, 2003; UNIDO, 2009, World Bank, 2010).

The financial performance of most power utilities in Africa are poor, many of which are heavily indebted due to the inability of the utility to collect enough revenues, and tariffs that are lower than the costs. Along with the debt owed by customers, Government and its parastatals' mostly happened to constitute the large amount of the utility debt (Karakezi and Kimani, 2002). Most power utilities in Africa remain state owned (Eberhard et al., 2008; Eberhard et al., 2011; Eberhard and Shkaratan, 2012; IMF, 2013; Iwayemi, 2002; Karakezi and Kimani, 2002; Mkhwanazi, 2003; UNIDO, 2009, World Bank, 2010). They are severely capital rationed. Governments are constrained in their ability to borrow for the expansion of electricity capacity (UNEP 2014; UNIDO and ECREEE, 2012). The constraint on private sector economic development in the region is to a considerable extent due to the lack of a reliable electricity supply. Power systems are facing a shortage of capacity and the frequent blackouts and brownouts are a consequence of system failures. Due to the heavy indebtness of their governments, sufficient capital has not been available to make the investments in the power sector to correct the problem. This borrowing constraint has led to a situation where the mix of generation capacity technologies installed in the past is often far from that which would allow the utilities to generate electricity at least cost. The situation is expected to worsen over time as the demand for electricity grows. This has been recognised as being a critical issue for the economic development of Africa (USAID East Africa, 2010).

Power utilities in Africa have deficient electricity generation capacity, with about three quarters of it located in North Africa and South Africa[1]. Total installed generation capacity in the 47 sub-Saharan African (SSA) countries, excluding

[1]Generation capacity of North Africa (Algeria, Egypt, Libya, Morocco and Tunisia) and South Africa (The Republic of South Africa) are 57 and 44 GW respectfully (EIA, 2011).

Republic of South Africa, is around 36 gigawatts (GW) about the same as Sweden's (EIA, 2011). About a quarter of this capacity is not available due to aging plants and poor maintenance (World Bank, 2010). Yepes and Pierce, and Foster (2008) compares Africa with South Asia to demonstrate the inability of the former to converge with the rest of the developing world in terms of power generating capacity expansion. Although Africa has started with triple that of South Asian generating capacity (per million people) in 1980, by 2000 South Asia had nearly twice as much generation capacity (per million people) as Africa. Africa was indeed the slowest in expanding the generating capacity than any other region in the developing world.

Annual average growth rate of GDP in SSA of between 2000 and 2010 has been estimated as 5.2% (AfDB, 2013a; World Bank, 2013), the demand for electricity increased at the similar rate, yet generation capacity grew at barely 2.6% per year[2]. Based on historic trends, demand is forecasted to grow at 5% annually in SSA (Eberhard et al., 2011). Electricity supply has to grow with similar rate as GDP so that it does not become a constraint to economic growth. Therefore, the power sector in Africa needs to build an additional 7000 megawatts (MW) each year in order to satisfy the overwhelming demand, to keep up with the economic growth, and to expand the electrification rate. The amount of expenditure in the power sector is currently US$ 11.6 billion, or just little more than the one-quarter of what is required (World Bank, 2010).

[2]This is an author's estimate based on the EIA (2011) International energy statistics data between 2000 and 2011. Angola, Benin, Cape Verde, Comoros, Equatorial Guinea, Ethiopia, Sudan and South Sudan were excluded as the outliers with growth rates of 10 to 16 percent.

Electricity generation technologies that are renewable in nature are appealing to many developing countries, including some African countries, as they have the potential to attract subsidised financing from donors. Some African countries have ambitious goals of increasing the share of renewable energy generation, especially of grid connected solar photovoltaic (PV) technology. For example, Cape Verde is planning to increase the share of renewable energy generation to 50% till 2020, Mauritius to 65% till 2028, and Madagascar to 75% up to year of 2020 (UNEP, 2012). The National Energy Plan for Kenya outlines the expectations of installed PV capacity to increase to 100 MW_p in 2016, to 200 MW_p in 2022, and to 500 MW_p in 2030 (UNEP, 2014). Some utility scale solar PV projects have been already developed and others are underway. For example, Masdar built a 15MW solar PV power plant in the Islamic Republic of Mauritania in 2013. This is the first utility-scale solar power installation in Mauritania. SolarReserve announced in 2014 the completion of South Africa’s 96 MW Jasper solar PV power plant, and it is now fully operational. Scatec Solar has won a contract from the Ghanian government to build a 50 MW solar PV power plant in the country. The project has been scheduled to become operational by 2015.

Recently solar PV system costs have been falling rapidly worldwide. These system costs have decreased mainly as a result of falling module prices, the biggest cost component of the PV system. The installed system costs have also decreased as a result of decreasing non-module costs. As module costs have fallen at a much faster rate than non-module costs, they have decreased as a share of total system costs.

Global markets exist for the separate hardware parts of the PV systems, such as modules, inverters, and cables. As a consequence, the prices of these hardware parts do not differ much around the world, yet total solar PV system costs vary significantly worldwide, by continent, and by country. This can be attributed to different levels of maturity and competition in local PV markets, to dissimilar regulations and permission fees, and to the existence or absence of various incentives for the development of PV technology (Barbose et al., 2013; Bazilian et al., 2013; Chase, 2013; Jäger-Waldau, 2013; Salvatore, 2013). Compared to other conventional power-generation technologies, solar PV markets are still in an early phase of development. They are expected to converge as the market matures (Barbose et al., 2013; IHS, 2011).

The decreasing trend in solar PV system costs is expected to continue, although at a slower rate in the near future. Some argue, however, that current prices do not represent the true manufacturing costs, as there is currently a large over-supply of PV manufacturing capacity (UNEP, 2014). Costs might even need to increase as the industry consolidates and tries to reach a profitable level (Barbose et al., 2013; Mints, 2012). The list of companies that recently announced bankruptcy could be seen to support this view: Q-cells (Germany) in 2011, Solon (Germany) in 2012, First Solar (USA, has stopped its operation in Europe) in 2012, and Solyndra (USA) in 2011. Suntech (China) announced a default of US$541 million US bond payment in March 2013, and afterwards Chinese banks filed to place Suntech's main unit, Wuxi Suntech Power Holdings Co., Ltd., into insolvency.

This study aims to assess the economic feasibility of introducing solar PV facilities in capital constrained African countries in the context of the falling prices and costs of the solar PV technology. The economic analyses are done comparing solar PV technology with the low-carbon fossil fuel technologies like the combined cycle power plants, as well as diesel power plants in terms of economic net present value and environmental impact. The economic analyses are carried for both on-grid and off-grid application of the solar PV technology.

The dissertation is organized as follows. A literature review is given in Chapter 2. Chapter 3 provides a description of the methodologies used and the data specifications of the power plants analysed. In Chapter 4 the feasibility of the solar PV technology is examined as an option for rural electrification in sub-Saharan African countries. In Chapter 5 an economic appraisal of solar PV electricity generation versus combined cycle power generation is investigated for capital constrained African countries. In Chapter 6 an economic appraisal of solar PV electricity generation is studied against diesel power generation plants, the most common emergency power generation technology, in African countries with inadequate power supplies facing capacity shortages. Chapter 7 provides the overall conclusions of the study and some policy implications and suggestions for further study. Appendix provides the full version of the tables given in Chapter 5 and 6 due to space constraints shortly.

Chapter 2

LITERATURE REVIEW

Photovoltaics, one of the three major solar active technologies, is a method of generating electrical power by converting solar radiation into direct-current (DC) electricity using PV cells, and semiconductors that produces the photovoltaic effect (Eskom, 2013). PV cells are interconnected to form a module, several modules can be wired together to form an array. PV modules or arrays together with a set of system components (e.g. inverters, batteries, electrical components, and mounting structures) form a PV system (IEA, 2010). PV systems may be used as a source of energy in isolated locations or as one of the technologies for the supply of energy to a grid.

Solar insolation is the rate of solar radiation (kWh/m^2) over an area. It is used as an indicator of solar energy potential. With insolation levels ranging from 4 to 7 $kWh/m^2/day$, the African continent receives a higher amount of solar energy on its surface than the rest of the world (PY's Solar Weblog, 2013). Hence, investments in solar electricity generation projects in African countries would appear to have the potential to be economically attractive. The question is whether it is correct to have a policy to promote the implementation of solar PV power in such developing countries in which the priority is the long-term development of electricity systems that will provide reliable energy at as low a cost as possible.

A variety of views are currently being expressed as to the value of investments in renewable energy sources. Some strongly advocate renewable energy sources (Sovacool, B. K., 2008a; 2008b; 2009a; 2009b; 2009c; Sovacool and Watts, 2009).

The main arguments given by the proponents in support for renewable energy sources over conventional ones are:

- Renewable power supply would have the ability to generate electricity with fewer negative externalities per kWh than any other power source. According to Sovacool (2008a), the negative externalities (¢/kWh) for coal power plants are 21 times higher than those for solar PV plants, and the ones from gas oil combined cycle power plants are 30 times larger than those for wind farms;

- Renewable fuels are free, widely available, and non-depletable. They are less likely to suffer from speculations, do not need to be transported, and make the power sector less dependent on foreign oil suppliers;

- When emissions from the entire lifecycle are taken into consideration, renewable energy technologies emit fewer greenhouse gas (GHG) emissions than other sources of electricity (Gagnon and Belanger, and Uchiyama, 2002);

- Compared to thermoelectric and nuclear facilities, renewable power supply uses less water;

- Distributed renewable power generators can improve energy security through geographic diversification, reduce the need to build transmission infrastructure, lessen congestion, offer ancillary services, and improve grid reliability (Sovacool and Watts, 2009);

- Renewable energy sources promote the local economic growth and create more jobs. Renewable energy technologies like wind and solar can provide three to ten times more jobs per average installed megawatts of capacity compared to coal or gas fired power generation (Kammen and Kapadia, and Fripp, 2004);

- Increased use of renewables will decrease the demand for fossil fuels and bring down their prices;

- Solar PV system costs and market prices have decreased dramatically, and have reached 'competitiveness' (Bazilian et al., 2013).

Sovacool and Watts (2009) even claim that it is desirable, technically feasible, and achievable with the right mix of policy framework and political guidance to have a completely renewable energy sector at least in New Zealand and The United States. Sovacool (2009a) after conducting 62 interviews with various utility managers, system operators, energy consultants, and government experts came to the conclusion that the intermittency of renewables can be predicted, managed, and mitigated. He also claims that the current technical barriers to renewables may not be technical at all, rather more of social, political, and practical inertia of the traditional electricity generation system.

On the other hand, opponents of the renewables assert that the renewable energy sources are intermittent, non dispatchable and the investment costs are still much higher than the conventional power generation technologies.

Solar resource is both variable (mostly predictable daily and seasonal variations) and intermittent (largely unpredictable short term variations). Therefore, solar PV power generation is non dispatchable, that is the power output of solar PV plant cannot be adjusted at the request of power grid operators. In order to maintain the secure and stable operation of the electricity system, a continuous balance between demand and generation must be maintained. The intermittent nature of renewables increases the variance of generation patterns in the power system (Baker et al., 2013).

The introduction of intermittent generation will affect the way the electricity system operates in two ways: system balancing impacts and reliability impacts. Both of these impacts have costs associated with them. The 'system balancing impacts' relates to need by the system operator to manage and accommodate the short term fluctuations in the intermittent source of energy from seconds to hours. This implies that system operator has to purchase additional response and reserve requirements to keep the system balanced. The 'reliability impacts' relates to the issue of the system reliability. The system with intermittent generation has to have an additional capacity to build and retain on the system to ensure the defined level of reliability is maintained during the peak demand (Baker et al., 2013; UKERC, 2006). A solar PV plant with a 20% capacity factor can actually replace much less than a third of a diesel plant with a 60% capacity factor, if system reliability is to be maintained[3]

[3]Energy produced by a generator as a percentage of what it could generate if the generator operated at its full capacity 100% of the time (UKERC, 2006).

(Frank, 2014). Hence, this requires greater reserve and response by the system increasing the costs of capacity, synchronised reserve and response. Not only may additional supply from renewable sources impose these costs directly on the system, but by offsetting more flexible conventional generation methods, it reduces the ability of the system operator to manage those costs (Ilex Energy, 2002).

The Nuclear Energy Agency (OECD and NEA, 2012) has published a report providing grid-level system costs of integrating different power generation technologies into the power systems in selected OECD countries. Those grid-level system costs comprised of backup costs, balancing costs, grid connection costs, and grid reinforcement and extension costs per MWh of power generation. The system costs for dispatchable technologies were found to be relatively low and usually below US$ 3 per MWh. They turned out to be much higher for intermittent technologies, and could go up to US$ 40 – 45 per MWh for wind farms and up to US$ 80 per MWh for solar PV.

Borenstein (2012) and Michaels (2008) argue that justifications given in support of renewables are generally not supported empirically and in some cases are based on faulty reasoning. For example, there is an ‘energy security’ argument that says countries should produce a higher share of energy they use, and should reduce the use of fossil fuels to decrease the dependency on oil exporting countries. Increasing the use of renewables, the arguments go, will decrease the prices of these fossil fuels. However, Borenstein (2012) states that USA does not use any oil in producing electricity. Moreover, even in oil-importing countries, where oil is a substantial source of electricity generation, the amount of oil used for electricity generation is negligible in comparison to the world oil market. Replacing them with renewables would not likely have a large effect on world oil prices. Michaels (2008) claims that there are few if any important relationships between renewables and energy security for any nation.

Borenstein (2012) gives the examples of Spain and Germany, as an objection to the argument that renewables 'create jobs'. Spain was the biggest market for new solar PV generation in the world in 2008. However in 2009, when the country cut back subsidies, its manufacturing and installation of new capacity nearly disappeared. The same goes with Germany, the solar PV panel manufacturing in the country has decreased dramatically when China and Taiwan have made massive investments in panel manufacturing. Therefore, there is certainly a doubt on renewables creating 'green jobs'. Moreover, Michaels (2008) argue that renewable projects attract workers from other jobs, while many industries shrink insignificantly. He claims that this is more a transfer of workers, rather than a creation of new jobs for workers.

Currently, many governments around the world have created policies to promote renewable generation directly through subsidies or mandates. The main public policy argument for promoting electricity generation from renewable sources is the unpriced pollution externalities from burning fossil fuels. Subsidies for green power have been depicted as almost the same thing as pricing externalities. However, Borenstein (2012) claims that subsidizing "green" power (through feed-in-tariffs) for reducing pollution is not the same thing as taxing "brown" power to reflect the marginal social damage. They would not have the same effect due to the fact that the end-use electricity demand is not completely inelastic and each green and brown power is not completely homogeneous. The main problem here is the market failure of underpricing of brown power, not of overpricing of green power. When green power is subsidized from government revenues, he argues, it artificially depresses the price of power and discourages the efficient energy consumption. Second, the heterogeneity within green power sector and among brown power sources that are being displaced is not fully realized. It is very difficult to identify the alternative generation emissions avoided by renewable energy sources when displacing brown power even after the fact. Third, subsidizing green power creates an opportunity for benefit leakage from the immediate place where the policy goal takes place to somewhere else. This is because subsidizing green power addresses the policy goal only indirectly (Borenstein, 2012).

Critics of taxpayer-sponsored investment in renewable energy point to the bankruptcy in the US government supported solar PV panel producer Solyndra, as an example of how misguided the push for solar and wind power has become (Ball, 2012). Ball (2012) argues that the objective is not wind turbines or solar panels; rather it is an affordable, convenient, secure, and sustainable energy. Whether it is provided by wind turbines or solar panels should depend on their cost effectiveness. They should generate electricity only if they can produce it economically, not because of some ideological arguments.

Instead, Baker et al. (2013), Ball (2012), Borenstein (2012), Greenstone and Looney (2012), and Michaels (2008) suggest to price environmental externalities properly so that they reflect the true social costs of the pollution. This would allow the policymakers to choose the right mix of the generation facilities that would increase the economic efficiency.

From the environmental prospective however, it has been noted that solar PV in its both on-grid and off-grid applications is by no means a cost effective way of GHG abatement (Baker et al., 2013; Begg et al., 2000; Borenstein, 2012; Frondel et al., 2010; Mulugetta and Nhete, and Jackson, 2000). For example, the amount of GHG emissions caused by kerosene and candle burning for lighting by rural households in African countries in comparison to other sectors, such as mining and industry, is insignificant. The installation of GEF solar home system (SHS) project[4] to mitigate GHG emissions caused by kerosene and candle burning for lighting in Zimbabwe was likened by Mulugetta et al. (2000) to 'using a sledgehammer to crack a nut'. Begg et al. (2000) in an initial evaluation of Clean Development Mechanism (CDM) projects in developing countries found that the cost savings with SHS were as high as US$ 390-770 per tonne of emission avoided. Frondel et al. (2010) have found the similar high abatement cost estimates for on-grid solar PV projects in Germany, EUR 716 per tonne.

With increased utilization of rooftop solar PV systems, electric power utilities in Europe and USA are now facing a problem of infrastructure investment shortages. In USA, electric utilities collect revenues from residential customers in a form of a consolidated tariff consisting of a fixed monthly fee (metering and billing expenses) and a commodities charge (expenses associated with supply of both energy and demand). The largest component of the energy expense is the fuel costs. The biggest part of the demand expense is the fixed costs related to the infrastructure investments to provide central station service to the customer. The growth of rooftop solar PV systems is reducing the amount of energy that goes through residential utility meters from the utility to the end customer. Often, rooftop solar even reverses the flow so

[4]The details of the GEF project are provided in Section 4.1.1.

that rooftop solar PV systems deliver energy to the electric grid (Lively and Cifuentes, 2014). As an outcome the electric utilities are not collecting enough revenues to finance infrastructure investments. Even those customers with rooftop solar still will need to receive some electricity from the electric grid when the sun is not shining or their demand is higher than the capacity of the unit installed on the roof, or when the rooftop unit is damaged or out for maintenance. Electric power utilities have to have enough capacity to provide this service of backup electricity. Bushnell (2015) raises a question on this issue asking about how and who will pay for the energy infrastructure when the volume of kWh consumed is decreasing due to the increased use of rooftop solar PV facilities? Liveley (2014) and Lively and Cifuentes (2014) suggest to implement a demand charge which will reduce the subsidies that standard residential customers would otherwise have to pay to support the installation of rooftop solar.

