WHY NOT GO GREEN?
- AN ANALYSIS OF THE VIABILITY OF SOLAR PV MINI-GRIDS IN TANZANIA

- EN ANALYSE AV SOL PV-SYSTEMER FOR ISOLERTE KRAFTNETT I TANZANIA

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Preface

The work on this master thesis has been carried out during the final semester (January to mid-May) of a five year master programme in Industrial Economics at the Norwegian University of Life Sciences.

The thesis subject was introduced by Norplan/Multiconsult as part of a Norad assignment, involving several assessments related to rural electrification in developing countries.

Selecting a thesis subject within the matter of rural electrification in Tanzania, have raised issues far beyond my prior knowledge. Therefore, I would like to thank those who made it possible to overcome the range of barriers discovered in the process.

First of all, I would like to thank my university supervisor Tor Kristian Stevik for his engagement and support of my work. He has been able to ask the important questions along the way and has given invaluable advice on how to structure and focus the thesis. Secondly, I want to thank Norad, in particular represented by Vegard Willumsen, for providing financial support to conduct field work in Tanzania and for introducing me to the Tanzanian energy sector. Thirdly, but not least, I want to thank Ryan Glenn Anderson in Multiconsult for giving me a great opportunity by introducing this subject as a potential master thesis and linking me up with Norad. He has provided continuous feedback and shared his extensive knowledge and engagement in all aspects of rural energy development.

I also want to extend great thanks to Tanesco, for providing me with important data, allowing me to visit one of their diesel-based power plants. Furthermore, I want to thank the REA for sharing updated data and assisting me in conducting a field trip to a rural, non-electrified village. In general, the help from several individuals within the Tanesco and REA, along with the University of Dar es Salaam and a range of other institutions within the Tanzanian energy sector, has been crucial in order to carry out this assessment.

Ås, 15.05.2013

Christopher Ruud

Executive summary

Currently, practically all off-grid power systems supplying electricity access in rural Tanzania are diesel-based. The operator, Tanesco, spend more than US$ 45 million per year purchasing more than 50 million liters of diesel fuel, maintaining a diesel-based generating capacity of about 55 MW in total. The ambitious plans of increasing the level of rural electrification and limited ability to extend the existing power grid, introduces small off-grid power systems (mini-grids) as a viable option for electricity access in remote rural areas. Despite a certain level of hydropower and biomass resources being evident, the lion's share of mini-grid candidates will call for other solutions, currently pointing toward diesel, PV or diesel-PV hybrid concepts.

The aim of this thesis has been to assess under which circumstances PV systems can be implemented for cost-competitive and viable power production on mini-grids in rural Tanzania. The capability of PV systems to provide certain levels of supply security in comparison to more conventional generating technologies depend on meteorological conditions, in addition to establishment of system design and operation criteria. Domestic solar insolation ranges from less than 3.5 kWh/m^{2}day and high seasonal variation in the Kilimanjaro area of the North Eastern Highlands zone, to about 6.0 kWh/m^{2}day and very low seasonal variation in Central Tanzania. Standard deviations in the average annual insolation data has been estimated to less than ±5 % for all conducted measurements, suggesting a high potential for relatively predictable PV power production in most zones.

An LCOE of 0.61 US$/kWh estimated for a base-case PV system under average irradiation conditions is within the willingness to pay for low-consumption electricity (estimated to range from 0.8 US$/kWh to 1.2 US$/kWh). The results also suggest that PV systems are significantly less costly than diesel-based generation, and competitive to diesel-PV hybrids. The technical modularity of PV systems may enable developers to implement stepwise capacity expansion, in order to reduce initial expenditure and provide gradual development of electricity access to rural communities.

While it makes good economic sense to pursue solar energy on mini-grids, there are several meaningful and challenging barriers. The high initial costs of PV systems, combined with income uncertainty in rural areas due to low customer affordability introduce high financial risk, which makes it somewhat difficult to attract private investors. In addition, LCOE estimates obtained for PV systems involve a high degree of configuration dependence and sensitivity to availability of the solar resource and operational criteria. In particular, the supply security required from a PV system will determine the extent of battery storage capacity needed, which typically represents about 30 % of overall initial costs.

Up-front donor support to developers presenting economically viable operational models and business plans for off-grid electrification projects, may contribute to overcome capital boundaries and promote a broader utilization of solar and other renewable resources on mini-grids in Tanzania.

Sammendrag

I dag er alle mindre, isolerte kraftnett i rurale Tanzania diesel-baserte. Operatøren, Tanesco, bruker hvert år over 45 millioner US$ på å kjøpe mer enn 50 millioner liter diesel til disse små kraftverkene, for å drifte en relativt beskjeden installert kapasitet på totalt 55 MW. Ambisiøse planer om å øke tilgangen til elektrisitet på landsbygda, kombinert med begrenset mulighet til å bygge ut det eksisterende sentralkraftnettet, gjør at små, isolerte kraftnett (mini-grids) er et bærekraftig alternativ i distrikter og landsbyer som er lokalisert langt unna eksisterende nett. Bortsett fra enkelte vannkraft - og biomassepotensialer, vil mange kandidater til implementering av mini-grid ha behov for andre løsninger. For øyeblikket er diesel-generatorer, PV-systemer eller diesel-PV hybrid-systemer de mest relevante alternativene.

Målet med denne oppgaven har vært å undersøke under hvilke omstendigheter PV-systemer kan implementeres på en bærekraftig måte og være et konkurransedyktig alternativ for kraftproduksjon på isolerte nett i Tanzania. PV-systemers evne til å oppnå et gitt nivå av forsyningssikkerhet sammenlignet med mer konvensjonell teknologi, avhenger sterkt av meteorologiske forhold, samt systemdesign og drift. Nasjonal solinnstråling varierer fra mindre enn 3.5 kWh/m^2dag og betydelige sesongvariasjoner i Kilimanjaro-området i det nordøstlige Tanzania til omtrent 6.0 kWh/m^2dag og lave sesongvariasjoner i sentrale deler av landet. Standardavvik i gjennomsnittlig årlig innstråling har blitt målt til mindre enn ±5 % ved alle målestasjoner, noe som antyder et betydelig potensiale for relativt forutsigbar PV kraftproduksjon i de fleste av Tanzanias soner.

En LCOE på 0,61 US$/kWh estimert for et basis-scenario med gjennomsnittlige innstrålingsverdier er lavere enn antatt villighet til å betale for lav-konsum av elektrisitet (som er antatt å ligge mellom 0,8 US$/kWh og 1,2 US$/kWh). Resultatene antyder at PV-systemer er langt billigere enn diesel-basert kraftproduksjon og konkurransedyktig sammenlignet med diesel-PV hybrider. Teknisk modularitet hos PV systemer muliggjør trinnvis kapasitetsbygging, som kan bidra til å redusere oppstartskostnader og muliggjøre gradvis implementering av tilgang til elektrisitet til lokalsamfunn på landsbygda i Tanzania.

Til tross for at det kan være økonomisk bærekraftig å implementere PV-systemer for isolert kraftforsyning, hindres utviklingen av flere utfordrende barrierer. Høy finansiell risiko som følge av høye kapitalkostnader og usikkerhet knyttet til forbrukernes betalingsevne, gjør det vanskelig å tiltrekke private investorer. LCOE-estimatene for PV-systemer avhenger i tillegg sterkt av ressursgrunnlag og systemdesign, og er derfor trolig mer usikre enn for mer konvensjonell teknologi. Spesielt er forsyningssikkerheten som kreves i en gitt landsby avgjørende for nødvendig batterikapasitet, som typisk utgjør omtrent 30 % av kapitalkostnadene.

Støtte fra donorer til utviklere med bærekraftige driftsplaner og forretningsmodeller kan bidra til å overkomme investeringsbarrierer og promotere en bredere utnyttelse av sol og andre fornybare energikilder i Tanzania.

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Acronyms and abbreviations

RE	Rural Electrification
REF	Rural Energy fund
REA	Rural Energy Agency
PV	Photovoltaic
AC	Alternating current
IDO	Industrial Diesel Oil
G.O	Gas Oil
BoS	Balance of system
DC	Direct current
RPO	Rated Power Output
STC	Standard testing conditions
PR	Performance ratio
EH	Efficient hours
CF	Capacity Factor
DOD	Depth of discharge
GHI	Global Horizontal Insolation
KIA	Kilimanjaro International Airport
DIA	Dodoma International Airport
LCOE	Levelized Cost of Energy
NPV	Net Present Value
DPP	Diesel power plant
RET	Renewable energy technology
WACC	Weighted average cost of capital
CAPEX	Capital expenditure
OPEX	Operating expenditure
IRR	Internal rate of return
O&M	Operation and maintenance
kW	kilo-watts
kWh	kilo-watt-hour
$\mathbf{W_p}$	watt peak
kV	kilo-volts
AHPL	Average household peak load
PP	Power plant
HPP	Hydropower plant
Ah	Ampere-hours
DOA	Days of autonomy
MDC	Maximal daily consumption
MDI	Minimum daily insolation
TIB	Tanzania Investment Bank
US$	United States Dollars
IED	Innovation Energy Development

1 Introduction

1.1 Motivation

Access to electricity is considered to be one of the main criteria for successful economic development and increased welfare of developing countries. Electrical power is the basis of any modern welfare society, and the social benefits of electrification are undisputable. The poorest populations in the world are often characterized by none or very limited access to electricity. The lion's share of non-electrified communities in the world is found in the rural areas of the African continent, especially in the sub-Saharan part. Sub-Saharan Africa has an overall rural electrification level rate of less than 15 percent (table 1). [1]

Several governments in Sub-Saharan countries dedicate comprehensive resources and political focus to the cause of increasing rural electrification levels. Despite a slow paced development in the process over the past decades, there is a broad international acknowledgement of rural electrification as a prerequisite to economic growth. Energy development is becoming an increasingly important issue amongst international donors and a significant share of funding to Sub-Saharan countries is granted for the purposes of rural electrification. [1]

Table 1: Rural electrification levels in Africa. [1]

	Population without electricity (millions)	*Electrification rate (%)*	*Urban electrification rate (%)*	*Rural electrification rate (%)*
Africa	589	40	66,8	22,7
North Africa	2	98,9	99,6	98,2
Sub-Saharan Africa	587	28,5	57,5	11,9
Tanzania	40	15	27	2,6

In remote locations, connection to a centralized electricity distribution network may not be a technically or economically viable option. As a natural consequence, several rural communities throughout African have been electrified by installing isolated off-grid power systems to meet the growing power demand. Until today, off-grid electrification projects in rural districts have mainly been powered by diesel generators. This conventional technology has several advantages in meeting an acute electricity demand, and it has over the past decades also been considered the most cost efficient solution. Acknowledging the main disadvantages represented by high carbon emissions, fuel transportation issues and sensitivity to diesel prices, such matters might not be a priori when the need for electricity is considered acute. Nevertheless, it is now widely recognized that renewable energy technologies can offer energy at lower costs than diesel on off-grid projects under the right conditions. In most rural African villages, renewable energy options are available when determining which electricity generating system to install. Yet, throughout Africa utilities continue to install diesel generators at a large scale to meet the increasing rural demand for electricity. [2]

1.2 Objectives and limitations

In this thesis, the compatibility of solar PV systems to provide technically and economically sustainable off-grid electricity access to communities in rural Africa is assessed. The overall aim of this study is to:

- Establish a better understanding of the necessary conditions for successful implementation of PV technology on isolated off-grid power systems in rural areas, in particular with respect to security of supply.
- Highlight the primary drivers to the costs of PV systems, the financial risk involved, and how these barriers may be overcome by project developers in a sustainable manner.
- Identify eventual political and institutional barriers and drivers to a broader utilization of PV systems and other RETs on mini-grids.

Hereunder, mini-grids ranging from a system loads of about 10 kW to 500 kW are assessed in particular due to a high relevance for villages in several rural African areas. With respect to levelized cost of energy (LCOE), this study will seek to compare PV systems to other relevant technology options, hereunder:

- Conventional diesel-based generation
- Diesel-PV hybrid generation
- Small hydropower*
- Biomass gasifier

The current performance of diesel-based generation is assessed in particular, due to its widespread utilization on mini-grids.

1.3 Case study: Tanzania

Tanzania has been chosen as a case study due to its low level of rural electrification, combined with an extensive potential for utilizing renewable energy resources, including solar. More than 60 percent of the Tanzanian population of roughly 45 million is located in rural areas and the RE level of less than 3 percent is low even by sub-Saharan standards (table 1). [3] The Government of Tanzania is currently developing ambitious plans for increasing domestic RE levels, with support from several international donors. During the spring of 2013, a 122 million USD donation was granted to the Rural Energy Fund of Tanzania (REF) by the Norwegian Government, thus representing the largest donation in the history of the fund since established in 2005. [4] In that context, the Norwegian Minister of International development has expressed a hope that Tanzania will be able skip a phase of thermal electricity generation in their further rural energy development by utilizing their renewable energy resources. The fund granting authority is with the Rural Energy Agency (REA), which was established in 2007 to promote RE development. [5] Continued implementation of diesel generators on mini-grids might not be the most sustainable or cost-efficient way to increase the rural electrification rate throughout the country. Hopefully, the results from this case study can be helpful in understanding not only how to promote a switch from diesel-based mini-grids to e.g. PV systems in Tanzania, but be extended to a significant part of the African continent.

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* There are various ways of classifying hydropower. In this thesis, small hydropower will be used as a common reference to anything less than 10 MW.

1.4 Outline of the thesis

Chapter 2, 3 and 4 provides some background information about the current generating capacity of Tanzania and an introductory description of the main components in PV systems.

Chapter 5 assesses the size and nature of mini-grid candidate villages in Tanzania, while chapter 6 aims to highlight the primary issues and considerations facing developers of PV systems in these locations.

Chapter 7 assesses the primary LCOE drivers, the uncertainty related, and the financial risk in PV projects. A basis for LCOE comparison across other relevant technology options for power generation on mini-grids is established.

Key findings are presented in chapter 8 and chapter 9, and discussed in chapter 10. Conclusions and some notes on further work are provided in chapter 11 and chapter 12, respectively.

2 Overview of installed capacity in Tanzania

2.1 National grid generation and transmission

The electricity generation on the national grid system of Tanzania is currently at an installed capacity of roughly 1000 MW (table 2). Hydropower contributes to 56 percent of the total; adding up to 561 MW installed capacity. The remaining capacity is mainly thermal generation plants based on natural gas. [6]

Table 2: On-grid generating capacity in Tanzania. [6]

Name	*Type*	*Capacity (MW)*
Kidatu	Hydro	204
Kihansi	Hydro	180
Mtera	Hydro	80
Pangani	Hydro	68
Hale	Hydro	21
Nyumba ya Mungu	Hydro	8
Ubungo	Natural gas	100
Tegeta	Natural gas	45
IPPs	Natural gas/Diesel	282
Imports	Uganda/Zambia	13
Total		1001

The power supplied to the national grid is consumed by a fraction of roughly 15 percent of the population. [3] The customers are mainly located in urban or sub-urban areas. On-grid power supply in Tanzania is highly unstable due to various technical, economic and political reasons. Hence, customers on the national grid are frequently subject to power outages and load shedding. [7]

Figure 1 shows the national transmission system and the geographical distribution of on-grid power generating units. As indicated by the existing and proposed transmission lines on the national grid, the southern, central and western central parts of the nation in particular will to a great extent remain off-grid in foreseeable future. The grid map also indicates the isolated grids currently operating in Tanzania, marked as black triangles (figure 1). Off-grid power systems are found across the entire country, but are most dense in the southern part. [7]

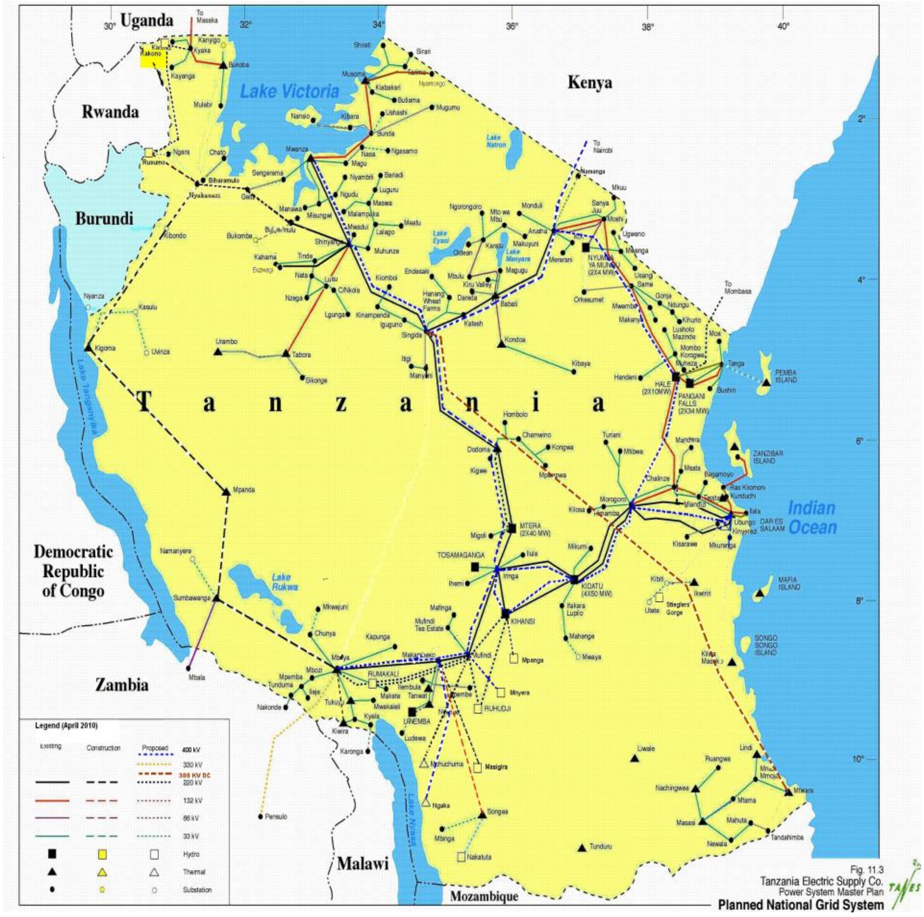

Figure 1: National transmission network and generation distribution map of Tanzania. [7]

2.2 Existing off-grid capacity

As indicated in figure 1, the extension of the power network in Tanzania is limited. Due to very slow extension of the national grid, several development centers and industrial towns have been electrified by isolated power systems. Most of the off-grid capacity is diesel-based, except for two relatively large plants fueled by natural gas (table 3). The operator, Tanesco, spend more than 45 million US$ per year purchasing more than 50 million liters of diesel fuel, maintaining a modest diesel-based generating capacity of about 55 MW in total. [8] In addition to the official off-grid plants, several smaller diesel gensets in the capacity order of 300 W to 10 kW adds to the total off-grid capacity of the country. The exact number of smaller diesel gensets operating nationwide remains unknown, but the total capacity of unofficial diesel-based power generation is estimated by to be in the order of between 40 MW and 50 MW. Small diesel gensets are widely utilized to supply electricity for private households, small to large businesses and a wide range of private and public buildings. The lion's share of small diesel generators is to be found with customers on the national grid as necessary backups to compensate for on-grid power outages. However, small diesel aggregates are also readily utilized for small-scale power generation to private or public institutions in rural areas. [7]

Table 3: Official isolated (off-grid) generating capacity of Tanzania. [9]

No	*Name*	*Units*	*Capacity (MW)*	*Fuel type*
1	*Kigoma*	14	12.5	IDO
2	*Songea*	6	8.2	IDO
3	*Mpanda*	4	2.7	IDO
4	*Mbinga*	2	2.0	IDO
5	*Biharamulo*	2	1.0	IDO
6	*Ngara*	2	1.0	IDO
7	*Mafia*	2	0.9	IDO
8	*Tunduro*	4	2.0	IDO
9	*Ludewa*	3	1.3	GO/IDO
10	*Liwale*	2	0.8	IDO
11	*Somanga*	3	7.5	Natural gas
12	*Sumbawanga*	4	5.0	IDO
13	*Kasulu*	2	2.5	IDO
14	*Kibondo*	2	2.5	IDO
15	*Loliondo*	2	5.0	IDO
16	*Namtumbo*	1	0.3	IDO
17	*Mtwara*	9	18.0	Natural gas
18	*Bukoba*	4	2.4	IDO
19	*Masasi*	3	4.5	IDO
	Total		79.9	

In addition to the thermal off-grid power generation, a few small hydro power plants are proposed or in construction for similar purposes, ranging from about 1 MW to 5 MW installed capacity. There are numerous solar PV home systems in some rural areas, usually consisting of one module supplying a single household with lightning and cell phone charging. Around the country there are also an unknown number of micro-scale solar PV installations on very small isolated grids, usually supplying power to a few households, schools, dispensaries, ground water pumps, village administration offices or small businesses. Finally, a few villages have micro-scale centralized solar PV stations (multifunctional platforms) where people can go to charge electrical equipment, use computers and other power-consuming services. [7]

2.3 Mini-grids for rural electrification

2.3.1 Mini-grid definition

A mini-grid can be defined as a set of electricity generating units interconnected to an isolated electricity distribution network, supplying power to a localized consumer group. Mini-grids are by nature different from single consumer systems (e.g. a solar cell panel supplying a single house with electricity), where there is no interconnection between customers. They also differ from centralized grid systems, where electricity produced by de-centralized generators is distributed at high voltage to meet the demand of dispersed consumer groups. The most attractive feature of a mini-grid for RE is that it can operate autonomously and supply electricity to isolated consumer groups in rural areas, where connection to the centralized grid is out of economical range. However, the system may be designed to be compatible for integration on a centralized grid if this becomes economically viable in the future. Once a mini-grid is part of a centralized distribution network, it can still operate separately should it be necessary due to problems occurring on the central grid. In other words a mini-grid may represent a flexible, future-oriented concept for rural electrification. [10]

In terms of capacity there are various ways to define or classify off-grid power systems. In this study, mini-grid applications are village – and district-level isolated networks with loads between 5 kW and 500 kW. [11] This definition is consistent with that of the World Bank. As the section 5.1 assessments will indicate, mini-grids by this definition are currently relevant concepts for RE development in Tanzania. Arguably, one could extend the load interval in the definition to cover a more extensive range of village sizes. However, limitations are necessary in order to conduct a credible assessment of compatibility and cost across technology options for power supply.

2.3.2 Mini-grids vs. grid extension

To a certain extent, grid extension is likely to be the cheapest way to electrify rural areas in proximity to an existing transmission line with some level of excess capacity. However, depending on the distance to the closest existing or planned transmission line and the terrain in between, it comes to a point where grid extension is not economically viable (figure 2). Recognizing the importance of always considering grid extension as an option, a detailed review of this matter is not conducted in this study. As outlined in chapter 5 and mentioned in the introduction, many rural areas in Sub-Saharan Africa are outside the range of grid extension in foreseeable future, and isolated systems are determined to be best practice for a significant share of non-electrified villages and districts. [3]

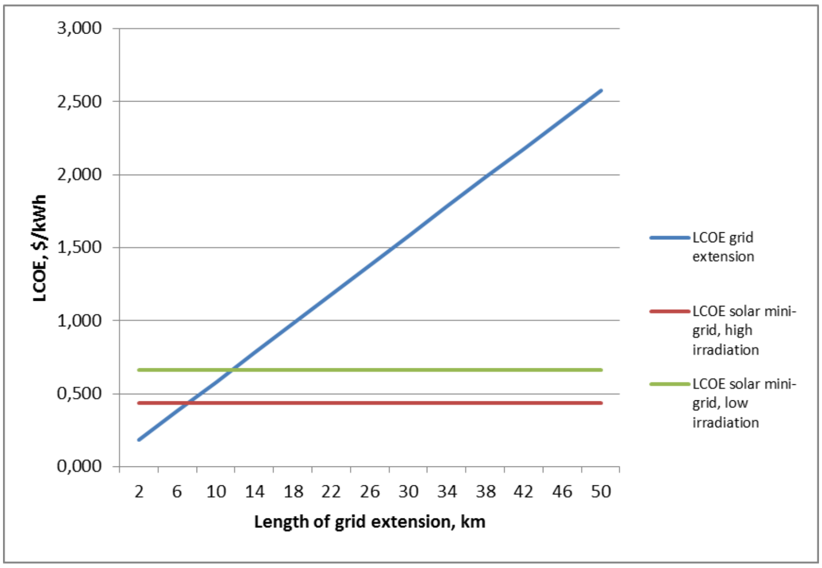

Figure 2: Levelized cost of energy (LCOE*) by grid extension in rural Africa. [12]

2.3.3 Solar PV mini-grid development

Currently, the most frequent utilization of the solar resource for electricity generation is found in Europe, where the potential is not nearly as high as at latitudes closer to the equator (figure 3). [13] The large solar energy potential and rapidly growing economy in several developing countries of has caused increasing interest from the international community in developing the solar energy sector in these markets. Over the past decade, several rural villages have been electrified by PV mini-grid systems throughout the world. India, Nepal and several African countries host the larger fraction of these projects. [1] Most are in the capacity order of 10 kW_p to 50 kW_p, typically having up to about 500 connections (e.g. households), although some larger projects have been implemented. A 200 kW_p installation in Namibia [14] and a 1400 kW_p solar PV installation on the Tokelau islands in the Pacific [15] provide examples of such projects. The Tokelau PV system is currently assumed to be the largest off-grid solar PV installation in the world. [15]. Despite a certain level of development, the frequency of solar PV mini-grid projects being implemented is still somewhat modest, mainly due to high installation costs. [11] Consequently, construction of diesel-solar PV hybrids has been far more comprehensive in developing countries. The performance of such is further reviewed in the following section. [13]

*Further description of LCOE is provided in chapter 4.

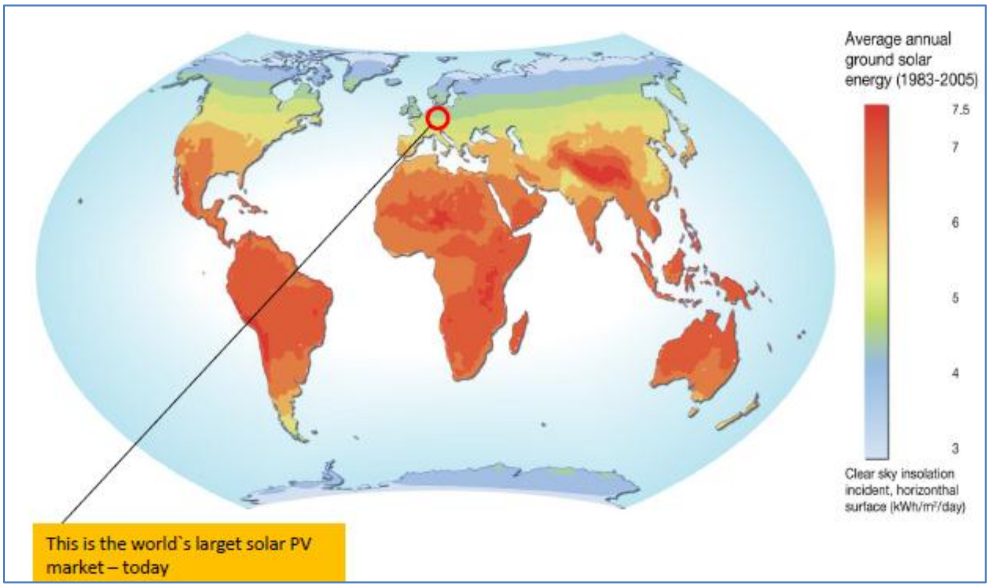

Figure 3: Global solar insolation map. [13]

2.3.4 Diesel-Solar PV hybrid mini-grids

The high capital costs of pure PV systems (mainly due to the need of energy storage capacity), combined with the extensive operating costs of a pure diesel-based system has introduced an increasing commitment to diesel-PV hybrids in several rural areas. [1] The larger fraction of such installations is in practice diesel-based systems, where PV modules are added to supply some of the consumption during daytime, hence reducing overall fuel costs. Such systems may typically yield from about 20 % to 30 % of solar energy output depending on load characteristics, while the remaining is diesel fueled. However, introducing a certain level of storage capacity may increase the solar yield to account for 50 % to 80 % or in practice as much as the system designer finds to minimize costs at a certain level of supply security. [1]At low diesel prices and a stable diesel supply, diesel-PV hybrids have proven to be a successful concept for rural electrification. [2] However, in rural areas, diesel supply is often costly and unstable due to extensive transport distances. Increase in diesel prices may have a detrimental effect on project economy in the long run. Over the past 3 to 5 years costs of PV modules have decreased significantly, thus making pure PV systems more competitive. The same price reduction has not been evident for PV system batteries, which constitute up to 30 % of capital costs in off-grid PV systems without diesel capacity. [16] Yet, recent studies suggest that PV systems can be cost competitive with diesel-PV hybrids under certain conditions (figure 4). [12]

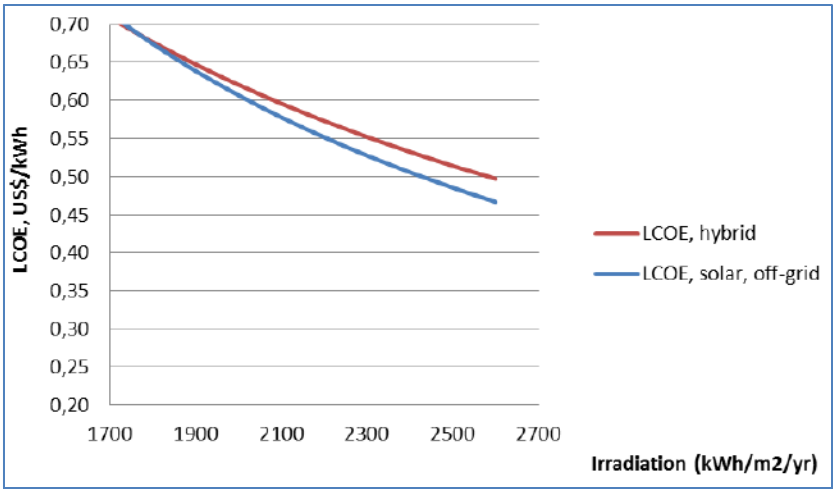

Figure 4: LCOE of PV and diesel-PV hybrid systems in rural Africa. [13]

2.4 Performance of diesel-based generation

2.4.1 The diesel genset

A diesel-based electricity generator utilizes a conventional diesel engine, creating mechanical power to rotate a shaft which again rotates a loop of conducting wires in a magnetic field (electrical generator). The varying magnetic field due to the mechanical rotation induces current in the conducting wires. Consequently, AC power is generated, and no inverter is needed for AC mini-grid distribution. In addition to the engine and the generator, a frequency controller and a voltage transformer are the key instruments required before supplying power to customers. In order to optimize generating performance and avoid damage to the engine, a control system for maintaining minimum and maximum generator load is also required. Diesel generating sets (gensets) as described here are produced in a range of sizes up to 2500 kW on a single genset, occupying a space from about 10-15 m^3 for a 200 kW genset up to 50-100 m^3 for the largest gensets. Most diesel power plants on mini-grids have several gensets (units) of equal size contributing to the total capacity of the plant. Most mini-grids are supplied by 1-4 units (table 2), each with a generating capacity ranging from 200-2500 kW depending on total size. [17]

The diesel gensets found in Tanzania are water cooled. Adding to the size of the genset and control systems are water tanks in the order of 5-10 m^3 per MW installed capacity, depending on genset specifications, along with pipes and pumping systems to maintain the water cooling cycle. [7]

2.4.2 Fuel consumption and storage

Fuel consumption of a diesel aggregate depends on the efficiency of the genset, varying from 0.25-0.50 liters per kWh produced at the generator terminals. Table 4 shows typical production and fuel consumption data for the diesel power plant on Mafia Island, Tanzania. According to Tanesco, who runs all the diesel-based off-grid systems in the country, the Mafia grid is representative for the lot when it comes to load levels, relative fuel consumption and overall performance. [7]

Table 4: Representative diesel-based power plant specifications. [7]

Mafia Island isolated diesel-based grid	
Units (gensets)	2
Total capacity (kW)	900
Connections (customers)	1400
Daily production (kWh)	11000
Fuel type	IDO
Capacity factor (%)	51
Average daily fuel consumption (l)	4000
Average unit fuel consumption (l/kWh)	0,36

The fuel storage capacity of a plant depends on average fuel consumption, the safety of fuel supply to the plant and the economy of the plant. A large fuel storage capacity reduces the risk of power outage due to failure of fuel supply. However, fuel tanks are costly and relatively space demanding. In certain areas, large fuel storage might also increase risk of fuel theft and extend the need for plant security, if gensets operate on GO which can be used for some car engines and small commercial diesel gensets. [7]

Fuel transportation is carried out by tanker trucks, and the reliability of fuel supply depends primarily on [7]:

- Distance from power plant to the closest supply center, mainly harbors on the east coast
- Quality of access roads
- Density of similar fuel consumers in the proximity of the power plant

The existing mini-grids require from 6 to 20 hours of handling and transportation for each unit of fuel traveled from existing supply harbors under optimal road conditions. However, road conditions vary according to weather conditions and other factors, which in periods might strongly delay the time taken for diesel transportation to these locations. Furthermore, many of the non-electrified off-grid candidates are more remote and have poorer quality of access roads than the mini-grids currently operating. [7]

2.4.3 Sludge handling

Most diesel gensets operate on IDO, which is not pure diesel and needs to be processed before entering the diesel engine in order to function properly and prevent engine damage. The separator pumps mechanically processed diesel to the engine tank, while the remaining product consist of water and sludge. Sludge is a low-quality oil product which cannot be utilized for any productive means. The water is separated from the slug and drained or used for engine cooling. The sludge is pumped to a storage tank, and then burned on a regular basis, or in some instances dumped in nature. [7]

2.4.4 Overall performance of diesel mini-grids in Tanzania

In terms of supply security, the performance of the diesel power plant can be measured by the amount of time it successfully supplies the full power demand of customers on the grid. Load shedding occurs when technical failure of one or more power generating units causes power outage for a certain share of customers. If the failure is not immediately corrected, operators normally switch power supply between customers, so that all customers receive power at certain times during the day. This is referred to as load shedding or demand management. Load shedding is a common exercise on existing isolated grids in Tanzania. According to Tanesco, the overall performance of the diesel power plant on Mafia Island is representative when it comes to the level of load shedding carried out by operators (table 5). Figure 3 displays the average load shedding level over the past year for the diesel-based system at Mafia Island. Load shedding levels normally vary from full power outage to 50 % outage due to failure of half the capacity (i.e. one of the gensets). [7] Two pictures from the diesel-based power plant at Mafia Island are provided in appendix A.

