MSc Program
Renewable Energy in Central and Eastern Europe

Technical, economic, environmental and socio-political potential assessment for hybrid mini-grids for rural electrification in developing countries - A case study for a 100% renewables mini-grid configuration in Thailand

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Affidavit

I, **Georg Schoen**, hereby declare

1. that I am the sole author of the present Master Thesis, “technical, economic, environmental and socio-political potential assessment for hybrid mini-grids for rural electrification in developing countries - a case study for a 100% renewables mini-grid configuration in Thailand”, 127 pages, bound, and
2. that I have not used any source or tool other than those referenced or any other illicit aid or tool, and that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The thesis demonstrates the important role of hybrid mini-grid systems for rural electrification in developing countries. It undertakes a technical, economic, environmental and socio-political potential assessment for hybrid mini-grids for rural electrification in developing countries. First, it characterizes the market potentials and growth forecasts for hybrid mini-grids for rural electrification in developing countries building upon the latest trends in international development. Then it undertakes a rigorous technical assessment of the mini-grid distribution infrastructure, hybrid mini-grid configuration options and renewable energy generation technologies focusing on solar and wind energy. Consequently, the thesis develops an economical feasibility study for a mini-grid system based on 100% renewables on a remote island in Southern Thailand using the energy modeling software HOMER. Several simulations are run and the results are discussed and contextualized. Business model options for hybrid-mini grids are discussed and important factors characterized, such as tariff schemes and financing modalities. Contrasting economic and technical feasibility of hybrid mini-grids with local factors determining their implementability, adds the socio-political dimension to the analysis on hybrid-mini grids for rural electrification in developing countries. Finally, the regulative and policy framework for hybrid mini-grids is discussed, as only an enabling environment allows large scale and sustainable deployment of hybrid mini-grids for rural electrification in the developing world.

Table of Content

List of Tables

List of Figures

Figure 51: Market segmentation for PV/diesel hybrid systems for rural electrification in developing countries (type of system with upfront investment cost). Source: IEA PVPS Task 09/CLUB-ER 2013, page 18.

List of Maps

Acronyms

AC	Alternating Current
AGECC	UN Secretary-General's Advisory Group on Energy and Climate Change
ARE	Alliance for Rural Electrification
AWEA	American Wind Association
BOP	Bottom of the Pyramid
DC	Direct Current
ESCO	Energy Service Company
ESMAP	Energy Sector Management Assistance Programme
GEF	Global Environmental Facility
GMSA	Global System For Mobile Communication Association
HDI	Human Development Index
IEA	International Energy Agency
IFC	International Finance Corporation
IEA PVPS	International Energy Agency Photovoltaic Power Systems Program
IRENA	International Renewable Energy Agency
LPG	Liquefied Petroleum Gas
NREL	National Renewable Energy Laboratory
ODA	Official Development Assistance
O&M	Operation and Maintenance
PVGIS	Photovoltaic Geographical Information System
PPP	Public Private Partnership
PPA	Power Purchase Agreement
RES	Renewable Energy Sources
R&D	Research and Development
SHS	Solar Home System
SoC	State of Charge
SMWE	Small and Medium Wind Energy
UNDP	United Nations Development Programme
WB	World Bank

1. Introduction

1,3 billion people have no access to electricity today. If investments in energy access are not accelerated substantially in the coming years, 1 billion people will remain without access to electricity in 2030, with even worsening trends in Sub-Sahara Africa compared to today (IEA 2011). This is an enormous global development challenge, now tackled by the “UN Sustainable Energy For All Initiative”. Mini-grids are considered to be the most important approach for rural electrification in developing countries, as extension of national grids to remote areas is often too costly, and off-grid solutions do not provide sufficient electricity to enable local economic development. A mini-grid typically uses low AC voltage (220 or 380V) with centralized production and storage and has an installed capacity of between 5 and 300kW (ARE 2011b). A hybrid mini-grid power system uses renewable energy as a primary source and a genset (most of the time diesel fed but potentially with gasoline and LPG) as a backup resource (ARE 2011b, page 27). The IEA projects that around 600 million people will get access to electricity through mini-grids. Renewables will become the main energy source for mini-grids, as hybrid mini-grids with a high renewable energy fraction are already competitive with diesel-only systems in many locations around the world. Hybrid mini-grids have distinct advantages compared to diesel-only systems, such as reduced fuel costs and fuel dependency, improved reliability and availability of power, environmental and health benefits. The thesis shows that off-the-shelve technologies are available and ready for deployment, the bottom of the pyramid electricity market offers already today considerable business opportunities, and market potentials and growth forecasts are enormous. But the thesis also proves that a sole perspective on the technical and economic feasibility of hybrid mini-grid systems falls too short. To go beyond the technical and economic feasibility of a single application in a given locality, and to seize the full potential of hybrid mini-grids for rural electrification in developing countries, an integrated perspective is required that places socio-political conditions into the center of analysis. Large scale deployment of hybrid mini-grids depend on an enabling regulatory and policy environment, political stability, functioning governance and market structures, technical capacities, public awareness, entrepreneurs and innovative business models, creative tariff structures that relate to the ability and willingness to pay, the availability of innovative financing mechanisms or the elimination of unsustainable subsidies for fossil fuels. Thus, the thesis aims to transcend a mere economical, technological and environmental assessment of hybrid mini-grids, and enrich the discussion through an ecosystem-centered perspective that places socio-political realities into the center of analysis.