One thing that almost all agree on is that the capital costs of renewable power generation technologies are high compared with those for conventional power generation technologies (Baker et al., 2013; Borenstein, 2008; Breeze, 2005; CRS, 2008; IEA, 2010; Michaels, 2008; Sovacool and Watts, 2009). Cost reductions are needed in order for solar technologies to be able to compete with conventional power generation technologies. Borenstein (2008) came to a conclusion, that even after adjusting for its timing and transmission advantages, the market benefits of installing the solar PV technology are lower than its costs. Furthermore, he found that taking into the consideration the GHG mitigation by solar PV did not make the net social return on these investments positive.

Solar PV has been considered by some energy analysts as an unfeasible energy technology for off-grid application for Africa owing to its prohibitively high prices (Karakezi, 2002; Karakezi & Kithyoma, 2002; Mulugetta et al., 2000; Oparaku, 2003; Wamukonya, 2007). Even those who promote solar PV technology in Africa accept that the prices are high (Gustavsson & Ellegard, 2004; Van der Plas & Hankins, 1997). Szabó et al. (2013) was the only one who has used a value for capital costs of off-grid PV systems per kWp in Africa much smaller than the world average, and almost comparable to that of Germany (the lowest PV system cost country in Europe). Sako et al. (2011) has considered solar PV as a cost effective energy option for off-grid application only if the energy demand in those rural areas is extremely low and the area is very far from national utility grid.

In Africa solar PV system costs are generally above the global average (Moner-Girona et al., 2006). Solar PV system costs and prices are still high in developing countries, especially in SSA, because markets in these countries remain inefficient on the retail side and SHS require expensive logistics (GTZ, 2010). Although solar PV system costs are falling in Africa over time, they remain much higher than the world average, and unless political, financial, and economic situations stabilize in the region the situation is unlikely to change in the near future.

For most of the inhabitants of Africa solar PV continues to be a technology that is out of reach, and this is not expected to change in the short to medium term, in spite of falling PV prices and finance innovations (Deichmann et al., 2010; GTZ, 2010; Lighting Africa, 2010). Deichmann et al. (2010) came to the conclusion that for a majority of households in Africa, decentralised power supply (solar PV as well) is unlikely to be cheaper than grid supplies any time soon.

Many African countries have guaranteed to support SHS hoping to increase the electrification rate in their countries. Policies and financial commitments to SHS projects show this support. However, Wamukonya (2007) argues that most of these SHS projects have also been supported by northern aid and largely pushed by entrepreneurs from the developed world to expand their markets and as a means of a technology transfer. Therefore, the decisions to install SHS are influenced by such support among other implicit motives. Mulugetta et al. (2000) and Wamukonya (2007) question the pace of pushing SHS into African countries, where rural and peri-urban consumers can hardly afford this SHS. In fact, there is pervasive concern that donors are ignoring the national interests of the poor countries and push their own interest as the primary concern. Indeed, for many donor projects the preconditions of the aid may not be in line with the poor countries development priorities (Mulugetta et al., 2000). Green technology initiatives need to be in line with countries' development needs; technologies should be designed to fit the socioeconomic characteristics of countries, firms, regulatory structures and communities where they are to be used (AfDB, 2013a).

In an attempt to attract donor funded SHS projects, many African countries found themselves drawn into financial obligations to fund those projects. The total country shares amount to 50-94 percent of the total solar PV project costs (Wamukonya, 2007). This number shows the high level of commitment by the host governments in the 'donor-funded' projects. Unless it is subsidized, or donated, Wamukonya (2007) argues that it is better for African markets, where the funds are limited and where the poorest of the poor live, wait until the costs of SHS get competitive with other conventional technologies on service basis and until the solar PV technology matures.

Another important point raised by several analysts is the fact that SHS could only provide energy for a limited number of services such as lighting, radios, and TV (Bambawale and D'Agostino, and Sovacool, 2011; Mulugetta et al, 2000; Van der Plas and Hankins, 1997; Wamukonya, 2007). Many of those who could afford a SHS preferred to switch over to the power company if grid connection became available in their vicinity (Bambawale et al., 2011; Lemaire, 2011; Mulugetta et al., 2000; Van der Plas and Hankins, 1997). Several essential questions were raised on this issue by Bambawale et al. (2011): Is solar PV an appropriate technology for the needs of the rural poor? Are people able to pay for the technology they desire? Do village-level micro-grids offer a midway solution between grid connection and off-grid electrification? People prefer grid connection to an off-grid solar PV system because it allows them to use electricity for income-generating activities such as rice milling or refrigeration of fish they have caught.

Some energy analysts suggest that village based hybrid micro grids, solar PV/diesel with energy storage batteries, are the most appropriate technological option for the electrification of remote areas (Azoumah and Yamegueu, and Py, 2012; EC, 2008; Nayar, 2010; PWC, 2013; Schmid and Hoffmann, 2004).

On-grid solar PV projects are comparably a new phenomenon in Africa. There is not much literature available on cost, environmental effect and sustainability of on-grid solar projects in Africa (UNEP, 2014). Based on the levelized cost of energy (LCOE) estimates, Ondraczek (2013) came to the conclusion that on-grid solar PV is now becoming cost competitive with conventional energy sources in Kenya. Beyond Kenya however, he argues that solar PV most likely has not reached the cost competitiveness with the conventional energy technologies. The African Technology

Policy Studies Network (ATPS, 2013) have made a feasibility analysis of 1 MW grid-connected solar PV project in Ghana and came to the conclusion that under the prevailing tariff conditions in the country, the project is not financially viable without incentives such as grants and feed-in tariffs.

Chapter 3

METHODOLOGY AND DATA SPECIFICATIONS

3.1 Methods

The feasibility of off-grid solar PV systems in SSA is analysed in Chapter 4 focusing on five major issues: cost-effectiveness, affordability, financing, environmental impact, and poverty alleviation. First, a comparison is made between the cost-effectiveness of the solar PV systems versus small diesel generator sets. In order to make this comparison of the alternative technologies the levelized cost per kWh of energy (LCOE) is estimated using the formula:

$$\text{LCOE}=\frac{\sum_{t=1}^{n}\frac{I_t+FOC_t+VOC_t}{(1+r)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+r)^t}} \qquad (1)$$

where I_t is the investment expenditures in year t, FOC_t is the fixed operating expenditures in year t, VOC_t is the variable operating expenditures in year t, E_t is the quantity of electricity produced in year t in kWh, r is the discount rate, and n is the economic operational lifetime of the system.

Second, the affordability of the solar PV systems is considered in comparison with the current budget allocation of households using kerosene lamps. Using the estimates of the LCOE for the solar PV systems, the annual cost of a solar PV system is estimated and compared with the annual household expenditure on kerosene lamps.

Third, issues related to the financing of the solar PV systems are examined from the households' point of view. Fourth, the environmental impact and costs of replacing kerosene lamps with solar PV systems are considered. A calculation is made of the CO_2 emissions avoided by solar PV systems, and the costs per tonne of CO_2 avoided are estimated. Fifth, the impact of solar PV rural electrification on poverty alleviation is examined.

A scenario analysis is carried to find out how long it will take for solar PV systems to become competitive with diesel generators for electricity generation. The number of years (*N*) needed for a solar PV system to have the same LCOE as a diesel generator set when the capital cost of a solar PV system is decreasing is calculated using the formula:

$$N = log_{(1-i)} \frac{LCOE_s}{LCOE_d} \qquad (2)$$

where $LCOE_s$ and $LCOE_d$ are the LCOE of the solar PV system and diesel generation set, respectively, and i is the rate of decrease in the solar PV system capital cost. In this estimation a zero decrease in the cost of diesel generators is assumed.

Next, the feasibility of on-grid solar PV systems in Africa is analysed in Chapter 5 and 6. A comparison is made in terms of economic net present value as well as greenhouse gases (GHG) savings if the same amount of scarce capital were invested in solar PV facility versus a combined cycle (CC) thermal power generation in Chapter 5 and in a diesel thermal power generation in Chapter 6.

To make this analysis possible, the expected energy output for each type of power plant is calculated using the parameter values given in Sections 3.4–3.6. The amount of electricity generated annually by the solar PV system, E_S (kWh), is calculated using the following equation:

$$E_s = P_k \cdot PR \cdot G \qquad (3)$$

where P_k is the installed peak power, measured in watt-peak (W_p), PR is the system performance ratio and G is the yearly sum of global irradiation on a tilted plane of the PV module (kWh/m^2/year) (Suri et al., 2007). The amount of electricity generated annually by a thermal plant, E_{th} (kWh), is calculated using the following equation:

$$E_{th} = NAC \cdot PLF \cdot h \qquad (4)$$

where NAC is the net available capacity for sale in watts (gross available capacity minus auxiliary usage). The gross available capacity is the available capacity after degradation multiplied by the availability factor. PLF is the plant load factor, and h is the number of hours in a year.

The amount of fuel saved and GHG emissions avoided are calculated on the basis of the energy output estimated previously. The amount of fuel saved by the solar PV plant, FS_s (litres), is measured by the equation:

$$FS_s = E_s \cdot f_{ex} \qquad (5)$$

where f_{ex} is the fuel requirement needed to generate 1 kWh of energy by existing thermal plants (litres/kWh). The amount of fuel saved by a thermal plant, FS_{th} (litres), is measured by the equation:

$$FS_{th} = E_{th} \cdot (f_{ex} - f_{th}) \qquad (6)$$

where f_{th} is the fuel requirement needed to generate 1 kWh of energy by a thermal plant (litres/kWh)[5].

The amount of GHG emissions avoided by a solar PV plant is measured in kilograms and calculated using the following formula:

$$GHGe = E_s \cdot (m_{kWh}^{fossil\,fuel} - m_{kWh}^{solar}) \qquad (7)$$

where $m_{kWh}^{fossil\,fuel}$ is the carbon dioxide equivalent per kWh of electricity generation using HFO (kg CO_2E/kWh) for various types of generator and turbine, and m_{kWh}^{solar} is the carbon dioxide equivalent per kWh of electricity generation for solar PV technology (kg CO_2E/kWh). The amount of GHG emissions avoided by a thermal plant is measured in kilograms and calculated thus:

$$GHGe = FS_{th} \cdot m_{litre} \qquad (8)$$

where m_{litre} is the carbon dioxide equivalent per litre of fossil fuel burned (kg CO_2E/litre).

The expected economic benefit of solar PV and thermal plants is calculated using a cost–benefit analysis approach, making comparisons between the scenarios with and without the projects. Economic benefits, costs and net present value for each plant type can be expressed by the following equations:

$$NPV = \sum_{t=0}^{26}(1 + EOCK)^{-t} \cdot (EB_t - EC_t) \qquad (9)$$

$$EB_t = FS_t \cdot P_{ft} + SOM_t + a \cdot GHGe_t \cdot SCC_t \qquad (10)$$

$$EC_t = I_t + FOC_t + VOC_t \qquad (11)$$

[5] $f_{th} = \frac{3.6MJ}{Energy\ transformation\ efficiency\ (\%) \cdot Fuel\ heat\ content(\frac{MJ}{litre})}$, because 1 kWh=3.6 MJ.

where EB_t and EC_t are the economic benefits and costs of the plant, P_{ft} is the economic cost of fuel per litre, SOM_t is the savings on variable (non-fuel) operating and maintenance cost of the plant it replaces, SCC_t is the social cost of carbon per tonne, I_t is the investment cost of the plant, FOC_t fixed operating and maintenance cost of the plant, and VOC_t variable operating and maintenance cost of the plant, all at time t and in US dollars. $EOCK$ is the economic opportunity cost of capital in %. FS_t is the amount of fuel saved by the plant in litres at time t. $GHGe_t$ is the amount of GHG emissions avoided by the plant in tonnes at time t. a is a coefficient equal to 0 in analysis from country's point of view and 1 from global point of view. Finally, a comparison is made between these two power plants (solar versus CC in Chapter 5, and solar versus diesel in Chapter 6). The levelized cost (LCOE) per kWh of energy is estimated for both solar PV and thermal plants by using the formulae 1[6].

A scenario analysis is undertaken in Chapter 5 and 6 to find out how long it will take for the solar PV plant to become competitive with the thermal plants for electricity generation. Using benchmark utility-scale solar PV system prices projections from the National Renewable Energy Laboratory (Goodrich and James, and Woodhouse, 2012) for the period from 2010 to 2020, the average annual expected percentage decrease in overall real system costs is estimated by the author to be 7.67%[7]. However, based on solar PV projects costs projections from Chase (2013), of Bloomberg New Energy Finance, from 2010 to 2020, the average annual expected

[6]It is not strictly accurate to compare the LCOE of these two technologies to determine the one that is preferred. The problem arises because the electricity generated by the solar PV system is non dispatchable and hence not as valuable as the electricity generated by the thermal plant which is dispatchable. However, if the LCOE of the solar PV facility is greater than that of the thermal plant, than it is clearly the more costly technology. The opposite conclusion cannot be made if the LCOE of the thermal plant is greater than that of the solar PV plant.

[7]Naam (2011) has projected a 7% decrease in the cost of solar technologies.

percentage decrease in overall real system costs is estimated to be 4%. Therefore, both values will be used in the analysis in Chapter 5 and 6. It is assumed that there will be no change in the real CC and diesel plants' capital costs per MW over time.

The number of years (*n*) needed for a solar PV plant to have the same NPV as a combined cycle power plant when the capital cost of a solar PV plant is now decreasing by *i* percentage per year is calculated by:

$$n = \log_{(1-i)} \frac{\sum_{t=2}^{26} \frac{NCF_s}{(1+r)^t}}{\sum_{t=2}^{26} \frac{NCF_{cc}}{(1+r)^t} - 0.06K} \qquad (12)$$

where NCF_s and NCF_{cc} are the net cash flows of the solar PV and combined cycle plants respectively (capital costs are not included), r is the discount rate, i is the rate of decrease in the solar PV plant capital cost, K is the capital cost of the original 30 MW solar PV plant. The coefficient of the subtrahend in the denominator of the above equation is the simplification of the expression ($\frac{K}{1+r} - 0.56K - \frac{0.44K}{1+r}$), where the coefficients come from the assumptions that it will take one year (year 1) to build a solar PV plant and two years (56% of the capital cost in year 0 and 44% in year 1) to build a combined cycle plant. The subtrahend in the denominator of the equation 12 will be equal to zero for diesel plant, as it is assumed that solar PV and diesel plants will have an equal construction period.

3.2 Data on Off-Grid Solar PV System Costs

Table 1 summarizes the most recent data available (2013 and later) on the capital and operating and maintenance (O&M) costs of off-grid solar PV systems in developed PV markets around the world. The data have been compiled from multiple current sources of cost information. The world average capital cost for small residential solar PV systems varies from US$3,000 to US$3,500 per kWp (Lazard, 2013). The estimated annual O&M costs for these systems are estimated to be 1.5% of the total initial investment cost of the PV system (Jäger-Waldau, 2013).

Table 1. Capital and O&M costs of solar PV systems in developed PV markets (2013)

Region/Country	Typical system size (kWp)	System cost (US$/kWp)	O&M costs (US$/kW/yr)
USA	2–5	4,200–5,000	
Germany	2–5	1,928[a]–2,670[a]	52[a]
Italy	2–3	3,100	
Japan	3–5	5,900	
France	<3	4,800	
Australia	<5	3,100	
World		3,000–3,500	13–20, 1.5%[b]

Notes:
[a] Original cost data was in euros; the 2013 exchange rate of 1.48 US$/euro was used.
[b] O&M is given as a percentage of the initial investment cost of solar PV system.
Sources: Barbose et al. (2013); Chase (2013); Jäger-Waldau (2013); Kost et al. (2013); Lazard (2013); Salvatore (2013).

System capital costs exhibit significant economies of scale, making smaller systems more expensive than larger systems on a per-kW basis. The annual O&M costs of the various systems, however, do not differ much according to system size on a per-kW basis annually.

The solar PV system costs are much higher in some parts of the world than others. For example, in the USA the capital cost of solar PV systems is above the world average owing to the much higher costs of licences, fees, insurance, etc. that are prevalent in USA (Barbose et al., 2013). O&M costs in Europe are higher because of high wages.

The latest cost data (2013) on off-grid solar PV systems was gathered for SSA and for the developing world (Table 2). The capital costs of PV systems per kWp in SSA have decreased, being in the range US$6,000–12,000 for off-grid systems, compared to an average of US$18,000 in 2002 (Karakezi & Kithyoma, 2002), US$14,000 in

2006 (Moner-Girona et al., 2006), and US$12,000 in 2010 (Lighting Africa, 2010). There are few recent estimates on the annual O&M costs for these systems.

Table 2. Capital and O&M costs of solar PV systems in SSA and developing world (2013)

	Off-grid		
Country	Typical system size (Wp)	System cost ($/kWp)	O&M cost (% of the initial investment cost)
Kenya	25–30	12,000	
Malawi	40–65	12,500	
Zambia	20–100	6,000–10,000[c]	
Bangladesh	50	8,000	
Africa			2.5
Developing world	40	8,750	

Notes:
[a] O&M is given as a percentage of the initial investment cost of solar PV system.
[b] Cost was given in $/kWh.
[c] Author's estimate based on system costs and sizes given in the source.
Sources: Bertheau et al. (2014); Guevara-Stone (2013); KEREA (2014); Kornbluthn and Pon, and Erickson (2012); Samad et al. (2013); Szabó et al. (2013); WHO (2014).

In Africa solar PV system costs are generally above the global average (Moner-Girona et al., 2006). Off-grid solar PV system costs and prices are still high in developing countries, especially in SSA, because markets in these countries remain inefficient on the retail side and SHSs require expensive logistics (GTZ, 2010). The same is true for on-grid solar PV systems. The transaction costs of renewable energy projects such as resource assessment, siting, permitting, planning, developing project proposals, obtaining financial support, and negotiating power purchase agreement contracts may be much higher than that of conventional power plants on a per kilowatt capacity basis. Therefore, these transaction costs add to the costs of renewable projects making them even higher (UNIDO and ECREEE, 2012). Although solar PV system costs are falling in SSA over time, they remain much higher than the world average, and unless political, financial, and economic situations stabilize in the region the situation is unlikely to change in the near future.

Szabó et al. (2013) used a value of €1,900 (US$2,819[8]) as the estimate of capital costs of off-grid PV systems per kWp in Africa. This value has been disregarded from the data sample, as it does not seem to match reality: it is smaller than the world average, and almost comparable to that of Germany (the lowest PV system cost country in Europe).