Table 5: Overall performance of representative isolated diesel-based grid. [9]

	Load shedding cause (% of total)	*Average load shedding (hours/month)*
Failure of fuel supply	20	40
Failure of spare part supply	25	50
Replacement of fuel filters	30	60
Other issues	25	50
Total	100	200
	Fuel consumption (IDO)	*Approximate CO_2 yield*
Per unit	0,36 l/kWh	680 g/kWh
Per month	120000 l	224,4 tons
Per year	1440000 l	2693 tons

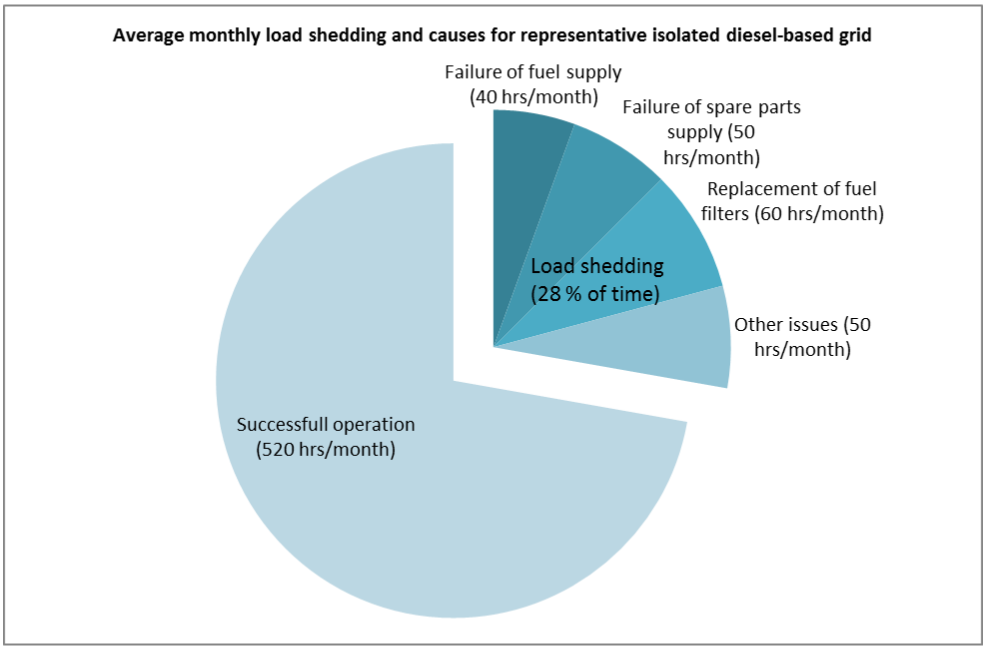

Figure 5: Overall performance of a representative isolated diesel-based grid in Tanzania [9]

3 Solar photovoltaic technology

3.1 PV systems

Solar photovoltaic power systems or photovoltaic systems (PV systems) convert solar energy into electricity. PV systems can be fit for mini-grid applications due to a high degree of location independence, fuel independence and generally a high level of equipment durability. [11] However, the main concern of a PV system on mini-grids is the uncertainty of supply caused by the variability of solar irradiation experienced by any site. The power generation of PV systems also tends to peak during the day when demand is usually low (at least for private consumption) and vice versa. [7] This fact introduces the need for energy storage, followed by several challenges that might represent barriers preventing implementation of PV systems on mini-grids. This chapter will assess the main components in off-grid PV concepts. [18] A typical mini-grid PV system consists of the following parts (figure 6) [18]:

1. Photovoltaic generator (array of PV modules)
2. Power storage (battery)
3. Power control subsystems (inverter, battery controller and other balance of system (BoS) instruments).

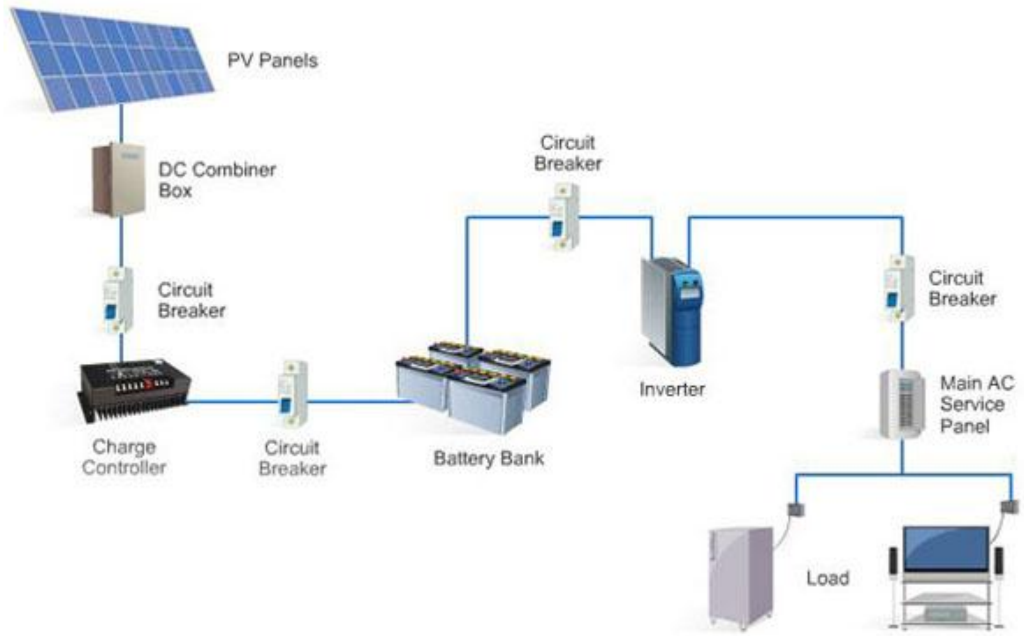

Figure 6: PV system structure with central PV array (panels), battery bank, charge controller and inverter [19]

3.1.1 Photovoltaic generator

A typical PV generator utilizes solar cells based on crystalline silicon*. Such cells convert solar energy (from solar insolation) into direct current (DC) electricity. One solar cell typically produces an electrical power output of about 2 W to 7 W at a voltage of 0.5 to 0.7 V under standard conditions (standard conditions are reviewed in section 3.1.2). The electrical characteristics of a solar cell are typically represented by the IV-curve, giving the relationship of current (I) and voltage (V) generated in the cell (figure 7). The cell is configured to operate at V_{MPP}, the voltage level where maximum power output is obtained (P_{MPP}). From this relation, the power output P produced in the cell is (formula 1) [18]:

$$P_{MPP}\ (W) = I_{MPP}V_{MPP} \qquad (1)$$

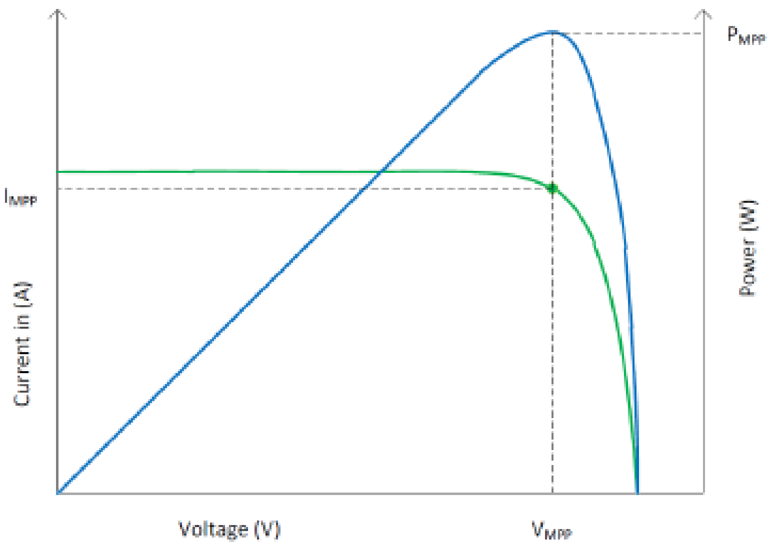

Figure 7: Current, voltage and power relation for a PV cell. [20]

The solar cells are interconnected in series to form PV modules, each module consisting of for example 36 cells. Consequently, when connected in series, a module typically provides from 50 W to 250 W at a module voltage of 15 to 30 V under standard conditions. Today, a typical module produces between 150 W_p and 250 W_p (watt peak), has a surface area of 1 m^2 to 2 m^2 and a typical weight of 15 kg to 20 kg. [18] The definition of watt peak is reviewed in section 3.1.2.

PV modules (may also be referred to as panels) are interconnected in series to form strings, and each string is interconnected in parallel to form an array of modules (figure 8). The configuration and number of modules in the array is determined by the required output voltage and current. Arrays can be interconnected to form a large PV array, consisting of all the modules interconnected and mounted on a mechanic support construction (a ground steel framework or a building roof). The total amount of modules and hence the size of the array is determined by the total power required from the PV generator, but is in theory only limited by available space on site. [18]

* Several other material types are also used in PV cells. This is not reviewed in detail here.

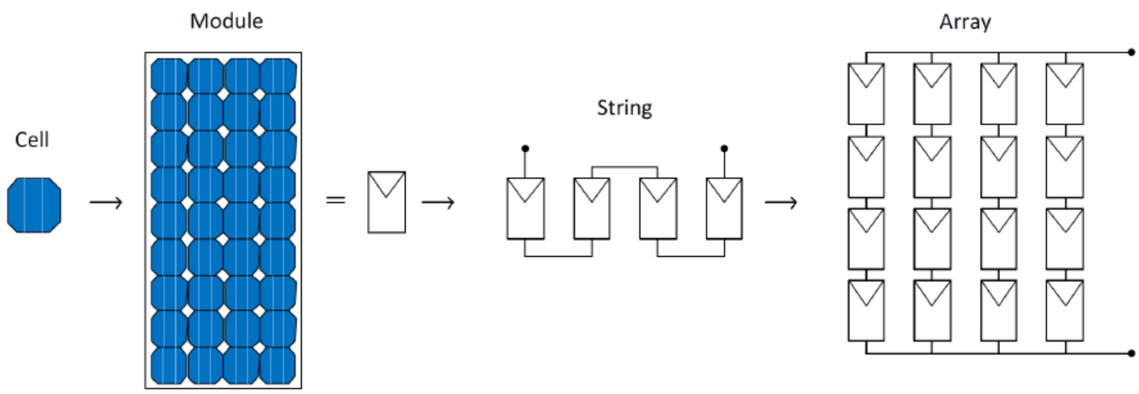

Figure 8: Configuration of a PV array. [20]

3.1.2 Rated output of PV modules

The rated power output (RPO) of PV modules is normally stated in watt peak (W_P) or kilowatt peak (kW_p) by the producer. A module rating of 220 W_p means that the power output delivered by the module under standard test conditions (STC) is 220 W. Standard test conditions are defined as irradiation power (corresponding to bright sunlight) of 1000 W/m^2 at a cell temperature of 25 °C. The rated output of an array is simply obtained by multiplying the module output with the total number of modules in the array. The actual output yielded by the panel depends on the actual solar irradiance and GHI (mentioned in section 3.2.2), along with a variety of other factors. For all practical purposes, the actual output on average during the life-time of a module is likely to be substantially lower than the rated output. Rated output under STC provides a good overall estimate of modules needed and the approximate installed capacity of the PV generator. Nevertheless, in order to successfully design a PV system to supply power to a specific load, a more accurate measure of average output is needed. This is done by estimating the actual average energy output (e.g. per day, month or year) in kWh (formula 2). [18]

$$\text{Actual average energy output (kWh)} = \text{RPO } (kW_p) \times \text{EH (h)} \times \text{PR} \qquad (2)$$

Efficient hours (EH) are the total number of hours with sunlight (direct or diffuse) during an average day, a month or a year. The *performance ratio* (PR) is the average fraction of power produced relative to the rated output. Hence, multiplying with the performance ratio corrects the rated output into real output, considering the variation of irradiation intensity and incident angle, losses due to imperfect load matching and imperfect module configuration, heat losses in wiring, inverter losses and battery losses. For a well-designed PV system the PR may typically be between a factor of 0.7 and 0.8. [18]

3.1.3 Capacity factor

An overall measure of energy output useful to system planners is the capacity factor (CF). The CF simply gives the ratio of actual produced output relative to the output that would be produced if the PV system operated at rated output 24 hours per day at all times (formula 3). The reason why the CF is a useful measure is that it relates installed capacity of the system (in kW) to the expected energy production over time (in kWh) (average day, month or year). [18]

$$\text{CF} = \frac{\text{Actual energy output}}{\text{Rated energy output}} \qquad (3)$$

For example, the rated energy output (in kWh) for a 30 kWp PV system operating for one year would be equal to (30 kWp) x (24 h/day) x (365 days). Clearly, the CF of a PV system strongly depends on location, site conditions and system configuration and design. The higher the capacity factor, the lower the necessary number of modules to supply a certain load, and the lower the costs. It should be mentioned however, that increasing the PR might represent significant costs due to increased levels of planning detail and high-efficiency component costs. [18] In the following sections, the most important external factors influencing the PR are assessed: Irradiance, cell temperature and shadowing.

3.1.4 External factors affecting system performance

Irradiance variations

As reviewed in section 3.2, irradiance on a horizontal surface depends on a several factors and may vary strongly over time in an unpredictable manner. This certainly affects current and voltage, hence also power output from the PV cells (figure 9). [18]

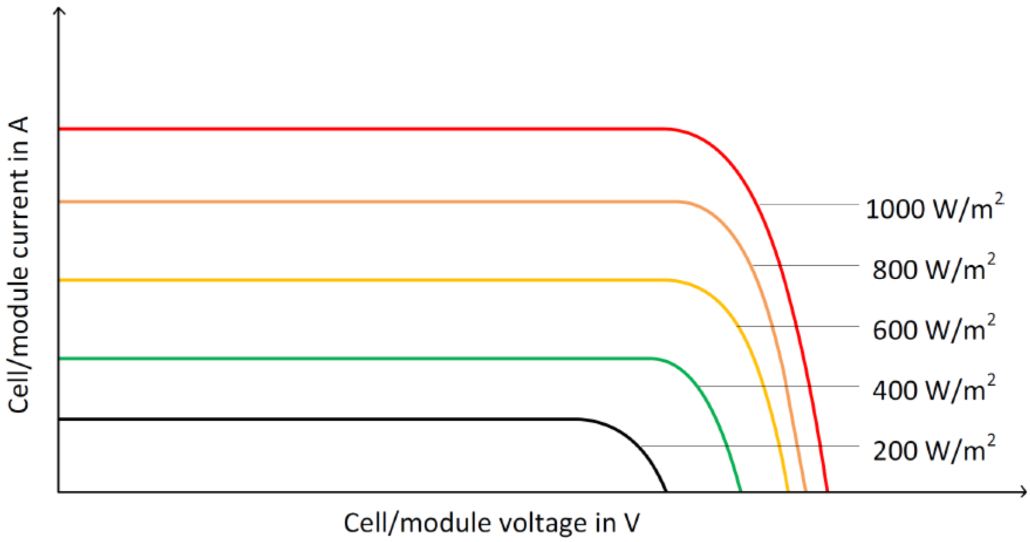

Figure 9: IV-curves at various levels of irradiance. [20]

Cell temperature variations

The power output from solar cells also depends on the temperature of the cells, which again is dependent on the ambient temperature and irradiance intensity. Increasing cell temperature reduces the cell or module voltage significantly, and causes a slight increase in cell current. The effects of cell temperature on current, voltage and power output is shown in figure 10 and figure 11 respectively. [18]

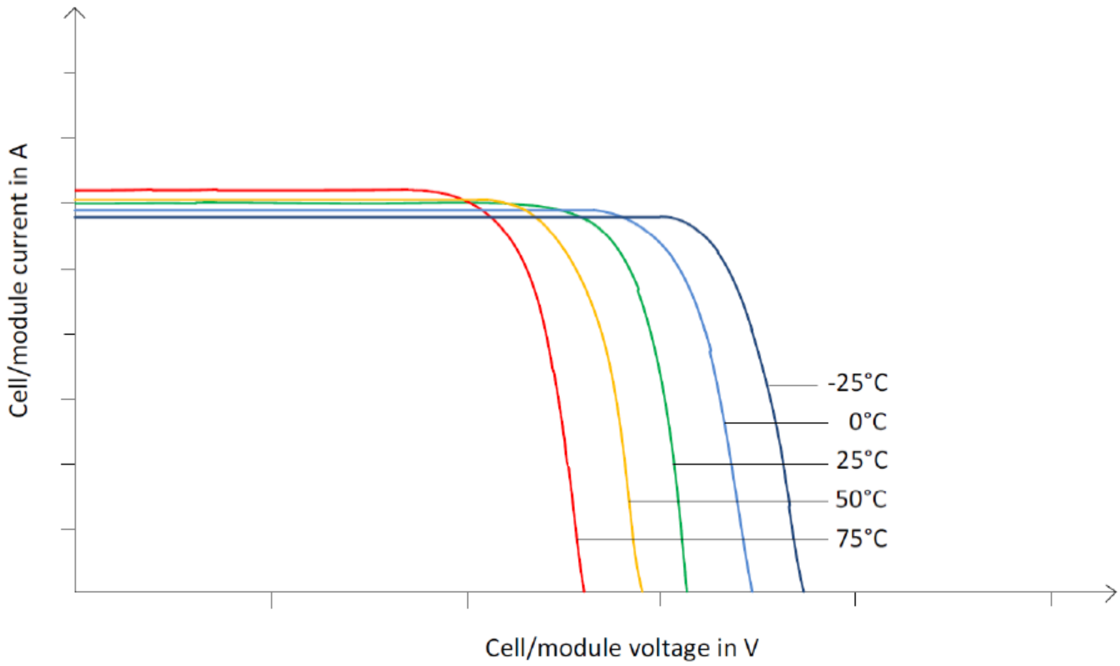

Figure 10: IV-curves at various cell temperatures. [20]

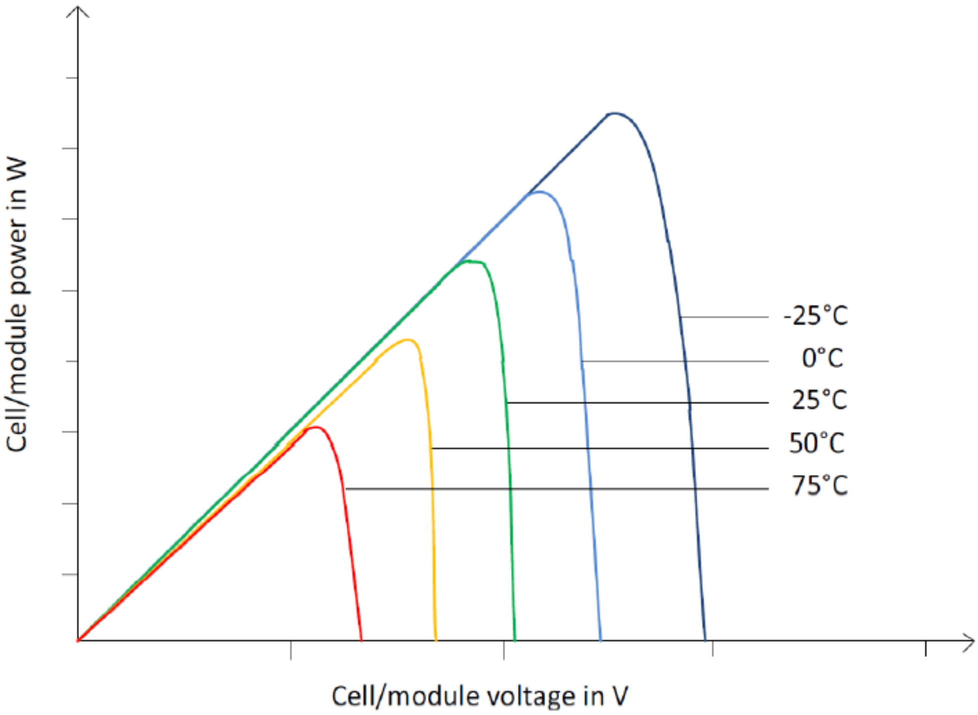

Figure 11: Cell power output at various cell temperatures. [20]

Shading and hot-spot heating

Shading of a solar cell occurs when a stationary or moving object gets in between the solar irradiance and the surface of the cell. This can for example be a tree shading the cells as the sun moves by behind it, a leaf blowing on to the cell surface or any other object blocking the sun to some extent. Shading may be partial, full (entire cell) or cover several cells in a module. [18]

Shading of one cell reduces the current and voltage (and so the power output) of that cell (figure 12). In figure 12, the cell to the left is not shaded, the cell in the middle is 50 % shaded and the one to the right is 66 % shaded. *Hot spot heating* occurs when the current decreases in one of the cells interconnected in series. This disturbs the current flow in the series connection and the power output of all the cells in the series is reduced. This power loss is dissipated as heat in a small area, and may cause melting and broken cells. However, the problem of hot-spots can be solved by simple devices referred to as bypass-diodes, which is standard equipment for practically all modules today. Bypass diodes are not explained in detail here, but it should be mentioned that such mechanisms in the cell coupling will increase module costs. The nature of eventual shading on a given module will decide to which extent measures must be taken to avoid hot-spot formation. Regardless of hot-spot formation and prevention of such, shading will always decrease power output. [18]

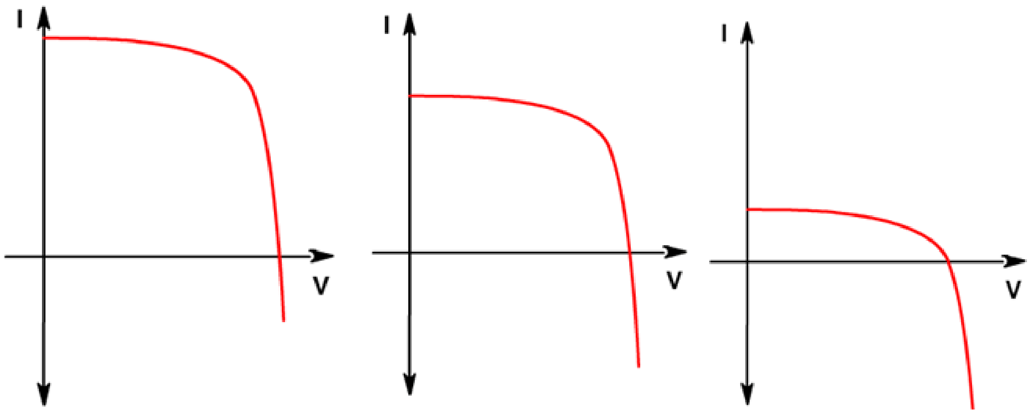

Figure 12: Shading effect on the IV-curve of a PV cell. [21]

3.1.5 Battery storage

The variability of solar irradiance is directly transferred to the power output performance of a PV system. This fact, combined with the security of supply demanded by consumers on the mini-grid, calls for energy storage capability. There are several ways to store energy. The only storage device assessed here are batteries, assuming this to be the most accessible and viable option in developing countries. There are several types of batteries, the most common currently being lead-acid batteries. A detailed description of battery types and internal functioning is not provided in this section, focus is dedicated to battery functioning and rating. In this context one should be aware that the different battery types may function differently in various operating conditions and project-specific measures must therefore be taken when choosing batteries.

Battery charging cycles

A PV system can utilize battery energy storage to improve security of supply for the consumers on the mini-grid. During daytime when irradiation is higher than the consumption, the battery is charged. In the afternoon and evening when consumption is higher than the capacity of the PV generator, the battery is discharged, supplying power to the mini-grid. This introduces a daily system cycle for the battery charge level, usually reaching a minimum during the night before sunset and a maximum during daytime. From the manufacturer, battery life-time is often stated in number of cycles (for a PV system usually meaning days) with respect to DOD levels (mentioned below). [22]

Battery capacity and performance

Battery capacity is measured in ampere-hours (Ah), meaning that a battery of 1000 Ah capacity can deliver 100 A for 10 hours or 10 A for 1000 hours. Thus given the current, power flow to or from the battery depends on the voltage of the battery bank (formula 1). If the battery bank voltage is 50 V and the current from the battery is 10 A, the power supplied by the battery is 500 W. [22]

There are a number of different battery types commercially available, but they can be separated into two categories [22]:

- Batteries with a low resistance to cycling
- Batteries with a high resistance to cycling

Resistance to cycling is the battery's ability to withstand variations in charging levels over time. Batteries with low resistance are typically cheap ones that are easy to come by, e.g. car batteries, while a high cycling resistance is a property of electric vehicle batteries or specialized PV system batteries. Such batteries are much more expensive than batteries with low cycling resistance. [22]

Another quality measure of batteries is the maximum depth of discharge (DOD). Some batteries may be designed to have a minimum charge level of 60 % of full capacity; this would be referred to as a maximum DOD of 40 %. Allowing the battery to be discharged to a lower charging level would cause battery life-time to decrease. Batteries usually have discharge depths of between 20 % and 70 %. A common rating is 50 %, which is often assumed in literature when assessing PV battery issues. It should be mentioned, that maximum DOD is not an absolute measure, in the sense that keeping charge levels even above the tolerated limit, will further increase battery life-time and performance. In general, all batteries will sustain longer if overall DOD levels are reduced (figure 13). Hence, oversizing the battery bank in a PV system will increase life-time and performance of batteries, but may represent significant cost increase. [22] High quality PV batteries can last the full life-time of a PV system (20 to 25 years) if operated at average daily cycle DOD levels of 20 % to 30 %. [12]

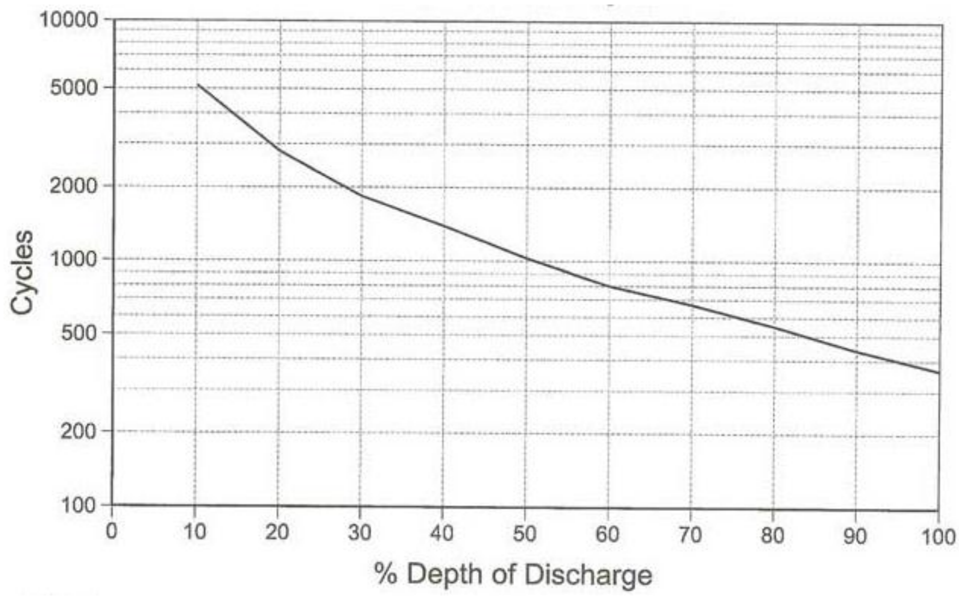

Figure 13: The life-time of a given PV system battery (here stated in number of charging cycles) as a function of average DOD levels. [23]

Battery efficiency

Along with being sensitive to operation characteristics, the efficiency of lead-acid batteries is also dependent on the temperature, which again depends on charge and discharge currents $I_{battery}$, as well as ambient temperature. Power losses P_{loss} in the battery occur due to the internal electrical resistance $R_{battery}$ of the battery (formula 4):

$$P_{loss}\ (W) = I_{battery} \times R_{battery} \qquad (4)$$

Furthermore, overall battery efficiency η_{batt} is given by the ratio of power P_{batt} supplied by the battery and the power P_m it receives from the PV modules (formula 5):

$$\eta_{batt} = P_{batt} / P_m = (P_m - P_{loss}) / P_m \qquad (5)$$

Internal resistance of batteries increases with average battery temperature over time (figure 14). The internal resistance at a given average temperature also increases solely as a function of time. This general effect reduces efficiency of all batteries over time, but the extent of such reduction depends on the battery type and operating characteristics.