1.1 Motivation

Last year the UN declared the "International Year of Sustainable Energy for All" and launched the "Sustainable Energy for All Initiative". It is placing energy access at the core of the international development agenda; is mobilizing countries, institutions and companies across the globe to commit to close the energy access gap; and presents an unprecedented opportunity to reach the 1,5 billion people yet not benefiting from modern energy services till 2030. Hybrid mini-grids play an important role in this context, as they allow for sufficient electricity provision to enable local economic development. The thesis aims to analyze the role of renewable energies for lifting millions of people out of extreme poverty and marginalization, while empowering them to shape their own local development aspirations in an energy autonomous world, and leapfrogging traditional unsustainable development pathways.

1.2 Core objective and question

The core objective of this thesis is to demonstrate the important role of hybrid mini-grid systems for rural electrification in developing countries, i.e. for closing the energy access gap and for providing sufficient electricity to enable local economic development. The core question that is driving this thesis is whether hybrid mini-grids (with a high degree of renewable energy fraction) for rural electrification in developing countries present a technically feasible, economically viable, and socio-politically achievable electrification alternative.

The thesis applies a multifaceted approach and integrated perspective to answer this question. First, it characterizes the market potentials and growth forecasts for hybrid mini-grids for rural electrification in developing countries building upon the latest trends in international development. Then it undertakes a rigorous technical assessment of the mini-grid distribution infrastructure, hybrid mini-grid configuration options and renewable energy generation technologies focusing on solar and wind energy. Consequently, the thesis develops an economical feasibility study for a mini-grid system on a remote island in Thailand based on 100% renewables using the energy modeling software HOMER. Several simulations are run and the results are discussed, contextualized and contrasted by key issues found in the hybrid-mini grid literature. Then the focus of the thesis shifts to practical implementability. This places socio-political conditions into the center of analysis. Business model options for hybrid-mini grids are discussed and important factors characterized, such as tariff schemes and financing modalities. Finally, the regulative and policy framework for hybrid mini-grids is explained, as only an enabling environment allows large scale and sustainable deployment of hybrid mini-grids for rural electrification in developing countries.

1.3 Citation of main literature

Publications of the International Energy Agency were of crucial importance in order to gain an understanding about the market potentials of hybrid mini-grids in the context of the energy access debate. A key publication quoted by many other literatures in the field is “Energy for All. Financing Access for the Poor. Special early excerpt of the World Economic Outlook 2011” (IEA 2011). One of the achievements of this literature is to simulate the grid, off-grid and mini-grid approaches for closing the energy access gap, by calculating concrete numbers of deployment for each of these electrification approaches.

There are several flagship publication that focus on the technical and economical assessments of hybrid mini-grid technologies. The “Mini-Grid Design Manual” (ESMAP 2000) offers a technical assessment of the electricity distribution infrastructure, and the WB publication “Technical and economic assessment of off-grid, mini-grid, and grid electrification technologies” (WB 2007) describes in detail a wide range of available generation technologies, assigns costs to technology and electricity generation, and develops cost forecasts which are still useful for benchmarking purposes.

Publications of the IEA Photovoltaic Power Systems Programme (PVPS), especially publications delivered by the Task 9 “Deploying PV services for regional development” and Task 11 “PV hybrid systems within mini-grids”, where important for gaining a detailed understanding of specific technical and operational issues, such as applicable control methods and strategies, grid connection or communication between different components in hybrid mini-grids (e.g. IEA/PVPS Task 11 2012 or IEA/PVPS Task 09 2013).

Several publications of the Alliance for Rural Electrification (ARE) helped to put hybrid mini-grid systems in the context of rural electrification and the broader development discourse. Its flagship publication “Hybrid Mini-Grids for Rural Electrification. Lessons Learned” can be considered as one of the most important publications in this field, quoted by most of the current literatures reviewed (ARE 2011). It puts the technical and economical assessment of hybrid mini-grids into a broader picture and includes chapters on business models and the enabling regulatory and policy environment. Other more sectoral publications on “The Potential of Small and Medium Wind Energy in Developing Countries” (ARE 2012) or “Using Batteries to ensure clean, reliable and affordable universal electricity access” (ARE 2013) were extremely helpful to enter particular fields.