The capital costs of off-grid PV systems implemented in Africa fall within the range US$6,000–12,000 per kWp. In this study the mean value of US$8,000 per kWp is used. For O&M costs, the world average estimate of 1.5% of the total initial investment cost of the PV system is employed (Jäger-Waldau, 2013). A standard size of solar PV system is chosen as 50 Wp, this being the size that would typically provide useful light at night for families of five–six persons in rural areas of SSA[9]. The estimated up-front cost of such a system then, excluding the cost of financing and VAT, would be US$400. Assuming a value of 1.5% of the total initial investment cost of solar PV systems as an annual O&M cost per kW, maintenance costs would translate into O&M costs of US$6 per year (US$4.5 at the low end, US$9 at the high end) for a 50 Wp system.

3.3 The Electricity Generation System

Chapter 5 and 6 examine a typical small power system in Africa with a total nominal generation capacity of about 1000 MW, consisting of open cycle gas turbine (OCGT) power plants for base load and diesel power plants for peak load each fuelled by HFO. The reason why HFO was chosen as a fuel for these thermal power plants is

[8]The exchange rate of 1.48 US$/euro was used.

[9]The average number of persons per household was found to be five in a study done in five countries in SSA (Lighting Africa, 2011).

due to its ease in terms of transportation, and the fact that the vast majority of thermal power plants (both gas turbine and diesel) in Africa are using HFO or diesel rather than cheaper natural gas (IMF, 2013). The average daily load curve (Fig. 1) and the annual load duration curve (Fig. 2) derived from it show the pattern of demand for electricity generation capacity over the day and year for such a typical low-income country in Africa. In constructing the average daily load curve and hence annual load duration curve the pattern of electricity demand over the day in fifteen different countries of Africa was used for which data are available[10]. However, the absolute amount of capacity demanded was later normalised for a system with a 1000 MW peak capacity demand in order to be descriptive of systems in which utility scale solar PV projects are actually proposed and implemented. The load factor of the system is 76%.

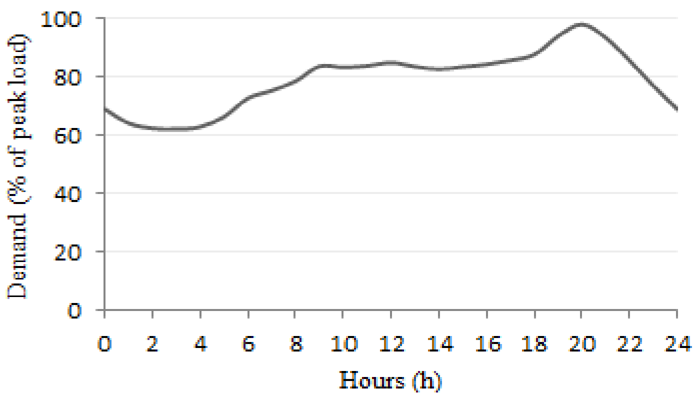

Figure 1. Average daily load curve

[10]The countries are Burkina Faso, Cameroon, Djibouti, Ghana, Kenya, Mauritius, Namibia, Nigeria, Rwanda, South Africa, Sudan, Tanzania, Uganda, Zambia, Zimbabwe (Bhurtun and Jahmeerbacus, and Dookhit, 1998; GRIDCo, 2010; Hatch Ltd., 2012; IRENA, 2013; JICA and GoC, 1993; Kaseke, 2013; LI, 2004; Ministry of Energy, Republic of Kenya, 2011; Norconsult Africa, 2013; SNC-Lavalin, 2011; Tembo and Merven, 2013; UNDP, 2013; Vernstrom, 2010; Vo Consulting, 2012). The shape of the average load duration curve is very similar to the one given in a study of Bertheau et al. (2014) for Africa.

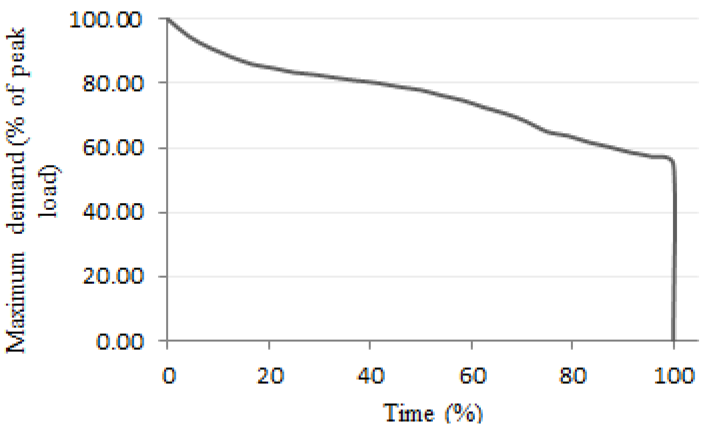

Figure 2. Annual load duration curve

Even with current demands for electricity such systems are already facing problems of blackouts and brownouts as the available generation capacity is insufficient to meet the demand, particularly during peak periods. With the expected growth in electricity demand in such systems over time there will be a need to invest heavily in generation capacity in order to avoid chronic blackouts and brownouts. Based on historic trends, demand for electricity is forecasted to grow at 5% annually in Africa (Eberhard et al., 2011). Fig. 3 shows the projections for the electricity load duration curves for such systems, assuming a 5% increase in demand in both capacity and total energy per year. As can be seen in Fig. 3, in order to maintain sufficient generation capacity to meet the growing demand, there will be a need to increase generation capacity by fifty percent within 10 years and increasing of capacity by two and a half times within 20 years. These systems will need to be commissioning generation plants in sizes that are substantially larger than those employed today. The capital constraint on the electric utilities in these countries will only tighten in the future.

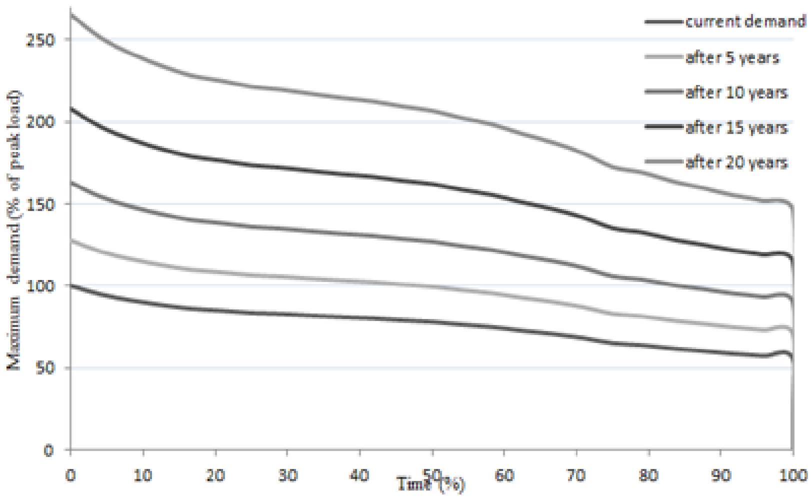

Figure 3. Projection of demand for electricity^

3.4 Solar PV Power Plant Data Specifications

The grid connected solar PV plant envisioned in Chapter 5 and 6 has a generation capacity of 30 MW, with an estimated cost of US$ 2.8 million per MW, making a total investment cost of US$ 84 million. The capital cost per MW for installed solar PV generation for this typical African country is estimated as the average cost for such plants being built and/or proposed by independent power producers (IPPs) in 2013-2015[11]. For O&M costs, the world average estimate of 1.5% of the total initial investment cost of the PV system is employed (Jager-Waldau, 2013).

The total grid-level system cost of introducing solar PV generation into the African power systems is missing. In the absence of such studies on Africa, we have taken the estimate made for the EU countries, of US$ 11.91 (EUR 8.97) per MWh as an

[11]The projects are in Burkina Faso (Zagtouli, 30 MW; Windiga, 22 MW), Egypt (Terra Sola, 2GW), Ghana (Scatec, 50 MW; Blue Energy, 155 MW), Kenya (Canadian Solar, 50 MW), Mauritania (Masdar, 15 MW), Rwanda (Goldsol II, 10 MW; Scatec, 8.5 MW), and South Africa (Jasper Solar, 96 MW; Sunedison, 60 MW; Scatec, 75 MW, 40 MW) (African Review, 2015; EC, 2015; Electric Light & Power, 2015; Energiyaglobal, 2015; Mugisha, I. R., 2014; OPIC, 2015; Pincent Masons LLP, 2015; PVTech, 2015; Renewable-Technology, 2015; Scatec, 2015; SeeNews, 2015; The Financial Times, 2015; UNEP, 2014; Wikipedia, 2015).

approximate estimate of total grid-level system cost of solar PV (Pudjianto et al., 2013). The grid integration cost per MWh of solar generation is for the lowest level (2%) of PV penetration.

The size of this solar plant is typical of many that are being proposed for countries in Africa today. This proposed plant will be connected to the electricity grid of the country. It is assumed that the construction period will be one year for a solar PV plant, and that it will have an operating life of 25 years. Annual degradation is assumed to be 0.6%. The annual solar radiation on angled panels is taken as 2190 kWh/m^2 per year; this value is calculated by author as a yearly average irradiation on optimally inclined modules for African continent[12].

Carbon dioxide equivalent, a measure used to compare the emissions from various greenhouse gases based on their global warming potential (OECD, 2001), per kWh (CO_2E/kWh) of electricity generation for solar PV technology is 32 grams (Fthenakis and Kim, and Alsema, 2008)[13]. This value is a lifecycle estimate of greenhouse gases per kWh of electricity generation for solar PV systems.

One might argue that solar PV technologies do not emit any greenhouse gases as they do not burn any fossil fuel to generate electricity. Although solar PV plants do not use any fossil fuel to generate the electricity, the emissions from photovoltaic life

[12]These are average radiation values for the period 1985-2004 from PVGIS-Helioclim database provided by European Commission, Joint Research Centre, Institute for Energy and Transportation, Renewable Energies Unit. Power plant performance ratio is 75%. The annual solar radiation on angled panels is taken as 2023 kWh/m2 per year for SSA countries.

[13]Assuming insolation of 1700 $kWh/m^2/year$, a performance ratio of 0.8, and a lifetime of 30 years.

cycles are the consequence of utilizing fossil-fuel-based energy to produce the materials for solar cells, modules, and systems, and also due to smelting, production and manufacturing facilities (Fthenakis et al., 2008). Therefore, in order to be consistent, this value of the carbon dioxide equivalency per kWh of electricity generation for solar PV should be subtracted from the same life cycle value of the carbon dioxide equivalency per kWh of electricity generation using HFO for various types of generators and turbines to find the amount of greenhouse gases avoided by solar PV plant.

3.5 Combined Cycle Power Plant Data Specifications

A calculation is made for Chapter 5 of the number of MW of capacity of HFO-fuelled CC plant that can be financed for an equivalent amount to that of a 30 MW solar plant with a cost of US$ 84 million. The installed capacity (rated plant capacity) of a CC plant that can be purchased for US$ 84 million at an estimated capacity cost of US$ 1.8 million per MW is 47 MW[14]. These costs are approximately 200% of the costs of such installed capacity in the United States (EIA, 2013; Lazard, 2013; Salvatore, 2013; Tidball et al., 2010). They are likely to be an overestimation of the financial and economic costs if the plants were to be built by a public utility (Phadke, 2009). The operating life of the CC plant is assumed to be 25 years, the same as for the solar PV plant, but the construction period for the CC plant will be two years.

The energy transformation efficiency of the CC plant is assumed to be 54% (EPRI, 2011). This value is an industry average of the fuel transformation efficiencies of the

[14]The capital cost per MW for installed CC generation for this typical African country is estimated as the average cost for such plants being built and financed by independent power producers (IPPs) in 2012-2013 (MoEP, 2012; MEM, 2013).

actual or planned CC power projects. Although the main biggest manufacturers of the CC plants like General Electric (2013) and Siemens (2013) claim that the CC plants manufactured by them have reached the fuel efficiencies of up to 60% (General Electric - 60% and Siemens - 59.7%), taking this average value might be more plausible. To present the best possible scenario in terms of the economic viability of the solar generation project, a lower efficiency level is used for the CC plants.

The maximum plant availability will be 91% of installed capacity. The average availability of the plant will be 89% of available capacity after degradation. The plant load factor is 80% of the total net potential generation capacity. The fuel requirement is 0.16 litres per kWh. The annual increase in fuel requirement is 1%. The capacity degradation factor (annual deterioration) will be 1% of the maximum available capacity.

The variable (non-fuel) operating and maintenance cost of the CC plant is estimated to be equal to US$ 4 per MWh, that of the open cycle gas turbine and diesel power plant being replaced. The fixed operating and maintenance cost of the CC plant is assumed to be equal to US$ 7.5 per kW-year. All of the above values are consistent with those used for developing the electricity system master plan 2012 for Tanzania (MEM, 2013). Total grid-level system cost of CC plant is taken as US$ 0.56 per MWh. This value is the highest estimate provided by the Nuclear Energy Agency for the OECD countries (OECD and NEA, 2012).

3.6 Diesel Power Plant Data Specifications

A calculation is made for Chapter 6 of the number of MW of capacity of HFO-fuelled diesel plant that can be financed for an equivalent amount to that of a 30 MW solar plant with a cost of US$ 84 million. The installed capacity (rated plant capacity) of a diesel plant that can be purchased for US$ 84 million at an estimated capacity cost of US$ 0.65 million per MW is 130 MW[15]. The operating life of the diesel plant is assumed to be 25 years, the same as for the solar PV plant. The construction period for the diesel plant will be one year.

The energy transformation efficiency of the diesel plant is assumed to be 41.6% (Wärtsilä, 2013). This is the smallest value amongst of the fuel transformation efficiencies of different engine types given by Wärtsilä, the main biggest manufacturer of the diesel plants, in a range of 41.6% to 46.8%. To present the best possible scenario in terms of the economic viability of the solar generation project, a lower efficiency level is used for the diesel plants.

The maximum plant availability will be 91% of installed capacity. The average availability of the plant will be 89% of available capacity after degradation.

The plant load factor is 80% of net available generation for sale. The fuel requirement is 0.21 litres per kWh. The annual increase in fuel requirement is 1%. The capacity degradation factor (annual deterioration) will be 1% of the maximum available capacity.

[15]The capital cost per MW for installed diesel generation for this typical African country is taken as an average of the costs given for different countries in studies by Deichmann et al. (2010), Lazard (2013), and Pauschert (2009).

The variable (non-fuel) operating and maintenance cost of the diesel plant is assumed to be equal to zero and the fixed operating and maintenance cost is US$ 15 per kW-year (Lazard, 2013). Total grid-level system cost of diesel plant is taken as US$ 0.56 per MWh.

3.7 Other Technical Specifications

Given the non dispatchable nature of the solar, its operation will result in a reduction in the generation by the open cycle and diesel power plants. Hence, in this analysis the amount and the value of the fuel savings are computed on the fuel efficiency of the open cycle and diesel power plants being approximately 0.246 litres of HFO per kWh. Owing to the degradation of the existing plants, annual fuel consumption will increase by 1% per year.

Oil price projections are based on US$ 464 per tonne (US$72.68 per barrel) which corresponds to the average price for HFO over the past 10 years (Insee, 2015). The real price of crude oil is held constant at this level over the life of the plants. Hence, the delivered cost of HFO will average US$ 0.79 per litre, expressed in 2015 prices.

The carbon dioxide equivalent per kWh of electricity generation using HFO is 778 grams (3.126 kg CO_2E/litre[16]). This value is a lifecycle estimate of greenhouse

[16]This value is obtained by using CO_2 emissions factors based on fuel mass or volume, CH_4 and N_2O emission factors by fuel type and sector (EPA, 2008), and Global Warming Potential (GWP) factors (CAPP, 2003). Only CO_2, CH_4 and N_2O gases are used in calculating CO_2E, because over 99% of the total CO_2E is due to CO_2 emissions (EPA, 2008), and other greenhouse gases like HFCs are used as refrigerants, while PFCs and SF6 are used as manufacturing aids in the metal and semi-conductor industry (CAPP, 2003). The assumption made here is that the lifecycle estimate of greenhouse gases per litre of burning HFO to generate electricity will be the same for various types of generator and turbine except for the difference in the energy transformation efficiency.

gases per kWh of electricity generation using HFO for various types of generator and turbine (Gagnon et al., 2002).

The gross calorific value of HFO is 41.73 MJ/litre (The Australian Institute of Energy, 2013). The social cost of carbon emissions (SCC) is taken to be US$ 39 per tonne for 2015. There is also upward trend in the SCC of 1.92% a year, as proposed by EPA (2013).

Chapter 4

OFF-GRID SOLAR PV: IS IT AN AFFORDABLE OR AN APPROPRIATE SOLUTION FOR RURAL ELECTRIFICATION IN SUB-SAHARAN AFRICAN COUNTRIES?

4.1 Introduction

Solar photovoltaic (PV) electricity generation is not a new phenomenon in sub-Saharan Africa (SSA): solar PV technology has been used in development projects for rural electrification since the 1960s, yet the electrification rate of SSA is only 26% (Legros et al., 2009). Solar PV has been perceived as one of the most appropriate solutions for rural electrification in the form of decentralized and off-grid power for SSA (Szabó et al., 2011; Szabó et al., 2013; UNEP, 2012; Van der Plas and Hankins, 1997). In this region grid connections are usually mainly in the major cities and their suburbs. Electric utilities have deficient generation capacity and lack sufficient infrastructure to expand electricity access (Eberhard et al., 2008; Eberhard et al., 2011; Eberhard and Shkaratan, 2012; IMF, 2013; Mkhwanazi, 2003; World Bank, 2010). Universal access to electricity through grid extension is prohibitively expensive in SSA owing to the human geography of the region, in which a large percentage of the population lives in rural areas and in small settlements (Eberhard and Shkaratan, 2012; IMF, 2013; World Bank, 1996). It is estimated that 62.7% of the population of SSA resides in rural areas (World Bank, 2013), and 89% of this rural population does not have access to electricity (Legros et. al., 2009). Some of these residents live within sight of the national grid, yet they cannot afford the initial cost of a connection (Eberhard et al., 2008; Eberhard et al., 2011; Lighting Africa, 2011). Therefore, the majority of solar PV projects implemented in SSA have been off-grid systems targeted at urban poor and rural residents.

The aim of this chapter is to examine the feasibility of off-grid solar PV technology in SSA in the context of the falling prices and costs of these solar PV systems. Only off-grid power systems will be considered here.