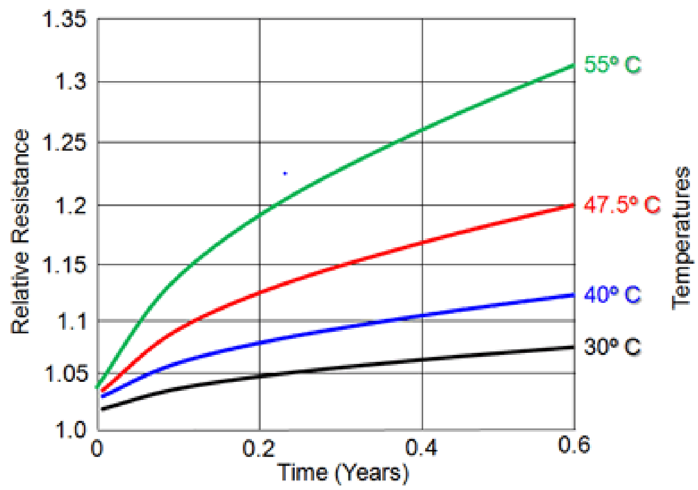

Figure 14: Internal battery resistance at various average battery temperatures. [20]

In a PV system, the battery is usually one of the components most sensitive to damage. Reduced battery lifetime will significantly increase maintenance costs and reduce security of supply. Damage to the battery is mainly caused by excess battery discharge or overcharging. [22]

3.1.6 Power control subsystems

Firstly, the power generated by the PV modules, needs to be controlled and conditioned into a shape in which it may be delivered to the mini-grid and utilized by consumers. [15] Secondly, the instruments doing this must be configured and interconnected in a way that optimizes the lifetime of each component in order to ensure security of supply and minimize life-cycle costs. [15] In the following, two standard power control subsystems will be assessed:

1. Battery charge regulation
2. DC/AC converter (Inverter)

Battery charge regulation systems

As discussed above, battery charge should be regulated to prevent battery damage. The simplest regulation utilizes a blocking diode to separate the PV generator and the battery. This self-regulating mechanism determines the direction of the DC current bound by the relative voltage level of the generator and the battery. This mechanism is cheap, but requires precise configuration of the PV generator operational voltage level, to match the optimal battery charge levels. The simplicity of this mechanism introduces a high risk of battery damage and in practice it often yields inefficient performance. [22]

More sophisticated systems for battery charge regulation use a variable resistance connected in series (series regulator) or parallel (shunt regulator) with the battery, adjusting the charge current entering the battery according to its voltage level. At high battery voltage the charging current will be very small and vice versa. The downside to using a resistor is that a significant amount of power is dissipated in this device. However, this loss can be reduced by introducing a switch in series with the battery. This switch couples out the battery at a certain maximum voltage, and in at a certain minimum. This reduces the average charging current, and therefore reduces the power dissipated in the series regulator. [22]

Inverter (DC/AC converter)

When AC is chosen for distribution on a mini-grid, the DC generated by the PV system is converted to AC by an inverter. This is a standard device, feeding AC power to the grid. The inverter also transforms the voltage of the DC current input to required AC output voltage. Inverters come in a wide range of capacities in terms of accepted voltage and current levels. The fact that an inverter can operate at a range of input voltages is convenient for a PV system, as output voltage from a PV array will vary continuously due to the various factors mentioned in this chapter (figure 15). The efficiency of inverters in transmitting power to the distribution grid ranges from 75 – 95 %, depending on the load. [18]

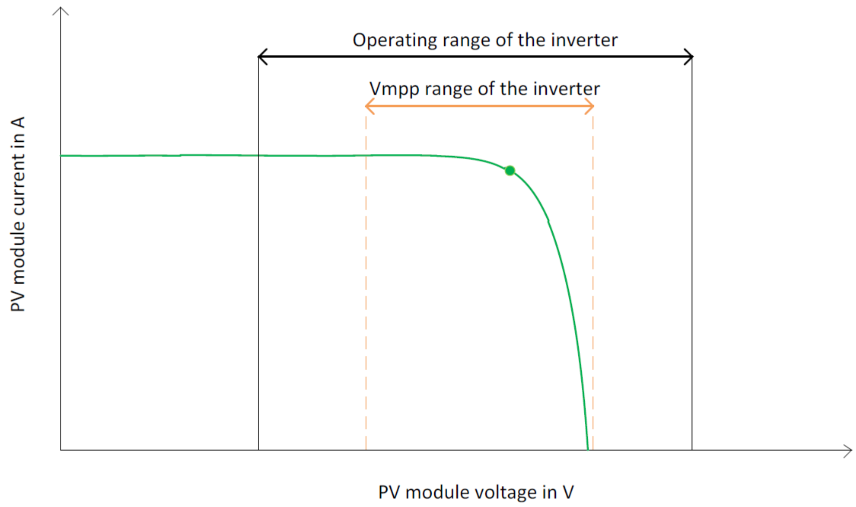

Figure 15: Operating range of an inverter. [20]

3.2 The solar energy resource in Tanzania

3.2.1 Solar radiation components

Solar radiation may be divided into two main categories:

1. Direct beam radiation
2. Diffuse radiation

Direct radiation on a surface is sun beams reaching the surface of the earth without being reflected back to space by the atmosphere or scattered by molecules or clouds (figure 16). It may also be enhanced by direct beams reflected being off other nearby surfaces, then reaching the surface in question. On a sunny (cloudless day) direct irradiance may represent up to 90 % of the total irradiance on a surface area on earth. Approximately 10 % at least will always be diffuse radiation. Diffuse radiation is sun beams that are scattered by molecules in the atmosphere or clouds. On a heavily clouded day, all the radiation may be diffuse. The share of diffuse radiation depends on the weather and may vary during the day. The higher the share of direct beam radiation, the higher is the solar power incident on the surface. The incident solar power on a surface is measured in W/m^2. For any location on earth, a radiation of around the mentioned STC level (section 3.1.2) 1000 W/m^2 would mean relatively clear skies. However, the actual irradiance at a given site depends on location, the relative position of the sun and weather conditions. [18]

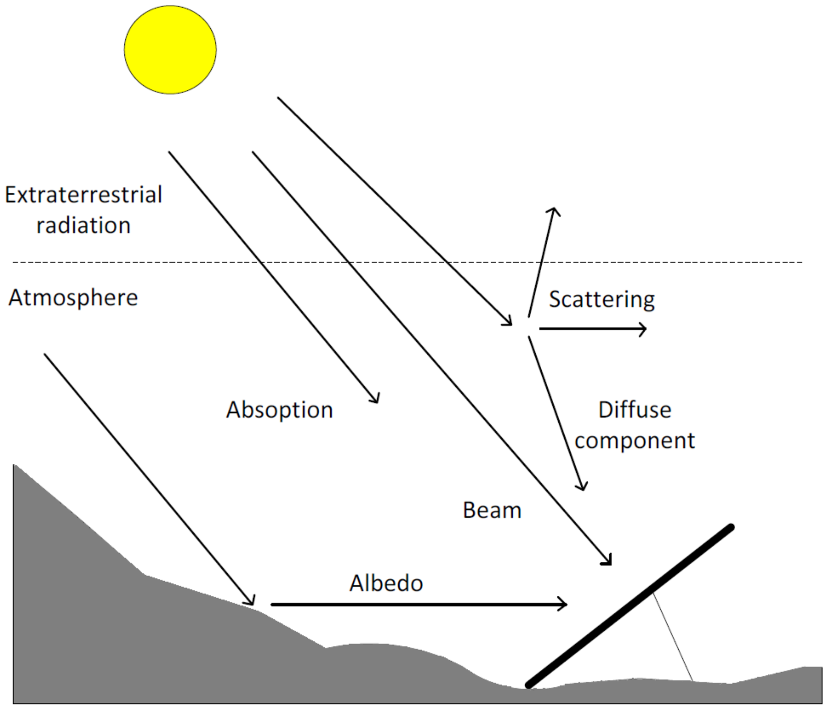

Figure 16: Solar radiation reaching a solar panel. [20]

3.2.2 Global horizontal insolation

Global horizontal irradiance is the sum of direct and diffuse solar radiation incident on any horizontal surface (at earth ground level), measured in W/m^2 (figure 17). For a given site it will indicate the maximum available solar power at a certain time. For a PV system developer it may provide the available power during both cloudless days, heavily clouded days and anything in between. When assessing solar energy potential, one might be more interested in the total insolation received on a horizontal surface area over a period of time. Such a measure is referred to as global horizontal insolation (or irradiation) (GHI) and is measured in for example kWh/m^{2}month or kWh/m^{2}year. [18] Insolation can be defined as the integral of irradiance over time. Hence, it provides the total available energy per area over a certain period of time. Based on measured or estimated GHI data for a given location, a PV developer may forecast the expected average available energy per area per day, month or year. The GHI is one of the most important parameters when measuring the solar energy potential in any location. It can provide a good basis for planning and designing a PV generator to produce a certain amount of electrical energy throughout its lifetime. [18] Figure 18 displays average annual GHI of different geographical zones in Tanzania, in total constituting the mainland area of the country. The zone areas and the respective sites of measurements are attached in appendix B. [24]

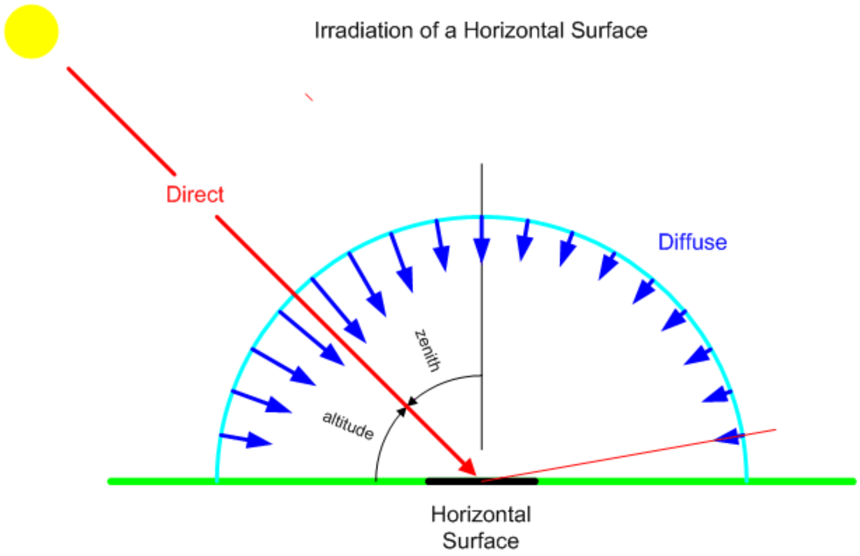

Figure 17: Solar irradiation on a horizontal surface. [20]

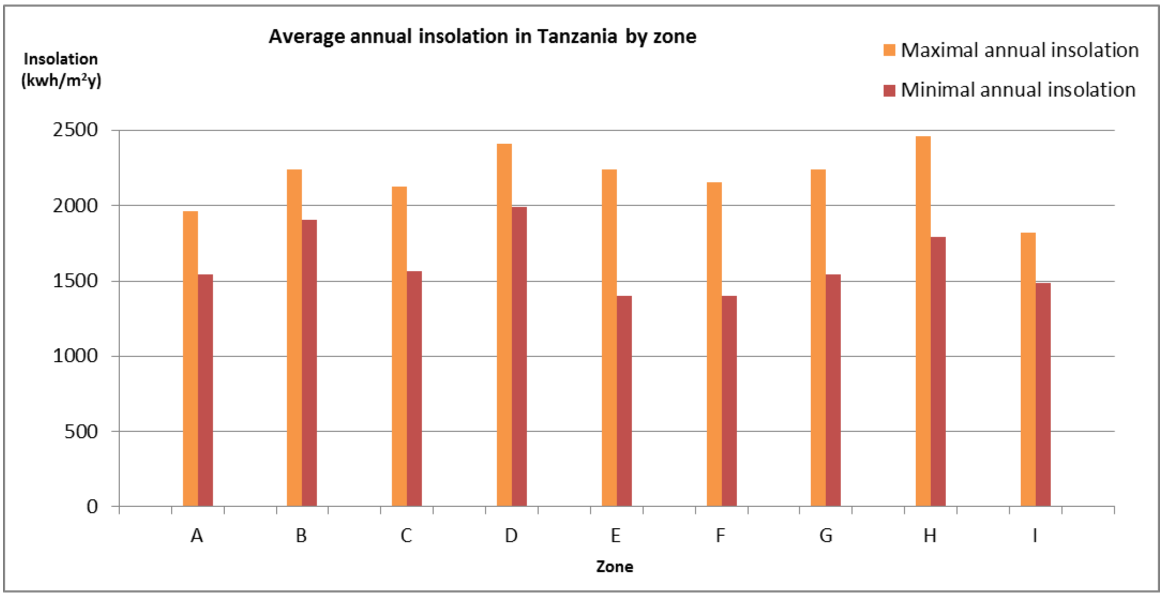

Figure 18: Maximum and minimum average annual insolation in Tanzania by zone. [24]

The seasonal variation of average daily insolation for some selected zones is shown in figure 19. The maximum average insolation across all months is found in Dodoma (zone D) while the overall minimum is measured at Kilimanjaro International Airport (zone E) in June. [24] The curves of the remaining zones are to a good estimate evenly distributed in between these zones, with similar shapes. Estimates are based on data collected from 1965 to 1990, and the standard deviation of average annual insolation is found to lie within -5% and + 5% for all zones. [24]

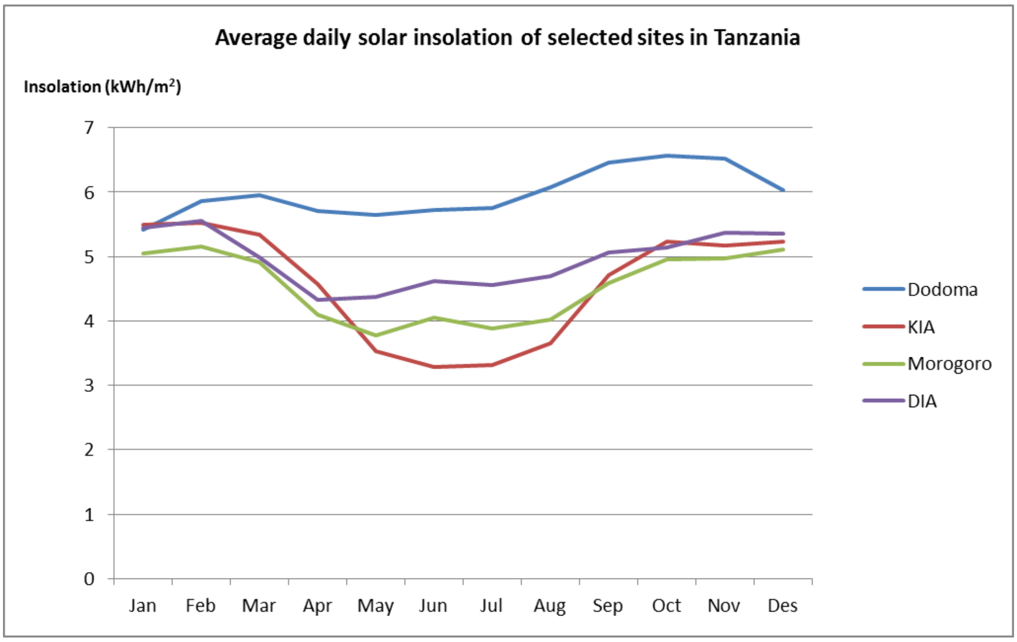

Figure 19: Average daily insolation of selected sites in Tanzania. [24]

4 Levelized cost of energy

In order to compare the life-cycle costs of technology options, the measure of levelized cost of energy (LCOE) is introduced. The LCOE is calculated as per unit cost of energy (e.g. per kWh) and it is based on the net present value of the total life-cycle cost of the project. In other words, the LCOE is the net present value of total life-cycle costs divided by total life-cycle energy production (formula 6). The life-cycle of a project is the expected economic life-time of the power system components bearing the lion's share of the capital investment. [11]

$$LCOE = \frac{Life\text{−}cycle\ costs\ (currency)}{Life\text{−}cycle\ production\ (kWh)} \tag{6}$$

4.1 Net present value calculation

In order to calculate the value today of an investment with annual cash flows through the economic life-time of the project (income and expenditure), a net present value (NPV) is calculated. The NPV discounts future cash flows by applying a certain discount rate. The discount rate used by a project developer or investor depends on the nature of the project, in particular the financial risk involved. The discount rate must be at least the rate of return the investor can obtain from more or less risk-free investments (typically a bank account). This is called the internal rate of return (IRR). For a project with some level of risk, the discount rate will be higher, as taking higher risk will set a higher demand of return. When subject to a discount rate r, the NPV of a project with economic life-time of n years is given by: [25]

$$NPV = -I_0 + \sum_{n=1}^{i} \frac{C_n}{(1+r)^n} \tag{7}$$

Where:

I_0 = Initial cost

n = year number

r = discount rate

C_n = Net cash flow in year n

i = economic life-time of investment

4.2 Real LCOE calculation

The LCOE calculations carried out in this section are *real* (formula 8), i.e. real discount rates are applied. As opposed to *nominal* LCOE estimates, these discount rates are not corrected for assumptions regarding inflation. Real LCOE estimates may serve well as an overall comparison of technologies. From a developers perspective a nominal LCOE would normally be the preferred estimate, due to a higher level of financial detail yielded by inflation corrections. Consequently, one disadvantage of real LCOE estimates is that it ignores the effect of inflation on O&M costs and fuel prices. For RETs this effect is normally very low and not likely to significantly influence LCOE calculations. For DPPs however, it may increase the LCOE depending on the inflation factor, due to high annual fuel cost levels. Furthermore, the real estimate also ignores the effect of inflation incident on capital costs (weighted average capital costs, WACC). This may have significant effect on RETs especially, which in general represent high CAPEX levels. For comparison purposes however, real estimates are in general considered to provide sufficient financial detail. Prediction of inflation rates is a complex exercise introducing a high level of uncertainty, making nominal LCOEs more relevant for projects yielding very high annual cash flows than for mini-grid electrification projects. [11]

$$LCOE = \frac{Capex + \sum_{n=1}^{i} \frac{AC}{(1+r)^n} - \frac{AR}{(1+r)^n}}{\sum_{n=1}^{i} \frac{AEP\ (kWh) * (1-Lf)^n}{(1+r)^n}} \tag{8}$$

Where:

AC = Annual costs

AR = Annual revenue

AEP = Annual energy production

Lf = annual loss factor (system efficiency decrease rate)

Capex = Capital expenditure (initial cost)

n = year number

i = economic life-time of generating system

Part II - Methodology and approach

5 Power consumption of villages in rural Tanzania

5.1 Mini-grid villages and estimation of loads

Identification of future mini-grid candidates and their nature have been done partly by reviewing the GEOSIM data obtained by the REA. In addition, two field trips to relevant sites, stakeholder interviews and a broad literature review have been carried out. The expected power consumption of private households in relevant rural villages was assessed using load data from existing mini-grids, along with customer interviews conducted during field trips. The potential for productive uses of electricity in off-grid candidates have been assessed through stakeholder interviews and field trips, along with a literature review of agriculture and industrial activity in rural Tanzania.

5.1.1 Identifying mini-grid villages

Currently, the Tanzanian government represented by REA is developing a detailed prospectus for rural electrification to be implemented mainly during the next ten years. Planning and implementation of the electrification projects covered by the prospectus will be carried out in cooperation with several international donors. The overall rural electrification plan is twofold [3]:

1. Extension of the national grid
2. Off-grid electrification

To the extent it is technically and economically viable REA will seek to expand the existing national grid in order to reach a number of rural villages. The current idea is to extend the grid to all villages within a 5 km range of existing 33 kV lines. In addition, the plan is to extend the grid to all development centers located up to 40 km from existing or planned 33 kV transmission lines. Development centers are villages or clusters of villages where a certain degree of economy and a potential for productive uses of electricity is evident. [3]

Parallel to the grid extension project planning, the REA has identified villages that are considered too remote to be reached by such extension during the prospectus period. These localities are candidates for intermediate or permanent off-grid electrification. Through their recent data collection, the REA has identified more than 1600 villages suitable for mini-grid implementation. The total population of these villages is estimated to more than 4.5 million, constituting about 10 percent of Tanzania's inhabitants (table 6). [3]

Table 6: Identified candidates to off-grid electrification [3]

Criteria		*Distribution*			
Population	*No of households*	*No of villages*	*Total households*	*Total population*	*Percentage of total population*
0–800	0 – 160	392	50102	245500	
800–2000	160 – 400	530	178571	875000	
> 2000	> 400	695	704694	3453000	
	Total	1617	933367	4573500	10

When considering which technical solutions to apply for mini-grid candidates, it is necessary to assess the village size in terms of number of connections (number of customers), private household consumption and eventual consumption for public or private institutions. In general, public and private institutions are limited, and their electricity consumption will normally constitute an equivalent to a few households [3]. Therefore they are not specifically handled here. Furthermore, productive or industrial uses of electricity can strongly influence total consumption and total peak load on the grid. This matter will be discussed in section 5.3. Table 7 shows the average number of households per off-grid village.

Table 7: Average number of connections per village [3]

Criteria		*Distribution*		
Population	*No of households*	*No of villages*	*Average no of households per village*	*Average no of people per household*
0–800	0 - 160	392	128	
800–2000	160 - 400	530	337	
> 2000	> 400	695	1014	
	Total	1617	577	4,9

For villages with more than 2000 inhabitants, the average population is approximately 5000 and the average number of households is 1014. However, most of these villages are in the range of 400-800 households, while a few towns of up to 4000-5000 households increase the average significantly [26]. In general, potential productive uses of electricity across the candidate villages are expected to be relatively low, so assessing household consumption is likely to provide a good basis for estimating total village load.

5.1.2 Estimating mini-grid load

<u>Private household energy consumption</u>

Interviews with habitants of non-electrified villages in rural Tanzania and energy sector stakeholders indicate that a wide range of electrical appliances are wanted for private household consumption. [27] Despite of varying priorities amongst villagers, the awareness of existing equipment is high and households are specific and concrete when listing their need for electrical appliances. Table 8 shows electrical appliances identified as welfare-increasing, time-saving or household expenditure reducing by a diverse group of inhabitants in the village of Matipwili in rural Tanzania. [27] The list is consistent with the actual appliances found in households connected to the diesel-based mini-grid on Mafia Island, Tanzania. [7]

Table 8: Relevant electrical appliances on mini-grids in rural Tanzania. [23, 7]

Electrical appliance	*Nominal power (W)*
Large refrigerator/freezer	400 – 450
Small refrigerator/freezer	100 – 150
Average intensity light bulb	40
Medium size TV	150
Cell phone charger	4
Computer/laptop	100
Radio/clock radio	5
CD-player	40
Small electric kettle < 1 liters	500
Rice cooker	300
Egg boiler	300
Sewing machine	100
Small ceiling fan	30
Table fan	15
Electrical mosquito protection	20

To what extent the various appliances are used will vary across villages and the list does not directly provide basis for general assumptions regarding total household consumption. Several studies have estimated typical energy demand for a household in rural Africa, results ranging from 50 kWh per month up to 125 kWh per month (table 8). [28, 29] Actual consumption will depend on household affordability and might vary significantly between villages in different areas. Total electricity consumption of rural households may be classified by size in order to obtain scenarios for total demand on mini-grids. [7] An indication of required energy generation is necessary for successful choice of technology and system design. There is a relationship between the average daily household energy consumption of existing isolated grids in Tanzania, and the average daily peak household power demand on these networks (table 9). Tanesco production data from existing off-grid systems in 2012 [9] indicate that the average grid load is normally a factor of between 0.5-0.6 of peak load (occurring between 7 and 10 pm), including system losses. [7] By assuming a factor of 0.5 (sufficiently accurate for this purpose) the average load relative to peak load, the relationship presented in table 9 is obtained.

Table 9: Average monthly electricity demand of rural households [7, 28, 29]

Average peak household demand (daily) (kW)	*Average monthly household consumption (kWh)*	
0,15	54	*Typical estimate*
0,25	90	*High estimate*
0,35	125	*Maximum estimate*

Estimating peak load of households

When dimensioning the power plant for a mini-grid, both the peak load and the total daily consumption must be taken into consideration in order to avoid power supply shortage. However, expected peak load is the most critical parameter for successful sizing of the power station. [22] Underestimation of peak load can lead to frequent power outages on the mini-grid due to insufficient generating capacity or battery storage capacity. [29] Based on the relationship of household consumption and their average household peak load (AHPL) (table 9), total peak load (or demand) for villages of various size and average consumption levels can be roughly estimated. [29] Figure 2 shows how different village sizes and average household peak load configurations affect the total peak load expected to be incident on the power plant.

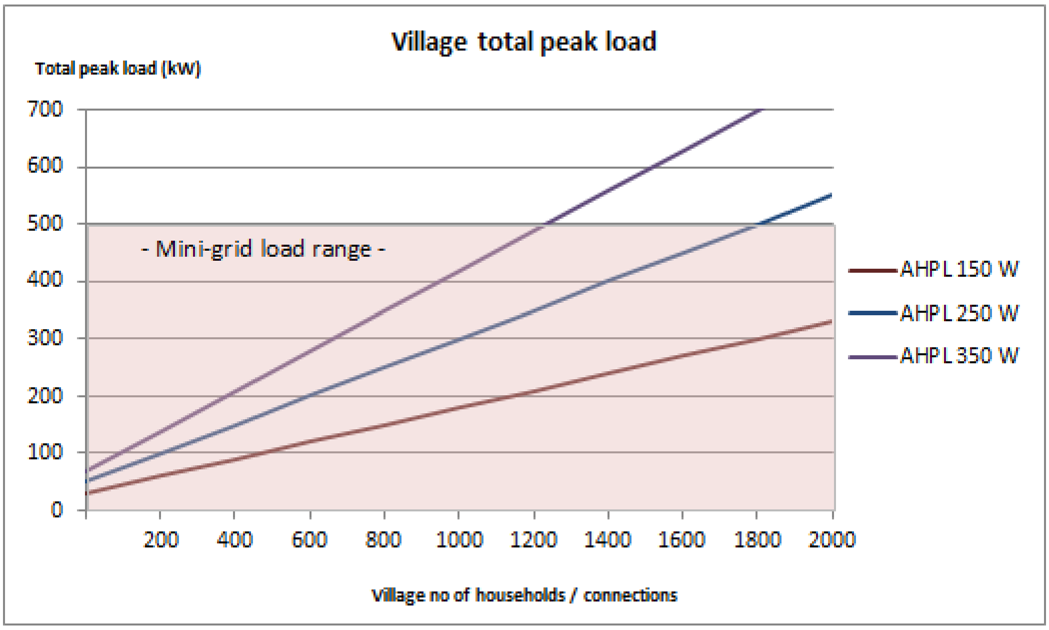

Figure 20: Linear total peak load estimates for rural villages. [9]

Figure 20 indicates that the total peak load estimates for the larger fraction of identified off-grid candidates are within the peak load range for a mini-grid (< 500 MW) per definition. Mini-grids are potential options also for some of the largest villages in the scope (> 2000 households), given the assumptions made on the range of AHPLs. For an average size village of 577 households the total peak load does not exceed 300 kW for an AHPL of 350 W, which would be very high by rural Tanzanian standards. [30]

Productive use and industrial loads

The above estimation of total peak load does not include the contribution from productive or industrial uses of electricity, which is expected to represent higher loads than households in general. Depending on the type of industry, such use may significantly influence the total power consumption, especially for the smaller mini-grids. However, productive use mainly requires power during daytime, while the peak load of households in rural Tanzania is expected to occur between 7 and 10 pm. [26] Hence, with relatively low levels of productive use, the peak load from eventual productive uses during the day is not likely to exceed the peak load from private households in the evening. This makes sizing of the battery capacity an important design criterion, even for systems with low storage capacity. In the event of a very small village combined with local industry of relatively high power demand, the peak load might occur during daytime. Consequently, developers should always assess the expected load represented by productive users on the mini-grid. [31]

5.2 Typical village layout

A typical rural village is shown in figure 21. In general, village household density is relatively large, often more dense than indicated in the figure. Village density tends to increase with the number of households [26], which means that distribution costs per household is likely to decrease with increasing village size. The village density will affect sizing of generating capacity primarily due to the following reasons:

- Low household density might call for medium voltage distribution, which will affect configuration of the generating capacity.
- Low household density will increase overall cable length and therefore increase distribution losses. This must be compensated for by extending generator capacity.

In principal, there are two main means of distributing power in rural villages. Depending on number of connections (households or other institutions) and village density, project developers might consider direct low voltage distribution directly from PP to customers or a higher distribution voltage network via distributed transformers to low voltage consumer delivery. [11]

5.2.1 AC distribution

In the further assessment, AC distribution will be assumed due the size of relevant loads. DC networks may be applicable for very small systems, but will not be considered here. DC networks also limit the range of electrical appliances available (special DC appliances needed). From a consumer perspective, DC equipment is less available and likely to be more expensive. DC networks will also raise significant distribution safety issues if applied in the relevant villages. [2, 31]

5.2.2 Single phase vs. three phases

For productive uses utilizing large electrical motors, three phase power may be necessary in order to transmit power at a sufficiently low current (to withhold safety requirements). [2]Facilities receiving three phase power will normally receive power at higher voltage (e.g. 400 V) than households (usually about 220 V). Three phase distribution will be natural for medium voltage distribution (large village, low density). In such systems, single phase can be chosen for most facilities, while three phases can be delivered to a few facilities if required. For small, dense villages one might distribute one phase directly from the power plant. However, three phases may still be delivered to some facilities. For diesel aggregates three phase power is generated, providing flexibility in providing both three phase and single phase by phase splitting. For solar plants some more consideration must be taken (inverter configuration), this is assessed in chapter 6. [2]

Figure 21: Typical layout of a rural Tanzanian village. [29]

5.3 Availability of renewable energy resources

Tanzania has a vast potential of utilizing renewable energy resources. For mini-grid candidates, hydropower, biomass and solar potentials of different scales have been identified (figure 22). All sites have solar potential in practice, but hydropower or biomass is likely to be preferred when available due to lower generating costs in general (reviewed in chapter 8). [3]

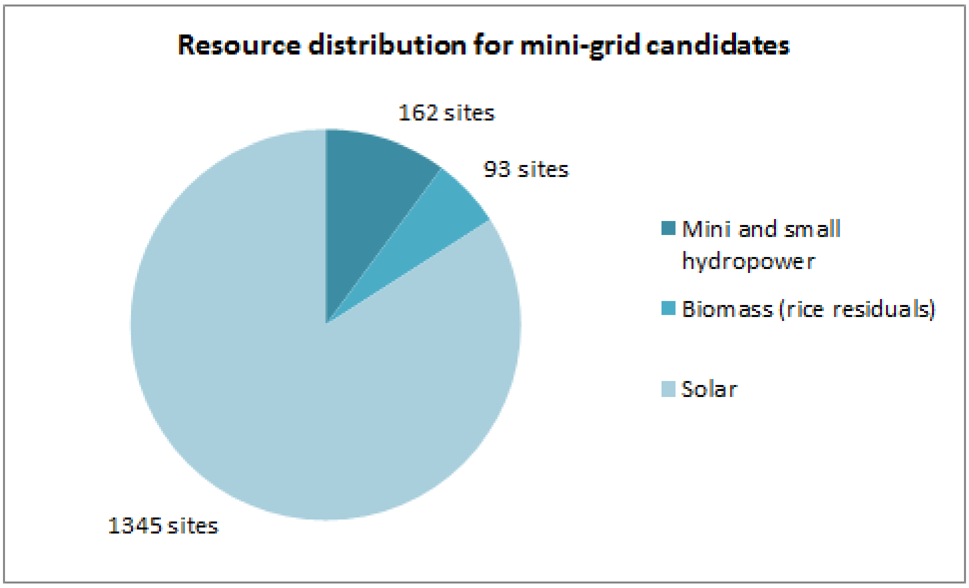

Figure 22: Identified renewable energy resources for mini-grid candidates. All villages have solar potential to some extent, while hydropower and biomass resources are significant but limited [3]

6 PV systems for mini-grids

In this section technical assessment of PV systems for mini-grid applications will be carried out with respect to the size range and nature of mini-grid objects in rural Tanzania. The aim will be to assess under which conditions the concept may provide a certain level of supply security, and to highlight the primary design and operational considerations facing PV system developers.

6.1 Mini-grid compatible PV configurations

With respect to the previous section assessment, a general PV system layout for rural mini-grids may be established for further assessment. Due to the modularity of modules and batteries, there are many ways to configure a PV mini-grid application. Three main ways are listed here [18]:

- Centralized ground mounted PV array
- Distributed ground mounted PV arrays
- Distributed roof mounted PV arrays

Centralized ground mounted arrays are most common on existing PV mini-grids. Such configurations provide some operational advantages. Having the PV array and all subsystems in one place simplifies construction, operation and maintenance of the plant. Distributed arrays have the advantage of not occupying one very large space, which may be an issue in dense villages. However, available area is certainly not an issue in most rural villages, and even very large arrays will practically never introduce spacing problems. Very large PV arrays may be reasonable to construct in the outer circumference of the village, but this may not necessarily increase distribution costs significantly. It is usually necessary to elevate the modules to some extent, in order to avoid shading and reduce the impact of dirt and dust on the module surfaces. Roof mounted arrays or modules have the advantage that construction and costs of large array frameworks (usually steel constructions) may be escaped. For large capacities, many roofs will be required, and costs of such distributed mounting may exceed those of a large steel framework. In addition, in rural villages roofs are in general of very varying quality and usually relatively small, which introduces need for improvised mounting solutions. Last but not least, roof mounting locks the tilt and orientation of the modules, which may significantly reduce power output. Optimal tilt angle and orientation is assessed further in section 6.2.6. [18, 31]

With respect to the above discussion, centralized ground mounted systems are considered in further assessment. It should be mentioned however, that distributed solutions may be applicable for very small loads (> 10 kW). [31] A simplified illustration of a centralized array with battery pack feeding power to a mini-grid is illustrated in figure 23.*

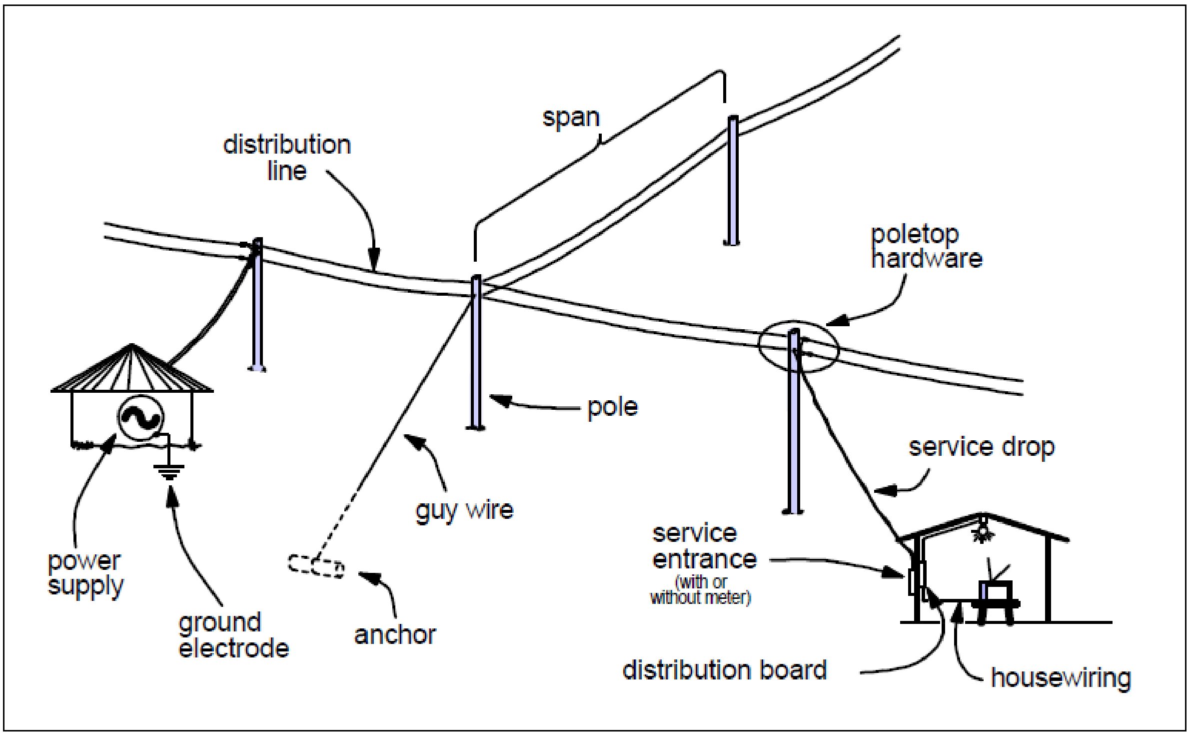

Figure 23: Basic mini-grid distribution layout for mini-grids with intermediate three-phase distribution and single phase to houses. [22]

PV three phase distribution

Three phase distribution from PV systems does not imply significant technical challenges. [2] However, it does affect the configuration of modules, battery packs and especially inverters. [18] This is assessed in section 6.2.4. Once a detailed estimate of peak load, average load and annual production has been established with respect to the mentioned considerations in chapter 5, PV system design may be initiated for a relevant range of system configurations (table 10).

* Note that figure 23 is illustrated with a three-phase generator (diesel), but the picture would be the same principally for a PV system with inverters.

Table 10: Approximate size order range assumed for relevant PV configurations [7, 12]

Resource assumptions	*Smallest PV mini-grids*	*Largest PV mini-grids*
-High irradiation (kWh/m^2/year)*	2400	2400
-Low irradiation (kWh/m^2/year)**	1700	1700
Demand assumptions		
- Peak load (kW)	10	500
- Average load (kW)	3-5	200-300
Technical assumptions		
- Installed module capacity (kW_p)	30-50	1000-1500
- Life span modules (years)	25	25
- Life span batteries at DOD 20% (years)	25	25
- Capacity factor (%)	20-30	20-30
- Battery autonomy (days)	3-7	3-7

* Based on overall insolation data for Tanzania.

**Somewhat higher than the absolute minimum of several zones. However, minimum estimates are based on measurements from the most inappropriate sites; hence the further assessment will ignore these. [24]

6.2 PV system implementation for mini-grids in Tanzania

Today, PV systems are designed using software simulations. [20] Several applications are available for determining size and configuration of PV systems under given conditions and loads. Software can recommend voltage levels, detailed module and battery bank configuration and suggest specific components from a wide selection. Nevertheless, a range of qualitative and quantitative assumptions must be made to establish simulation criteria. [16]

6.2.1 Door to door load estimation

In order to estimate expected load represented by the mini-grid customers, a thorough mapping of electricity consumption by households and other facilities must be conducted. This may be a comprehensive and time-consuming task requiring translation for international developers, which calls for good planning. Non-electrified communities may not have a precise idea of what their actual consumption might be, and it is likely that the developer must set concrete limitations with respect to installed capacity and considering consumer affordability. [30]

6.2.2 Distribution losses

Although distribution is not assessed in particular here, it is important to keep in mind that depending on the size of the village and type of distribution (voltage level and single/three phase) distribution losses may represent a significant share of power supplied to the grid. Hence, this must be assessed to detail, and appropriate oversizing must be implemented accordingly. [22, 31]

6.2.3 Insolation

The uncertainty of insolation and its effect on production yield is further discussed in section 7.3, demonstrating the importance of successful data collection and software simulations to appropriate module capacity sizing.

6.2.4 Sizing the battery pack and inverter capacity

In PV projects where security of supply is not of great importance (e.g. for a PV system connected to a centralized grid), the primary optimization issue is to maximize total yearly power generation. However, for a PV system on an isolated grid, security of supply is usually a primary concern. The level of safety of supply depends on the accepted probability of battery discharge, i.e. for the radiation to be sufficiently low over a certain period of time to cause complete discharge of the battery pack (figure 24). [22] This probability will be very site specific, and in general an issue in the rainy season. The probability is calculated based on daily radiation data for the mini-grid site, and the uncertainty of probability calculations depend on the amount of statistical radiation data and climate forecasts available for a given site. The accepted level of discharge probability by the mini-grid developer (agreed with customers) will yield the required autonomy capacity of the battery pack. The accepted discharge probability will primarily depend on the required level of supply security of the mini-grid customers and accepted battery costs of developers. [16]

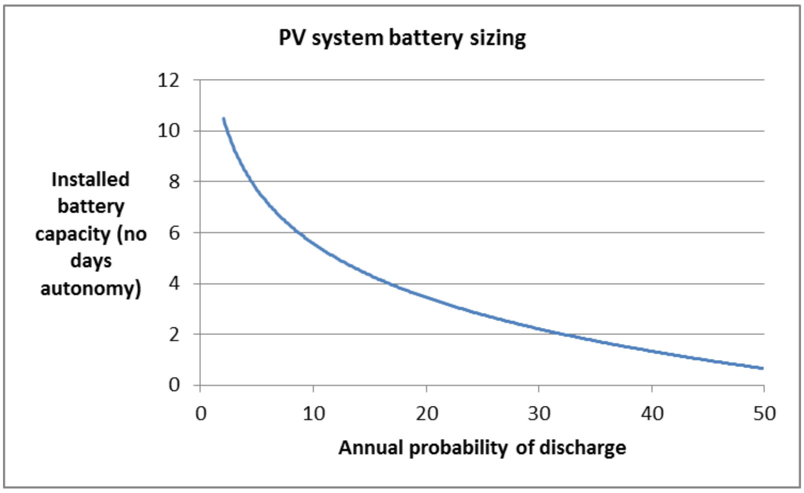

Figure 24: Required battery capacity for achieving a certain probability of battery discharge to accepted DOD levels (example) [31]

When estimating required battery capacity for a mini-grid, the following inputs are required [16] [18]:

- Required days of autonomy (DOA)
- Maximum daily consumption (MDC, kWh)) during autonomy* (including system losses and battery self-discharge)
- Minimum daily insolation during autonomy (MDI, kWh) (e.g. only diffuse irradiation)
- Individual voltage (V) and capacity (Ah) of each battery
- Inverter output voltage
- Battery DOD
- η_{batt}

Having carefully assessed the above listed variables, the required battery capacity can be estimated to a good approximation (some more level of detail will be required for specific projects). Total battery capacity in terms of energy (kWh) is calculated as:

$$\text{Total battery capacity (kWh)} = \frac{\text{DOA x (MDC – MDI)}}{\eta\text{batt}} \qquad (9)$$

Then, since batteries are rated individually in Ah, the total Ah-rating may be calculated by dividing with the planned voltage of the battery bank (formula 10). If the inverter output is set to be for example 400 V, the battery bank voltage may typically be 48 V. The battery bank voltage depends on system size, PV array voltages and inverter output voltages. These calculations assume that the rated battery capacity from the manufacturer is corrected for DOD. This means that if the battery has an accepted DOD of 50 % and a total capacity of 2000 Ah, the rated capacity is 1000 Ah. If the manufacturer rating is not corrected for DOD, equation 9 must be divided by the DOD factor (i.e. here a factor of 0.5). [18]

* Note that autonomy does not mean solely running on batteries, due to diffuse irradiation. The matter of calculating battery capacity is best performed using software. However, this section provides a basic outline of the problem.

$$\text{Total battery capacity (kAh)} = \frac{\text{Total battery capacity (kWh)}}{\text{Battery bank voltage (V)}} \quad (10)$$

The voltage of the battery pack depends on the distribution voltage on the grid (other side of inverter). The configuration of the battery pack can be done by numerous configurations. The general approach is that batteries are coupled in series to obtain the necessary voltage. Then, the series are connected in parallel to increase the capacity. If the overall voltage of the battery pack is to be 48 V (voltage entering the inverter), then e.g. a number of eight 6 V batteries can be coupled in series to obtain 48 V. However, if the capacity rating of each battery is 1000 Ah at 6 V, the capacity of the series coupling is still 1000 Ah, but now at 48 V. In order to increase capacity, the series are coupled in parallel. If two of the eight-battery series mentioned above were connected in parallel, their total capacity would be 2000 Ah at 48 V (figure 25). In general, there are limitations to how many battery series that can be coupled in parallel between the same inverter/PV module set. An extensive amount of series coupled in parallel to the same inverter will increase the risk of uneven charging / discharging of different series, which may reduce life-time of those batteries being more stressed (especially with respect to DOD levels). Consequently, usually not more than two or three battery series are interconnected in parallel feeding the same inverter. [32]

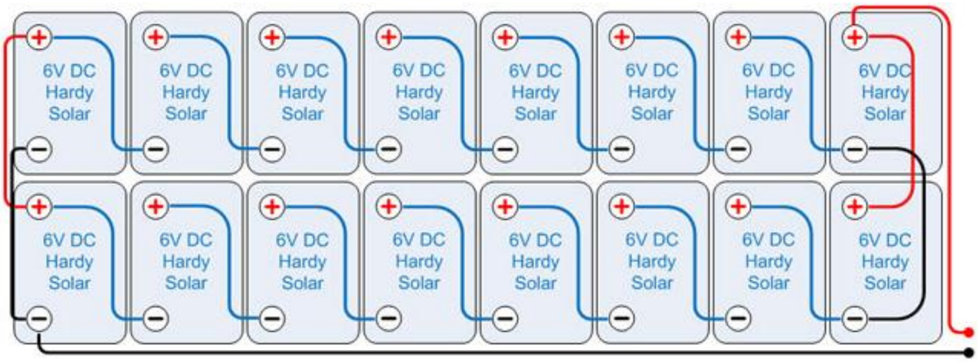

Figure 25: Eight battery series coupled in parallel between a PV module set and an inverter. [23]

The choice of battery in terms of individual voltage and capacity (in Ah) depends on technical factors and will be project-specific. However, since several different battery types in a variety of sizes may serve the same purpose, battery price will be important. [16] Like the PV array, the sizing flexibility of the battery bank is very modular. This gives the developer an opportunity to select from a wide range of battery types. It also means that any autonomy level required is theoretically possible, from very low to very high safety of supply. Hence, costs (and perhaps spacing) are the primary limitations. [18] The matter of supply security is assessed further in section 7.1.5. As for inverters, the same modularity and variety of ratings apply. Also here, price will be a determining factor. [31] Besides the PV array, the battery room and the inverter room (may also have both in one room) represent the most area-demanding components of the PV power plant (figure 26 and 27).


Figure 26: Battery bank of Atafu mini-grid. [15]

Three phase distribution and inverter configurations

As mentioned, the DC from each battery parallel coupling flows to an inverter, in which it is converted to AC and the required output voltage. For three phase distribution, the current from the batteries is directed to one three phase inverter (converting DC current to three phase AC). In addition, one can choose to apply three single phase inverters and balance them to yield three phase output power. Which one of these solutions the developer prefers, will mainly be a matter of system compatibility and inverter cost. [18]


Figure 27: The inverter room of the Atafu plant. [15]

6.2.5 Sizing the PV array

Once the available irradiation, mini-grid load data and required battery size has been estimated, the PV array may be sized accordingly (figure 28). The module generating capacity required depends on the respective estimates. As discussed in the previous section, the number of inverters required will be determined by the distribution configuration (phases), and the DC current from the PV modules will be directed to the same inverters, normally via the battery bank (figure 6, section 3.1). [31] The following (equation 11) may provide a rough estimate of the minimal daily generating capacity of the PV generator.

$$\text{Minimum daily generating capacity (kWh)} = \text{MDC}^* + \frac{\text{Full battery bank capacity}}{d} \quad (11)$$

In equation 11, d is the accepted number of days for full battery recharge. Thus, d is another important measure of supply security. If batteries have been fully discharged (down to allowed DOD), what is the probability that the following period will yield 1, 2, 3 or more days of sun? Assessment of this probability is important. If the probability of several upcoming days of sun is high, the PV module capacity may not need to be able to fully recharge the batteries in one day. Actually it may be designed only to recharge a little more than nighttime consumption each day, in order to reach full a state of full capacity. [32] These considerations will depend on the required level of supply security discussed in the previous section, and site-specific weather data. Software simulations are crucial in order to optimize sizing of the PV array. [31] When minimum daily generation acquired from the PV array is estimated, the rated total capacity of the PV array can be approximated (equation 12). [31] The estimation of the capacity factor CF was assessed in section 3.1.3 and module configuration was reviewed in section 3.1.1.

$$\text{Rated capacity (kW}_p) = \frac{\text{Minimum required daily generation (kWh)}}{24 \text{ x CF}} \quad (12)$$

Figure 28: PV array of Atafu mini-grid. [15]

When PV systems are designed properly they have normally adapted a certain level of module oversizing relative to the average daily power consumption, in order to maintain a certain level of supply security. This causes some energy to be spilled during normal operation, e.g. by the BoS instruments disconnecting some module connections. This is more likely to occur in the afternoon when the batteries are fully recharged from their nighttime discharge and the modules are producing more energy than what is demanded on the mini-grid. [22] This is the case on the Tokelau mini-grid; in which energy is typically spilled from 14:00 hours to about 19:00 hours (figure 29). [15]

*MDC includes all system losses.

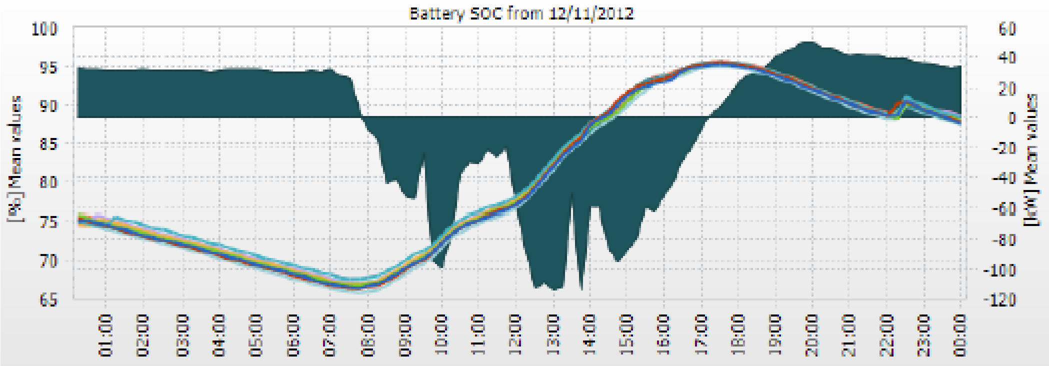

Figure 29: Battery charging level (DOD is 50 %) of the Tokelau mini-grid. The line indicates battery charge level and the area shows the integral consumption on the mini-grid. Energy is spilled from 14:00 hours [15]

6.2.6 Fixed panel orientation and tilt

The power output of the PV modules depends on the solar insolation incident on the panels. Maximal irradiance is achieved when the solar beams are normal to the solar panel surface. By mounting the PV array on a flexible tracker system, one can optimize panel orientation by continuously adjusting position to maximize solar insolation on the panels. [22] Utilizing a tracking system will significantly increase both capital and operating costs however, and tracking systems is not further assessed in this study, due to the low economic margin of off-grid rural electrification projects. [22]

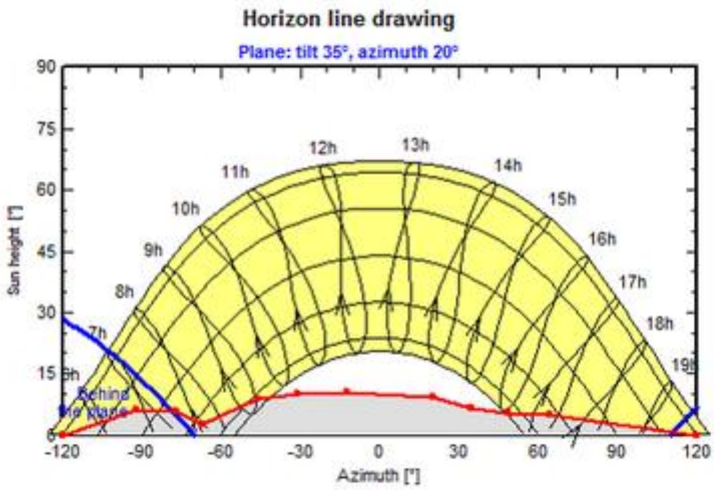

Figure 30: Hourly sun position on horizon throughout the year.[*] Red and blue lines indicate shading (example).

Fixed panel orientation is the most common array configuration for smaller PV systems, due to low cost and need for maintenance. [22] Choosing a panel orientation which maximizes incident sunlight is crucial in order to maximize system capacity factor. Optimal orientation depends on site location. [22] In general, a rule of thumb for fixed panel orientation is to face it towards the equator (facing north for locations south of the equator and vice versa), and the tilt angle is often set equal to the latitude of the site, at least to a good approximation [18]. In Tanzania, latitudes vary from roughly 0 degrees in the north (just at the equator) to about 12 degrees south in the very south (table 11) [24], thus causing optimal tilt to be close to horizontal for all locations.

* Note that in Tanzania the sun height will be closer to 90° at 12h the whole year for all zones.

When setting the tilt equal to the latitude, the solar beams will be approximately normal to the panel surface in the middle of the day all year long in locations relatively close to the equator, which is the case for Tanzania. [31] Optimal panel tilt is best determined by plotting coordinates into software, which recommend tilt and orientation based on the suns position on the horizon (figure 30).

Table 11: Latitude span of measurement points within the 9 zones of Tanzania [24]

Zone	Zone name	Latitude span (degrees south)
A	Lake Victoria Basin zone	1-4
B	Northern zone	1-4
C	Western zone	5-9
D	Central zone	6-7
E	North Eastern Highlands zone	1-5
F	Eastern zone	6-9
G	North Coastal and Highland zone	4-7
H	Southern Highland zone	7-10
I	Southern zone	10-11

6.3 PV system construction and operation

6.3.1 PV plant layout

The basic components of off-grid PV power plants will be (regardless of plant size):

- PV array on steel/wooden mounting structures
- Protected cables from arrays to power control house
- Power control house containing:
  - Battery room
  - Inverter room
  - Control room with charge controllers, other BOS instruments, distribution boxes, system monitoring server and access computer

Optimal layout configuration will be site-specific, but some typical considerations proven important for PV systems in Tanzania. Arrays should be mounted on steel or wooden structures (wood might be cheaper due to high accessibility in many rural Tanzanian areas). [30] Mounting should lift the modules about 1.5 to 2 meters above ground level. This has proven to significantly reduce collection of dust and provide some cooling effect on modules. [31] However, simplicity of routine maintenance should be considered when choosing array height. Cables from array to control house should be protected by i.e. solid plastic pipes and perhaps routinely sprayed with anti-rodent substances. Experience have shown that rodents (e.g. rats) frequently cause damage on cables if allowed, causing significant problems to system operators if not prevented. [33]

6.3.2 Shading and dust

As mentioned in chapter 3, shading effects may have detrimental effect on module performance. Hence, it is crucial for system design and operation to minimize eventual factors causing module shading. In Tanzania, due to the proximity to the equator, shading from one array on another is not likely to be an issue due to the horizontal (or very small tilt angle) positioning of modules. [18]However, shading from tall trees around the arrays might occur, especially when the sun is low. Removal of trees might be necessary. In addition leaves, bird droppings or other airborne objects finding its way to the modules are likely to remain due to the horizontal positioning. [31] Dust can collect relatively fast on PV modules in most areas of rural Tanzania, due to sandy ground surface and winds. Routine module cleaning is necessary to avoid reduced module power output. [31, 33]

6.3.3 Plant perimeter security

Theft of modules is not reported as widely recognized issue in rural Tanzania. [47] This is mainly due to strong local support and engagement in electrification and its benefits. However, it has been a problem in other countries, and plant perimeter security should be considered and discussed with village administration. [47] As a minimum, fencing will usually always be required in order to keep away animals and in some cases children. [33]

6.3.4 Communication

Establishment of communication from PV system to a centralized server that can be accessed by the developer has proven crucial to sustainable operation of rural PV systems. Such systems are readily available from system suppliers, and the exceptional mobile network quality throughout Tanzania has already proven to be sufficient for successful communication to systems even in very remote areas. [33] Mobile communication between system developer and the local operator is also important. Due to the relatively low level of English skills found in most rural areas, native tongue capacity with the system maintenance contractor is an advantage, especially in order to remotely assist in solving system operation issues. [31]

6.3.5 Payment collection

With respect to the above discussion, the mentioned communication lines are also crucial for system developers to monitor payment collection. In existing rural PV systems in Tanzania, prepaid power meters in all connected houses and facilities (figure 31) communicating with system server has proven as very successful in terms of confirming payments and as a helpful tool to improve load forecasts. [33] Meters are programmed with adjustable maximum power limits, further enhancing system operation predictability and stability. When properly communicated with customers, this may also help customers plan consumption and understand the nature of their service. [33] Such systems also provide a good basis for more intelligent load management on the mini-grid. [34] The matter of load management is discussed further in section 7.2.

Figure 31: Power meter in private household in the village of Matipwili, rural Tanzania.

7 LCOE estimation of PV systems in rural Tanzania

For cost comparison across power generating technologies LCOE estimates are frequently used by project developers, governments and policy makers. LCOE calculation is less complicated for adjustable generation technology such as conventional thermal generation (here fueled by diesel or biomass), hybrids with thermal capacity and hydropower (assuming sufficient water availability throughout the year). Under some basic assumptions of resource availability (diesel fuel, biomass yield or water), a certain level of supply security can be established. For pure PV systems with limited storage possibility, power output is usually less predictable. [16] Consequently, before comparing PV systems to the above mentioned options, it is necessary to assess the sensitivity of PV LCOE to the range of technical considerations outlined in the previous chapter. In the following sections the cost components of PV systems on mini-grids and their influence on LCOE will be reviewed.

7.1 LCOE sensitivity to system size and configuration

7.1.1 Linearity of main component costs

For village loads assessed in this study, the technical components and thus the capital cost components of PV systems for mini-grid power generation are relatively equal across the range of system sizes. Configuration details like battery bank sizing, single or three phase distribution and site conditions will introduce a non-equal distribution of capital cost components within the projects, but the overall components involved are the same. In addition, the modularity of solar PV systems (including batteries), makes unit capital costs quite linear when system size increases. [16] Recent experience from off-grid PV projects in rural Africa indicate that the decrease of module prices over the past years have introduced batteries as the most important component capital costs (figure 31), typically constituting more than 25 % of total capital expenditure (table 12). [13]

Table 12: Capital and initial cost distribution in off-grid PV systems [13]

Modules	10-15 %
On ground supports, wind proof	5 %
Inverters & battery chargers	10-15 %
batteries (5 days autonomy)	25-40 %
Other BoS, distribution boxes, cables	2-5 %
transport to site, inside Africa	10-20 %
Civil works & foundations, fence (incl. control room)	10-20 %
Project management, installation and testing	10-15 %

For a given level of autonomy and external conditions, the costs of main components of solar PV systems (modules, inverters, batteries, Other BOS, distribution boxes and cables) have proven to be relatively linear for projects of different generating capacities. However, a certain decrease of unit costs (per kW_p) may be expected with increasing project size. This is mainly because most suppliers of PV systems introduce a certain level of volume discounts for large projects. [16]

Hence, one can expect a lower unit capital cost for PV systems on large mini-grids than on the smallest ones. However, due to the relatively narrow range of capacities assessed here, a linear unit cost for equipment will be assumed for simplicity in LCOE estimates. A conservative approach is thus taken by estimating LCOEs based on cost data from small-scale mini-grid projects (30 kW_p). [13]

7.1.2 Single phase vs. three phase compatibility

Implementing three phase distribution compatibility in the PV system does indeed change the configuration of the system (or parts of the system), but as outlined in chapter 6, the overall number of inverters does not necessarily change. If three balanced single phase inverters are applied, the overall number of inverters will be approximately equal for a given capacity of single or three phase power output. [31] However, balancing of the three phase inverter configuration, will to some extent increase costs of power conditioning and control equipment. The overall number of inverters is reduced if specialized three-phase inverters are utilized, but the cost of such inverters is significantly higher than single phase inverters. *Hence, it is considered reasonable to assume no significant difference in unit capital costs for single and three phase distribution compatibility from PV systems.* [31] It should be mentioned that the extent of three phase distribution network within the mini-grid as a whole may have a stronger influence on capital costs, but distribution costs are not assessed in detail here, and will be relatively similar for a given project regardless of generating technology applied. [11]

7.1.3 LCOE sensitivity to component prices

The large share of initial costs accounted for by modules, batteries and inverters in off-grid PV systems makes projects sensitivity to changes in market price. As inverters, charge controllers and other BoS components are relatively cheap and established technology, the main price sensitivity is expected to lie with modules and, in particular, batteries. Due to the strong decrease in module prices over the past years, industry actors express uncertainty regarding further development of module prices. [16] However, it is stated by PV developers that neither a dramatic decrease nor increase is expected in a 5 to 10 year perspective, due to a combination of historically low module prices and increased focus on both off-grid and on-grid PV energy worldwide. [35] However a 5 % to 10 % change in either direction is considered likely [35] and a conservative approach of ±10 % is taken into consideration for LCOE estimates here. Battery prices for PV systems are expected to experience significant price decrease in a 5 to 10 year perspective. [16] The main drivers are PV system battery subsidies implemented in Germany and widespread efforts within battery research, as this is recognized as the primary cost issue in any off-grid PV system. [36] Some developers claim that a battery cost reduction of up to 50 % during the next 5 years may be witnessed. [16] However, some are more conservative, expecting a decrease of 10-20 % in a 5 year perspective [35], thus the more conservative approach of a 15 % battery price reduction will be taken for LCOE sensitivity testing here.