4.1.1 Lessons Learned From Donor-Driven Solar PV Projects

International development organizations, regional banks, and donor countries have supported numerous solar PV projects in SSA; donor-driven solar PV projects have been implemented in many countries in Africa. The Energy Service Company (ESCO) project in Nyimba, Zambia, was initiated in 2000. ESCO was a part of a pilot project carried out by the Government of Zambia for the dissemination of solar PV technology in rural areas. It was supported by the Swedish International Development Authority (Sida) with the Stockholm Environment Institute (SEI) as advisers. ESCO owns and operates 100 (50 Wp) solar home systems (SHSs). ESCO charges the customers a service fee, but the fee does not include the capital cost of the system. Most of the rural households would otherwise be unable to use solar lighting, as they simply could not afford to pay the initial capital cost. Although customers' energy payments have increased, customers are satisfied with the service they receive. Rural households do not have to worry about the maintenance and breakdown of the system, as professional specialists from ESCO take care of the repairs, changes, and installation of PV system parts. This has been the key to the system's success. Surprisingly, the number of light hours did not increase significantly from the previous situation in which there was no SHS. However, the quality of light improved, leading to an increase in domestic work and studies at night, somewhat changing the lifestyle of the households. Children, even in households that did not have SHSs, were the group who benefited most, by having more opportunity to study at night (Gustavsson and Ellegard, 2004).

Another important example is the Global Environmental Facility (GEF) project in Zimbabwe, which had outcomes much below expectations. The GEF solar project was implemented in the period 1993–1997 with total funds amounting to US$7.5 million. It was sponsored by the United Nations Development Programme (UNDP) and the Government of Zimbabwe to disseminate solar PV technology in rural areas by installing 9,000 lighting systems of 45 Wp each. Zimbabwe qualified for GEF funding mainly because it was one of the first countries to sign and affirm the UN Framework Convention on Climate change (UNFCCC), agreeing to fulfil its global obligations, either on its own or as part of global actions. Unfortunately, the project attempted to simultaneously address too many ambitious and incompatible targets, such as the fulfilment of the UN Millennium Development Goals, mitigation of greenhouse gas (GHG) emissions, abatement of rural poverty, expansion and strengthening of the domestic solar PV industry, and employment creation. As a consequence, it achieved very few of them. For example, the amount of GHG emissions caused by kerosene and candle burning for lighting by rural households in Zimbabwe in comparison to other sectors, such as mining and industry, is insignificant. The installation of this project to mitigate GHG emissions caused by kerosene and candle burning for lighting was likened by Mulugetta et al. (2000) to ‘using a sledgehammer to crack a nut’.

The biggest criticism of the GEF project is the absence of interest and a follow-up mechanism from the donors after the end of the project. Many similar donor-driven projects in developing countries failed to foresee the significance of post-project support, mistakenly supposing that solar PV systems are maintenance-free and can be maintained by untrained local people (Foley, 1995). The GEF project did succeed, however, in providing lighting for 9,000 households within the intended project deadline, although it fulfilled very few of its other goals. Unfortunately, many of the donor-driven rural electrification projects have been of this type: pushing a high-cost technology into rural and peri-urban areas of SSA as a condition for donor assistance, to the poorest of the poor who could not afford it (Wamukonya, 2007).

4.2 Results

4.2.1 Cost-Effectiveness Issue

Using Eqn. (1), the LCOE for solar PV systems using a 10% discount rate is estimated at US$0.83 per kWh[17]. This is a very high cost per unit of electricity generated compared to the conventional grid system tariff rates in Africa of between US$0.08 and US$0.16 per kWh (Eberhard et al., 2011). However, comparisons with conventional grid system tariffs may not be valid, as those do not usually reflect the true cost of power generation in many countries in SSA. The LCOE for small diesel generators would be a better benchmark for comparison.

[17]The amount of energy generated by solar PV systems is calculated as an average of energy generated by solar PV systems in different countries of SSA using values for the period 1985–2004 from PVGIS-Helioclim database provided by European Commission, Joint Research Centre, Institute for Energy and Transportation, Renewable Energies Unit. It is assumed that a solar PV system has an operating life of 20 years. Annual degradation is assumed to be 0.6%. Performance ratios (PR) of the grid-connected solar PV plants are usually in the range 65–85% (Jahn et al., 2000; Woyte et al., 2013); the average is 75%, and this is the value most commonly used by researchers. PRs of off-grid PV systems were found to be in range of 10–60% in a study carried by IEA-PVPS Task 2 (Jahn et al., 2000). In order not to intimidate solar PV, the current author is using a value of 60% as a PR estimate. Discount rate is assumed to be 10% (Bertheau et al., 2014).

The LCOE for a small diesel generator is estimated at US$0.42 per kWh[18]. This value is in the middle of the range of in-house electricity generation costs accrued by households and firms estimated by Foster and Steinbuks (2009) for countries in Africa. Therefore, the cost per unit of electricity generated is much higher for solar PV energy than for diesel generators.

With the initial investment amount spent on a 100 Wp solar PV system, one could alternatively buy up to a 1.2 kWp (1,230 Wp) diesel generator that would increase electricity generation more than twenty-fold[19]. Although running costs of diesel generators are higher (PWC, 2013; Sako et al., 2011), households could use increased electricity generation for other activities such as water pumping, milling, irrigation, or in any income-generating activities, rather than just lighting, radio, or TV (Karakezi and Kithyoma, 2002). This makes diesel generators the most frequently used off-grid technology today in rural areas (EC, 2008), namely in SSA,

[18]A capital cost of US$650 per kWp is assumed for household diesel generators, taken as an average of the costs given for different countries in studies by Deichmann et al. (2010), Lazard (2013), and Pauschert (2009). IEA (2013) gives a value of US$400 per kWp for diesel gensets in Africa, yet the aim is not to promote diesel generators, so the current author have decided to use the higher value. For the calculation of the amount of power generated by diesel generators, the same assumptions were made as those of Deichmann et al. (2010). Diesel price is taken as US$1.3 per litre as an average value calculated for SSA countries based on the data given by GIZ (2013); heat rate is taken as 10,000 Btu/kWh; fixed O&M costs are taken as US$15/kW/yr (Lazard, 2013). Because the smallest diesel generator supplies more electricity than a single household solar PV system, it is likely that it would be connected to more than one household. In such a case, some investment would be needed to set up this micro distribution system. Such costs likely to be relatively small, and are not included in these LCOE estimations. However, as we are using a cost of the generator that is at the top of the range of prices, the overall cost of the diesel generation system used here likely to be close to actual experience.

[19]This comparison ignores the fact that a solar PV system, even with a storage battery, is a much less reliable supply than a diesel generator. In a given day, if there is a greater need to use electricity for more activities, a diesel generator can be used for more hours. In contrast, with a solar PV system, once the battery has run down one must wait until the sun begins to shine again (see note 4 for assumptions).

and they will remain the source of choice in the near future (GTZ, 2010). The very important difference between solar PV (intermittent and high cost) and diesel generators (conventional and low cost) is that diesel power generators do not just generate electricity for household consumption. Because of the greater reliability of the source, the electricity generated by these generators can be used in income-generating activities. These have the potential to increase the economic well-being of at least some of the households much more than the solar PV systems could.

Operating and maintenance (O&M) and repair costs are the second or third largest cost factors of the total solar PV system costs. They comprise the costs of foreseeable repairs, maintenance, and exchange of components such as batteries, and the costs of the annual degradation of the solar modules. (Jäger-Waldau, 2013). Consumers are often unaware of the technical unreliability and reduced durability of the main parts of the PV system. The O&M costs are often underestimated, particularly for lower-quality systems (GTZ, 2000). Failure to maintain the system appropriately causes the breakdown of components, leading to the benefits from the system either reducing or being completely eliminated. Financial schemes usually concentrate on the initial investment cost, and do not sufficiently consider the O&M costs. Consumers need to be capable of paying the credit, and at the same time of coping with O&M costs, which are the main reason why the rural poor simply cannot afford solar PV systems, even with most favourable credit schemes and subsidies (GTZ, 2000).

Gustavsson and Ellegard (2004), in a survey conducted in Zambia, found that the clients of the PV ESCO project (who were paying O&M costs only) were paying more for energy services than their neighbours without the PV system. This shows that O&M costs on their own can be much higher for rural residents than the amount previously spent by them on energy services such as kerosene, dry cell batteries, car batteries, and candles.

There is a lack of standard after-sales service structures and a lack of private sector involvement. People are left on their own with their solar PV systems after purchasing them. There is no quality control, norms and standards in terms of renewable energy technologies' performance, manufacture, installation and maintenance. Therefore, there is high risk of importing poorer quality solar PV systems (UNIDO and ECREEE, 2012). Many of those who could afford a solar PV system preferred to switch over to the power company if grid connection became available in their vicinity (Bambawale et al., 2011; Lemaire, 2011; Mulugetta et al., 2000; Van der Plas and Hankins, 1997). Several essential questions were raised on this issue by Bambawale et al. (2011): Is solar PV an appropriate technology for the needs of the rural poor? Are people able to pay for technology they desire? Do village-level micro-grids offer a midway solution between grid connection and off-grid electrification? People prefer grid connection to an off-grid solar PV system because it allows them to use electricity for income-generating activities such as rice milling or refrigeration of fish they have caught.

4.2.2 Affordability Issue

Except for a few recent grid-connected projects, the solar PV projects implemented in SSA have been off-grid systems. Households' access to electricity in SSA is very low. The situation is even worse in rural areas. Therefore, off-grid solar systems were targeted at rural residents.

In SSA, over three quarters of poor people live in rural areas (IFAD, 2010). More than half of the population lives below the international poverty line of $2 per day

(PPP, purchasing power parity) in three quarters of the countries in SSA, and under $1.25 per day (PPP) in one third of SSA countries (World Bank, 2013). Table 3 gives the poverty headcount ratio and the rural population data for a number of countries in SSA to illustrate the severity of the situation in the region.

Table 3. Rural population and percentage of the population living below the international poverty line

Country	Poverty headcount ratio at $1.25 a day (PPP) (% of population, surveys 2000–2011)	Poverty headcount ratio at $2 a day (PPP) (% of population, surveys 2000–2011)	Rural population (% of total population, 2010)
Burundi	81.30	93.5	89.0
Ethiopia	39.00	77.6	82.4
Ghana	28.60	51.8	48.5
Kenya	43.40	67.2	77.8
Nigeria	64.70	57.5	50.2
Tanzania	67.90	87.9	73.6

Source: World Bank (2013).

The vast majority of the rural poor cannot afford the up-front cost of a solar PV system as they have low and/or irregular income that makes it difficult to save money and to pay the whole amount at once (GTZ, 2000; Lighting Africa, 2011; UNIDO and ECREEE, 2012). In Africa the average household of five members has a monthly budget of less than US$180 (US$60 in the lowest quintile, US$340 in the highest) (Eberhard et al., 2011). Table 4 gives the average monthly household incomes in selected countries in SSA.

Solar PV has been considered by some energy analysts as an unfeasible energy technology for SSA owing to its prohibitively high prices (Karakezi, 2002; Karakezi and Kithyoma, 2002; Mulugetta et al., 2000; Oparaku, 2003; Wamukonya, 2007). Even those who promote solar PV technology in SSA accept that the prices are high (Gustavsson and Ellegard, 2004; Van der Plas and Hankins, 1997). For most of the inhabitants of SSA solar PV continues to be a technology that is out of reach, and this is not expected to change in the short to medium term, in spite of falling PV prices and finance innovations (Deichmann et al., 2010; GTZ, 2010; Lighting Africa, 2010).

Table 4. Average monthly income

	Ethiopia	Ghana	Kenya	Tanzania	Zambia
Monthly household income (US$)	115.7	115.9	153.6	90.0	150.9

Source: Lighting Africa (2011).

Using the estimates of the LCOE for the solar PV systems of $0.83/kwh, the annual cost of a solar PV system would be US$51 (US$4.2 per month), or 2.3% of household income[20]. This can be compared with household expenditure on kerosene lamps, which are the most common alternative lighting source, followed by dry cell batteries and candles (Adkins and Oppelstrup, and Modi, 2012; Apple et al., 2010; Bacon and Bhattacharya, and Kojima, 2010; Begg et al., 2000; Lam et al., 2012a; Lam et al., 2012b; Lighting Africa, 2010; Lighting Africa, 2011; Lighting Africa, 2013; Mills, 2000).

Expenditure on glass-covered kerosene lamps (taking into consideration the average purchase cost of the device, the monthly operating cost, the average lifetime of the product, and the number units of the device per household) is estimated to be US$40–98 per household per year in countries in SSA (Lighting Africa, 2011). This represents an average annual expenditure of US$57 per household (US$4.75 per month), or 2.6% of monthly household income[21]. Household expenditure on

[20]The average monthly household income is assumed as US$180 (Eberhard et al., 2011).
[21]A study by the World Bank found that it was 2.1% for Kenya and 1.5% for Uganda (Bacon et al., 2010).

kerosene is roughly equal to the amount a household would have to pay to finance a PV system under annuity conditions.

4.2.3 Issues with Financing

From the households' point of view, however, there are many important differences between these two alternatives. First, with solar PV, households are burdened with a long-term financial obligation involving the repayment of a sizeable debt, whereas with kerosene lighting they are free to buy energy sources in accordance with their needs and budget constraints (GTZ, 1995). Second, the annualized cost of solar PV is calculated by spreading the cost of financing over the entire 20-year lifetime of the project, which does not match reality. Micro-finance institutions or commercial banks usually require both a short payback period, making the periodic payments much higher, and some type of collateral, which many rural customers cannot offer. Third, in most rural areas regular monthly household income is available in only a small number of households in which there are teachers, nurses, or civil servants. With an irregular income stream, it is very difficult to obtain and pay for a loan, which is the case with a solar PV system. Fourth, traditional energy expenditure is an average value, and it does not necessarily reflect the regular monthly expenditure on energy. For example, during times of economic crisis, expenditure on traditional energy sources can be cut or adjusted to suit income constraints. However, monthly repayments to financial institutions cannot usually be cut or adjusted. Fifth, the instalment of a solar PV system does not necessarily induce households to stop purchasing traditional energy sources. There is anecdotal evidence supporting this. Some households who can afford it continue to use kerosene lamps in order that the electricity from the solar PV system can be conserved for TV viewing (Martinot et al., 2002). Finally, even for households with regular income, an evaluation of solar

PV should be based on households' income constraints, and not on hypothetical energy expenditure. The quantity in which PV electricity is consumed depends on the marginal utilities per unit of cost derived from both consumption goods. Only when marginal utility of the PV electricity is higher than that of traditional energy applications per unit of cost would consumers be willing to pay higher amounts for it (GTZ, 1995).

Today, there are a few working micro-finance institutions in the world offering SHS credit for ESCO-type service schemes. Moreover, those loans that are available are mainly designed for income-generating activities such as farming and crop cultivation. Financial institutions generally require a 'productive use of credit' from loan applicants, which SHSs do not usually satisfy (GTZ, 2000). The solar PV systems discussed here are systems that, because of their size and the intermittent nature of the solar resource, generate electricity to provide some lighting and to power communication devices. Such systems create very little, if any, additional cash flow for rural households. Therefore, users should finance solar PV systems from their current income and savings, paying not only the initial investment cost, but also the O&M costs occurring throughout the lifetime of the system.

Due to high initial investment costs, renewable energy provides less installed capacity per dollar invested in comparison to conventional HFO or diesel generation. Therefore, renewable energy requires a higher level of financing for the same capacity. Financial institutions may require a risk premium in lending rates as more capital is being risked up-front in comparison to the conventional power generation projects. Some financial institutions also perceive renewable energy technologies as unreliable and lacking long-term viability (UNIDO and ECREEE, 2012).

The financing cost of solar PV systems is too high for most rural households, so solar will be automatically excluded from lighting options (Hankins, 2013).

4.2.4 Environmental Issues

Solar PV technology is often promoted in SSA for health and global environmental reasons. Burning kerosene indoors for lighting emits fine particles, carbon monoxide, nitric oxides, and sulphur dioxide, which increase the risk of respiratory illnesses and lung cancer (Apple et al., 2010; Lam et al, 2012b). The elimination of kerosene and candles for lighting could reduce GHG emissions, thus improving the health of the local people who are using them, and would also have a positive effect on the environment. However, the amount of GHG emissions caused by kerosene and candle burning for lighting by rural households remains relatively small, particularly when compared to the GHG emissions from household cooking. The cost of reducing CO_2 emissions through solar PV rural electrification is in the range 150–626US$/t$CO_2$[22], which is extremely high compared to the current price of CO_2 emission permits being traded anywhere in the world today. It is also high as

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[22]Simple wick kerosene lamps are the cheapest and the most frequently used kerosene lamps in developing countries (Adkins et al., 2012; Apple et al., 2010). A study conducted in five countries in SSA found that the kerosene lamp with a glass cover is the most frequently used lamp in Kenya, Ghana, and Tanzania, while in Ethiopia the most frequently used lamp is the kerosene lamp with a simple wick, and in Zambia 80% of the consumers use candles as the main source of lighting (Lighting Africa, 2011). The calculations are made for all types of lamps based on the following assumptions. Average fuel consumption rates of kerosene lamps: simple wick – 14.9 g/h, small hurricane – 14.4 g/h, large hurricane – 20.5 g/h, and pressure – 74.1 g/h (Apple et al., 2010). Average number of kerosene lamps per household: simple wick – 1.44, hurricane – 1.48, and pressure – 1.1 (Lighting Africa, 2011). Kerosene lamps are operated for an average of 4 hours a day (Adkins et al., 2012; GTZ, 1995; Hoque and Das, 2013; Lighting Africa, 2010; Van der Plas and Floor, 1995). The amount of CO_2 emissions produced by burning kerosene is assumed to be 2.5 kg/litre (Hoque and Das, 2013; Lighting Africa, 2010). The results are as follows: the cost of mitigating CO_2 through a solar PV system is 622 US$/t$CO_2$ if households were using simple wick kerosene lamps as the main lighting source, 626 US$/t$CO_2$ for small hurricane kerosene lamps, 440 US$/t$CO_2$ for large hurricane kerosene lamps, and 150 US$/t$CO_2$ for pressure lamps.

compared to current estimates of the marginal economic cost of CO_2 emissions (Greenstone and Kopits, and Wolterton, 2011).

There are many ways to reduce carbon emissions that have costs per tonne far lower than these values (Creyts et al., 2007). The UK Department for International Development made an initial evaluation of Clean Development Mechanism (CDM)-type projects in developing countries and found that improved cooking stoves (ICSs) had a much higher impact than solar PV in terms of reducing GHG emissions, because cooking makes up a greater proportion of household energy use. The household cooking energy comprises almost 90% of total primary energy demand in low income countries (Beyene et al., 2015b). The cost of reducing GHG emissions through ICSs is between −190 and −40US$/t$CO_2$ (Begg et al., 2000). Begg et al. (2000) also found that solar PV systems have no effect on the environment: they score 0 out of 100. Therefore, the introduction of ICSs has far better outcomes than solar PV lighting systems in terms of reducing GHG emissions; hence, solar lighting systems are the least preferred option on the basis of emissions reduction and cost (Begg et al., 2000). This should be noted by decision makers when considering solar PV projects in developing countries for carbon emission-reduction mechanisms such as CDM defined by the Kyoto Protocol.