7.1.4 LCOE sensitivity to battery capacity and required supply security level

Due to the modularity of batteries and the linear relationship between days of autonomy and battery amount, costs related to increased storage capacity are assumed to be linear. The increase of module capacity and number of inverters in the system is proportional to increased battery bank size. Consequently, LCOE estimates can be derived for various levels of autonomy (i.e. security of supply) by a linear approach. [31] Experienced solar PV off-grid system developers recommend battery bank sizing to allow for an average DOD of 20 %, which allows modern PV system batteries to sustain the full life-time (25 years) of projects if operated carefully. Operating at larger DODs will reduce battery life-time. Even though this can reduce initial costs (less batteries), it introduces the issue of periodical replacement costs. Consequently, LCOE estimates here will assume battery bank capacity oversizing in order to maintain an average DOD of 20 %. [13]. Less costly batteries may also be applied with routine replacement plans, but this option is not assessed here. [13]

7.1.5 LCOE sensitivity to security of supply level

For most sites, autonomy levels of 10 days would practically mean 100 % safety of supply, even during the rainy season. [31] However this would be very costly and 5 days of autonomy is considered reasonably secure for most sites. [12] In the sunniest locations, 3 days autonomy may even yield close to full-time safety of supply. Even lower autonomy levels may be chosen, depending on the required safety of supply required by customers and their willingness to pay for improved service (table 13). [31] The nature of weather variations and probability of low insolation over time causes battery sizing with respect to supply security to be non-linear. Consequently, increasing supply security e.g. from 95 % to 99 % may e.g. double the capital costs related to batteries (figure 24, section 6.2.4). Hence, determining the level of supply security actually required by the rural customers and to what extent they can pay for it is crucial. In rural Tanzania, customers may not require full supply security (or be able to pay for such) and especially during the rainy season one might get acceptance for reduced power supply during this period. Clear communication and cooperation with village population may result in agreement according to what supply security is acceptable at a certain cost. [33] Assessing this matter to detail may significantly reduce overall LCOE for solar PV systems. [16] For certain facilities (e.g. dispensaries), a higher level of supply security may be required than for less crucial loads as for instance private consumption. Load management as a tool to manage supply security across facilities in order to reduce overall LCOE is assessed further in section 7.2.

Table 13: Levels of supply security (as percentage of total time where full power supply is provided) at various levels of battery autonomy in Tanzania. Autonomy provided will be site specific [37]

	Autonomy*	Security of supply
Low	0-3 days	50-80 %
Medium	3-5 days	80-90 %
High	5-7 days	> 90 %

* Note that autonomy levels incorporate oversizing to sustain low DOD levels. Hence, autonomy of 5 days and DOD of 20 %, will only discharge to 80 % of total capacity during normal operation (discharge at night only), but may sustain 5 days of low irradiation *once in a while* when necessary, thus close to complete discharge of batteries. However, frequent full discharge will reduce battery life-time. [16]

7.1.6 Transportation costs, installation costs and remoteness sensitivity

Transportation costs in rural African locations account for a significant share of costs (figure 31). In Tanzania, solar PV systems are most likely to be shipped from Germany or China. Mini-grid candidates may be one, two or three days of trucking away from the closest harbor. [16] Transport costs being fairly proportional to distance, a three day drive would cost approximately three times as much as one, indicating a remoteness sensitivity in such projects. [31] Regarding project size (amount of equipment being transported), increasing size is likely to yield some advantages due to most Tanzanian transport companies providing some unit discount for large contracts. [31] In the further assessment of LCOEs a conservative approach is taken, assuming two day transportation for the base-case. With respect to project size, transport costs are assumed to be linear, although having mentioned unit costs might decrease for larger projects. Transport costs of PV systems to remote areas represent a significant share of initial costs, introducing an incentive for project planners to optimize packing and handling of components in order to minimize the amount of truck loads required. [16]

Installation costs will be assumed linear here, although experience has shown unit installation costs have a tendency to decrease for larger projects. This is mainly due to the large share of fixed costs related to having an installation team brought to a rural destination. [16, 33]

7.1.7 LCOE sensitivity to operating costs

Annual operating costs of a small (30 kW_p) off-grid PV system in rural Africa will in general represent less than 1 % of capital costs. [13] This is mainly due to the low income level in rural areas, making the costs of a local system operator relatively insignificant. Experience has shown that training in basic system monitoring and maintenance may be provided by the installation team during system construction [16]. If designed implemented successfully, off-grid PV systems with battery storage are extremely durable and require a minimum of maintenance [16].

Table 14: Example of representative *fixed* annual operating costs of a 30 kW_p solar off-grid system in rural Tanzania [13]

Village operator (entrepreneur):	300	USD/year
Night guard:	400	USD/year
After sale service:	300	USD/year
Insurance (0.11% of system cost):	178	USD/year
Total fixed annual O&M costs:	1 178	USD/year

The operating costs outlined in table 14 are based on assumptions of no equipment failure or extraordinary system maintenance. In practice, some errors are likely to occur. However, due to the modularity of the system, failure of a cell (or a module), an inverter or a battery does not necessarily call for comprehensive repair, but a single replacement of the component(s) in question. Some repair will not necessarily be within the know-how of the village operator, and some extra costs will be inflicted by transporting an expert to site. Hence, operating costs are sensitive to the quality of the plant design and operation, and operating costs may increase in a detrimental matter if expert entrepreneurs and spare parts are frequently needed on site. According to experienced solar PV entrepreneurs in Tanzania, developers should account for some variable operating costs to occur during a 25 year economic life-time. [30]

7.2 Reducing required storage capacity by load management

As mentioned previously, load management can be implemented to reduce power consumption in periods of low irradiance (especially during rainy seasons), in order to reduce the necessary storage capacity. A well-tested method for such controlled load shedding is dividing the mini-grid connections into essential and non-essential loads. For existing mini-grids in rural Tanzania, essential loads typically account for less than 20 % of the total village load. [37] This introduces a potential for reducing required battery capacity significantly by disconnecting non-essential load in periods of low insolation. [37]

Typical essential loads (10-20 % of total village load) [33, 37]:

- Dispensary / hospital ward
- Village administration
- Police station
- Water pumping facilities

Typical non-essential loads (80-90 % of total village load) [33, 37]:

- Private household consumption
- Shops
- Village street lightning
- Other productive uses

Most sites in Tanzania are unlikely to utilize more than 5 day autonomy more than twice per year (during the rainy season in November or March/April) for a full load. [31] This may provide a certain level of predictability for operators and customers. A partly reduction to essential loads only in these periods can thus reduce the necessary overall storage capacity of the PV system significantly, implying relatively predictable and limited extent of load shedding on grid customers. [31]

To what extent load management needs to be implemented and which loads are considered essential will be site specific. However, rural Tanzanian villagers in general have a high level of acceptance for load management. [27, 30, 33] Going from having no electricity access to having electricity access with periodical limitations is still considered a great improvement. A key to achieving customer acceptance is providing good communication and information regarding the nature of load management and the implications on customers. [30]

7.3 Uncertainty in photovoltaic production yield and income

7.3.1 Average annual insolation

The most important site-specific external factor to production yield is the solar insolation one may expect to receive. When assessing a PV mini-grid candidate, the LCOE estimate will be affected by insolation data, as expected production is proportional by the installed capacity and the applied capacity factor. For a given site in Tanzania, banks granting loans to off-grid PV projects apply an uncertainty of ±5 % of average annual insolation to expected production yield. This uncertainty level of solar insolation forecast have been confirmed by other studies on the field, addressing between 5 % and 10 % uncertainty (relative to expected yield) for solar insolation and climate variations all together. [38] In Tanzania, the maximum deviation from average annual insolation is found to be within ±5 % for all points of measurements [24]. However, the uncertainty of average annual insolation is site specific and in this assessment the more conservative approach of ±10 % uncertainty is taken into account. This allows for other factors affecting actual yield from solar insolation such as shading and dust. [38] Hence LCOE sensitivity will be tested for a ±10 % increase or decrease of average annual insolation here. It seems fair to mention that this may be considered as very conservative by some PV developers. [16]

7.3.2 Other uncertainty elements affecting overall capacity factor

The capacity factor of the solar PV system is not only sensitive to solar insolation (previous section), but also other external factors such as dirt accumulation on modules and shadowing. [38] Depending on location and positioning of the PV array, such factors may have significant impact on power output. A common literature assumption of capacity factor for PV systems in Africa is 20 %. However, experienced system developers claim that a range of 20 % to 30 % may be expected for well-designed systems utilizing high-efficiency (13-14 %) modules. [16] [31] In the further assessment here, a capacity factor interval between 20 % and 30 % will be assumed, with a base-case capacity factor of 25 %. Some increase in capacity factor may be expected for larger systems due to overall higher voltage levels [31], but studies of rural off-grid PV systems in Africa indicate capacity factors of roughly 25 % to be a realistic assumption even for low voltage installations. [13] Unfortunately for system developers, capacity factors cannot be assumed constant over the project life-time. [38] Efficiency decrease is reviewed in the following section.

7.3.3 Annual loss factor

The overall efficiency of PV systems decline as a function of time, mainly due to decrease in module efficiency. [38] In project planning, the most common approach is to assume a linear decrease by an annual factor, referred to as annual loss factor. The annual loss factor of off-grid PV systems today is expected to be somewhere within the range of 0.3 % and 0.8 %, [38] In Germany however, banks currently operate with annual loss factors of 0.2 or 0.3 %, In LCOE assessments here, a conservative approach is assumed, with loss factors ranging from 0.2 % to 0.8 %. A loss factor of 0.5 % is a common assumption for off-grid PV systems in rural Africa [13] and will therefore be taken as a base-case assumption here.

7.4 Base-case scenario for solar PV LCOE and annual NPV calculations

Based on the section 7.1 through 7.3 discussions, base-case assumptions for LCOE estimations may be suggested (table 15). Cost data are based on recent studies of PV system costs in rural African countries. [12] LCOE calculations are attached in appendix C.

Table 15: Solar PV base-case assumptions [12]

LCOE input variable	*PV system base-case*
System life span (years)	25
Installed capacity (kVA, kW_p)	30
Capacity factor (%)	0.25
Battery autonomy (days)	5
Annual loss factor (%)	0.5
Capital costs (US$/kW)	7230
Annual O&M costs (% of capital costs)	0.5
Discount rate (%)	10
Annual insolation (kWh/m^2year)	2050

Furthermore, with respect to the above discussions, sensitivity ranges of the assessed variables can be established (table 16). LCOE sensitivity calculations are conducted by manually changing input variable of the LCOE calculation procedure spreadsheets attached in appendix C.

Table 16: Sensitivity range of solar PV base-case assumptions

LCOE input variable	*Sensitivity range*
Capacity factor (%)	0.2 - 0.3
Battery autonomy (days)	3 - 7
Annual loss factor (%)	0.2 - 0.8
Discount rate (%)	10 - 30
Annual insolation (kWh/m2year)	+- 10 %
Battery costs (US$/kW)	+- 15 %
Module costs (US$/kW)	+- 10 %
Annual O&M costs (% of capital costs)	0.5 - 2

7.5 Comparing LCOE across technologies

A number of inputs are required to obtain total costs and expected production, and a wide range of assumptions must be made about the technical and economic scenario facing the power plant in question. For various technologies, project costs will in general not be proportional to the generating capacity of the power plant, but may vary in a less systematic manner. Other factors such as project location, existing infrastructure and availability of fuel or the renewable resource will influence total costs. Hence, it is crucial to maintain consistency in the assumptions made across technologies. If assumptions are conducted in a consistent manner across different concepts and external factors are treated equally, LCOE estimates may provide a solid base for cost comparison. [11] Sections 7.5.1 and 7.5.2 outline the overall considerations and scope of LCOE estimation across technologies.

7.5.1 Cost estimation

Total costs include capital costs, installation costs, distribution costs and costs of operation and maintenance (including fuel costs for diesel, diesel-PV hybrids and biomass generators). High and low cost estimates are applied, yielding LCOE intervals. The respective estimated are based on high and low utilization of the primary cost drivers of each technology. To which extent the cost drivers affect LCOE is site specific, and the cost intervals may provide a more flexible LCOE comparison across the assessed technologies.

Distribution network costs depend on connection number, customer density, rated output of plant and voltage levels. [11] Costs related to distribution network within the mini-grid are therefore not included in the LCOE calculation. For hydropower however, the power plant will normally be at some distance and transmission costs for power from PP to village are therefore included as a LCOE variable for this option. In general, distribution costs are not assumed to have very significant effect on overall LCOE estimates. [12] Costs of feasibility studies, market assessments and other planning exercises are not specifically included in the LCOE. The nature of these respective costs for each alternative and how they might affect total cost are assessed in the following paragraph.

7.5.2 Feasibility studies, early-stage planning and market assessments

The amount of time and resources required for feasibility studies in order to successfully plan and configure a mini-grid depends on availability of existing and available data regarding the renewable resource, consumer affordability and willingness to pay for electricity, expected household consumption, potential productive uses and other site-specific measurements. [30] In general, RETs will demand more feasibility studies than diesel generation due to the dependence on availability of more unpredictable resources. Hydropower is likely to be the RET demanding the biggest pre-project efforts, in the incidents where long-term water flow data is not available. A solar resource can somewhat less comprehensively be assessed based on historical weather data and forecasts covering larger geographical territories. For biomass resources, assessments of biomass yields form agricultural or other activity needs to be conducted, which can be an extensive exercise representing a significant level uncertainty. [30] For market assessments there is no difference across technologies, but the extent of work required for making a detailed consumption forecast and affordability assessment will strongly depend on the size and nature of the village in question. [30] Due to the high level of site dependence, costs related to these matters are not included in LCOEs estimated in this study.

7.6 Financial risk in mini-grid projects

The financial barriers to RETs on mini-grids are assessed from a traditional financial theory perspective with a primary focus on identifying the range of risk drivers related to such projects. The analysis is based on technical and economic data accessible for technology options covered. Both qualitative risk factors (technical, resource-related, political, social) and quantitative (cost profile, technology-specific risk premiums) have been assessed. [25]

7.6.1 Uncertainty of income

The primary risk driver in any rural electrification project is uncertainty of income due to low affordability of consumers. For off-grid projects such risk is highly relevant. As opposed to grid connected power plants, where income is ensured by feeding excess production to the centralized grid through SPPAs, the entire return of investors is now resting on the affordability of rural consumers. The economy of rural consumers may be insecure and depend on a range of external factors. As most villages have an economy based on agriculture, practically all villagers' income will be directly or indirectly affected by crops. For coastal or lake-near areas, economy will also depend on the not fully predictable success of fishing. For villagers in business with urban or sub-urban customers for their goods or services, income will to a great extent depend on demand on these markets. Such demand is also unpredictable, depending on international trade markets, political factors and urban affordability in general. [30]

Even though uncertainty of income usually introduces a certain level of risk in off-grid rural electrification projects, it is strictly independent of generating technology. Uncertainty of income is proven to be a barrier to RE in general, but it is not technology-specific. The affordability of villagers and the related uncertainty will vary between off-grid candidates and will not be assessed in detail here. However, the nature of this risk has now been mentioned as a fundamental barrier to any mini-grid project to introduce the further discussion. The following sections will assess the cost - and technology-specific risks related to RETs and conventional power generation on mini-grids. [30]

7.6.2 External technology-specific risk

As outlined in the previous section there are several financial risk elements that are technology-specific. Such site-specific risk drivers may be accounted for and handled through the planning process of each individual mini-grid project. Nevertheless, external risk elements also arise in the long run that might affect both single projects, but also the development of a certain energy technology as a whole. Such external drivers can be technical, resource – or climate-related or political. It is primarily a matter of how external factors, international or domestic, affects the future supply and price of various technologies. Future operational, maintenance and rehabilitation costs of installing a certain technology on mini-grids today are to some extent sensitive to the above mentioned elements. For example, governmental policies might strongly affect technology demand and prices for a given technology. When introduced, external factors may affect risk premiums of technologies significantly. [39]

In chapter 6, the technical maturity of PV systems was investigated with respect to safety of supply, to identify some necessary considerations for successful design and operation. If installed and operated in a manner that provides a required level of supply security, one can argue that any technology-specific risk is eliminated across alternative concepts. Translated to financial risk, the probability of lacking income due to failure of power supply is practically equal (and preferably very low) between technologies when implemented under the necessary conditions. However, as described above, there will be external risk elements affecting the discount rates of technologies. These externalities are beyond the control of mini-grid project planners and developers and may be very difficult to predict in the long run. As many qualitative factors are in play, quantifying technology-specific risk premiums may also be a difficult exercise. However, recent studies have estimated current and long-run discount rates of RETs and conventional power generation technologies (table 17).

Table 17: Technology-specific discount rate estimates for various technology options [39]

	2010 Estimates		2020 Estimates		2040 Estimates	
	Low	High	Low	High	Low	High
Diesel	6	9	6	9	5	8
Solar PV	6	9	6	9	5	8
Hydro	6	9	6	9	5	8
Biomass	9	13	8	11	6	8

The discount rate estimates (table 17) are based on a number of assumptions about the future development of technology costs, energy prices and governmental policies. Consequently such risk premiums are subject to some degree of uncertainty. The estimates are also intended to represent international standards, which raises the question of to what extent they can describe the situation in Tanzania. Regardless of the estimates precision in a given country, the study suggest that between most of the technologies covered here, no significant differences in discount rates due to external factors are evident. [39] Hence, the component of discount rates with respect to *external* technology-specific factors will be assumed equal across technologies. Therefore, due to the other internal technology-specific assumptions established (such as system size or CF), LCOE comparison will be carried out at equal discount rates.

7.6.3 Irreversibility of capital investments

Before assessing risk related to cost profiles of technology options, it should be mentioned that the risk related to capital investments depends not only on income uncertainty and technical issues, but also on the irreversibility of the capital investment. The irreversibility describes to which extent the capital investment can be regained. For a fully irreversible investment, the CAPEX is entirely viewed as sunk cost, introducing the full potential of the investment risk. A reversible investment leaves developers with the opportunity to resell or utilize the capital investment in another project without significant extra costs. Irreversibility of mini-grid investments will depend on several factors, some which are technology-specific and some which are not. The primary factors determining irreversibility of mini-grid CAPEX are listed here [40, 41]:

- Compatibility of power generation technology and distribution system
- Project size and individual component sizes
- Remoteness of project, i.e. distance to eventual other sites for potential capital utilization and local infrastructure
- Social and political project irreversibility

The following section will assess the general irreversibility of the mini-grid concepts considered for coat comparison, with respect to point 1 to point 3 in the above list. Social and political irreversibility will be assessed at the end of this section.

Diesel-based mini-grids

Diesel gensets in the relevant sizes here are quite mobile. This also counts for power control subsystems, cooling water tanks, fuel storage tanks and fuel separators. Diesel-based power generation is also site independent, which makes it an option for any mini-grid candidate. However, considering the prerequisites of diesel supply availability and the required infrastructure for this service will limit the number of viable alternatives on a domestic level. Resale value on the international market is likely to be low due to relatively high transport costs. [41]

PV and diesel-PV hybrids

PV systems are very mobile due to their modularity. The same counts for lead-acid batteries, inverters and transformers of relevant size. PV systems are also highly site independent, in the sense that they can be adapted to a smaller or larger load by configuring the number of components. However, for large mini-grids (> 500 kW) the number of modules and components reaches volumes where removal, transport and re-installation costs are likely to become extensive. This fact also strongly contributes to reduce the value of international resale. For diesel-PV hybrids nature of CAPEX irreversibility will be a combination of the two. Due to specific configurations of the technology interaction within the hybrid system, compatibility with other sites (representing different loads) is likely to be somewhat poorer than for single-technology systems. [41]

Small hydropower

HPP configurations including turbine, generator, dams and piping are very site specific. The turbine and generator may be utilized elsewhere, but in general the costs of removing and reinstalling are likely to be very high. The range of loads that can be supplied in a viable way by the turbine/generator system is strongly limited, as is the range of water pressures incident on the turbine. As the hydropower resource is often at a significant distance from the village center and likely to have limited accessibility of both intake and power station, dedicated road construction is often necessary. This also increases the required volume of transmission lines for the project. Such project-specific infrastructure is usually sunk cost for the developer. In some cases others might take interest in access roads in certain areas, creating an opportunity for sharing infrastructure costs between several stakeholders. [41]

Regardless of technical and economic potential of reversing capital investments on mini-grids, social and political considerations cannot be omitted. In any rural electrification project in Tanzania there will be strong political incentives to keep projects alive. This is given by the considerable political focus and resources engaged in RE. In a social perspective, installing a full mini-grid power system to a consumer group followed by a permanent removal due to lack of income, technical or resource-related issues is hard to imagine. Once a community receives electrical services, local investments and welfare increase immediately takes place. Developers and politicians involved take on a great social responsibility of sustaining power supply which is not easily escaped. If capital funding or other governmental support is involved, the developer might also have more formal obligations to ensure successful operation of the mini-grid. Project losses sufficiently large to consider reversing a mini-grid investment would in many cases point towards poor demand assessment or inadequate technical planning, implementation or operation by the developer. [40, 41]

7.6.4 Capital expenditure levels

The cost profiles of the RETs described here differs from that of a diesel genset due to significantly higher levels of capital expenditure (CAPEX). Simplifying this analysis is the fact that the ratio of the CAPEX level of diesel gensets relative to any of the RETs covered in this thesis is more or less similar (figure 11). Hence, as maintenance costs are relatively low for both HPPs and PV, they may be compared to DPPs under basically the same financial criteria. If the LCOE of renewable options are lower than LCOE of DPPs, why may investors still hesitate to engage in RET mini-grid projects? What financial implications are investors facing and how do they differ from low CAPEX diesel-based solutions? The key question to answer is how the CAPEX level affects financial risk related to rural electrification projects. [25, 41]

Should a business model for the local energy market prove not to ensure financiers income, the potential losses are greater in high CAPEX projects than for projects demanding less CAPEX. Consequently, the risk related to a renewable energy mini-grid project is greater than that of a diesel-based mini-grid. In a local energy market, the main risk is related to uncertainty of future income from electricity consumers. Assuming that the risk of non-successful collection of payment is equal regardless of technology, the risk related to a mini-grid investment is to a large extent determined by the CAPEX level of the investment. The size of the capital investment does not affect the risk premium or discount rate of the investment in financial theory; it simply increases the potential consequence of the financial risk involved. [25, 41]

7.6.5 Adjusting discount rates for risk

In order to quantify the risk related to a certain investment, developers or investors include risk premiums – resulting in an increase of the discount rate applied in NPV calculations. The typical market discount rate in developing countries of 10 % is usually not representative for what is applied by investors in high-risk projects (they would rather invest in something less risky). According to experienced economists within the Tanzania energy sector, private investors in off-grid RE projects may use discount rates of up to 30 %. [42] However, the assessments of this study will focus on LCOE comparison from a more social perspective. Nevertheless, one must keep in mind the severe impact high discount rate may yield for PV systems, due to the high capital costs. [42]

7.6.6 Willingness to pay for electricity in rural Tanzania

Affordability of rural villages in Tanzania will be site specific. Hence, project specific assessment on willingness to pay (WTP) for a certain level of electricity consumption is a crucial part of project planning. However, some efforts have been made to estimate the benefit range of low-consumption electricity access for private households in rural Africa (50-100 kWh/month) by the World Bank. [28] According to Tanzania Investment Bank, which is managing the REF, the WTP of rural Tanzanian consumers is expected to be somewhat lower than these estimates [30] (table 18).

Table 18: Benefit range and expected willingness to pay for electricity (low consumption) in rural Tanzania [28, 30]

	Minimum (US$/kWh)	Maximum (US$/kWh)
WB electricity benefit range estimate	1.0	1.5
TIB WTP estimate for rural Tanzania	0.8	1.2

Due to lack of other updated studies on the matter and uncertainty estimates, the WTP maximum and minimum assumptions by the TIB is taken into consideration in the further assessments of income here, as the more conservative approach. As mentioned however, WTP will be strictly site specific and may be a show-stopper for any electrification project in the poorest areas.

7.7 Base-case scenario for LCOE comparison

With respect to the discussions in sections 7.5 and 7.6, base-case scenarios may be established for PV LCOE comparison across other relevant technologies for mini-grid applications. Cost data for diesel and diesel-PV hybrids are retrieved from recent assessments conducted for Norad by Norplan. [12] Cost data for micro hydropower and biomass are provided by cost assessments carried out by the World Bank for rural electrification in Africa [11], and recent REA assessments, respectively. [3] LCOE calculation procedure spreadsheets (Microsoft Excel) are attached in appendix C.

Table 19: LCOE base-level assumptions [3, 11, 12]

	Diesel	*Diesel- Solar PV hybrid**	*Small hydropower*	*Biomass gasifier*
System life span (years)	25	25	25	25
Installed capacity (kVA, kW_p)	30	30	20	20
Capacity factor (%)	0,45	-	0,45	0,8
Capital costs (US$/kW)	700	6660	2470	1200
Fuel costs (US$)	52000	2700	-	-
O&M costs (% of capital costs)	16	5	2	15
Discount rate (%)	10	10	10	10
Fuel or RES availability**	High	High	High	High
Minimum LCOE	1,30	0,77	0,79	0,60
Maximum LCOE	0,92	0,54	0,21	0,25
Average LCOE	1,11	0,65	0,50	0,43

* Here, a diesel-PV hybrid with 1 day battery capacity is assumed, thus assuming only 3 hours diesel generator use each day on average. Note that most existing diesel-PV hybrids have no storage, thus having much lower capital costs, but fuel costs up to 70% or 80% of a pure diesel concept. [26]

** Costs related to lack of diesel supply, eventual draught for hydropower plants and severe lack of biomass yield are not included (thus high availability).

PART III - Key findings and discussion

8 LCOE of PV systems and other technology options

8.1 LCOE of solar PV mini-grids

8.1.1 Solar PV LCOE and willingness to pay for electricity in rural Tanzania

LCOE estimates for off-grid PV systems are sensitive to several project-specific factors (figure 33). The primary *individual* input variables determining the LCOE level in off-grid PV systems is the solar insolation (which is proportional to the production), and the required battery capacity, due to its large impact on capital expenditure. [13] At a given level of battery capacity, high and low annual solar insolation can be translated into high and low LCOE estimates, providing an indication of what may roughly be expected in a site with a certain annual insolation level (figure 32).

Average LCOE estimated for 5 days battery autonomy and average annual insolation of 2050 kWh/m^{2}year is 0.61 US$/kWh (figure 32). LCOE levels ranging from about 0.4 US$/kWh for optimal solar insolation yields and 3 days of battery autonomy to about 0.9 US$ for low-end average insolation and 7 days of battery autonomy is significantly below the assumed willingness to pay for low-consumption electricity (from 50 kWh/month to 100 kWh/month) in rural Tanzania. Thus, the willingness to pay for electricity is sufficiently high for economically sustainable implementation on mini-grids in a social perspective (assuming a market discount rate of 10 %). The maximal willingness to pay is assumed to be ranging from 0.8 US$/kWh to 1.2 US$/kWh depending on village economy (figure 32).

LCOE calculation procedures in Microsoft Excel spreadsheets are attached in appendix C.

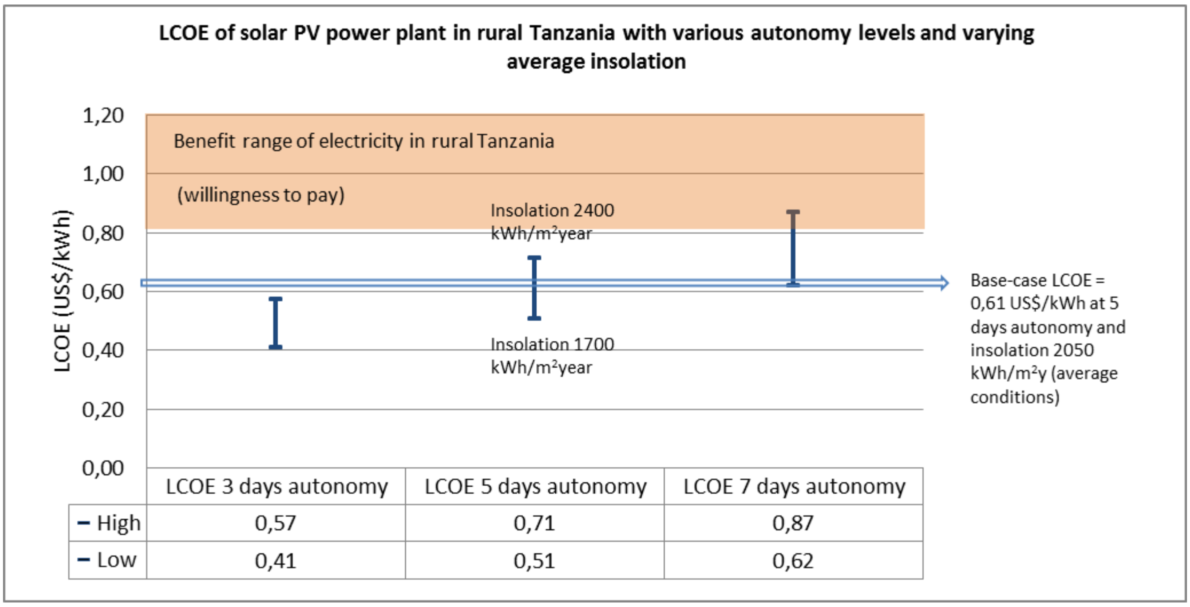

Figure 32: LCOE of various battery autonomy levels (DOD 20%). Willingness to pay for electricity ranges from 0.8 US$/kWh to 1.2 US$/kWh. The base-case LCOE of 0.61 US$ is marked by the horizontal line.

8.1.2 Solar PV LCOE sensitivity

The overall capacity factor (CF) depends on both the average solar insolation incident on the modules and the performance ratio (PR), which again depends on a range of component efficiencies, system design and system losses. Hence, determining the overall CF is a complex exercise, and LCOE estimates are highly sensitive to unsuccessful estimation (figure 33). Although uncertainty related to the system PR can be minimized by system simulation and testing, the uncertainty of solar insolation and climate forecasts is inescapable, as it is based on historical data. Critical handling of insolation data and software simulations are key criteria in order to minimize production uncertainty, to which LCOE estimates are highly sensitive (figure 33).

Furthermore, LCOE attained by a specific PV mini-grid project in rural Tanzania is sensitive to project remoteness and main component costs (figure 33). PV module prices have been subject to comprising decrease over the past few years, currently being historically low. Furthermore, inverters are widely utilized, efficient and relatively cheap. Therefore, the greater potential of LCOE reductions in the future is related to hopes of reduced battery costs.

With respect to the discussion in chapter 7, uncertainties related to annual loss factor of the PV system, installation costs and operating costs are found to have relatively small impact on LCOE estimates and are therefore not included here.

LCOE sensitivity calculation procedures in Microsoft Excel spreadsheets are attached in appendix C.

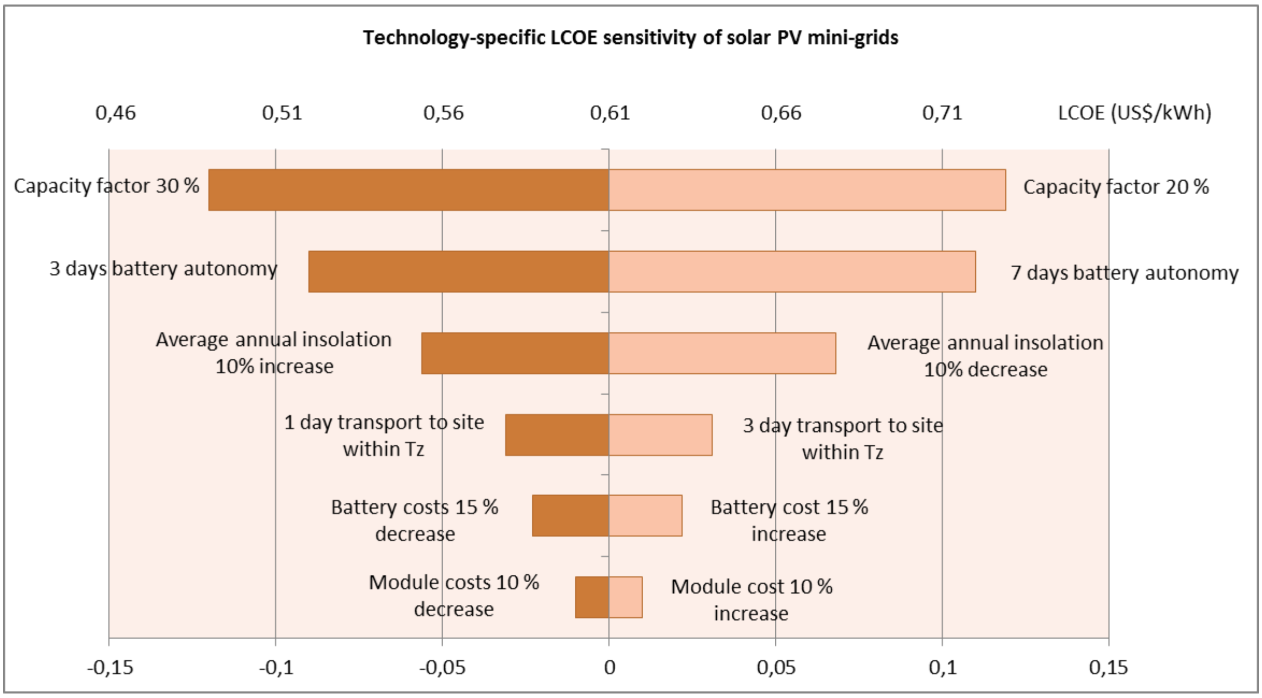

Figure 33: PV system LCOE sensitivity to configuration or uncertainty in the most determining input variables.

8.1.3 Capital cost distribution

The high capital cost of off-grid PV systems is the most crucial barrier to a broader utilization of the solar energy potential in rural Tanzania. In contrast to grid connected PV systems, the need for battery storage capacity increase capital costs by 20 % to 30 % for off-grid applications (figure 34). Another very significant cost driver is the remoteness of rural villages and districts, introducing high transportation costs. One, two or three days of transportation within Tanzania can be necessary due to long distances and poor road quality. Equipment transportation costs accounts for 15 % to 25 % of initial expenditure, depending on project remoteness.

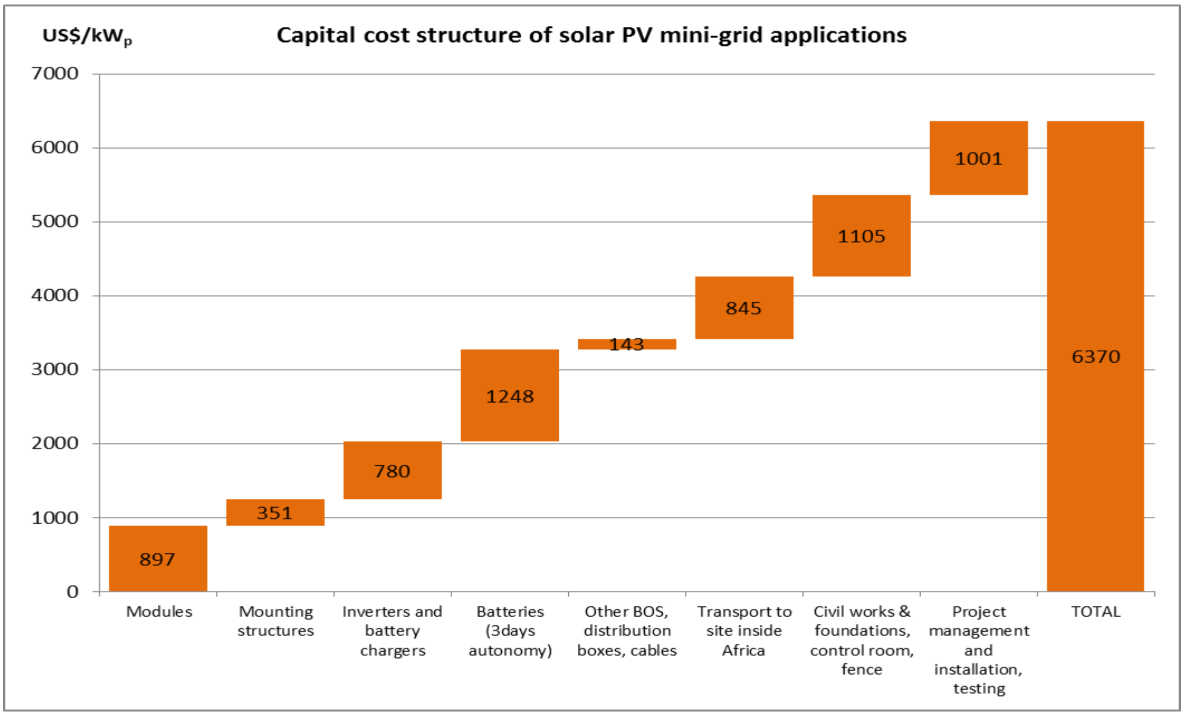

Figure 34: Capital cost compilation of off-grid PV systems in rural Africa. Costs are based on a 30 kWp generating capacity with 3 days of battery autonomy.

8.1.4 Battery sizing and supply security

Due to its large share of capital costs (i.e. also LCOE) and high level of modularity, sizing the battery storage capacity turns out to be a primary key to success in PV system mini-grid implementation. Consequently, determining the appropriate level of supply security on the mini-grid with respect to customer's willingness to pay for the service and the site-specific insolation data is crucial. The key criteria to successful determination of storage capacity and sustainable battery operation are summarized in figure 35.

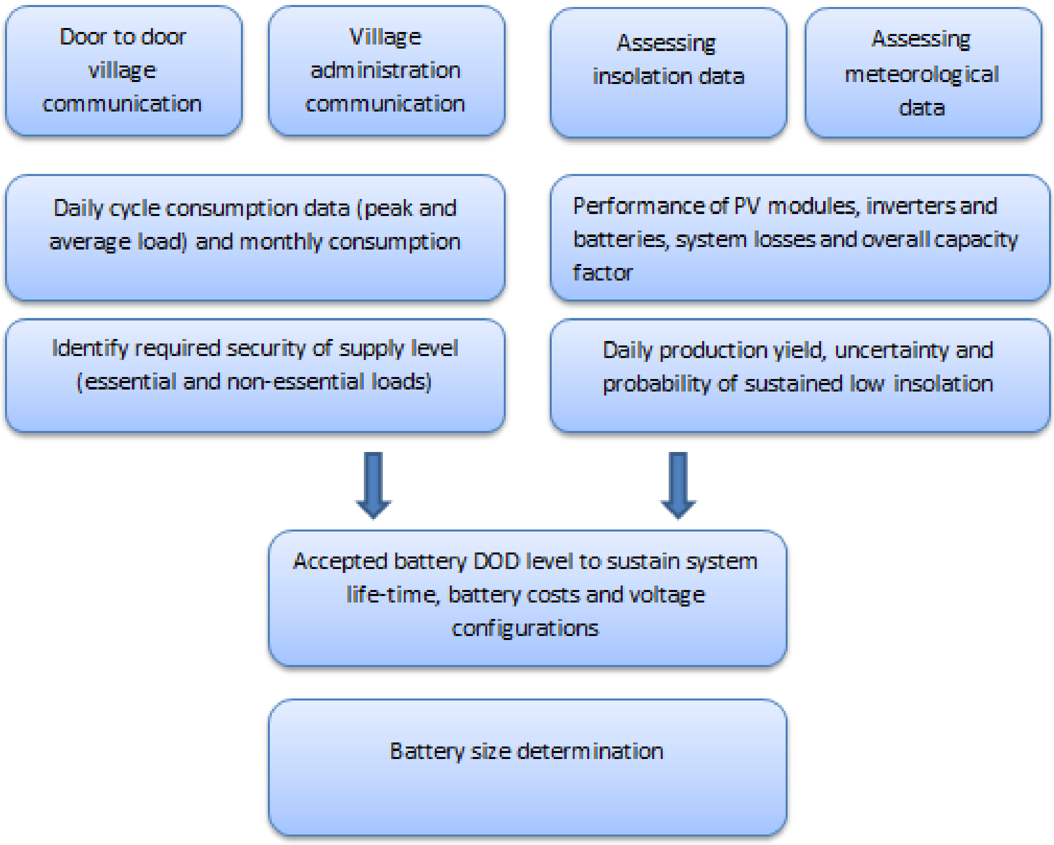

Figure 35: Key criteria to consider for optimal battery sizing and minimized battery costs.

8.1.5 Criteria to sustain low O&M costs

The low operating costs of PV system is a great advantage in rural mini-grid projects. Equipment is durable and annual loss factors are very low for modern PV modules. However, low operating costs are only achieved as a result of successful design and operation management. The primary criteria identified to obtain successful and sustainable implementation of PV systems for mini-grid power generation are listed below:

Implementation:

- Size the battery pack for low DOD operation. The best lead-acid batteries may last 25 years if operated at an average DOD level of about 20 %. Proper testing is crucial before proceeding to mini-grid operation.
- Careful system design with respect to retrieved village load data, insolation data and other meteorological or climate data
- Software simulations
- Extensive system testing by end of installation period

Operation:

- Maintain low DOD in daily battery operation. Monitoring of battery charge levels is crucial in order to conduct capacity increase at an early stage if found necessary.
- Educating local system operator (s) in basic maintenance, power sales and customer care
- Establishing plant perimeter security
- Isolating internal power plant cabling
- Implementing power plant operation monitoring system, communicating with centralized server (placed with developer / technical maintenance contractor)
- Ensuring safe communication system from local operator to system developer for quick-response expert maintenance when necessary (when problems cannot be remotely fixed through system server or by instructing local operator)
- Implementing smart power meters in all connected facilities that communicate with centralized server (monitored by plant operator and remotely monitored by system developer)
- Implementing pre-pay power purchase by cell-phone conducted by customer or by local operator on demand

If not the above criteria are not fulfilled, maintenance costs related to module, inverter or battery replacements are likely occur. The modularity of PV systems make component replacements relatively uncomplicated, but extensive need for extraordinary maintenance can have detrimental effect on project economy.

8.2 Break-even point of solar PV system investments

Assessments of annual cash flows over a 25 year economic life-time of PV systems indicate that at a fixed electricity price (tariff) equal to lowest maximal willingness to pay (0.8 US$/kWh) will suffer extensive time to break-even point. Depending on the project, investors may expect from 15 to 20 years pay-back time, which is much higher than what most private investors demand, especially in high-risk projects (figure 36). However, it is found that a fixed tariff of 1.0 US$ can significantly reduce the break-even time of off-grid PV projects (figure 37). This indicates that within the range willingness to pay in rural Tanzania, tariffs that may sustain the demands of private investors may be viable in certain villages.

Annual NPV calculation procedures in Microsoft Excel spreadsheets are attached in appendix C.

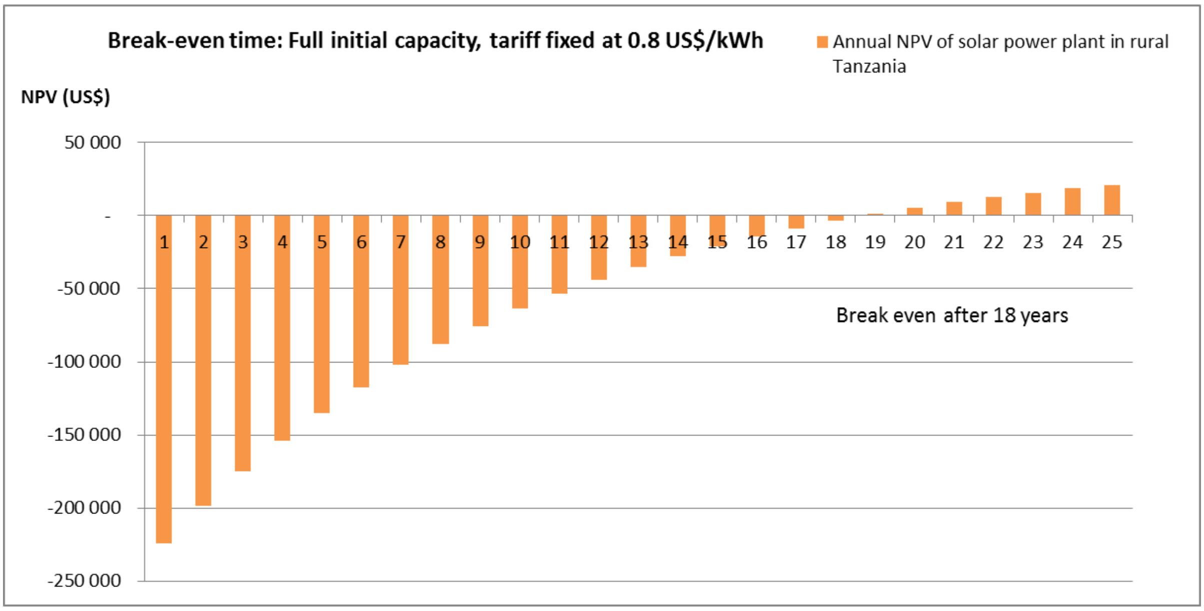

Figure 36: Break-even of solar PV investment at 0.8 US$/kWh electricity cost

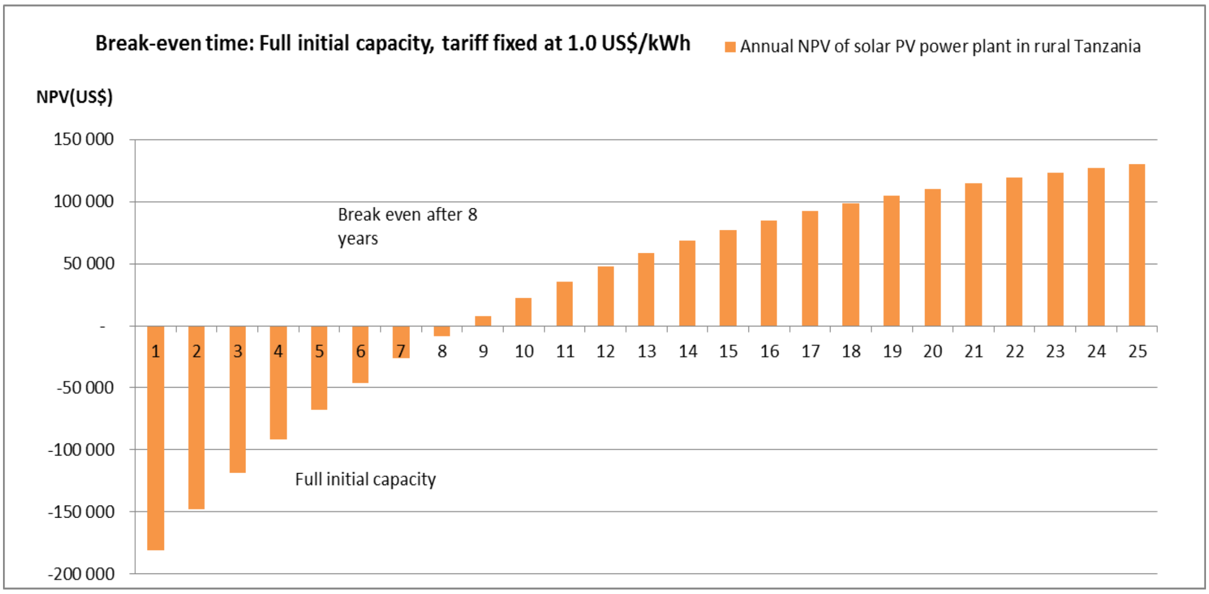

Figure 37: Break-even of solar PV investment at 1.0 US$/kWh electricity cost

8.2.1 Reducing financial risk by implementing stepwise capacity installation

Calculations indicate that the financial risk related to high capital expenditure of off-grid PV systems may be reduced significantly by implementing stepwise capacity expansion without compromising the break-even time of projects in any detrimental manner (figure 38). By e.g. installing a PV power plant on a rural mini-grid in a threefold process with two year intervals (installing at the start of year 1, 3, and 5) the comprehensive amount of capital needed can be dispersed to a certain degree, reducing overall risk.

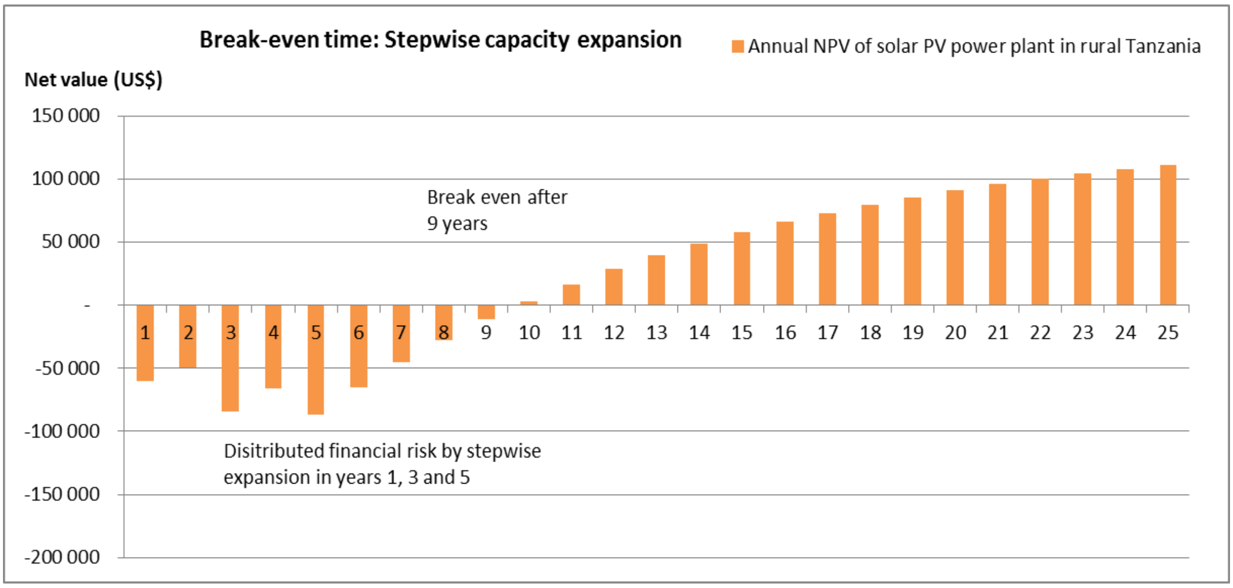

Figure 38: Break-even point of stepwise solar PV investment at 1.0 US$/kWh electricity cost

8.2.2 Maximal funding effect

Capital funding may be provided to off-grid electrification projects trough REA. Normally capital funding will not exceed 30 %. This level of funding has great impact on the viability of PV projects from a developer perspective, reducing initial costs and the break-even time of the investment (figure 39 and figure 40).

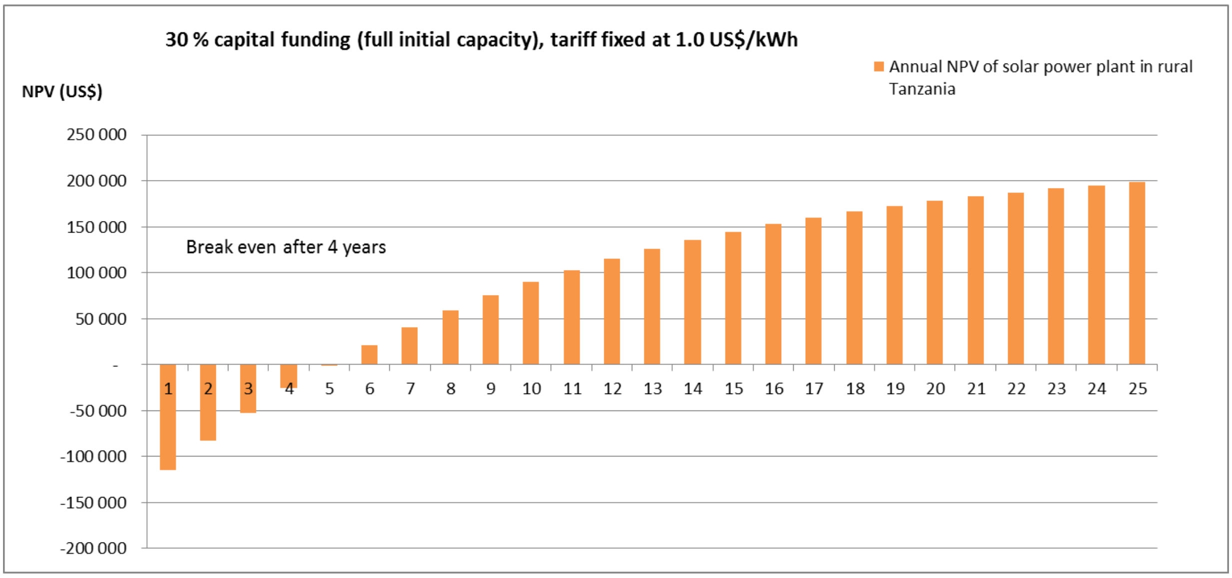

Figure 39: Capital funding (30 %) effect at fixed tariff of 1.0 US$/kWh

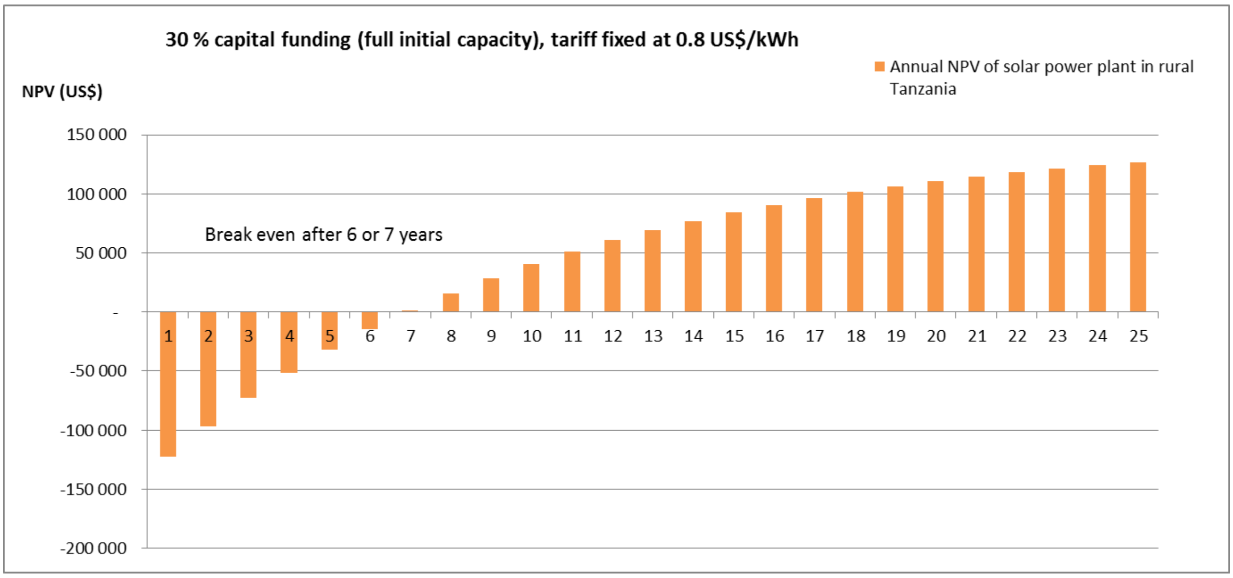

Figure 40: Capital funding (30 %) effect at fixed tariff of 0.8 US$/kWh

8.3 Overall LCOE comparison

The LCOE comparison across technologies confirm expectations of hydropower and biomass power generation on mini-grid applications to be the least cost option of the relevant alternatives when available. Hydropower costs strongly depend on proximity of the resource, but hydropower yields the cheapest alternative when close to the village. Biomass resources depend on the availability of biomass fuel, and thus the need for complementation with commercial fuels. However biomass gasifier power generation is likely to be less costly than PV systems when biomass is readily available.

Diesel-based generation is clearly not cost competitive, even at low diesel cost. Diesel-PV hybrid concepts are competitive with respect to pure solar PV systems, although they come out as slightly more expensive. However, due to the uncertainty of LCOE input variables, these estimates does not provide basis for any conclusion on that exact matter.

Due to the high risk in rural electrification projects (mainly due to uncertainty of income), experienced actors in the Tanzanian energy sector claim that the discount rates of private investors are likely to be significantly higher than market discount rates, ranging up to 30 %. Due the high capital costs of PV systems, this may have a detrimental impact on the economy of such projects. It is not within the scope of this study to speculate in investor discount rates. However, it is in the interest of the Tanzanian government to engage the private sector in rural electrification, and the subject is therefore left for discussion in chapter 10.

LCOE calculation procedures in Microsoft Excel spreadsheets are attached in appendix C.

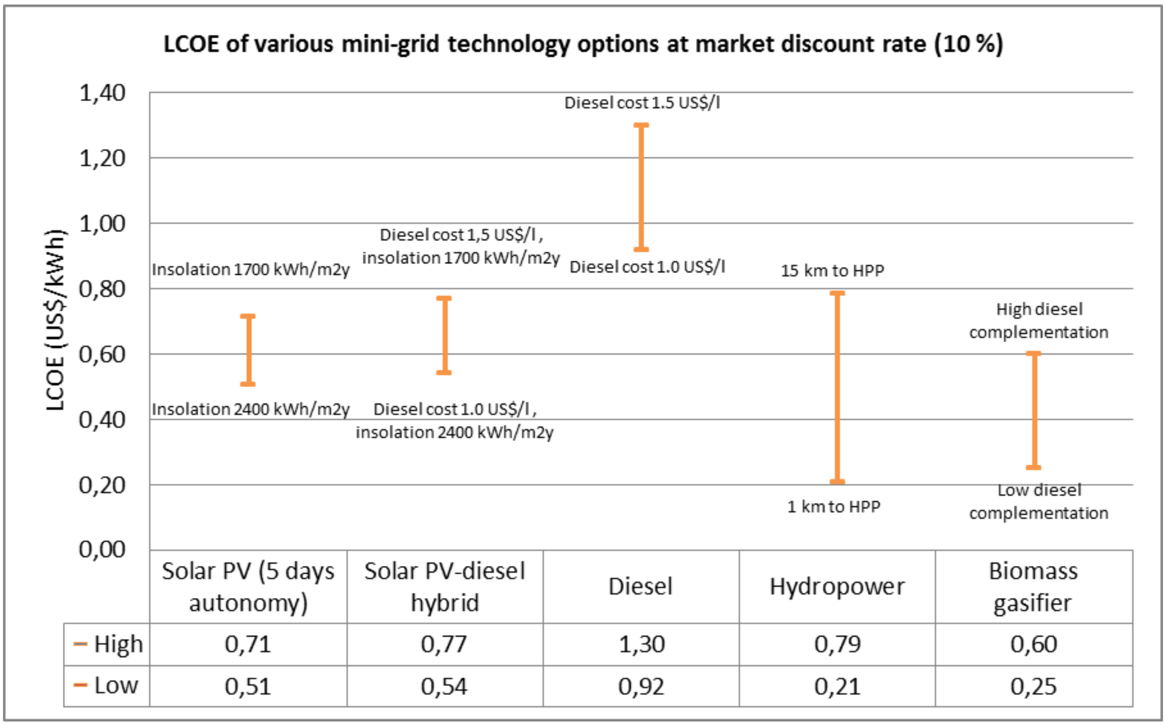

Figure 41: Overall comparison of LCOE across mini-grid technology options at market discount rate. High and low estimates are based on sensitivity to the primary LCOE driver of the technology in question.

9 Political and institutional drivers and barriers to RET on mini-grids

Even if technical and economical assessments should indicate that RETs are competitive in terms of costs and security of supply, a range of institutional and political barriers may still prevent a broader utilization of solar energy and other renewable resources on mini-grids. An assessment of the following has been conducted:

1. Governmental policies
2. Frameworks and electricity market regulation
3. The mindset of stakeholders in rural electrification projects

9.1 Governmental policies and initiatives

A review of Tanzanian governmental policies on rural electrification has been carried out to identify eventual barriers (or drivers) to RET on mini-grids. Governmental policies range from master electrification plans, renewable energy initiatives, funding and educational programs.

The Tanzanian energy subsector under the Ministry of Energy and Minerals have indeed experienced a reform over the past five to ten years. Up to this all electricity generation and distribution had been in the hands of state-owned Tanesco, who completely dominated the domestic energy sector. [4] To some extent they still do, but several important changes have taken place over the last decade. The Electricity Act (2008) invites national and international private companies to engage in the Tanzanian energy sector with regards to power generation specifically. With this act the Ministry seeks to increase private investment and speed up the process of increasing total generating capacity along with the ambitious plans of grid extension. In a long term perspective, Tanesco will eventually narrow down their capacity to focus on transmission grid construction and operation only. The task of regulating the national electricity market was devoted to EWURA, established in 2006. As for RE specifically, the overall responsibility of increasing the rural electrification rate lies with REA. Consequently, practically all off-grid projects fall under the umbrella of REA as candidates to receive planning and implementation support or funding from the agency. [4] REA may grant funds to rural electrification projects by both public and private applicants. Support provided to qualified applicants in mini-grid projects may involve [37]:

- Identification of potential sites (demand, affordability, available energy resources and infrastructure).
- Feasibility studies guiding and support
- Data collection support
- Capital funding (normally < 30 % of total capital costs)

Apart from an outspoken intention to utilize the potential of RES in Tanzania, there are no concrete mechanisms favoring the applicants developing mini-grids based on either diesel gensets or RETs. [37] In REA practice, the primary criteria for recommending generation technology on mini-grids, is selecting the least-cost option. The least-cost practice does in general not incorporate environmental cost or take in consideration the many issues of fuel transportation to diesel-based mini-grids. [37] However, the Prospectus for the rural electrification master plan of REA presented during the spring of 2013 states that the use of diesel gensets is a far more costly way to generate power on mini-grids than with relevant RETs. Diesel hybrid concepts are still being mentioned as a cost efficient solution under the right circumstances. For mini-grids not subject to hydro or biomass potential, REA have to a good extent concluded that diesel hybrid solutions are necessary, and excluded pure solar PV systems as a mini-grid option, accordingly due to extensive capital costs introduced by the large battery capacity required for such systems. However, REA also state that their conclusion is partly due to a currently insufficient analysis of PV systems on Tanzanian mini-grids. They intend to assess this potential more closely by the end of the Prospectus preparation and might change their view on the matter. Wind turbine generation for mini-grids has not been assessed in detail as it is initially not considered cost competitive. As hydro and biomass potentials are limited, many mini-grids will be candidates for PV solutions. The primary question arising for all such projects will be weather to develop solar-PV hybrids or pure solar systems. [3]

9.2 Frameworks and electricity market regulation

For developers (private or others) willing to engage in off-grid rural electrification projects, there are not identified significant barriers related to regulatory issues. In practice, all permissions (land occupation, construction layout etc.) are granted by local leadership (usually a village administration). There will be no authority interference here. [43] However, developers may apply and receive REA support on the matters listed in section 8.1.