4.2.5 The Problem of Priorities and Poverty Alleviation

Households that can barely afford to buy a PV system might find themselves drawn into long-term debt through purchasing a solar PV system which would add little to their living standards. The problem here is the issue of priorities: the sum spent on a solar PV system could be spent on something else that would increase the economic well-being of households much more than lighting would. There are many other issues that are more fundamental in the lives of households in SSA, such as malnutrition, health, and the education of their children. Over 600 million people in SSA still rely on solid fuels – traditional biomass and charcoal – as their primary cooking fuel. There is strong evidence of a link between smoke from solid fuel use and three important diseases: childhood pneumonia, chronic obstructive pulmonary disease (COPD), and lung cancer. Large amounts of smoke are released from the incomplete combustion of solid fuels as a result of using indoor open fires and inefficient stoves in households. The biggest groups affected by these diseases are children and women, as they are more exposed to the smoke. Such exposure increases the risk of contracting pneumonia 2.3 times for children up to the age of 5, of developing COPD 3.2 times for women, and of contracting lung cancer 1.9 times for women. Almost 30% of the deaths in SSA are attributable to solid fuel use (Legros et al., 2009).

These problems would not be solved, but would be relieved by the introduction and promotion of ICSs. According to the World Bank (1996), relatively simple and inexpensive ICSs can reduce the amount of fuel needed for cooking by 30%, reducing the amount of smoke and causing less damage to the domestic environment and householders' health. In a study done in Ethiopia it was found that ICSs on average reduce fuelwood consumption by 634 kilograms per household per year. This implies to savings of 0.94 tons of CO_2 emissions per household per year (Beyene et al., 2015b). Several other studies done in different low income countries show that ICSs can reduce the consumption of biomass fuels by the households considerably and lessen the indoor air pollution (Adkins et al., 2010; Bensch and Peters, 2013; Beyene et al., 2015a; Beyene et al., 2015b; Burwen and Levine, 2012; Dresen et al., 2014; Johnson et al., 2009; Masera et al., 2007; Smith et al., 2007; Thakuri, 2009). Only 34 million out of 777 million people use ICSs in SSA (Legros et al., 2009). The amount spent on solar PV systems could be spent on these ICSs, which would improve the well-being of households much more than lighting provided at high cost.

One of the important drivers of attempts to disseminate solar PV in SSA has been the belief that solar PV technology will alleviate poverty (Wamukonya, 2007). However, there is no strong evidence of rural development benefits occurring as a result of renewable energy. There are certainly social benefits from lighting, TV, radio, and the powering of telecommunication devices by solar PV systems, and even some economic benefits from reduced kerosene and candle use (Martinot et al., 2002). For instance, as previously mentioned, the ESCO project in Zambia has improved household welfare, but mainly as a result of electric light: an improvement in the quality of the light is the main benefit accrued, especially in terms of opportunities to study more at night (Gustavsson and Ellegard, 2004). However, productive economic development has not followed rural electrification projects if these were not supported by the necessary economic infrastructure and skills. Economic benefits from rural renewable energy are more likely to occur in areas where economic development is already taking place. Moreover, only those who can afford solar PV systems and the necessary infrastructure to convert energy into useful services and productive activities can derive the most benefit from the availability of the energy (GTZ, 1995; Martinot et al., 2002; Weaving, 1995; World Bank, 1996).

GTZ, based on its experience with the dissemination of small-scale PV systems in developing countries, noted that there is little evidence that these systems have an impact on poverty alleviation. GTZ concluded that rural households buy SHSs for improved services such as longer TV viewing and better lighting quality, not because these SHSs actually reduce their energy costs (GTZ, 2000). Begg et al. (2000) conducted a multi-attribute decision analysis of different CDM projects in developing countries. SHSs scored 0 out of 100 in poverty alleviation, whereas ICSs, for example, scored 90. This shows that the emphasis on high technology does not necessarily lead to direct poverty alleviation.

At a household level, the acquisition of a solar PV system is a lower priority for rural households than other basic needs and commodities. Solar PV systems become an option only after these other needs have been satisfied (GTZ, 2000; Lighting Africa, 2011). For the poorest of the rural population, lighting is not always a priority.

Solar PV technology has been suggested as a pre-grid electrification option for use before residents in rural areas receive an electricity connection through a power utility (Van der Plas and Hankins, 1997). It is certainly the case that unless households' demand for electricity increases, power utilities will not extend power grids to them. Yet using solar PV in the meantime until a grid connection is provided in their vicinity is the most costly way of dealing with the current situation prevailing in SSA.

In summary, despite the notable cost decreases in solar PV systems, this continues to be an expensive method of rural electrification. Therefore, encouraging rural households in SSA to purchase solar PV to supply household electricity is not a sound policy for the promotion of their economic development.

4.3 Scenario Analysis: Reductions in the Cost of Solar PV Technology over Time

Solar PV system costs have fallen and continue to decrease. Expectations of continuing cost reductions prevail. A scenario analysis was undertaken to find out how long it will take for solar PV systems to become competitive with the diesel generators for electricity generation. The expected average annual percentage decrease in system costs (i) is calculated as 4%[23]. It is assumed that there will be no change in the capital costs of diesel generators over time.

Substituting this percentage change in system costs into Eqn. (2), it is calculated that it will take 16.8 years for solar PV systems to become competitive with diesel generators, *ceteris paribus*. As is well known from the theory of economic cost–benefit analysis, when the investment cost of a project decreases over calendar time, it is often better to postpone such an investment. With the current costs and falling prices of solar PV systems it is not advisable for rural communities in SSA to invest in this technology until about 2030.

4.4 Conclusions and Policy Implications

Despite substantial worldwide cost decreases in recent years, off-grid solar PV systems remain an expensive power option for SSA. Although solar PV system costs have fallen in SSA over time, they remain much higher than the world average, and unless political, financial, and economic situations stabilize in the region, the situation cannot be expected to change in the near future. Most of the rural poor, at whom off-grid solar PV systems have been targeted, cannot afford to buy even the smallest system at the most favourable rates. More than half of the population

[23]Based on the system cost projections given by Chase (2013).

continues to live below the international poverty line of $2 per day (PPP) in three quarters of the countries in SSA.

Solar PV systems power a limited number of services such as lighting, radios, and TV, which do not generate any income for rural households. The environmental effect of off-grid solar PV technology is insignificant, and the costs of reducing GHG emissions are extremely high. The costs and prices of solar PV systems have been falling. Many renewable energy supporters promote solar PV technology, as they claim that this technology has reached 'grid-parity', and that the LCOE of the solar PV energy has decreased. Energy planners should be cautious in their interpretations because although the values of such energy benchmark tools have been improved over time, they may still be high compared with conventional power-generating options.

As is well known in economic benefit–cost analyses, if the costs of the project continue to fall and the benefits stay constant, it is better to postpone such investments. Therefore, as the prices and costs of solar PV systems are decreasing, it is recommended that investments in such technology be postponed until it becomes competitive with conventional power-generation technologies. Accordingly, in SSA solar PV might be the technology of the future, rather than the present. Subsidizing poor people to buy or use a technology that is forecasted to be obsolete and much cheaper to purchase in the future is usually not a recommended strategy for economic development.

Although there can be no doubt about the impact of electricity access on the economic growth and well-being of any society, a systematic policy and plan for the expansion of electricity services at the margins by national or local electricity grids seems at the present time to be a more promising strategy for eventually achieving a higher degree of rural electrification. Promoting costly renewable technologies such as solar PV to increase electricity access in rural areas of SSA is not an effective anti-poverty policy to follow. Unless the technology is subsidized from abroad, it is the relatively poor consumers of Africa who will pay the high cost of these renewable energy technologies. The only clear beneficiaries are the commercial interests in developed countries that are supplying these technologies.

Chapter 5

AN ECONOMIC APPRAISAL OF SOLAR VERSUS COMBINED CYCLE ELECTRICITY GENERATION FOR AFRICAN COUNTRIES THAT ARE CAPITAL CONSTRAINED

5.1 Introduction

The electricity generation systems in most African countries are small, largely consisting of hydro generation plus open cycle gas turbine and diesel plants that are relatively fuel inefficient. The severe droughts experienced in parts of Africa have reduced the efficiency of many of the hydro plants in these countries, and hence thermal generation capacity has been increased in order to reduce the dependency on weather conditions. Most of the thermal capacity was installed when fuel prices were much lower than they are today. Hence, the generation mix in many utilities is fuel inefficient at today's prices for petroleum. As a general observation the increase in fuel costs would in the future lead to a greater emphasis on installing fuel-efficient combined cycle (CC) power plants to replace the supply that is currently being generated by open cycle gas turbine or diesel generators.

For example, the Tanzanian power system has an installed capacity of 1205 MW (53% thermal: open cycle gas turbine, diesel and steam turbine power plants) (SNC-Lavalin, 2009); the Kenyan system has an installed capacity of 1533 MW (34% thermal: open cycle gas turbine, cogeneration and diesel power plants) (Ministry of Energy, Republic of Kenya, 2011); the Ghanaian system has an installed capacity of

2186 MW (46% thermal: combined cycle gas turbine, open cycle gas turbine and diesel power plants) (GRIDCo, 2010). Very small utilities have limited options for generation: for example, the Djiboutian power system has an installed capacity of 123 MW (100% thermal: diesel power plants), while the Rwandan power system has an installed capacity of 79 MW (53% thermal: diesel and open cycle gas turbine power plants) (SNC-Lavalin, 2011). With the exception of Ghana, there are no combined cycle power plants in any of these systems.

Combined cycle power plants, a combination of two different technologies: a gas turbine and a steam turbine, have a comparative advantage over conventional coal and nuclear power plants as they have lower investment costs, shorter lead times and can operate at a fraction of the personnel costs. The other valuable features of the CC plants are a high efficiency in utilizing energy resources, low emissions, short construction period, low initial investment cost, low operation and maintenance cost, and flexibility of fuel selection (Poullikkas, 2004). The heat of the exhaust gas from the gas turbine is used to raise steam in the heat recovery steam generator for the steam turbine to generate additional power (Henderson, 2007), making the energy transformation efficiency of the advanced CC plants to increase up to levels of 52 to 60% as compared to the range of typical efficiencies of 35% to 42% for the open cycle thermal plants (Vatopoulos et al., 2012).

This chapter is an economic analysis that compares the savings in fuel and greenhouse gas (GHG) emissions, from investing capital in solar PV power generation plants as compared to investing the same amount of funds into fuel-efficient CC power plants. A comparison is made of the economic net present value (ENPV) of the fuel savings versus the capital cost of these power plants assuming the current high oil prices remain at this level for the next twenty years. Such plants would be built as a component of the electric utility's overall least cost system expansion plan. This is not implying that the immediate capacity decision is to invest either in a solar PV plant or a CC plant. Rather the debt of the utility or government is incurred now to finance an expensive solar facility will inhibit its ability to finance efficient thermal plants in the future. Therefore, three different scenarios are considered: investing in solar PV plant now versus investing in CC plant today or alternatively 3 years from now, or 5 years from now.

A sensitivity analysis is carried out for alternative future world crude oil prices to see how these affect the returns on investment for both plant types. A sensitivity analysis is also carried out for different levels of capital costs of solar PV to find the level that solar PV would become the preferred option. Also a calculation is made for how long it will take for a solar PV plant to become as competitive as a CC plant, and at what level the social cost of carbon should be priced for the solar PV project to become attractive.

5.2 Results and Discussion

The following analysis first considers the option of investing in a solar PV plant, which will reduce the level of electricity currently generated by existing thermal generation plants. This is followed by a similar analysis of the investment of the same amount of capital now used as part of the financing of a CC plant.

5.2.1 Economic Evaluation of Solar PV Technology

On an average day, the solar plant starts generating a small amount of electricity at 8 a.m., generates the maximum amount between 12 noon and 2 p.m., and nothing after 6 p.m. For some daytime hours during the year there will be no sunshine, and hence no electricity generated.

With the introduction of a solar PV power plant to the system, the average daily load curve is shown in Fig. 4.

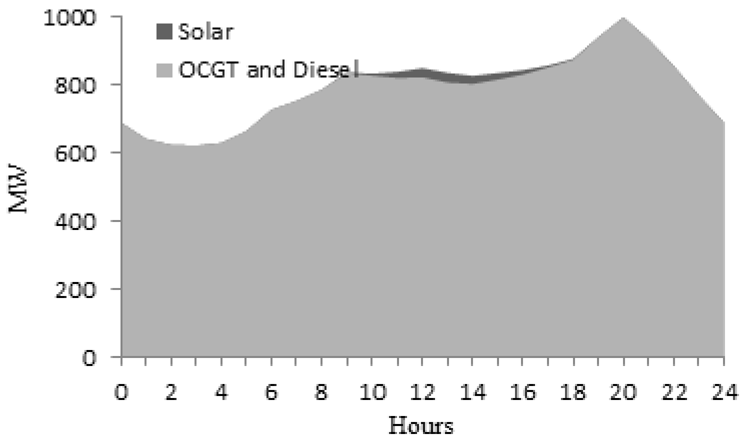

Figure 4. Average daily load curve with solar and thermal supplies of energy

Peak electricity demand in most of the SSA countries is observed during the evening hours. Therefore, there is a mismatch of the evening peak with solar radiation at that time of the day (UNIDO and ECREEE, 2012). Solar generation does not eliminate the chronic blackouts and brownouts in a system that already has a reserve deficit as it does not increase the capacity of the system. Instead, it replaces the electricity generated by the thermal plants, hence saving fuel, mainly in the intermediate load periods, which can be seen in Fig. 5.

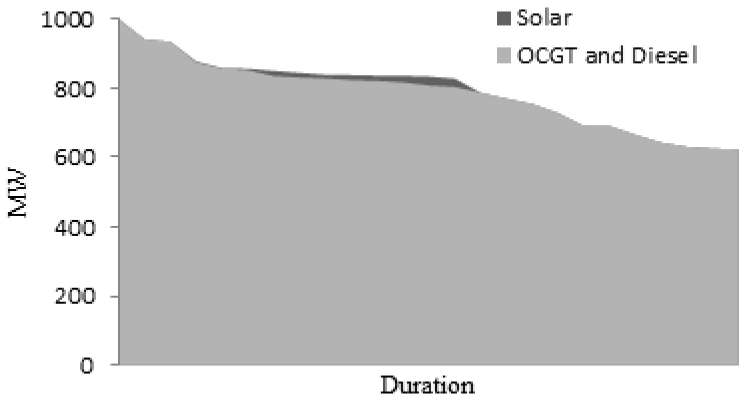

Figure 5. Annual load duration curve for thermal system with solar supply

In such situations, solar PV power generation will replace the thermal generation and save fuel. Table 5 shows the amount of fuel savings, the financial value of the fuel savings and the amount of greenhouse gas emissions avoided.

Table 5. Fuel savings and revenue from solar generation

Year	0	1	2	3	…	26
Total electricity production (MWh)	0	0	49,275	48,979	…	42,648
Total fuel savings (litres 000)	0	0	12,122	12,169	…	13,321
Financial value of fuel savings (US$ 000)	0	0	9,639	9,677	…	10,594
GHG emissions avoided (tonnes)	0	0	36,759	36,539	…	31,815

The main benefits of the solar PV plant are the savings on the amount of fuel, and operating and maintenance costs of the thermal plant whose electricity generation it replaces. In this case, the solar PV plant is replacing generation by the open cycle gas turbine and diesel power plants. The economic resource flow for the solar PV plant is evaluated and the results from country's point of view are shown in Table 6. The

ENPV at a real discount rate of 12% has a negative value –US$ 18,790 thousand and with an economic internal rate of return (EIRR) is 8.35%[24].

Table 6. Economic resource flow statement for solar PV plant: country's point of view (US$ 000)

Year	0	1	2	3	…	26
Economic value of fuel savings	0	0	9,513	9,551	…	10,455
Savings on O&M costs of thermal plants	0	0	197	196	…	171
Total inflows	0	0	9,710	9,746	…	10,625
Operating cost	0	0	1,272	1,272	…	1,272
Capital cost	0	84,780	0	0	…	0
Grid-level system cost	0	0	587	583		508
Total outflows	0	84,780	1,859	1,855	…	1,780
Net resource flow	0	-84,780	7,851	7,891		8,845
ENPV (country, US$ 000) @ 12% = −18,790						

The economic resource flow for the solar PV plant from a global point of view is estimated, including GHG mitigation, and the results are shown in Table 7. Although the value of the ENPV improves from –US$ 18,790 thousand to –US$ 7,366 thousand, it is still negative. The EIRR has increased to 10.62%.

Table 7. Economic resource flow statement for solar PV plant: global point of view including greenhouse gases damage mitigation (US$ 000)

Year	0	1	2	3	⋯	26
Economic value of fuel savings	0	0	9,513	9,551	⋯	10,455
Savings on O&M costs of thermal plants	0	0	197	196	⋯	171
Economic value of GHG emission reductions	0	0	1,489	1,509	⋯	2,034
Total inflow	0	0	11,199	11,255	⋯	12,660
Operating cost	0	0	1,272	1,272	⋯	1,272
Capital cost	0	84,780	0	0	⋯	0
Grid-level system cost	0	0	587	583		508
Total outflows	0	84,780	1,859	1,855	⋯	1,780

[24] A 12% economic discount rate is used here because this is the rate that is used by international institutions such as USAID and the African Development Bank in the economic analysis of their investment operations. For example, the interest rates on equity in Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) in South Africa range from 12% to 14% (UNEP, 2014).

Net resource flow	0	-84,780	9,341	9,400	…	10,880
ENPV (global, US$ 000) @ 12% = −7,366						

From this analysis it is clear that introducing a solar PV plant into the electricity generation system is difficult to justify in terms of saving fuel oil by substituting for thermal generation. Its capital costs are greater than the value of fuel oil saved. Even when the economic value of the global damage caused by GHG emissions is included, the ENPV remains negative. The estimates used here for the global damage of carbon emissions, US$ 39 per tonne for 2015 and rising over time, are far above the prices of carbon credits being traded anywhere in the world today. For example, the price for CO_2 emission permits in the European Emissions Trading System fell dramatically to € 7.52 (as of June 26, 2015) (European Energy Exchange, 2015).