EWURA are currently developing new frameworks for mini-grids, introducing two important guidelines for mini-grid developers [44]:

- Standardized Power Purchase Agreement
- Standard Tariff Methodology

The standards are made to make planning and implementation of mini-grid power sales faster and easier for developers, with respect to the overall goal of increased RE rates. [44] When it comes to taxes, EWURA will tend to have a very light-handed consideration in small, off-grid RE projects. RE project are always welcome, and EWURA will not seek to destroy projects economy by implying high taxes on developers. However, an annual fee is set as a standard power sales fee regardless of technology utilized on the mini-grid. EWURA is currently considering reducing the annual fee in particular for projects implementing RETs. [43]

Regarding tariffs, developers are in practice free to agree a fixed tariff with the village administration. However, this may not be an easy exercise, and EWURA encourage developers to involve them so that they can assist as a third party in assessments of village affordability and electricity consumption, although it is not always required for generation capacities of less than 10 MW. Furthermore, EWURA will acquire insight in the LCOE estimations of developers, in order to ensure a social tariff (i.e. not allow extensive producer surplus). EWURA is authorized to regulate tariff agreements, but as mentioned their overall focus will be on supporting the developer in implementing a sustainable power sale. [43]

9.3 The mindset of stakeholders

A survey was conducted with 11 of the major stakeholders in rural electrification projects, in order to map the general understanding among the range of stakeholders, regarding issues related to implementation of RETs on mini-grids in rural Tanzania. The survey included 23 statements representing potential barriers to RETs on mini-grids, identified from recent literature and pre-survey dialogue with stakeholders. The key findings extracted from the survey results and semi-structured stakeholder interviews are outlined in the following sections (9.3.1 through 9.3.4). Full survey results are illustrated in figure 42, while survey outline and participant scheme are attached in appendix D.

The primary barriers to RETs (as viewed by a selection of stakeholders within RE development) on mini-grids identified by the survey are listed below:

- Insufficient access to RET spare parts if needed in rural areas
- Insufficient access to skilled personnel to operate and maintain RETs in rural areas
- Insufficient available funding from REA to cover high CAPEX of RETs on mini-grids
- Uncertainty of income from rural mini-grids make it difficult to attract private investors
- Domestic and local governments await for future grid extension, as they believe it is more cost efficient than off-grid solutions

9.3.1 Technical maturity of RET for mini-grids and security of supply

The survey and interviews indicates a general understanding amongst stakeholders that RETs can provide the same security of supply as diesel. It is widely accepted that RETs are ripe for a permanent switch on mini-grids. All interviews also indicate that stakeholders tend to suggest pure RET systems, not hybrids. The main argumentation states that hybrids will introduce the issues of unstable fuel supply, which according to Tanesco Thermal is the primary cause of load shedding and frequent power outages on their entire portfolio of diesel-based mini-grids. Tanesco Thermal also states that they are experiencing issues related to renewing spare part contracts, as several of their generators are relatively old. Conventional spare parts decreasing in availability (domestic or international) or in some instances running out of production, forces operators to utilize lower quality equipment or improvise when maintaining gensets. This fact introduces significant cost increase and reduces stability of power supply. [7] [45]

9.3.2 RET planning and project development capacity

Inadequate planning and implementation capacity of the leading institutions in rural electrification projects is introduced as a possible barrier by the survey. However, it is observed that the leading institutions themselves (REA and Tanesco) do not consider capacity to be insufficient. This is confirmed by IED consultants, which has been working closely with REA for six months. [26] The level of RET education amongst stakeholders is also a potential barrier according to the survey. The principal of the College of Technology at the university of Dar-es-Salaam states that the overall level of RET education in Tanzania is not sufficient for a massive off-grid RET development. According to the principal, awareness of renewable energy resources and how to utilize them is too low amongst all the major stakeholders. He believes that this fact slows down RET utilization on both off-grid and on-grid electrification projects. [45, 46]

9.3.3 RET equipment supply, installment and maintenance

The survey indicates that the supply chains of RETs are well mapped and accessible for project planners and developers. Several domestic entrepreneurs of solar PV, micro-hydro and biomass power systems are available, along with a number of international entrepreneurs. [37, 47] According to Tanesco, contractors for supply of full generation and distribution systems are readily available on the international marked for all the mentioned RETs. The challenge of accessibility is not construction of the power plant and the distribution system on the mini-grid, as stated in all interviews. However, as indicated by the survey, access to RET spare parts and skilled personnel in rural areas is low or non-existing. Engaging contractors for spare parts on any RET is not considered a barrier by any of the stakeholders, but it was pointed out that spare parts would mainly be provided by international contractors. As there is currently a very limited market for any of the RETs in Tanzania, all stakeholders viewed this as a barrier to RETs on mini-grids. Tanesco Thermal states that the main advantage of diesel on mini-grids is the high access to competence on diesel gensets throughout the country. [7] This statement is partially backed up by the survey results. [45]

9.3.4 Available funding and private investor engagement

The survey indicates that the primary barrier to RETs on mini-grids is high capital costs, this is especially true for solar PV. Although most stakeholders find RETs economically viable for mini-grids, the financial barriers of high risk and investment costs, causes most developers to require substantial capital funding to avoid undertaking extensive risk. However, TIB underlines that insufficient governmental funding needs not stop the development of such projects. TIB points out that affordability and willingness to pay for electricity in rural areas is higher than many developers expect and that the current demand for subsidies exceeds what is necessary for sustainable project development. According to TIB, the primary barrier for developers is attaining loans from domestic banks. Banks are currently very reluctant in lending to RET off-grid projects, and TIB states that this problem is mainly caused by project developers themselves. Project developers need to perform a more detailed assessment of expected consumption on the mini-grid, assessment of consumer ability to pay, more detailed technical plans on how to provide the service and they need to present credible business models for collecting payment. According to TIB this is the core problem facing developers of RET mini-grids. In addition, TIB states that greater efforts should be made in order to create awareness in the domestic banking sector of the sustainability in off-grid RET projects under the right conditions. According to TIB, many RET loan applications are refused due to a combination of poor technical and economical assessments by the project developers and little knowledge about RETs among lenders. [30, 45]

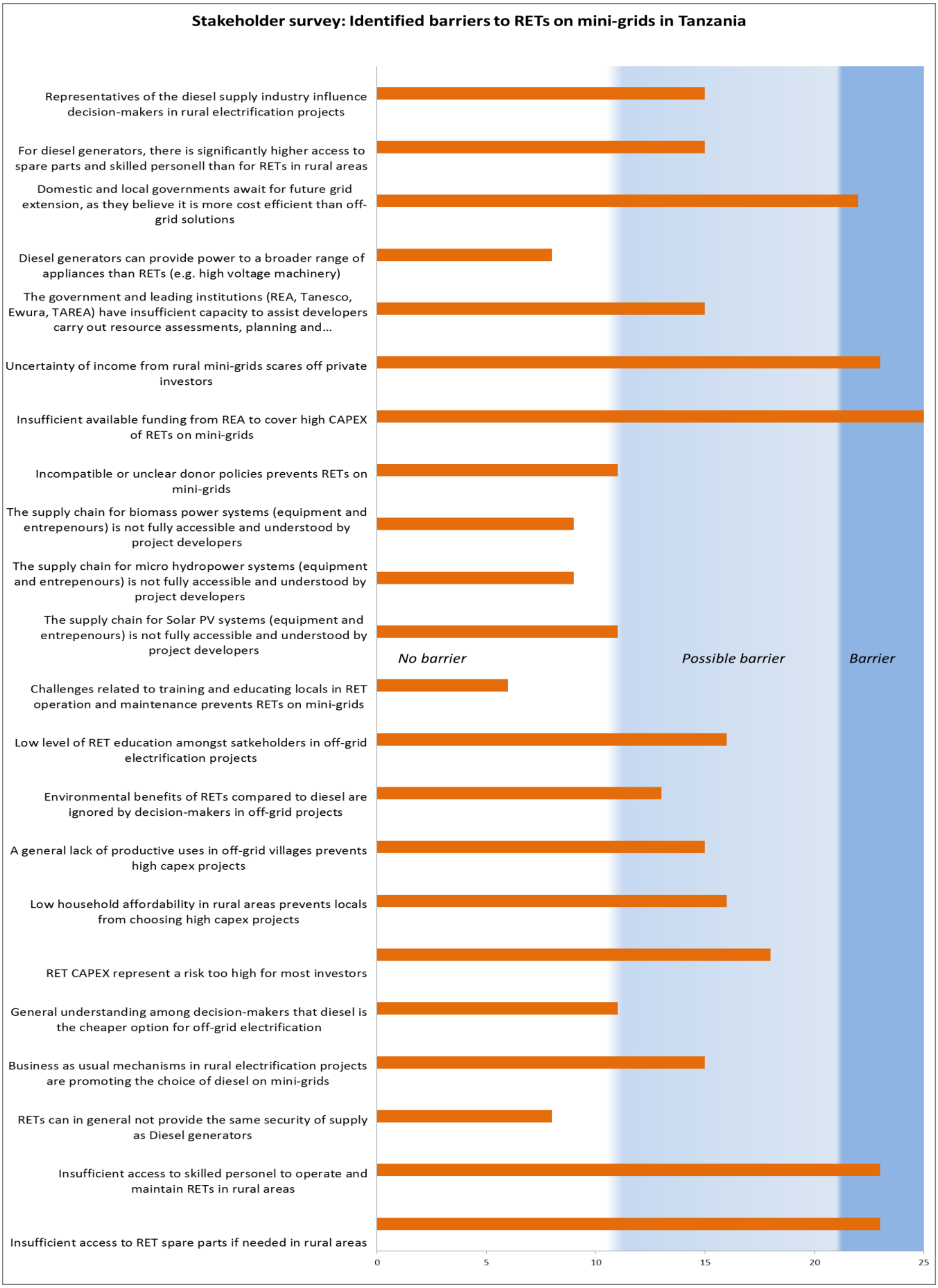

Figure 42: Survey results, identified barriers to RETs on mini-grids in Tanzania.

10 Discussion

10.1 Viability of PV systems on mini-grids in rural Tanzania

10.1.1 Technical maturity

A range of resource-related, design and operational criteria must be fulfilled before pure PV systems can provide power supply at competitive LCOE in a sustainable way. For isolated mini-grids in rural Tanzania, minimizing the battery capacity required and ensuring sustainable battery operation in particular, will be important to successful implementation of PV power supply.

The LCOE estimates ranging from about 0.4 US$ to 0.9 US$ suggest that PV systems with different levels of battery storage capacities may offer a cost competitive and viable option for mini-grids under the right circumstances. However, actual performance and life-time of batteries can be strongly reduced if operated at extensive DOD levels due to inadequate sizing, extensive load or insufficient insolation conditions. In addition, batteries may not always withhold theoretical performance as indicated by manufacturers. This concern is primarily due to limited experience with long-term operation of large battery banks in off-grid PV systems worldwide, introducing a significant risk of unforeseen battery replacements. [16] Furthermore, project planners should also be aware of the limitations in software simulations, due to uncertainty in the underlying assumptions regarding battery performance (along with other components). [46]

Due to the dependence on operational characteristics of battery sustainability, the ability of manufacturers to provide full life-time warranties is limited, hence translating the issue of unforeseen battery replacement into increased financial risk carried primarily by the financiers. [30] However, over the past couple of years low module prices have contributed to construction of high-capacity off-grid PV systems with large battery capacity, e.g. in India, Namibia and the Tokelau Islands. [14-16] Monitoring the battery performance of such installations could provide important experience to future development of PV mini-grid applications. [47]

Module performance and overall system capacity factor will also depend on successful configuration, load forecasting and operation. In addition, it is pointed out by PV developers that procedures to follow up and assist local operators are highly important to sustain system performance. This has been demonstrated on certain PV mini-grids in India, where increasing electricity demand has led to excessive load and therefore power outages and extensive battery discharge. [16] This also indicates the importance of creating customer awareness of the nature and limitations to their consumption, and may also call for a certain level of load management. [30] Load management through essential and non-essential loads has proven successful in e.g. Namibia. [48] Some mini-grids also utilize controlled load shedding and consumption limitation of households and facilities to avoid excessive loads, which can be done using smart power meters. Prepaid meters with maximum power limitations have already been successfully implemented on isolated micro-grids in Tanzania. [33]

10.1.2 Implications of PV LCOE sensitivity

For policy makers, investors, lenders and donors in rural electrification projects, LCOE estimates are established as an important base for comparison across power generating technologies, with respect to concept choice. Assessments in this study suggest that the LCOE of pure solar PV systems on mini-grids in rural Tanzania are sensitive to change in several input parameters. Uncertainty in PV LCOE estimates comprehends variability in meteorological conditions, system configuration with respect to battery capacity in particular, component performance and prices.

The sensitivity of PV LCOE estimates to the mentioned variety of input factors makes them somewhat less consistent and unconditional than what is perceived from other, more conventional power generating technologies. Insufficient effort by project developers to assess and incorporate this uncertainty and the financial risk it represents, may represent a potential barrier to PV systems on mini-grids. [30] Lack of thorough reviews of uncertainty in system costs and production yield (i.e. future income), may decrease bank willingness to grant loans to such projects. According to REF managers, inadequate feasibility studies and load forecasts may also significantly reduce funding granted to such projects. [30]

10.1.3 Reducing financial risk in PV projects

The high capital cost of PV systems causes investment pay-back time to be extensive. At a minimum willingness to pay of 0.8 US$, time to break-even is found to be more than 15 years, which is not likely to attract many private investors. At a tariff of 1 US$ pay-back time is reduced significantly. Still, the discount rates applied in this thesis (10%) is likely to be significantly lower than those applied by private investors. Hence, the effect of high capital costs of PV systems compared to other technology options is even more detrimental when high risk premiums due to the low affordability and weak economies in most rural areas are taken into account.

The assessments in this study suggest a high level of technical modularity of PV systems, as there are no severe technical limitations to stepwise capacity building of solar PV systems. Extension of battery capacity, module capacity or both does not necessarily inflict more additional costs than those related to additional engagement of entrepreneurs and perhaps reduced quantum rebates in capital expenditure and transport to site. [16, 47] This may introduce an opportunity of stepwise capacity extension on solar PV mini-grids as a tool to reduce both initial capital cost and the uncertainty of future income.

Stepwise implementation can allow for periodical assessment of PV system performance with respect to village load development, providing basis for decision on capacity extension. [31] Furthermore, developers can monitor the actual ability to collect payment and thus reduce uncertainty of income yield related to further extension of the mini-grid customer base. [1] Experience from other rural electrification projects indicate that stepwise building of mini-grid capacity may be the better approach regardless of generating technology. Incorporating electricity access to previously non-electrified communities is likely to be a somewhat gradual process due to affordability and consumer reluctance in general. [1, 37]

With respect to the above discussion, a primary issue of PV systems is that economic viability does not necessarily imply financial viability. Therefore, capital funding of PV systems by international donors and NGO's can significantly reduce pay-back-time and initial risk for PV developers, contributing to achievement of financial viability in projects that even without funding are economically viable (due to competitive LCOE). [42]

10.1.4 Electricity tariffs in Tanzania

Assumed willingness to pay in rural areas in this study suggests a potential market for PV systems with respect to LCOE levels. However, affordability in rural Tanzania is highly site-specific and uncertain. In addition, the average tariff on mini-grids in Tanzania in 2012 was 0.4 US$, which is not likely to be viable for any PV system developer.

To some extent, electricity tariffs in Tanzania have been controlled by the government and non-cost-reflective tariffs with political incentives is stated as a problem among stakeholders, disabling mini-grid developers in charging viable tariffs. [37, 42] Some stakeholders claim that willingness and ability to pay for electricity access in many rural areas are higher than some policy-makers expect. [43] It might be in the interest of international donors and other stakeholders in RE to promote the importance of affordability assessments, and for mini-grid developers to be able to charge cost-reflective tariffs. [34] The updated EWURA tariff standards for mini-grids in particular may simplify and improve tariff calculation methodology for mini-grids, in order to ensure viable and fair tariffs for both consumers and producers. [43]

10.1.5 Component costs

Price development of PV system components is likely to influence the extent of PV utilization for mini-grids. In particular, efforts being made on battery research and alternative energy storage technology around the world could reduce future battery costs. [16] In Germany, battery subsidies have been implemented to increase volumes and market competition. [49] In addition, increased utilization of batteries for other purposes than off-grid PV could be a cost reducing factor. For example, the Japanese government is currently installing a 60 000 kWh battery to store energy produced by their increasing number of on-grid PV power plants. [50] Thus, the increased focus on on-grid PV power production throughout the world may contribute to reduce costs of modules, inverters and other PV system components, to the benefit of off-grid applications. [16]

10.1.6 Mini-grid candidates and load forecasts

The linear approach taken in this study to total peak load and consumption with regards to village size might suggest a strongly simplified picture of the actual load characteristics facing rural mini-grid developers. It is not unlikely that the level of public and private facilities with productive electricity demand (social or industrial), may be somewhat higher in the largest towns, causing a non-linear relationship between load and village size. Although initial demand is likely to be very low, mainly due to low affordability, rapid consumption increase has been evident in most electrified parts of the world. [46, 51]

The level of productive electricity use on recent rural mini-grids in developing countries has proven to be modest. [28] Considering the low utilization of electricity for productive uses on existing diesel-based mini-grids in Tanzania today [7, 51], one might expect to witness the same situation on similar projects in the near future. However, domestic politicians and international donors would probably agree that not considering a certain increase in both private and productive electricity demand as a result of economy growth would undermine the very purpose of rural electrification. [5] Detailed load assessment and load development prediction is indicated as key to success in any mini-grid project, but the extent of demand increase may have inflictions on system design and technology compatibility that are not covered to detail in this study.

10.2 Diesel-based mini-grids

The site independence of diesel gensets and their reduced need for feasibility studies is a significant advantage in rural electrification, and the primary reason to why this concept has been implemented on a large scale on isolated grids in Tanzania. [2] To a great extent rural electrification is a political matter, and once electricity access is promised to a village or a district, fast implementation may be of greater importance than LCOE estimates and security of supply considerations in some instances. [42, 43] When fuel is successfully supplied, diesel gensets can provide secure and robust power supply, with the advantage of instant power regulation.

Diesel-based mini-grids seem to generate power at a significantly higher LCOE than any other option assessed here, a fact that is well accepted among stakeholders in the Tanzanian energy sector. According to Tanesco, the average LCOE of existing diesel-based grids are likely to be even higher than those estimated here, due to the frequency of load shedding and power outages. [7] However, it is also pointed out that it might be somewhat wrongful to entirely judge the feasibility of diesel-based mini-grids by existing grids in Tanzania. It is mentioned that several existing plants are old, and that their performance are not necessarily representative for more modern gensets, which have been performing better in e.g. Laos and the Ivory Coast. [43, 52] Furthermore, Tanesco is an organization currently experiencing severe financial issues. Their ability to provide diesel, spare part supply and in general operate plants in an adequate manner may be strongly reduced, causing performance to be worse than what might be seen for new off-grid plants at the hands of other developers. [30]

Some actors in the energy sector claim that political pressure towards electrification of certain communities may sometimes leave diesel-based operation as the only option for fast implementation. As a result of the comprehensive utilization of diesel-based power production, a relatively high level of technical competence within diesel genset operation and repair has arisen, perhaps being an advantage to further implementation on rural energy projects. [7]

10.3 Diesel- PV hybrids

Diesel-PV hybrids are well tested in rural areas in Africa, and have successfully reduced fuel consumption of several previously diesel-based plants. Diesel PV-hybrids may serve very well to reduce fuel costs of isolated grids in rural areas with relatively secure diesel and spare part supply. [7] However, it may not necessarily be the appropriate concept where diesel and spare part supply is more insecure. Some argue that the many challenges experienced by operators of existing diesel-based grids in Tanzania may be transferred to diesel-PV hybrids to some extent, due to the remoteness of mini-grid candidates in RE development. [37]

An interesting opportunity may arise from the many diesel gensets currently found in Tanzania, in terms of adding PV generating capacity to reduce fuel costs of existing grids. Similar projects have proven successful in other African countries, e.g. South Africa. [37] Adding PV capacity to existing diesel-based grids could result in permanent hybrid solutions or a gradual transition to pure PV systems for these locations. [16]

LCOE of diesel-PV hybrid depend on many factors, including the ratio of diesel-based and PV power generated, which can be configured in many ways. Hence, LCOE estimates obtained here (based on a high degree of PV generation) provide limited basis for conclusion on least-cost choice. However, the matter of depending on diesel to some extent, or not at all, may represent an important issue facing project developers in rural Tanzania.

10.4 Hydro and biomass power production

LCOE estimates suggest that both hydropower and biomass may represent least-cost options when available. Hydropower LCOE is dependent on distance from power plant to village, but due the general high potential of the hydro resources (< 1 MW) the opportunity of pooling several villages into one project is introduced in some locations. [3] According to actors in the Tanzanian energy sector, the relatively high level of hydropower competence within Tanesco and the REA is a driver to utilization of these resources. [46] In addition, it is argued that qualified flow measurement of several small hydro potentials has been conducted over the past decades. However, some point it out as a barrier that measurements are primarily carried out by public utilities that may be reluctant to share such information with private project developers. Making flow measurement data more readily available for private developers could be a driver to broader utilization of hydropower resources. [26]

Biomass gasifiers for biogas electricity production are found to yield a low LCOE, making it a very competitive concept for mini-grid applications. However, further assessments of the actual biomass potential and establishments of reference projects are stated as key to further development by assessments in the REA prospectus for rural electrification development. Additionally, it is expressed a certain concern of the variability in biomass yield (in particular from rice production) and to what extent complementation by other fuels (e.g. diesel) may be necessary. [26]

The actual potential and compatibility of hydro and biomass power generation for rural mini-grid candidates in Tanzania is not assessed here, but based on data from the Rural Energy Agency and stakeholder opinions. Hence, LCOE estimates obtained involve great uncertainty, but may still provide an indication that these energy sources are likely to be the least-cost options when available.

10.5 Environmental considerations and carbon finance

The survey conducted with stakeholders indicates awareness and focus on the environmental benefits of PV systems and RETs in general due to reduced carbon emissions. The policy of REA is however, to implement least-cost technology options in RE development. Still, for cost-competitive RETs, environmental benefits may affect decision-makers. [37, 47]

Furthermore, a broad utilization of RET as opposed to diesel-based generation in the eventual RE development of Tanzania, might introduce the opportunity of carbon finance in RE projects. This matter is not assessed to detail in this thesis, but the World Bank has enabled mechanisms for developing countries to benefit financially from implementing RETs. [53] The TIB is currently looking into the opportunity of implementing a carbon finance facility for RE projects. This could translate into lowered LCOE for PV systems and other RETs, making the concepts even more competitive. [30]

10.6 Importance of political and institutional barriers

Regarding the REA least-cost policy in RE development and the tariff calculation standards of EWURA, there are no specific mechanisms promoting RETs on mini-grids. However, stakeholder interviews indicate high awareness of the cost competitiveness of renewable alternatives, including solar PV [7, 30, 37]. Furthermore, the current poor performance of diesel-based plants is widely acknowledged by most stakeholders in RE development. [45] These factors, combined with the high competence level and engagement in RE development demonstrated within REA may be important drivers to RETs in Tanzania. Furthermore, the RET focus among international donors, having a close relationship to the REA organization, may also pose as an important driver on this matter. [54]

Among most stakeholders, uncertainty related to availability of RET spare part supply and skilled personnel to perform maintenance, in particular for PV systems and hydropower, seem to represent potential barriers to broader support of these technologies in the off-grid electrification debate. [45]

Regarding PV systems, the issues of high capital expenditure, income uncertainty and insufficient access to capital funding are pointed out as the most important barriers by all stakeholders. However, recent donations to the REF combined with further decrease in component prices and newly gained experience from off-grid PV installations with large storage capacity, could help attract private sector to PV development in rural areas. [45]

The value of the results from the survey and stakeholder interview provide very limited basis for conclusion on barriers related to stakeholder mindsets, due to the limited amount of participants and subjective answers. Nonetheless, keeping up to date with stakeholder interests and maintaining good communication between the parties involved in the process could help promote sustainable and efficient RE development in Tanzania. [54]

11 Conclusion

Under a range of design and operational conditions, solar PV systems can supply power to mini-grids in rural Tanzania at the same level of supply security, in a more sustainable way than what is found on existing diesel-based off-grid systems, at lower LCOE. Innovative measures can be taken by PV developers to reduce cost and promote system sustainability, such as load management and stepwise capacity expansion.

Where the least-cost options of hydro and biomass resources are not available, diesel- PV hybrid concepts enjoy more support than pure PV systems due to lower capital costs as battery capacity is not required to the same (or any) extent. Diesel-based generation have the advantages of high site independence, reduced need for comprehensive feasibility studies and instant power regulation. However, the detrimental effect of unstable and expensive diesel supply on the economy of existing diesel-based grids in Tanzania may also represent a challenge for future implementation of diesel-PV hybrids in increasingly remote areas.

There are good economic arguments for the viability of PV power generation on mini-grids. This is widely acknowledged within the Tanzanian energy sector, but there are real and meaningful barriers to a broader utilization of the solar resource. In particular, the high capital costs of PV systems with large energy storage capacity impede the process of engaging private investors. If capital funding can bring down investment barriers, and viable operational models can ensure economic sustainability net of the grant, public up-front support to such projects can be justified.

Current trends point towards increased viability of PV systems and it is likely this will only be strengthened in the future. Thus, by helping partners demonstrate viable technical solutions and business models, one can contribute to speeding up a transition to solar and other renewables. Finally, although it will be demanding, the analysis implies that efforts by donors to reduce the perceived risk associated with off-grid renewables could prove decisive in facilitating this transition in Tanzania.

12 Further work

This thesis should be considered a preliminary study to the development of PV systems on mini-grids in rural Tanzania, and perhaps some parallels could be drawn other countries in Sub-Saharan Africa in particular. In this thesis, there has been an overall focus on the primary design and operation considerations system developers should keep in mind in order to acquire a certain level of supply security. In addition, the current performance of diesel-based off-grid systems has been assessed for comparison. It has been focused on the primary LCOE drivers and the uncertainties involved, which are important financial risk drivers to be considered by RE developers. Hence, there are several issues that require further investigation. For example, a more updated study of solar insolation distribution than what is currently available could be made available for PV project developers, in order to simplify the process of identifying candidate villages. In addition, a more detailed mapping of the existing PV developers and entrepreneurs in Tanzania and a critical review of their competence and capacity could provide a better understanding of potential domestic contractors for long-term maintenance of PV systems, as a competitive option to international suppliers.

Finally, conducting software operation simulations of PV systems based on load forecast and insolation data collected from specific, representative rural Tanzanian villages in order to obtain more qualified, site-specific and less uncertain configuration criteria and LCOE estimates than those presented here would be beneficial. A range of concrete examples of expected performance and costs of pure PV systems in such areas, could serve as valuable input to the further discussion.

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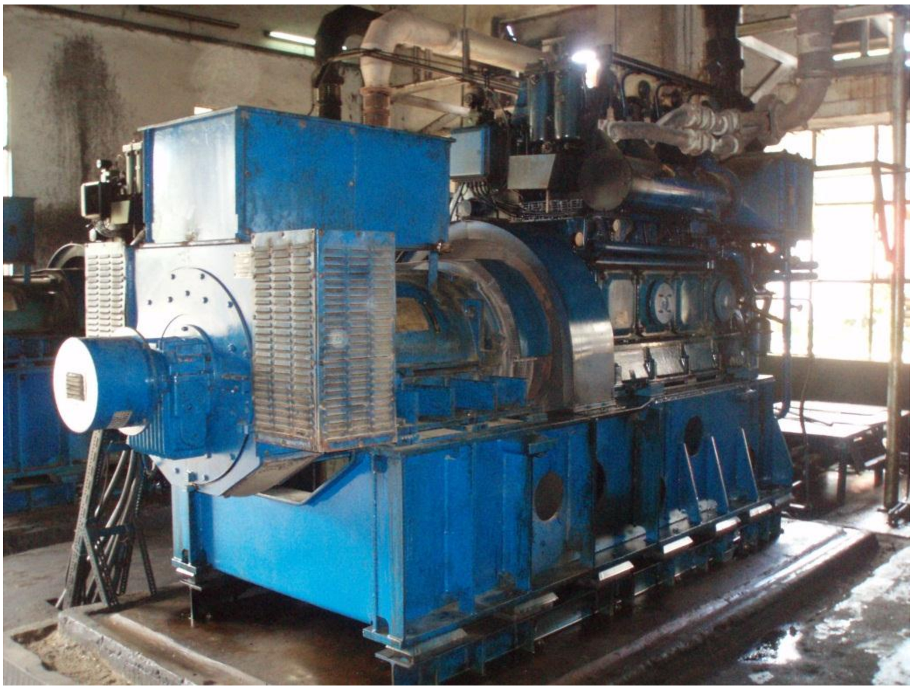
Appendix A

Photos from a representative diesel-based isolated grid in Tanzania (Mafia Island)

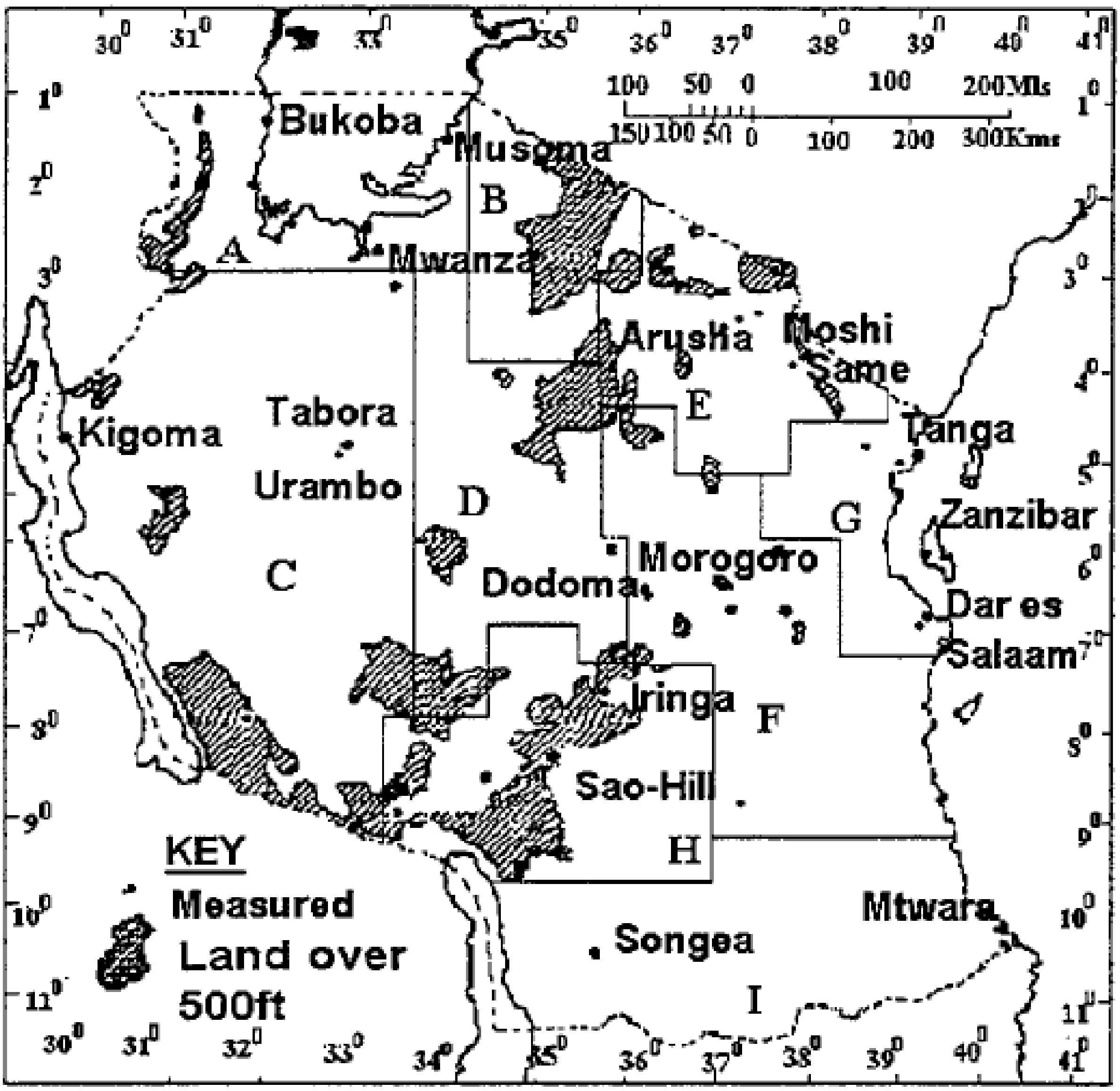


One out of two 450 kW diesel gensets at Mafia Island power plant.