Borenstein (2008) came to a similar conclusion, that even after adjusting for its timing and transmission advantages, the market benefits of installing the solar PV technology are lower than its costs. Furthermore, he found that taking into the consideration the GHG mitigation by solar PV did not make the net social return on these investments positive.

5.2.2 Economic Evaluation of Combined Cycle Technology

The economic valuation of the CC plant is considered in three different scenarios: first - investing the same amount of capital as a 30MW solar PV plant costs (i.e. US$ 84 million) in a CC plant today, second - 3 years from now, and third - 5 years from now.

A new CC plant is likely to be the most fuel-efficient thermal plant in the system, generating electricity for the base load. It can be easily illustrated by the help of merit order model, how a new CC plant will fit into the system and which load it will be serving[25].

Screening curves as drawn in the upper panel in Fig. 6 show the average cost of operating a generator with a specific capacity factor. The intercept of the screening curve is simply the fixed cost, whereas the slope of the curve is the variable cost of the generator for which the curve is plotted (Stoft, 2002). Screening curves of open cycle and combined cycle gas turbine power plants are drawn on the same graph (Fig. 6) to see how the costs of the different technologies move as the capacity factor of the plants increase. Intersections of the screening curves show the boundary between marginal levels of capacity factors for each type of the generator. Screening curves of open cycle and combined cycle power plants are intersecting at the capacity factor of approximately 10%, meaning that open cycle power plant should be used when the plant is required to operate 10% of the time or less[26].

[25]A merit order model ranks the generators from the lowest marginal running cost to the highest marginal running cost so that electric utility operates at minimum production cost. One could also use a full-information grid engineering models like MESSAGE, WASP or MARKAL. These models use dynamic optimization algorithms and require detailed information about the generators and transmission lines of the electricity system which make them cumbersome for this type of study where a generic system is postulated as a framework of analysis (Cullen, 2013).

[26] Given the costs of rapid start up and technical constraints for a CC plant, it is likely that in practice the CC plant will not operate at load factors as low as 10%.

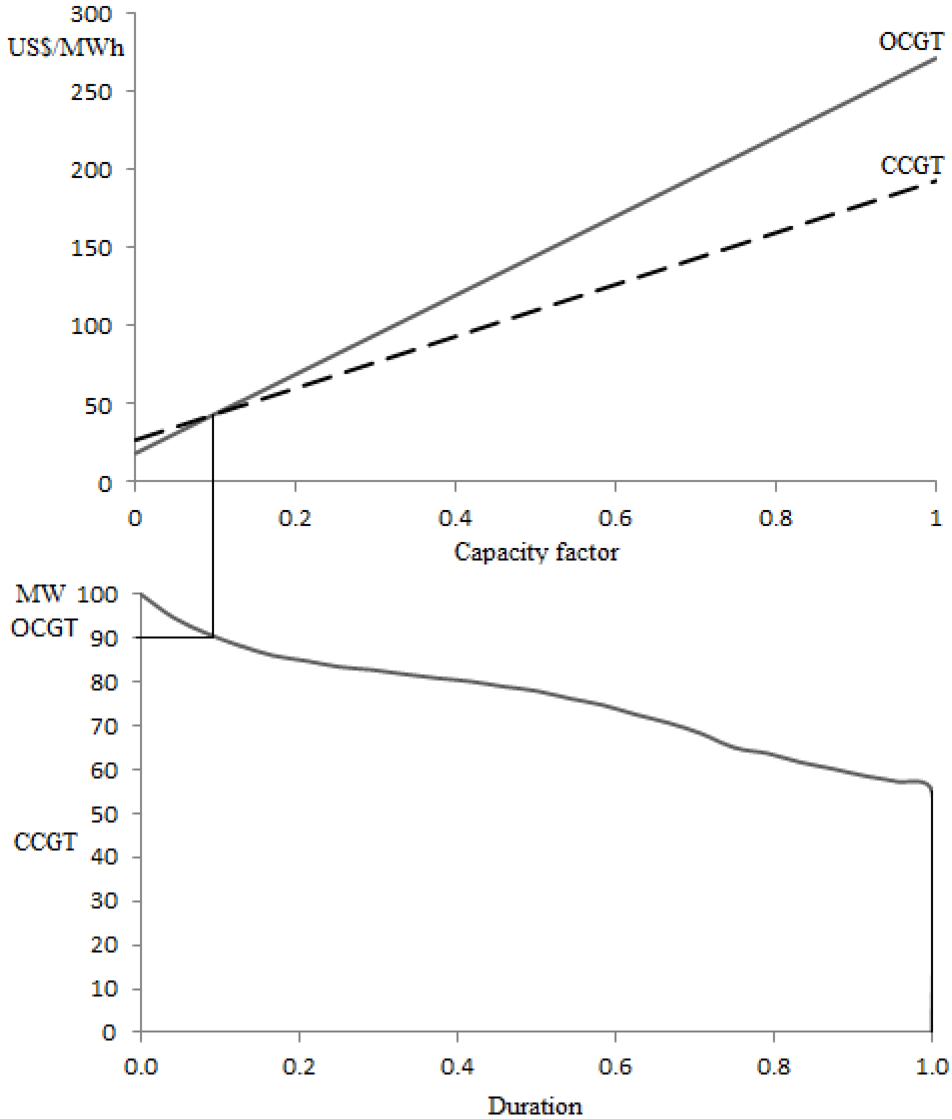

Figure 6. Merit order model. The cost estimates for OCGT is taken from MEM (2013).

The lower panel of Fig. 6, the load duration curve, shows how the model selects generator capacities. Above chosen capacities for each plant type are stacked up against the load duration curve. All load with duration greater than 10%, or about 876 hours per year, should be served by the combined cycle power plants, while loads of lesser duration should be served by open cycle power plants. This does not just show that combined cycle power plant is going to be a base load plant, but it also shows that this system needs efficient base load plants.

The CC plant adds to the capacity of the electricity system. The inefficient open cycle or diesel power plants will still be available to meet the peak load and to improve system reliability. In this way the CC plant will help to eliminate the chronic blackouts and brownouts in a system that has a reserve deficit.

Because the CC plant is more efficient than the open cycle gas turbine power plants, it will save fuel, and as a consequence less GHG will be released into the atmosphere. Table 8 shows the amount of fuel savings, the financial value of the fuel savings and the amount of GHG emissions avoided.

Table 8. Fuel savings and revenue from combined cycle generation

Year	0	1	2	3	⋯	26
Total electricity production (MWh)	0	0	270,671	267,964	⋯	212,660
Total fuel savings (litres 000)	0	0	23,343	23,341	⋯	23,287
Financial value of fuel savings (US$ 000)	0	0	18,563	18,561	⋯	18,519
GHG emissions avoided (tonnes)	0	0	72,966	72,959	⋯	72,791

The main benefit of the CC plant is the fuel saving that is the result of its energy transformation efficiency. Because it has been assumed that the variable operating and maintenance cost of the CC plant is equal to that of the open cycle and diesel power plants being replaced, the CC plant will produce no savings on operating and maintenance costs. Table 9 reports on the economic resource flow for the CC plant from the country's point.

Table 9. Economic resource flow statement combined cycle generation: country's point of view (US$ 000)

Year	0	1	2	3	…	26
Economic value of fuel savings	0	0	18,320	18,318	…	18,276
Total inflow	0	0	18,320	18,318	…	18,276
Operating cost	0	0	353	353	…	353
Capital cost	47,477	37,303	0	0		0
Grid-level system cost	0	0	152	150	…	119
Total outflow	47,477	37,303	505	503	…	472
Net resource flow	-47,477	-37,303	17,815	17,815	…	17,804
ENPV (country, US$ 000) @ 12% = 43,954						

The ENPV of the CC investment (using a discount rate of 12%) is equal to US$ 43,954 thousand. This is US$ 62,743 thousand more than for the solar PV plant. The EIRR is 18.76%. This is the type of efficient electricity generation technology that the electric utilities of Africa will need to have more of in the near future.

The economic resource flow for the CC plant from a global point of view is also estimated, including the GHG damage saved, and the results are shown in Table 10. The ENPV increases further to US$ 67,641 thousand, and the EIRR to 21.94%.

Table 10. Economic resource flow statement combined cycle generation: global point of view including greenhouse gases damage mitigation (US$ 000)

Year	0	1	2	3	…	26
Economic value of fuel savings	0	0	18,320	18,318	…	18,276
Economic value of GHG emission reductions	0	0	2,956	3,012	…	4,655
Total inflow	0	0	21,276	21,331	…	22,931
Operating cost	0	0	353	353	…	353
Capital cost	47,477	37,303	0	0		0

Grid- level system cost	0	0	152	150		119
Total outflows	47,477	37,303	505	503	…	472
Net resource flow	-47,477	-37,303	20,771	20,827	…	22,458
ENPV (global, US$ 000) @ 12% = 67,641						

These results show that adding a CC plant to a fuel-inefficient thermal generation system is a good investment decision. The amount of electricity generated by a CC plant with the same capital cost as a solar PV plant is 5.4 times greater. This has a dramatic positive impact from both the country's and the global point of view. The fuel savings from the CC plant are 1.9 times greater than those from the solar PV plant. As a consequence, the GHG emissions avoided by the CC plant are 2.1 times more than those from the solar PV plant. The CC plant will also improve the reliability of the overall system supply because the OCGT and diesel plants it displaces can now be used to meet the peak load demands.

A similar approach was taken by Frank (2014) in a study for the USA of the efficiency of reducing GHG by alternative renewable and conventional generation technologies. He found that a new solar PV plant when displacing old fuel inefficient plants reduces emissions per MW of capacity by less than any other kind of new plant, in particular the CC plant,. A new CC plant that displaces an old fuel inefficient plant in terms of avoiding carbon emissions per MW of new capacity is superior to solar PV plant, and has high positive net benefits. In contrast, the net benefits of a solar PV plant were found to be negative. Even at extremely high carbon prices as US$ 100 it continued to be negative. The reasons why solar is very costly from a social perspective is due to the solar PV power plants' high capacity costs, low capacity factors and lack of reliability as compared to modern efficient fossil fuel plants.

Table 11 shows how the ENPV of CC plant will change if the investment would be done 3 years from now or 5 years from now. Although the ENPVs for CC plant are lower than investing in it today, they are still large positive numbers. This shows that if investing in solar PV technology today will prevent the utility from investing in efficient CC technology, in even 3 or 5 years from the current period a very substantial net economic gain will have been forfeited.

Table 11. ENPV (US$ 000) of CC plant for different scenarios

3 years from now		5 years from now	
ENPV(country)	ENPV (global)	ENPV (country)	ENPV (global)
31,285	49,136	24,940	39,722

The LCOE is calculated as 0.2279 US$/kWh for solar PV and 0.1589 US$/kWh for CC plant, showing the cost effectiveness of CC technology over solar PV.

These very substantial net present values are arising because at the present time there are plants generating electricity that are less fuel efficient than the combined cycle plant. The CC plant should be operated instead of these plants and the CC technology is capable of running for most of the hours in the year. In contrast, while the solar PV system can generate electricity at a very low variable cost, the volume of electricity it can generate is constrained by the available sunlight. In addition, the capital cost of solar PV per MW of capacity is much greater than the capital cost per MW of a CC generation plant.

5.3 Sensitivity Analysis

A sensitivity analysis is carried out for a range of HFO prices, *ceteris paribus*. The results, which are shown in Table 12, show that the ENPV for the solar PV plant becomes positive only if the inefficient plants it is replacing are using fuel that costs of US$ 514 per tonne (US$ 80.51 per barrel) or more, whereas the ENPV for the CC plant is positive at any price above US$ 220 per tonne (US$ 34.46 per barrel).

Table 12. Sensitivity analysis of ENPV @ 12% of solar PV and combined cycle technologies to HFO prices

Oil price (US$/tonne)	ENPV Solar (US$ 000)	ENPV CC (US$ 000)
219	-43,501	-53
370	-21,230	41,669
464	-7,366	67,641
510	-581	80,351
514	8	81,456

It was shown earlier in Section 5.2.1 that the solar PV power generation is not competitive if the economic analysis is considered from country's and global point of view. What then is the level of social cost of carbon that would make solar PV power generation break even economically? As it can be seen in Table 13, the ENPV of the solar PV plant gets positive (as compared to continuing to generate with existing inefficient plants) only at a US$ 65 per tonne, which is an extremely high number compared to the current price of CO_2 emission permits. There are many ways to reduce carbon emissions that have costs/tonne far lower than US$ 65 per tonne (Creyts et al., 2007), including investing in CC generation plants.

Table 13. Sensitivity analysis of ENPV @ 12% of solar PV technology to SCC

SCC in 2015 (US$/tonne)	39	45	55	64	65
ENPV Solar (US$ 000)	-7,366	-5,608	-2,679	-43	250

The next task is to find the level of capital cost of solar PV that would make the ENPV of the solar PV plant equal to that of the CC plant, *ceteris paribus*. As it can be seen in Table 14, the capital cost of solar PV needs to drop to US$ 320 per MW in order to yield the same level of ENPV (US$ 67,641 thousand) as the CC plant. When comparing such alternatives the criterion is to choose the alternative that maximizes the ENPV. One should never select an option that leaves one just indifferent to the current situation. Such is the case when the ENPV is equal to zero.

Table 14. Sensitivity analysis of ENPV @ 12% of solar PV technology to capital cost

Capital cost (US$/MW)	2,826	2580	700	600	320
ENPV Solar (US$ 000)	-7366	-1	56,280	59,274	67,656

5.4 Scenario Analysis: Reductions in the Cost of Solar PV Technology over Time

There has been a noticeable fall in the cost of solar PV systems over at least the past 15 years owing to the decrease in the global PV module prices, the most expensive component of the solar PV system. Therefore, a scenario analysis is undertaken to find out how long it will take for the solar PV plant to become competitive with the CC plant for electricity generation. Given the percentage changes in system costs (see Chapter 3, Section 3.1) it is estimated that it will take from 9 to 18 years for the solar PV plant to become competitive with the CC plant, *ceteris paribus.* As in the analysis reported in Section 3.5 the number of MW of a CC plant that would have the equivalent cost to this 30 MW solar plant is also decreased to match the drop in the cost of the solar PV plant.

As is well known from the theory of economic cost–benefit analysis, when the investment cost of a project is decreasing over calendar time it is often better to postpone such an investment (Jenkins and Kuo, and Harberger, 2013). With falling solar PV system prices it is not advisable for electric utilities with the characteristics of the one described here to invest in this technology until at least 2025.

5.5 Conclusion

Most of the countries in the International Monetary Fund and the World Bank's HIPC (Heavily Indebted Poor Countries) Initiative are in sub-Saharan Africa; these include Angola, Benin, Burkina Faso, Burundi, Cameroon, Chad, Central African Republic, Republic of Congo, Democratic Republic of Congo, Ethiopia, The Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Madagascar, Malawi, Mali, Mauritania, Mozambique, Níger, Rwanda, São Tomé Príncipe, Senegal, Sierra Leone, Tanzania, Togo, Uganda, and Zambia[27]. The public electric utilities in most of these counties are capital constrained. Governments also are restricted in their borrowing for the purposes of expanding electricity capacity. This analysis suggests that it is only advisable for African countries to invest in such capital intensive solar PV technologies for on-grid electricity generation if their purchase is being subsidized by multilateral or bilateral donors, and these aid flows are completely tied to this type of technology.

Burdening the electric utilities now with debt or the payment obligations of power purchase agreements, for a solar facility that will save fuel inefficiently is not advisable. Such obligations will constrain the utilities in the future to finance efficient technologies that will considerably reduce their overall costs of generation.

[27]The aim of the HIPC initiative was to bring the debt burdens of HIPCs down to manageable levels. Although 30 out of 33 eligible African countries have reached the decision point and 26 have reached the completion point and also benefited from debt relief under the Multilateral Debt Relief Initiative (MDRI), one-quarter of HIPCs still face high debt vulnerabilities. Moreover, the HIPC Initiative was not intended to be a permanent mechanism to relieve the external debts of low income countries and it was effectively closed to new entrants in 2006 (IDA and IMF, 2011).

Combined cycle power plants enhance overall system reliability in these countries, while solar PV plants decrease reliability. The absence of a reliable supply of electricity is a major handicap of African economies. Not just in Africa, access to plentiful, reliable, and inexpensive energy is requisite of increasing living standards and strong economic development (Greenstone and Looney, 2012).

The fuel savings with a CC plant are two times greater than those obtained with a solar PV plant. As a result, the amount of GHG emissions avoided by using the CC plant is two times greater than that of solar PV plant with the same capital cost. It is clear that CC plants make a much greater contribution to environmental sustainability than solar PV generation in Africa.

Because of the shortage of capital many utilities in Africa and elsewhere have allowed their stock of electricity generation plants to age beyond the point where it would have been economically justified to be replaced. Careful systems planning and investing according to their plans would help to reduce the costs of generation and delivery of electricity over time. This should be the first priority of electricity policy in these countries.

Given the current costs of solar PV plants and the falling prices of solar PV systems, it is not advisable for such electric utilities in Africa to invest in this technology (unless subsidized from abroad) until the solar PV plants become competitive with CC plants. If unsubsidized, it is the relatively poor consumers of Africa who will pay for these inefficient technological choices.

Chapter 6

AN ECONOMIC APPRAISAL OF SOLAR PV VERSUS DIESEL ELECTRICITY GENERATION IN SUB-SAHARAN AFRICAN COUNTRIES

6.1 Introduction

It is well known that sub-Saharan Africa's (SSA) power supply is unreliable. Electrical power outages in SSA countries are woefully high: 13.9 outages per month in Benin, 7.2 outages in Gabon, and 32.7 outages in Central African Republic (World Bank, 2013). The level of system losses vary in SSA from 14.5% in Angola to 68% in Swaziland, with the average values ranging between 30% -50% in contrast to the accepted average of 7-10% by the developed world (Tallapragada et al., 2009). Inadequate power supplies impose heavy losses on the private sector. Recurrent power outages mean remarkable losses in forgone sales and damaged equipment (World Bank, 2010). Unreliable supplies of electricity by national electric power utilities have forced many users, from households to big enterprises, to invest in backup generators and generate their own electricity (AfDB, 2013b; Foster and Steinbuks, 2009; Karakezi and Kimani, 2002; World Bank, 2010). The size of own power generation units' ranges from 1 MW to 700 MW (Karakezi and Kimani, 2002), making up to 6 percent of total installed capacity in SSA, with the costs of generation varying between US$ 0.3-0.7 per kilowatt-hour, which is often three times higher than buying the electricity from the public grid (Foster and Steinbuks, 2009).

Capacity shortages have compelled power utilities to use leased emergency power generating units, mainly thermal oil-fired generators, to meet the suppressed demand for electricity. Countries enter into short-term leasing contracts, which are extremely expensive (UNEP, 2014). The costs of these contracts may approach 3 to 4 percent of GDP in some countries (Eberhard et al., 2008). An estimated 750 MW of emergency generation is operating currently in SSA. In some countries the emergency generation capacity represents a considerable part of the national installed capacity. For example, in Angola it accounts to 18.1% of the total installed capacity in the country, in Ghana – 5.4%, in Rwanda – 48.4%, and in Uganda – 41.7% (World Bank, 2010). Undoubtedly, the economic costs of inadequate power supplies in short-term are the cost of running backup generators, forgone production due to power outages, payments to leased emergency generation units, and in the long-run the drop of economic growth rate (Eberhard and Shkaratan, 2012, World Bank, 2010). Negative impact of deficient power sector infrastructure is one of the major constraints on economic development of the region (Foster, 2008).

These emergency power generating units can be installed in a few weeks, and then returned back to the private provider after being leased for up to two years, sometimes longer. This is not the only reason for the increased use of oil-fired power generators, namely the diesel power plants, for the emergency purposes in SSA. Contemporary diesel power plants are characterized by high fuel efficiency (even at low capacity utilization), with wide fuel and operational flexibility, low maintenance costs, high reliability and security, rapid start-up and black-start capabilities, and the modular concept for flexible capacity expansion (MAN Diesel & Turbo, 2014; Wärtsilä, 2013).

The aim of this chapter is to investigate the feasibility of solar PV technology in SSA countries where the majority of power utilities lack generation capacity. An economic analysis is carried out that compares the savings in fuel and greenhouse gas (GHG) emissions, from investing capital in solar PV power generation plants as compared to investing the same amount of funds into diesel power plants, which are the most used type of emergency power generation source. A comparison is made of the economic net present value of the fuel savings versus the capital cost of the solar plant assuming the current high oil prices remain at this level for the next twenty years. A similar analysis is carried out for same investments made in diesel power plant using heavy fuel oil (HFO). Moreover, three different scenarios are considered: investing in solar PV plant now versus investing in diesel plant today or alternatively 3 years from now, or 5 years from now.

A sensitivity analysis is carried out for alternative future world crude oil prices to see how these affect the returns on investment for both plant types. A sensitivity analysis is also carried out for different levels of capital costs of solar PV to find the level that solar PV would become the preferred option. Also a calculation is made for how long it will take for a solar PV plant to become as competitive as a diesel plant, and at what level the social cost of carbon should be priced for the solar PV project to become attractive.

6.2 Results

The following analysis first considers the option of investing in a solar PV plant, which will reduce the level of electricity currently generated by existing thermal generation plants. This is followed by a similar analysis of the investment of the same amount of capital now used to finance a diesel plant.

6.2.1 Economic Evaluation of Solar PV Technology

As it was mentioned in Section 5.2.1, solar generation does not eliminate the chronic blackouts and brownouts in a system that already has a reserve deficit as it does not permanently increase the capacity of the system at peak hours. The biggest benefits of the solar PV plant are the savings on the amount of fuel, and operating and maintenance costs of the thermal plant whose electricity generation it replaces. The economic resource flow for the solar PV plant is evaluated from the country's point. The ENPV at a real discount rate of 12% has a negative value –US$ 23,808 thousand and with an economic internal rate of return (IRR) is 7.30%.

The economic resource flow for the solar PV plant from a global point of view is also estimated, the value of the ENPV improves from –US$ 23,808 thousand to –US$ 13,256 thousand, yet it is still negative. The economic IRR has increased to 9.48%.

Similar conclusions are reached here as in Section 5.2.1. It is hard to justify the introduction of solar PV plant into the electricity generation system in terms of saving fuel oil by substituting for thermal generation. The value of fuel oil saved is much lower than the capital costs of the solar PV systems. Even when the economic value of the global damage caused by GHG emissions is taken into consideration, ENPV remains negative.

6.2.2 Economic Evaluation of Diesel Technology

A new diesel plant is likely to be the most fuel-efficient thermal plant in the system, generating electricity for the base load. Because the diesel plant is more efficient than the existing old thermal plants, it will save fuel, and as a consequence less GHG will be released into the atmosphere. Table 15 shows the amount of fuel savings, the financial value of the fuel savings and the amount of GHG emissions avoided.

Table 15. Fuel savings and revenue from diesel power generation

Year	0	1	2	3	…	26
Total electricity production (MWh)	0	749,550	742,054	734,634	…	588,905
Total fuel savings (litres 000)	0	29,285	29,282	29,280	…	29,215
Financial value of fuel savings (US$ 000)	0	23,289	23,286	23,284	…	23,233
GHG emissions avoided (tonnes)	0	91,539	91,530	91,521	…	91,320

The main benefits of the diesel plant are the fuel saving that is the result of its energy transformation efficiency and savings on the non-fuel variable operating and maintenance cost of the old thermal plants being replaced. Table 16 reports on the economic resource flow for the diesel plant from the country perspective.

Table 16. Economic resource flow statement diesel power generation: country's point of view (US$ 000)

Year	0	1	2	3	…	26
Economic value of fuel savings	0	22,983	22,981	22,979	…	22,928
Savings on variable O&M cost of old thermal plants	0	2,998	2,968	2,939	…	2,356
Total inflow	0	25,981	25,949	25,917		25,284
Operating cost	0	1,956	1,956	1,956	…	1,956
Capital cost	84,780	0	0	0		0
Grid-level system cost	0	420	416	411	…	330
Total outflow	84,780	2,376	2,372	2,368	…	2,286
Net resource flow	-84,780	23,605	23,577	23,549	…	22,997
ENPV (country, US$ 000) @ 12% = 98,940						

The ENPV of the diesel investment (using a discount rate of 12%) is equal to US$ 98,940 thousand. This is US$ 122,748 thousand more than for the solar PV plant. The EIRR is 27.67%. This is the type of efficient electricity generation technology that the electric utilities of SSA countries will need to have more of in the near future.

The economic resource flow for the diesel plant from a global point of view is also estimated, including the GHG damage saved, and the results are shown in Table 17. The ENPV increases further to US$ 132,223 thousand, and the EIRR to 32.36%.

Table 17. Economic resource flow statement diesel generation: global point of view including greenhouse gases damage mitigation (US$ 000)

Year	0	1	2	3	…	26
Economic value of fuel savings	0	22,983	22,981	22,979	…	22,928
Savings on variable O&M cost of old thermal plants	0	2,998	2,968	2,939		2,356
Economic value of GHG emission reductions	0	3,708	3,779	3,851	…	5,839
Total inflow	0	29,690	29,728	29,769	…	31,123
Operating cost	0	1,956	1,956	1,956	…	1,956
Capital cost	84,780	0	0	0		0
Grid- level system cost	0	420	416	411		330
Total outflows	84,780	2,376	2,372	2,368	…	2,286
Net resource flow	-84,780	27,314	27,356	27,401	…	28,837
ENPV (global, US$ 000) @ 12% = 132,223						

These results show that adding a diesel plant to a fuel-inefficient thermal generation system is a good investment decision. The amount of electricity generated by a diesel plant with the same capital cost as a solar PV plant is 16 times greater. This is even higher than that of a CC plant. Though the energy transformation efficiency of a CC plant is much higher than that of a diesel plant, the capital cost of a diesel plant per MW is much lower than that of a CC plant. This translates to a higher capacity of the diesel plant for the same amount of investment as of a 30 MW solar PV plant.

This has a dramatic positive impact from both the country’s and the global point of view. The fuel savings from the diesel plant are 2.5 times greater than those from the solar PV plant. As a consequence, the GHG emissions avoided by the diesel plant are 2.8 times more than those from the solar PV plant. The diesel plant will also improve the reliability of the overall system supply because the old thermal plants it displaces can now be used to meet the peak load demands.

Capacity factor is the ratio of the actual annual MW hours of electrical energy production per MW of capacity of a power plant divided by 8,760 megawatt-hours. The higher the capacity factor of a new plant, the bigger is the amount of emissions reduced per MW of new capacity, *ceteris paribus*. Solar PV plants can only avoid emissions when they are producing electricity, i.e. when the sun is shining, that is only at a fraction of the time (Frank, 2014). Solar PV facility has a capacity factor of 18% in SSA. Although this value is a very high value compared to the ones found anywhere in Europe, or in some other parts of the world, it is much lower than the capacity factors of the thermal power plants. For instance, the highly efficient thermal power plants can operate at a capacity factors - above 90%. The capacity factor of a diesel power plant was assumed as 66% in this analysis. Therefore, the diesel plants avoid more emissions per MW of new capacity, simply because diesel plants have a much higher capacity factor. The same is true for the CC plant.

Furthermore, due to intermittency of the energy source, solar PV plants without storage are less reliable. Additional investments in capacity are required to maintain the system's reliability. Thus a solar PV plant with a 20% capacity factor can actually replace much less than a third of a diesel plant with a 60% capacity factor, if system reliability is to be maintained (Frank, 2014). Moreover, currently the electricity storage costs are not yet economically viable. Therefore, it is not advisable to introduce a solar PV facility into a power system that is already facing the problems of inadequate power supply. Solar plant is not going to add to the capacity of the power system, nor is it going to improve the reliability of the power system.

Table 18 shows how the ENPV of diesel plant will change if the investment would be done 3 years from now or 5 years from now. Although the ENPVs for diesel plant are lower than investing in it today, they are still large positive numbers. This shows that if investing in solar PV technology today will prevent the utility from investing in diesel power plant, in even 3 or 5 years from the current period a very substantial net economic gain will have been forfeited.

Table 18. ENPV (US$ 000) of diesel plant for different scenarios

3 years from now		5 years from now	
ENPV(country)	ENPV (global)	ENPV (country)	ENPV (global)
62,878	85,272	50,126	68,671

The LCOE is calculated as 0.2467 US$/kWh for solar PV and 0.1632 US$/kWh for diesel plant, showing the cost effectiveness of diesel technology over solar PV[28].

6.3 Sensitivity Analysis

A sensitivity analysis is carried out for a range of HFO prices, *ceteris paribus*. The results, which are shown in Table 19, show that the ENPV for the solar PV plant becomes positive only if the inefficient plants it is replacing are using fuel that costs of US$ 562 per tonne (US$ 88 per barrel) or more, whereas the ENPV for the diesel plant is positive at any price above US$ 123 per tonne (US$ 19 per barrel).

Table 19. Sensitivity analysis of ENPV @ 12% of solar PV and diesel technologies to HFO prices

[28] The LCOE for solar PV plant is higher here than in Section 5.2.2 due to the difference in radiation levels for SSA and the whole of Africa.

Oil price (US$/tonne)	ENPV Solar (US$ 000)	ENPV Diesel (US$ 000)
123	-59,714	-162
124	-59,578	226
380	-24,700	99,612
464	-13,256	132,223
561	-40	169,882
562	96	170,270

It was shown earlier in Section 6.2.1 that the solar PV power generation is not competitive if the economic analysis is considered from the country's and global point of view. What then is the level of social cost of carbon that would make solar PV power generation break even economically? As it can be seen in Table 20, the ENPV of the solar PV plant gets positive (as compared to continuing to generate with existing inefficient plants) only at a US$ 88 per tonne, which is an extremely high number compared to the current price of CO_2 emission permits.

Table 20. Sensitivity analysis of ENPV @ 12% of solar PV technology to SCC

SCC in 2015 (US$/tonne)	39	60	70	80	87	88
ENPV Solar (US$ 000)	-13,256	-7,573	-4,868	-2,162	-268	3

The next task is to find the level of capital cost of solar PV that would make the ENPV of the solar PV plant equal to that of the diesel plant, *ceteris paribus*. As it can be seen in Table 21, even when the capital cost of solar PV drops to US$ 0 per MW (literally free) it does not yield the same level of ENPV (US$ 132,223 thousand) as the diesel plant, *ceteris paribus*.

Table 21. Sensitivity analysis of ENPV @ 12% of solar PV technology to capital cost

Capital cost (US$/MW)	2,826	2500	1500	500	0
ENPV Solar (US$ 000)	-13,256	-3,496	26,441	56,378	71,346

6.4 Scenario Analysis: Reductions in the Cost of Solar PV Technology over Time

A scenario analysis is undertaken to find out how long it will take for the solar PV plant to become competitive with the diesel plant for electricity generation. Given the percentage changes in system costs (see Chapter 3, Section 3.1) it is estimated that it will take from 14.2 to 27.7 years for the solar PV plant to become competitive with the diesel plant, *ceteris paribus.* As in the analysis reported in Section 3.5 the number of MW of a diesel plant that would have the equivalent cost to this 30 MW solar plant is also decreased to match the drop in the cost of the solar PV plant.

With falling solar PV system prices it is not advisable for electric utilities with the characteristics of the one described here to invest in this technology until at least 2030.

6.5 Conclusion

This analysis suggests that it is only advisable for SSA countries to invest in such capital intensive solar PV technologies for on-grid electricity generation if their purchase is being subsidized by multilateral or bilateral donors, and these aid flows are completely tied to this type of technology.

The fuel savings with a diesel plant are nearly three times greater than those obtained with a solar PV plant. As a result, the amount of GHG emissions avoided by using the diesel plant is almost three times greater than that of solar PV plant with the same capital cost. It is clear that diesel plants make a much greater contribution to environmental sustainability than solar PV generation in Africa.

These results show that adding a diesel plant to a fuel-inefficient thermal generation system is a good investment decision. The amount of electricity generated by a diesel plant with the same capital cost as a solar PV plant is 16 times greater. This is even higher than that of the CC plant. Moreover, for power utilities of SSA with capacity shortages, it is better to invest in diesel power plants rather than investing in high capital cost solar PV power plants and continue leasing emergency power generating units. This should be noted by the policymakers in deciding between different technology alternatives in SSA.

Given the current costs of solar PV plants and the falling prices of solar PV systems, it is not advisable for such electric utilities in Africa to invest in this technology (unless subsidized from abroad) until the solar PV plants become competitive with diesel plants. If unsubsidized, it is the relatively poor consumers of SSA who will pay for these inefficient technological choices.

Chapter 7

CONCLUSIONS AND POLICY DISCUSSIONS

Despite substantial worldwide cost decreases in recent years, off-grid solar PV systems remain an expensive power option for SSA. Although solar PV system costs have fallen in SSA over time, they remain much higher than the world average, and unless political, financial, and economic situations stabilize in the region, the situation cannot be expected to change in the near future. Most of the rural poor, at whom off-grid solar PV systems have been targeted, cannot afford to buy even the smallest system at the most favourable rates. More than half of the population continues to live below the international poverty line of $2 per day (PPP) in three quarters of the countries in SSA.

Solar PV systems power a limited number of services such as lighting, radios, and TV, which do not generate any income for rural households. The environmental effect of off-grid solar PV technology is insignificant, and the costs of reducing GHG emissions are extremely high. The costs and prices of solar PV systems have been falling. Many renewable energy supporters promote solar PV technology, as they claim that this technology has reached ‘grid-parity’, and that the LCOE of the solar PV energy has decreased. Energy planners should be cautious in their interpretations because although the values of such energy benchmark tools have been improved over time, they may still be high compared with conventional power-generating options.

Providing electricity access to rural inhabitants of SSA is of great significance and is a major challenge. Access to a reliable, cheap, and abundant energy source is one of the key drivers of economic development and the well-being of citizens.

Countries in SSA might succeed in increasing the rural electrification rate if they were to first develop well-planned rural electrification programmes. With no targets determined, there would be few, if any, achievements in the rural electrification field. Well-defined rural electrification goals and properly understood aims would lead to much better outcomes than blindly following any renewable dissemination project – in this case solar PV – and hoping that it would solve the rural electrification problem.

Countries with rural electrification programmes, with budgets devoted to these programmes, and with governments committed to increasing rural electrification have succeeded more than those with no rural electrification programmes or targets (Eberhard et al., 2011; Eberhard and Shkaratan, 2012). For example, Laos was able to increase its electrification rate from 16% in 1995 to 63% in 2009. Laos is one of the least developed countries in South Asia, and like many countries in SSA it lacks adequate power-generation capacity and infrastructure. Extending grid connections to rural areas is difficult and costly owing to the low population density and rugged terrain, yet the country has found ways to overcome these problems. The Government of Laos is committed to expanding domestic electrification, and it seems it has succeeded in meeting its aims. This has been achieved mainly through rural electrification projects undertaken in conjunction with multilateral donor organizations (Bambawale et al., 2011). In contrast, some countries in SSA do not even have a national energy policy (Mulugetta et al., 2000), let alone an explicit rural electrification policy (Onyeji and Bazilian, and Nussbaumer, 2012).

Rural electrification agencies exist in only half of the Africa Infrastructure Country Diagnostic (AICD) sample countries[29], and in only two thirds of these countries are there dedicated funds available for rural electrification (Eberhard et al., 2011; Eberhard and Shkaratan, 2012). Among the AICD sample countries, those with rural electrification policies have achieved almost four times the annual increase in rural connections than countries with no rural electrification policies. In the same way, countries with rural electrification agencies and funds dedicated to them have reached more than three times the annual increase in rural connections than countries with no rural electrification agencies and funds dedicated to them (Eberhard et al., 2011). Although it would be wrong to suppose that a policy framework would on its own be sufficient, it could be a good starting point. As noted by Eberhard et al. (2011), 'in an African context, it is legitimate to ask how far it is possible to make progress with rural electrification when the urban electrification process is still far from complete'.

Instead of promoting solar PV, or any other renewable technology, as a means of obtaining donor aid or finance, governments and power utilities in SSA should select technologies on the basis of demand-driven judgements, which could bring much higher benefits to the society as a whole, rather than of technology-push incentives of

[29]The countries are: Benin, Burkina Faso, Cameroon, Central African Republic, Chad, Comoros, Congo (Democratic Republic of Congo), Côte d'Ivoire, Ethiopia, Gabon, Ghana, Guinea, Kenya, Lesotho, Madagascar, Malawi, Mali, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, South Africa, Tanzania, Togo, Uganda, Zambia, and Zimbabwe. Data is not available for Central African Republic, Comoros, Congo (Democratic Republic of Congo), Gabon, Guinea, Mali, Mauritania, Togo, and Zimbabwe.

donors. Prerequisites for donor aid and support programmes differ, yet the most popular one is the environmental concern of the donors.