Power plant utility, gensets inside. Fuel storage tanks outside to the right.

Appendix B

Zone map for measured insolation data. In total, 35 weather stations distributed within the 9 zones (A through I) measure solar insolation.



Appendix C

LCOE estimation procedures and annual NPV calculation procedures

	A	B	C	D	E	F	G	H	I	J	K	L
1	**- Solar PV mini-grid LCOE calculation procedure (Values view) -**											
2												
3	**ASSUMPTIONS / INPUT:**											
4	Plant size:	30	kWp									
5	CAPEX for off-grid solar plant:	7 230	USD/kWp									
6	# of days autnomy (battery back-up):	5	days									
7	OPEX:	0,5 %										
8	System losses:	30 %										
9	GHI, high irradiation	2600	kWh/m^2/yr									
10	GHI, low irradiation	1700	kWh/m^2/yr									
11	Relationship between GHI and specific yield:	0,8										
12	Discount rate:	10 %										
13	**CALCULATIONS**			**Year number**	**…….up to and including year 25**							
14	**PV system:**		0	1	2	3	4	5	6	7	8	9
15	Installation cost, PV system:	USD	216 900									
16	TOTAL Investment costs:	USD	216 900									
17	OPEX	USD		1 085	1 085	1 085	1 085	1 085	1 085	1 085	1 085	1 085
18	TOTAL COSTS	USD	216 900	1 085	1 085	1 085	1 085	1 085	1 085	1 085	1 085	1 085
19	Total life cycle costs (NPV) over 25 yrs	USD	226 744									
20												
21	**Energy production, high irradiation (2600 kWh/m2/yr):**	kWh		62 400	62 400	62 400	62 400	62 400	62 400	62 400	62 400	62 400
22	Total life cycle energy production (NPV) over 25 yrs	kWh	566 407									
23												
24	**Energy production, high irradiation (1700 kWh/m2/yr):**	kWh		40 800	40 800	40 800	40 800	40 800	40 800	40 800	40 800	40 800
25	Total life cycle energy production (NPV) over 25 yrs	kWh	370 343									
26												
27												
28	**LCOE, solar PV off-grid system, high irradiation:**	**USD/kWh**	**0,400**									
29	**LCOE, solar PV off-grid system, low irradiation:**	**USD/kWh**	**0,612**									
30												
31												
32												
33	**CAPEX**	**Qty/size**	**Unit**	**USD**	**USD/kWp**							
34	Modules	30	kWp	27 000	900		12 %					
35	On ground supports, wind proof	3	tables	10 500	350		5 %					
36	Inverters & battery chargers	6	units	24 000	800		11 %					
37	batteries (5 days autonomy)	96	units	62 400	2 080		29 %					
38	Other BoS, distribution boxes, cables	1	set	4 500	150		2 %					
39	transport to site, inside Africa	1	units	25 500	850		12 %					
40	Civil works & foundations, fence (incl control room)	1	set	33 000	1 100		15 %					
41	Project man.mt, installation and commiss.	3	weeks	30 000	1 000		14 %					
42	**Total, PV village system:**			**216 900**	**7 230**							
43												

	A	B	C	D	E
1	**- Solar PV mini-grid LCOE calculation procedure (Formula view) -**				
2					
3	**ASSUMPTIONS / INPUT:**				
4	Plant size:	30	kWp		
5	CAPEX for off-grid solar plant:	=E42	USD/kWp		
6	# of days autnomy (battery back-up):	5	days		
7	OPEX:	0,005			
8	System losses:	0,3			
9	GHI, high irradiation	2600	kWh/m^2/yr		
10	GHI, low irradiation	1700	kWh/m^2/yr		
11	Relationship between GHI and specific yield:	0,8			
12	Discount rate:	0,1			
13	**CALCULATIONS**			**Year number....up to and including year 25**	
14	**PV system:**		0	=C14+1	=D14+1
15	Installation cost, PV system:	USD	=B4*B5		
16	TOTAL Investment costs:	USD	=SUM(C15:C15)		
17	OPEX	USD		=$C$16*$B$7	=$C$16*$B$7
18	TOTAL COSTS	USD	=C16	=SUM(D15:D17)	=SUM(E15:E17)
19	Total life cycle costs (NPV) over 25 yrs	USD	=NPV(B12;Solar!D18:AG18)+Solar!C18		
20					
21	**="Energy production, high irradiation ("&B9&" kWh/m2/yr):"**	kWh		=$B$9*$B$11*$B$4	=$B$9*$B$11*$B$4
22	Total life cycle energy production (NPV) over 25 yrs	kWh	=NPV(B12;D21:AB21)		
23					
24	**="Energy production, high irradiation ("&B10&" kWh/m2/yr):"**	kWh		=$B$10*$B$11*$B$4	=$B$10*$B$11*$B$4
25	Total life cycle energy production (NPV) over 25 yrs	kWh	=NPV(B12;D24:AB24)		
26					
27					
28	**LCOE, solar PV off-grid system, high irradiation:**	**USD/kWh**	**=C19/C22**		
29	**LCOE, solar PV off-grid system, low irradiation:**	**USD/kWh**	**=C19/C25**		
30					
31					
32					
33	**CAPEX**	**Qty/size**	**Unit**	**USD**	**USD/kWp**
34	Modules	30	kWp	=E34*$B$4	900
35	On ground supports, wind proof	3	tables	=E35*$B$4	350
36	Inverters & battery chargers	6	units	=E36*$B$4	800
37	batteries (5 days autonomy)	96	units	=E37*$B$4	=2080/5*B6
38	Other BoS, distribution boxes, cables	1	set	=E38*$B$4	150
39	transport to site, inside Africa	1	units	=E39*$B$4	850
40	Civil works & foundations, fence (incl control room)	1	set	=E40*$B$4	1100
41	Project man.mt, installation and commiss.	3	weeks	=E41*$B$4	1000
42	**Total, PV village system:**			**=SUM(D34:D41)**	**=D42/$B$4**
43					

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**- Hybrid diesel-PV mini-grid LCOE calculation procedure (Values view) -**													
2														
3	**ASSUMPTIONS / INPUT:**													
4	Plant size:	23	kWp											
5	CAPEX for off-grid solar plant:	6 464	USD/kWp											
6	# of days autnomy (battery back-up):	1	days											
7	Generator installed capacity	8,75	kVA											
8	Generator output	7	kW											
9	Generator cost:	6 000	USD											
10	Generator life-time:	10	years											
11	OPEX for solar system:	0,5 %												
12	OPEX for diesel system:	16,0 %												
13	Diesel price, low estimate:	1,00	USD/l											
14	Diesel price, high estimate:	1,50	USD/l											
15	Diesel price increase in rural areas (Dista	50 %												
16	Hours of generator use per day:	3,00	hrs/day											
17	Diesel conusmption:	2,30	l/hr											
18	Total diesel consumption per year:	2 519	l/yr											
19	GHI, high irradiation:	2 600	$kWh/m^2/yr$											
20	GHI, low irradiation:	1 700	$kWh/m^2/yr$											
21	Relationship between GHI and specific yi	0,8												
22	Average consumption/HH/yr:	600	kWh/yr											
23	Discount rate:	10 %												
24														
25	**CALCULATIONS**			**Year number ... up to and incl. year no 25**										
26	**Hybrid system, low diesel cost:**		0	1	2	3	4	5	6	7	8	9	10	11
27	Installation cost, PV system:	USD	148 668											
28	Generator cost:	USD	6 000										6 000	
29	TOTAL Investment costs:	USD	154 668											
30	OPEX:	USD		1 703	1 703	1 703	1 703	1 703	1 703	1 703	1 703	1 703	1 703	1 703
31	Diesel cost:	USD		3 778	3 778	3 778	3 778	3 778	3 778	3 778	3 778	3 778	3 778	3 778
32	TOTAL COSTS	USD	154 668	5 481	5 481	5 481	5 481	5 481	5 481	5 481	5 481	5 481	11 481	5 481
33	Total life cycle costs (NPV) over 25 yrs	USD	207 537											
34														
35	**Energy production, high irradiation:**													
36	Energy produced from PV system:	kWh		47 840	47 840	47 840	47 840	47 840	47 840	47 840	47 840	47 840	47 840	47 840
37	Energy produced from diesel generator:	kWh		7 665	7 665	7 665	7 665	7 665	7 665	7 665	7 665	7 665	7 665	7 665
38	Total energy produced from hybrid syste	kWh		55 505	55 505	55 505	55 505	55 505	55 505	55 505	55 505	55 505	55 505	55 505
39	Total life cycle energy production (NPV) (	kWh	503 821	16 %										
40														
41	**LCOE RESULT**	USD/kWh	0,412											
42														
43														

	A	B	C	D
1	**- Hybrid diesel-PV mini-grid LCOE calculation procedure (Formula view) -**			
2				
3	**ASSUMPTIONS / INPUT:**			
4	Plant size:	23	kWp	
5	CAPEX for off-grid solar plant:	=E80	USD/kWp	
6	# of days autnomy (battery back-up):	1	days	
7	Generator installed capacity	=+B8/0,8	kVA	
8	Generator output	7	kW	
9	Generator cost:	6000	USD	
10	Generator life-time:	10	years	
11	OPEX for solar system:	0,005		
12	OPEX for diesel system:	0,16		
13	Diesel price, low estimate:	1	USD/l	
14	Diesel price, high estimate:	1,5	USD/l	
15	Diesel price increase in rural areas (Distance to Port factor)	0,5		
16	Hours of generator use per day:	3	hrs/day	
17	Diesel conusmption:	2,3	l/hr	
18	Total diesel consumption per year:	=B16*365*B17	l/yr	
19	GHI, high irradiation:	2600	kWh/m^2/yr	
20	GHI, low irradiation:	1700	kWh/m^2/yr	
21	Relationship between GHI and specific yield:	0,8		
22	Average consumption/HH/yr:	=50*12	kWh/yr	
23	Discount rate:	0,1		
24				
25	**CALCULATIONS**			**Year number … up to and incl. year no 25**
26	**Hybrid system, low diesel cost:**		0	=C26+1
27	Installation cost, PV system:	USD	=$B$4*$B$5	
28	Generator cost:	USD	=$B$9	
29	TOTAL Investment costs:	USD	=SUM(C27:C28)	
30	OPEX:	USD		=$C$27*$B$11+$C$28*$B$12
31	Diesel cost:	USD		=$B$18*$B$13*(1+$B$15)
32	TOTAL COSTS	USD	=C29	=SUM(D27:D31)
33	Total life cycle costs (NPV) over 25 yrs	USD	=NPV(B23;D32:AB32)+C32	
34				
35	**Energy production, high irradiation:**			
36	Energy produced from PV system:	kWh		=($B$4*$B$19*$B$21)
37	Energy produced from diesel generator:	kWh		=+$B$8*$B$16*365
38	Total energy produced from hybrid system	kWh		=+SUM(D36:D37)
39	Total life cycle energy production (NPV) over 25 yrs	kWh	=NPV(B23;D38:AB38)	=D37/D36
40				
41	**LCOE RESULT**	USD/kWh	=C33/C39	
42				
43				

	A	B	C	D	E	F	G	H	I
1	**- Diesel mini-grid LCOE calculation procedure (Values view) -**								
2									
3	**ASSUMPTIONS / INPUT:**								
4	Plant size:	30,0	kVA						
5	Active power from the plant	25,5	kW						
6	Generator Cost	13200	USD						
7	Generator life-time	4	years						
8	Diesel price, high estimate:	1,00	USD/l						
9	Diesel price, low estimate:	1,50	USD/l						
10	Diesel price increase in rural areas	50 %		***Diesel operation and consumption***					
11	OPEX for diesel mini grid:	16 %							
12	Hours of generator use per day:	18	hrs/day	Annual diesel consumption	**49238**				
13	Capacity factor	44 %		Annual production	**97729**				
14	Total diesel consumption per year:	49 238	l/yr						
15	Discount rate:	10 %							
16									
17									
18	**CALCULATIONS**			**Year number….. Up to and including year 25**					
19	**Diesel Mini grid system, low diesel cost:**			1	2	3	4	5	6
20	Installation cost, Diesel mini grid:	USD	13 200				13 200		
21	TOTAL Investment costs:	USD	13 200						
22	OPEX:	USD		2 112	2 112	2 112	1 056	2 112	2 112
23	Diesel cost:	USD		73 857	73 857	73 857	73 857	73 857	73 857
24	TOTAL COSTS	USD	13 200	75 969	75 969	75 969	88 113	75 969	75 969
25	Total life cycle costs (NPV) over 25 yrs	USD	726 284						
26									
27	**Diesel Mini grid system, high diesel cost:**			1	2	3	4	5	6
28	Installation cost, Diesel mini grid:	USD	13 200				13 200		
29	TOTAL Investment costs:	USD	13 200						
30	OPEX:	USD		2 112	2 112	2 112	1 056	2 112	2 112
31	Diesel cost:	USD		110 786	110 786	110 786	110 786	110 786	110 786
32	TOTAL COSTS	USD	13 200	112 898	112 898	112 898	125 042	112 898	112 898
33	Total life cycle costs (NPV) over 25 yrs	USD	1 061 485						
34									
35	**Energy production:**			1	2	3	4	5	6
36	Energy produced from diesel mini grid	kWh		97 729	97 729	97 729	97 729	97 729	97 729
37	Total life cycle energy production (NPV) over 25 yrs	kWh	887 090						
38									
39									
40	**LCOE, low diesel price:**	**USD/kWh**	**0,82**						
41	**LCOE, high diesel price:**	**USD/kWh**	**1,20**						
42									
43									

	A	B	C	D	E
1	**- Diesel mini-grid LCOE calculation procedure (Formula view) -**				
2					
3	**ASSUMPTIONS / INPUT:**				
4	Plant size:	30	kVA		
5	Active power from the plant	=+B4*0,85	kW		
6	Generator Cost	13200	USD		
7	Generator life-time	4	years		
8	Diesel price, high estimate:	1	USD/l		
9	Diesel price, low estimate:	1,5	USD/l		
10	Diesel price increase in rural areas	0,5		***Diesel operation and consumption***	
11	OPEX for diesel mini grid:	0,16			
12	Hours of generator use per day:	18	hrs/day	Annual diesel consumption	**49238**
13	Capacity factor	0,44		Annual production	**97729**
14	Total diesel consumption per year:	=E12	l/yr		
15	Discount rate:	0,1			
16					
17					
18	**CALCULATIONS**			**Year number..... Up to and including year 25**	
19	**Diesel Mini grid system, low diesel cost:**			1	2
20	Installation cost, Diesel mini grid:	USD	=+B6		
21	TOTAL Investment costs:	USD	=SUM(C20:C20)		
22	OPEX:	USD		=$C$20*$B$11	=$C$20*$B$11
23	Diesel cost:	USD		=+$E$12*$B$8*(1+$B$10)	=+$E$12*$B$8*(1+$B$10)
24	TOTAL COSTS	USD	=C21	=+SUM(D20:D23)	=+SUM(E20:E23)
25	Total life cycle costs (NPV) over 25 yrs	USD	=NPV(B15;D24:AB24)+C24		
26					
27	**Diesel Mini grid system, high diesel cost:**			1	2
28	Installation cost, Diesel mini grid:	USD	=+B6		
29	TOTAL Investment costs:	USD	=SUM(C28:C28)		
30	OPEX:	USD		=$C$20*$B$11	=$C$20*$B$11
31	Diesel cost:	USD		=+$E$12*$B$9*(1+$B$10)	=+$E$12*$B$9*(1+$B$10)
32	TOTAL COSTS	USD	=C29	=+SUM(D28:D31)	=+SUM(E28:E31)
33	Total life cycle costs (NPV) over 25 yrs	USD	=NPV(B15;D32:AB32)+C32		
34					
35	**Energy production:**			1	2
36	Energy produced from diesel mini grid	kWh		=$E$13	=$E$13
37	Total life cycle energy production (NPV) over 25 yrs	kWh	=NPV(B15;D36:AB36)		
38					
39					
40	**LCOE, low diesel price:**	**USD/kWh**	**=C25/C37**		
41	**LCOE, high diesel price:**	**USD/kWh**	**=C33/C37**		
42					
43					

	A	B	C	D	E	F	G	H	I	J	K
1	**- Solar PV mini-grid annual NPV plot procedure with fixed tariff and annual loss factor (Values view) -**										
2											
3	**ASSUMPTIONS / INPUT:**										
4	Plant size:	30	kWp								
5	CAPEX for off-grid solar plant:	7 230	USD/kWp								
6	# of days autnomy (battery back-up):	5	days		***Annual NPV plot variables***						
7	OPEX:	0,5 %			Annual loss factor 0.5 %						
8	System losses:	30 %			Tariff fixed at 1 US$						
9	GHI, high irradiation	2400	$kWh/m^2/yr$								
10	GHI, low irradiation	1700	$kWh/m^2/yr$								
11	Relationship between GHI and specific yield:	0,8									
12	Discount rate:	10 %		10 %	10 %	10 %	10 %	10 %	10 %	10 %	10 %
13											
14											
15	**CALCULATIONS**			**Year number.... Up to and including year no 25**							………
16	**PV system:**		0	1	2	3	4	5	6	7	8
17	Installation cost, PV system:	USD	216 900								
18	TOTAL Investment costs:	USD	216 900								
19	OPEX	USD		1 085	1 085	1 085	1 085	1 085	1 085	1 085	1 085
20	TOTAL COSTS	USD	216 900	1 085	1 085	1 085	1 085	1 085	1 085	1 085	1 085
21	Total life cycle costs (NPV) over 25 yrs	USD	226 744								
22											
23	**Energy production, high irradiation (2400 kWh/m2/yr)**	kWh		57 600	57 600	57 600	57 600	57 600	57 600	57 600	57 600
24	Total life cycle energy production (NPV) over 25 yrs	kWh	522 838	*Loss factor*	0,9950	0,9950	0,9950	0,9950	0,9950	0,9950	0,9950
25				1,00	*Tariff*						
26	**Energy production, low irradiation (1700 kWh/m2/yr):**	kWh		40 800	40 596	40 393	40 191	39 990	39 790	39 591	39 393
27	Total life cycle energy production (NPV) over 25 yrs	kWh	356 932	216 900	216 900	216 900	216 900	216 900	216 900	216 900	216 900
28			**Annual surplus**	39 716	39 512	39 309	39 107	38 906	38 706	38 507	38 309
29			**Annual NPV plotted**	-180 795	-148 141	-118 608	-91 897	-67 740	-45 892	-26 132	-8 261
30											………
31											
32											
33											
34											
35											
36											
37											
38											
39											
40											
41											
42											
43											

	A	B	C	D	E
1	**- Solar PV mini-grid annual NPV plot procedure with fixed tariff and annual loss factor (Formula view) -**				
2					
3	**ASSUMPTIONS / INPUT:**				
4	Plant size:	30	kWp		
5	CAPEX for off-grid solar plant:	=E61	USD/kWp		
6	# of days autnomy (battery back-up):	5	days	***Annual NPV plot variables***	
7	OPEX:	0,005		Annual loss factor 0.5 %	
8	System losses:	0,3		Tariff fixed at 1 US$	
9	GHI, high irradiation	=2400	$kWh/m^2/yr$		
10	GHI, low irradiation	=1700	$kWh/m^2/yr$		
11	Relationship between GHI and specific yield:	0,8			
12	Discount rate:	0,1		0,1	0,1
13					
14					
15	**CALCULATIONS**			**Year number.... Up to and including year no 25**	
16	**PV system:**		0	=C16+1	=D16+1
17	Installation cost, PV system:	USD	=B4*B5		
18	TOTAL Investment costs:	USD	=SUM(C17:C17)		
19	OPEX	USD		=$C$18*$B$7	=$C$18*$B$7
20	TOTAL COSTS	USD	=C18	=SUM(D17:D19)	=SUM(E17:E19)
21	Total life cycle costs (NPV) over 25 yrs	USD	=(NPV(B12;Solar!D20:AG20))+Solar!C20		
22					
23	**="Energy production, high irradiation:"**	kWh		=$B$9*$B$11*$B$4	=$B$9*$B$11*$B$4
24	Total life cycle energy production (NPV) over 25 yrs	kWh	=NPV(B12;D23:AB23)	*Loss factor*	=1-0,005
25				1	*Tariff*
26	**="Energy production, low irradiation:"**	kWh		=$B$10*$B$11*$B$4*$D$25	=D26*E24
27	Total life cycle energy production (NPV) over 25 yrs	kWh	=NPV(B12;D26:AB26)	=$C$18	=$C$18
28			**Annual surplus**	=D26-D19	=E26-E19
29			**Annual NPV plotted**	=(-D27)+(NPV(B12;D28))	=(-E27)+(NPV(B12;D28:E28))
30					....
31					
32					
33					
34					
35					
36					
37					
38					
39					
40					
41					
42					
43					

Appendix D

Survey with stakeholders in Tanzanian rural electrification

A survey was conducted to identify political/institutional barriers to RETs on mini-grids. In addition, semi-structured interviews were conducted with each participant, in order to retrieve additional potential barriers not covered by the survey. The key findings are presented in Chapter 9.

Participant no	Institution/stakeholder
1	**Norwegian Embassy in Dar es Salaam**
2	**Tanesco**
3	**Tanzania Investment Bank, Rural Energy Fund manager**
4	**Tanzania Investment Bank, off-grid projects manager**
5	**Ensol Ltd. Solar PV developer**
6	**Department of Renewable Energy Technology, University of Dar es Salaam**
7	**Department of Environmental Sciences, University of Dar es Salaam**
8	**IED**
9	**REA**
10	**EWURA**
11	**Tanesco Thermal Departement**

Survey results

Question no	Participant no	1	2	3	4	5	6	7	8	9	10	11	
1		3	2	2	1	2	3	2	2	1	3	2	Score (0-4)
2		3	3	3	2	2	3	1	2	2	0	2	
3		0	2	0	0	0	0	3	0	2	1	0	
4		2	3	0	0	2	2	1	1	2	2	0	
5		1	0	1	0	2	0	3	0	2	0	2	
6		2	0	2	2	2	2	2	2	2	2	0	
7		2	0	0	0	2	3	2	0	2	3	2	
8		2	0	0	0	1	2	3	0	2	3	2	
9		2	2	0	0	2	3	3	0	1	0	0	
10		1	2	3	2	1	2	1	0	1	1	2	
11		1	2	0	0	1	0	0	0	2	0	0	
12		0	1	2	0	2	2	1	0	1	2	0	
13		0	1	2	0	2	2	1	0	1	0	0	
14			1	2	2	1	0	0	1	0	2	0	
15		0	0	1	0	1	2	3	0	1	1	2	
16		3	2	3	1	2	3	2	2	2	3	2	
17		2	3	1	1	2	3	3	3	2	3	0	
18		1	0	0	1	3	2	3	1	1	3	0	
19		1	1	0	0	0	2	2	0	0	0	2	
20		3	2	0	0	1	3	3	2	3	3	2	
21		1	3	1	0	1	2	1	2	1	1	2	
22		0	0	1	1	2	1	3	2	0	3	2	

Stakeholder survey results

2	23	2,090909091	**Barrier**	Insufficient access to skilled personel to operate and maintain RETs in rural areas
3	8	0,727272727	**Not**	RETs can in general not provide the same security of supply as Diesel generators
4	15	1,363636364	**Might**	Business as usual mechanisms in rural electrification projects are promoting the choice of diesel on mini-grids
5	11	1	**Not**	General understanding among decision-makers that diesel is the cheaper option for off-grid electrification
6	18	1,636363636	**Might**	RET CAPEX represent a risk too high for most investors
7	16	1,454545455	**Might**	Low household affordability in rural areas prevents locals from choosing high capex projects
8	15	1,363636364	**Might**	A general lack of productive uses in off-grid villages prevents high capex projects
9	13	1,181818182	**Might**	Environmental benefits of RETs compared to diesel are ignored by decision-makers in off-grid projects
10	16	1,454545455	**Might**	Low level of RET education amongst satkeholders in off-grid electrification projects
11	6	0,545454545	**Not**	Challenges related to training and educating locals in RET operation and maintenance prevents RETs on mini-grids
12	11	1	**Not**	The supply chain for Solar PV systems (equipment and entrepenours) is not fully accessible and understood by project developers
13	9	0,818181818	**Not**	The supply chain for micro hydropower systems (equipment and entrepenours) is not fully accessible and understood by project developers
14	9	0,818181818	**Not**	The supply chain for biomass power systems (equipment and entrepenours) is not fully accessible and understood by project developers
15	11	1	**Not**	Incompatible or unclear donor policies prevents RETs on mini-grids
16	25	2,272727273	**Barrier**	Insufficient available funding from REA to cover high CAPEX of RETs on mini-grids
17	23	2,090909091	**Barrier**	Uncertainty of income from rural mini-grids scares off private investors
18	15	1,363636364	**Might**	The government and leading institutions (REA, Tanesco, Ewura, TAREA) have insufficient capacity to assist developers in carrying out resource assessments, planning and implementation of RET rural projects
19	8	0,727272727	**Not**	Diesel generators can provide power to a broader range of appliances than RETs (e.g. high voltage machinery)
20	22	2	**Barrier**	Domestic and local governments await for future grid extension, as they believe it is more cost efficient than off-grid solutions
21	15	1,363636364	**Might**	For diesel generators, there is significantly higher access to spare parts and skilled personell than for RETs in rural areas
22	15	1,363636364	**Might**	Representatives of the diesel supply industry influence decision-makers in rural electrification projects

Quick Survey:

Diesel vs. Renewable Energy Technologies on mini-grids in rural Tanzania

Background: Renewable energy technologies like e.g. solar photovoltaic systems (Solar PV systems) and micro hydropower systems are now proving to be cheaper than diesel generators for small, isolated grids (mini-grids) in rural electrification projects. Yet, diesel generators are still being installed at a large scale throughout Africa.

This survey aims to identify the primary barriers preventing a switch from diesel-based mini-grids to renewable energy technologies for electrification in rural areas. Please read the following statements carefully and give *your own opinion* on to which extent the statement is true or not. Please do this by circling one of the five options.

<u>Example</u>: *You are a very helpful person.*

1. Not true **2. Somewhat true** **3. True** **4. Very true**

Thank you so much for your participation and honest opinion!

<u>Please fill in first:</u>

Your organization:

Your country of origin:

Your e-mail:

---

1. For renewable energy technologies in general, there is low access to required materials for maintenance in rural areas.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

2. For renewable energy technologies in general, there is low access to skilled/specialized personnel when maintenance is needed in rural areas.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

3. Solar PV systems cannot provide the required level of supply security in rural areas, due to low generating capacity and low storage capacity.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

4. Micro hydropower can in general not provide security of supply due to frequent periods of draught.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

5. Any renewable energy technology on an isolated grid needs to be combined with a diesel generator (hybrid), in order to ensure security of supply.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

6. There is a general understanding amongst investors and project developers in Tanzania that renewable energy technologies are more expensive than diesel generators in the long run for rural electrification.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

7. For investors, there is too much risk related to renewable energy projects (solar PV and micro hydro systems), due to a high level of capital costs.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

8. Poverty and low household affordability in rural areas are preventing technologies with high capital costs in rural electrification projects.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

9. Lack of productive uses (local industry) in rural areas is preventing technologies with high capital costs in rural electrification projects.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

---

10. The environmental benefits of renewable energy technologies (reduced carbon emission, reduced noise and reduced local pollution) are <u>not</u> considered and appreciated by decision-makers within rural electrification projects in Tanzania.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

11. The environmental benefits of renewable energy technologies are appreciated in Tanzania in general, but there is low access to information and knowledge about these technologies, which is why diesel generators are frequently chosen for rural electrification.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

12. For local operators in rural areas, there is low interest in gaining the necessary knowledge required to operate and maintain renewable technology power systems.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

---

13. The supply chain of solar PV systems (for installation and maintenance) is <u>not</u> fully accessible and understandable for the decision-makers in rural electrification projects.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

14. The supply chain of micro hydropower systems (for installation and maintenance) is <u>not</u> fully accessible and understandable for the decision-makers in rural electrification projects.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

15. Incompatible and/or unclear International Donor policies are <u>preventing</u> a switch to renewable energy technologies for rural electrification.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

16. There is generally not enough funding available for covering the high capital costs related to renewable energy solutions for rural electrification.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

17. Rural electrification projects are not attractive to private investors, due to uncertainty of income.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

18. The leading institutions and government in Tanzania have insufficient capacity and resources to carry out planning and implementation of site-specific renewable energy projects for rural electrification.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

19. Lack of competence and knowledge about renewable energy technologies within the REA and/ or Tanesco and or/other institutions in Tanzania prevents these technologies from being utilized in rural electrification projects.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

20. <u>Extension</u> of the existing national grid is considered a more cost-efficient and viable option amongst decision-makers than isolated grids for the purpose of rural electrification.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

21. Diesel generators are technically more reliable than Solar PV systems for rural electrification on small isolated grids.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

22. For diesel generators in rural areas, there is high access to required materials and skilled personnel for maintenance.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

23. The diesel supply industry has significant influence on decision-makers in rural electrification projects.

1. Not true **2. Somewhat true** **3. True** **4. Very true**

Thank you very much for participating in this survey!

Kind regards,
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