Mitigation of GHG emissions by developing countries is one of the main preconditions set by many bilateral and multinational institutions when considering aid-receiving countries as eligible for development aid (Deichmann et al., 2010). These prerequisites on their own need a great deal of careful consideration and discussion. Governments and power utilities in SSA could follow an energy policy that targets the priorities of the country. In such capital-scarce countries, economic efficiency should be promoted ahead of the political agendas of donors.

Diversified renewable energy policies would be more beneficial than simply following a single solar PV technology dissemination target. Renewable energy technology should be chosen based on cost-efficiency concerns, rather than considering only the availability of renewable resources. Of course, in a country where water resources are abundant, hydro-power solutions should be considered first. Likewise, where geothermal resources are available, geothermal power plants should be considered first. Yet all such decisions should be based on cost-effectiveness.

Although there can be no doubt about the impact of electricity access on the economic growth and well-being of any society, a systematic policy and plan for the expansion of electricity services at the margins by national or local electricity grids seems at the present time to be a more promising strategy for eventually achieving a higher degree of rural electrification. Promoting costly renewable technologies such as solar PV to increase electricity access in rural areas of SSA is not an effective anti-poverty policy to follow. Unless the technology is subsidized from abroad, it is the relatively poor consumers of Africa who will pay the high cost of these renewable energy technologies. The only clear beneficiaries are the commercial interests in developed countries that are supplying these technologies.

It is clear from this analysis that it is not advisable for African countries to invest in capital intensive solar PV technologies when capital resources are scarce. Burdening the electric utilities now with debt, or payment obligations of power purchase agreements, for a solar facility that will save fuel inefficiently in the future is not advisable. Such obligations will constrain the utilities in the near future to finance efficient technologies that will save much more fuel than will a solar facility in future year.

Combined cycle and diesel power plants enhance overall system reliability in these countries, while solar PV plants decrease reliability. The absence of a reliable supply of electricity is a major handicap of African economies. Not just in Africa, access to plentiful, reliable, and inexpensive energy is requisite of increasing living standards and strong economic development (Greenstone and Looney, 2012).

The fuel savings with the combined cycle or diesel plants are much higher than those obtained with a solar PV plant. As a result, the amount of GHG emissions avoided by using the combined cycle or diesel plants is many times greater than that of solar PV plant with the same capital cost. It is clear that combined cycle and diesel plants make a much greater contribution to environmental sustainability than solar PV generation in Africa.

As is well known in economic benefit–cost analyses, if the costs of the project continue to fall and the benefits stay constant, it is better to postpone such investments. Therefore, as the prices and costs of solar PV systems are decreasing, it is recommended that investments in such technology be postponed until it becomes competitive with conventional power-generation technologies. Accordingly, in Africa solar PV might be the technology of the future, rather than the present. Subsidizing poor people to buy or use a technology that is forecasted to be obsolete and much cheaper to purchase in the future is usually not a recommended strategy for economic development. It is not advisable from electric utilities' point of view also in Africa to invest in this technology (unless subsidized from abroad) until the solar PV plants become competitive with combined cycle or diesel plants. If unsubsidized, it is the relatively poor consumers of Africa who will pay for these inefficient technological choices.

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APPENDIX

Appendix A: Full Tables

Table 5-A. Fuel savings and revenue from solar generation

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Total electricity production (MWh)	0	0	49,275	48,979	48,685	48,393	48,103	47,814	47,527	47,242	46,959	46,677	46,397
Total fuel savings in (litres 000)	0	0	12,122	12,169	12,217	12,265	12,314	12,362	12,411	12,460	12,509	12,558	12,608
Financial value of total fuel savings (US$ 000)	0	0	9,639	9,677	9,716	9,754	9,792	9,831	9,870	9,909	9,948	9,987	10,026
GHG emissions avoided (tonnes)	0	0	36,759	36,539	36,319	36,101	35,885	35,670	35,456	35,243	35,031	34,821	34,612

Year	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Total electricity production (MWh)	46,119	45,842	45,567	45,294	45,022	44,752	44,483	44,216	43,951	43,687	43,425	43,165	42,906	42,648
Total fuel savings in (litres 000)	12,657	12,707	12,757	12,808	12,858	12,909	12,960	13,011	13,062	13,113	13,165	13,217	13,269	13,321
Financial value of total fuel savings (US$ 000)	10,066	10,105	10,145	10,185	10,225	10,265	10,306	10,346	10,387	10,428	10,469	10,511	10,552	10,594
GHG emissions avoided (tonnes)	34,405	34,198	33,993	33,789	33,586	33,385	33,184	32,985	32,787	32,591	32,395	32,201	32,008	31,815

Table 6-A. Economic resource flow statement for solar PV plant: country's point of view (US$ 000)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Economic value of fuel savings	0	0	9,513	9,551	9,588	9,626	9,664	9,702	9,740	9,779	9,817	9,856	9,895
Savings on O&M costs of thermal plants	0	0	197	196	195	194	192	191	190	189	188	187	186
Total inflows	0	0	9,710	9,746	9,783	9,820	9,856	9,893	9,930	9,968	10,005	10,042	10,080
O&M cost	0	0	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Capital cost	0	84,780	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	0	0	587	583	580	576	573	570	566	563	559	556	553
Total outflows	0	84,780	1,859	1,855	1,852	1,848	1,845	1,841	1,838	1,834	1,831	1,828	1,824
Net resource flow	0	-84,780	7,851	7,891	7,931	7,971	8,012	8,052	8,092	8,133	8,174	8,215	8,256

Year	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Economic value of fuel savings	9,934	9,973	10,012	10,051	10,091	10,131	10,171	10,211	10,251	10,291	10,332	10,373	10,414	10,455
Savings on O&M costs of thermal plants	184	183	182	181	180	179	178	177	176	175	174	173	172	171
Total inflows	10,118	10,156	10,194	10,233	10,271	10,310	10,349	10,388	10,427	10,466	10,506	10,545	10,585	10,625
O&M cost	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Capital cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	549	546	543	540	536	533	530	527	524	520	517	514	511	508
Total outflows	1,821	1,818	1,815	1,811	1,808	1,805	1,802	1,798	1,795	1,792	1,789	1,786	1,783	1,780
Net resource flow	8,297	8,338	8,380	8,421	8,463	8,505	8,547	8,589	8,632	8,674	8,717	8,759	8,802	8,845

Table 7-A. Economic resource flow statement for solar PV plant: global point of view including GHG damage mitigation (US$ 000)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Economic value of fuel savings	0	0	9,513	9,551	9,588	9,626	9,664	9,702	9,740	9,779	9,817	9,856	9,895
Savings on O&M costs of thermal plants	0	0	197	196	195	194	192	191	190	189	188	187	186
Economic value of GHG emission reductions	0	0	1,489	1,509	1,528	1,548	1,569	1,589	1,610	1,631	1,652	1,674	1,696
Total inflow	0	0	11,199	11,255	11,311	11,368	11,425	11,482	11,540	11,599	11,657	11,716	11,776
Operating cost	0	0	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Capital cost	0	84,780	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	0	0	587	583	580	576	573	570	566	563	559	556	553
Total outflows	0	84,780	1,859	1,855	1,852	1,848	1,845	1,841	1,838	1,834	1,831	1,828	1,824
Net resource flow	0	-84,780	9,341	9,400	9,460	9,520	9,580	9,641	9,702	9,764	9,826	9,889	9,952

Year	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Economic value of fuel savings	9,934	9,973	10,012	10,051	10,091	10,131	10,171	10,211	10,251	10,291	10,332	10,373	10,414	10,455
Savings on O&M costs of thermal plants	184	183	182	181	180	179	178	177	176	175	174	173	172	171
Economic value of GHG emission reductions	1,718	1,741	1,763	1,786	1,810	1,834	1,857	1,882	1,906	1,931	1,957	1,982	2,008	2,034
Total inflow	11,836	11,897	11,958	12,019	12,081	12,143	12,206	12,269	12,333	12,398	12,462	12,528	12,593	12,660
Operating cost	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272	1,272
Capital cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	549	546	543	540	536	533	530	527	524	520	517	514	511	508
Total outflows	1,821	1,818	1,815	1,811	1,808	1,805	1,802	1,798	1,795	1,792	1,789	1,786	1,783	1,780
Net resource flow	10,015	10,079	10,143	10,208	10,273	10,339	10,405	10,471	10,538	10,605	10,673	10,742	10,811	10,880

Table 8-A. Fuel savings and revenue from combined cycle generation

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Total electricity production (MWh)	0	0	270,671	267,964	265,284	262,632	260,005	257,405	254,831	252,283	249,760	247,262	244,790
Total fuel savings in (litres 000)	0	0	23,343	23,341	23,339	23,336	23,334	23,332	23,329	23,327	23,325	23,322	23,320
Financial value of total fuel savings (US$ 000)	0	0	18,563	18,561	18,560	18,558	18,556	18,554	18,552	18,550	18,549	18,547	18,545
GHG emissions avoided (tonnes)	0	0	72,966	72,959	72,951	72,944	72,937	72,929	72,922	72,915	72,908	72,900	72,893

Year	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Total electricity production (MWh)	242,342	239,919	237,519	235,144	232,793	230,465	228,160	225,879	223,620	221,384	219,170	216,978	214,808	212,660
Total fuel savings in (litres 000)	23,318	23,315	23,313	23,311	23,308	23,306	23,304	23,301	23,299	23,297	23,294	23,292	23,290	23,287
Financial value of total fuel savings (US$ 000)	18,543	18,541	18,539	18,537	18,536	18,534	18,532	18,530	18,528	18,526	18,524	18,523	18,521	18,519
GHG emissions avoided (tonnes)	72,886	72,878	72,871	72,864	72,857	72,849	72,842	72,835	72,827	72,820	72,813	72,806	72,798	72,791

Table 9-A. Economic resource flow statement combined cycle generation: country's point of view (US$ 000)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Economic value of fuel savings	0	0	18,320	18,318	18,316	18,314	18,313	18,311	18,309	18,307	18,305	18,303	18,302
Total inflow	0	0	18,320	18,318	18,316	18,314	18,313	18,311	18,309	18,307	18,305	18,303	18,302
Operating cost	0	0	353	353	353	353	353	353	353	353	353	353	353
Capital cost	47,477	37,303	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	0	0	152	150	149	147	146	144	143	141	140	138	137
Total outflow	47,477	37,303	505	503	502	500	499	497	496	495	493	492	490
Net resource flow	-47,477	-37,303	17,815	17,815	17,814	17,814	17,814	17,813	17,813	17,813	17,812	17,812	17,811

Year	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Economic value of fuel savings	18,300	18,298	18,296	18,294	18,292	18,291	18,289	18,287	18,285	18,283	18,281	18,280	18,278	18,276
Total inflow	18,300	18,298	18,296	18,294	18,292	18,291	18,289	18,287	18,285	18,283	18,281	18,280	18,278	18,276
Operating cost	353	353	353	353	353	353	353	353	353	353	353	353	353	353
Capital cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	136	134	133	132	130	129	128	126	125	124	123	122	120	119
Total outflow	489	488	486	485	484	482	481	480	478	477	476	475	474	472
Net resource flow	17,811	17,810	17,810	17,809	17,809	17,808	17,808	17,807	17,807	17,806	17,805	17,805	17,804	17,804

Table 10-A. Economic resource flow statement CC generation: global point of view including GHG damage mitigation (US$ 000)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Economic value of fuel savings	0	0	18,320	18,318	18,316	18,314	18,313	18,311	18,309	18,307	18,305	18,303	18,302
Economic value of GHG emission reductions	0	0	2,956	3,012	3,070	3,129	3,188	3,249	3,311	3,375	3,439	3,505	3,572
Total inflow	0	0	21,276	21,331	21,386	21,443	21,501	21,560	21,620	21,682	21,744	21,808	21,873
Operating cost	0	0	353	353	353	353	353	353	353	353	353	353	353
Capital cost	47,477	37,303	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	0	0	152	150	149	147	146	144	143	141	140	138	137
Total outflows	47,477	37,303	505	503	502	500	499	497	496	495	493	492	490
Net resource flow	-47,477	-37,303	20,771	20,827	20,884	20,943	21,002	21,063	21,124	21,187	21,251	21,316	21,383

Year	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Economic value of fuel savings	18,300	18,298	18,296	18,294	18,292	18,291	18,289	18,287	18,285	18,283	18,281	18,280	18,278	18,276
Economic value of GHG emission reductions	3,640	3,709	3,780	3,852	3,926	4,001	4,077	4,155	4,235	4,315	4,398	4,482	4,567	4,655
Total inflow	21,940	22,007	22,076	22,147	22,218	22,292	22,366	22,442	22,520	22,599	22,679	22,761	22,845	22,931
Operating cost	353	353	353	353	353	353	353	353	353	353	353	353	353	353
Capital cost	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	136	134	133	132	130	129	128	126	125	124	123	122	120	119
Total outflows	489	488	486	485	484	482	481	480	478	477	476	475	474	472
Net resource flow	21,451	21,520	21,590	21,662	21,735	21,809	21,885	21,962	22,041	22,122	22,203	22,287	22,372	22,458

Table 15-A. Fuel savings and revenue from diesel power generation

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Total electricity production (MWh)	0	749,550	742,054	734,634	727,288	720,015	712,815	705,686	698,630	691,643	684,727	677,880	671,101
Total fuel savings (litres 000)	0	29,285	29,282	29,280	29,277	29,274	29,271	29,268	29,265	29,262	29,259	29,256	29,253
Financial value of total fuel savings (US$ 000)	0	23,289	23,286	23,284	23,282	23,279	23,277	23,275	23,272	23,270	23,268	23,265	23,263
GHG emissions avoided (tonnes)	0	91,539	91,530	91,521	91,512	91,502	91,493	91,484	91,475	91,466	91,457	91,448	91,438

Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Total electricity production (MWh)	664,390	657,746	651,168	644,657	638,210	631,828	625,510	619,255	613,062	606,931	600,862	594,854	588,905
Total fuel savings (litres 000)	29,250	29,247	29,244	29,241	29,239	29,236	29,233	29,230	29,227	29,224	29,221	29,218	29,215
Financial value of total fuel savings (US$ 000)	23,261	23,258	23,256	23,254	23,251	23,249	23,247	23,244	23,242	23,240	23,237	23,235	23,233
GHG emissions avoided (tonnes)	91,429	91,420	91,411	91,402	91,393	91,384	91,374	91,365	91,356	91,347	91,338	91,329	91,320

Table 16-A. Economic resource flow statement for diesel power generation: country's point of view (US$ 000)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Economic value of fuel savings	0	22,983	22,981	22,979	22,976	22,974	22,972	22,969	22,967	22,965	22,962	22,960	22,958
Savings on variable O&M cost of old thermal plants	0	2,998	2,968	2,939	2,909	2,880	2,851	2,823	2,795	2,767	2,739	2,712	2,684
Total inflow	0	25,981	25,949	25,917	25,885	25,854	25,823	25,792	25,762	25,731	25,701	25,672	25,642
Operating cost	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956
Capital cost	84,780	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	0	420	416	411	407	403	399	395	391	387	383	380	376
Total outflow	84,780	2,376	2,372	2,368	2,364	2,360	2,356	2,352	2,348	2,344	2,340	2,336	2,332
Net resource flow	-84,780	23,605	23,577	23,549	23,522	23,494	23,467	23,440	23,414	23,388	23,361	23,336	23,310

Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Economic value of fuel savings	22,956	22,953	22,951	22,949	22,946	22,944	22,942	22,940	22,937	22,935	22,933	22,930	22,928
Savings on variable O&M cost of old thermal plants	2,658	2,631	2,605	2,579	2,553	2,527	2,502	2,477	2,452	2,428	2,403	2,379	2,356
Total inflow	25,613	25,584	25,556	25,527	25,499	25,471	25,444	25,417	25,389	25,363	25,336	25,310	25,284
Operating cost	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956
Capital cost	0	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	372	368	365	361	357	354	350	347	343	340	336	333	330
Total outflow	2,329	2,325	2,321	2,317	2,314	2,310	2,307	2,303	2,300	2,296	2,293	2,290	2,286
Net resource flow	23,285	23,259	23,235	23,210	23,185	23,161	23,137	23,113	23,090	23,066	23,043	23,020	22,997

Table 17-A. Economic resource flow statement diesel generation: global point of view including GHG damage mitigation (US$ 000)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Economic value of fuel savings	0	22,983	22,981	22,979	22,976	22,974	22,972	22,969	22,967	22,965	22,962	22,960	22,958
Savings on variable O&M cost of old thermal plants	0	2,998	2,968	2,939	2,909	2,880	2,851	2,823	2,795	2,767	2,739	2,712	2,684
Economic value of GHG emission reductions	0	3,708	3,779	3,851	3,925	4,000	4,076	4,154	4,234	4,314	4,397	4,481	4,566
Total inflow	0	29,690	29,728	29,769	29,810	29,854	29,899	29,946	29,995	30,046	30,098	30,152	30,209
Operating cost	0	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956
Capital cost	84,780	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	0	420	416	411	407	403	399	395	391	387	383	380	376
Total outflows	84,780	2,376	2,372	2,368	2,364	2,360	2,356	2,352	2,348	2,344	2,340	2,336	2,332
Net resource flow	-84,780	27,314	27,356	27,401	27,447	27,494	27,544	27,595	27,647	27,702	27,758	27,816	27,876

Year	13	14	15	16	17	18	19	20	21	22	23	24	25
Economic value of fuel savings	22,956	22,953	22,951	22,949	22,946	22,944	22,942	22,940	22,937	22,935	22,933	22,930	22,928
Savings on variable O&M cost of old thermal plants	2,658	2,631	2,605	2,579	2,553	2,527	2,502	2,477	2,452	2,428	2,403	2,379	2,356
Economic value of GHG emission reductions	4,654	4,742	4,833	4,925	5,019	5,115	5,213	5,312	5,414	5,517	5,623	5,730	5,839
Total inflow	30,267	30,327	30,389	30,453	30,519	30,587	30,657	30,729	30,803	30,880	30,959	31,040	31,123
Operating cost	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956	1,956
Capital cost	0	0	0	0	0	0	0	0	0	0	0	0	0
Grid-level system cost	372	368	365	361	357	354	350	347	343	340	336	333	330
Total outflows	2,329	2,325	2,321	2,317	2,314	2,310	2,307	2,303	2,300	2,296	2,293	2,290	2,286
Net resource flow	27,938	28,002	28,068	28,135	28,205	28,276	28,350	28,426	28,504	28,584	28,666	28,750	28,837