One additional WB publication was of paramount importance for developing an understanding about the range of regulatory and policy instruments required to create an enabling environment for hybrid mini-grid systems. The “REToolkit Issue Note. A Resource for Renewable Energy Development” (WB 2008) is a frequently quoted publication in this regard and provides the best overview about regulatory frameworks encountered in the research for this thesis. There are several publications commissioned by other multilateral development agencies and funds that help to acquire knowledge about national enabling frameworks for hybrid mini-grid systems for range of countries. They are a deep source for learning and comparative analysis (e.g. UNDP 2004 or UNDP 2005).

The IFC publication "From Gap to Opportunity: Business Models for Scaling Up Energy Access" (IFC 2012) is the most important publication currently available on commercial viable business models for hybrid mini-grid systems and the bottom of the pyramid electricity market. It demonstrates impressively that a potent market for modern energy services delivered by renewables already exists which needs to be seized by entrepreneurial pioneers, as poor people in many places currently pay far more for electricity delivered by traditional sources than they would pay for hybrid mini-grid solutions.

And last but not least, Graencen et al (2007) was instrumental for developing my own simulation case in HOMER. The publication is called "Renewable Energy Options on Islands in the Andaman Sea - A feasibility study for hybrid renewable energy/diesel systems in two Tsunami impacted communities". It offers a transparent access to the data sets and simulation exercise conducted in the energy simulation software HOMER. The feasibility study for the village Bahn Koh Pu on a remote island in Southern Thailand presented in this publication served as the base case scenario for my own HOMER simulation exercises. It is the most transparent and accessible publication of a HOMER simulation exercise on a hybrid mini-grid system encountered in the research and literature review for this thesis.

1.4 Structure of work

The second chapter of this thesis looks at the market potential for hybrid mini-grid systems for rural electrification in developing countries. The theoretical market potential is framed by IEA analysis, which indicates that an average annual investment of 30 billion USD is needed to achieve universal access to electricity by 2030. From the approximately 1,3 billion people lacking access to modern electricity provision today, around 600 million people will be electrified via mini-grids by 2030 (IEA 2012, page 539). The chapter presents a range of tools and instruments that can be useful to assess national and local markets. It emphasizes that research priorities currently shift from a focus on technologies to a focus on enabling market conditions. The theoretical market potential is contrasted with the immediate addressable market potential for hybrid mini-grids, which is estimated by the IFC at investments of 4 billion USD per year for mini-grids. This estimate is based upon the current cash expenditure patterns of bottom of the pyramid (BOP) energy consumers (IFC 2012, page 32). The chapter concludes with highlightening the hidden market potential of retrofitting already established diesel mini grids, e.g. in the rural telecom operators market.

The third chapter undertakes a technological, economic and environmental assessment of hybrid mini-grid system configuration options. A range of physical and technological components are described that form the backbone of mini-grid configurations. Each physical and technological component offers a variety of options that need to be assessed and chosen in the design and planning process of mini-grids in order to assure technological feasibility, cost-effectiveness and quality of supply. Hybrid mini-grids can be AC or DC coupled power systems. There are four options how AC power sources in the mini-grid perform the "grid forming" function to control the mini-grid frequency and voltage (IEA/PVPS Task 11 2012). Options for distribution line configuration encompass the single phase supply and the three-phase supply, each of them split in two sub-options. Together they form the four basic distribution line configurations for a village mini-grid. For the purpose of this thesis, only these components have been discussed in depth. The chapter concludes with a technical and economic assessment of power delivery. It characterizes the costs caused by the power delivery loss rate, which later on allows a more complete perspective of the total system costs of hybrid mini-grid systems.

The fourth chapter describes the renewable energy technology generation options for hybrid mini-grids and conducts an in depth technological and economical assessment of PV and wind power in the context of hybrid mini-grid deployment. The solar PV assessment starts with a detailed discussion about the PV technology and associated price developments for PV installations. It describes the multiple factors influencing the power output of PV systems, and explains the correlation between generation and load profiles in rural areas in developing countries. Several examples of PV micro-grids and hybrid PV/diesel mini-grids are discussed in length, highlightening the important role of island inverters. System costs for hybrid mini-grids are assessed based on an in-depth literature review and the market segmentation for hybrid mini-grids is characterized. The second part of this chapter makes a technological and economical assessment of Small and Medium Wind Energy (SMWE) in the context of hybrid mini-grid deployment. The assessment starts with a short market overview about SMWE technologies before analyzing in depth the available SMWE technologies, the multiple factors determining the wind energy output, as well as the costs of off-the-shelf SMWE technologies and wind electricity generation. The chapter concludes with a technological cost comparison of renewable energy generation technologies and hybrid mini-grid systems.

The fifth chapter uses the energy modeling software HOMER to simulate a number of hybrid mini-grid configurations with associated cost assessments. The first part of the chapter describes two examples of how HOMER is used for mini-grid system planning in order to create a reference framework for the thesis case study. The first one presents a real case taken from the Andaman Islands of Southern Thailand, and shows how existing scattered energy infrastructure of an island village can be integrated in a hybrid mini-grid system, utilizing HOMER to calculate the least cost option for the system configuration and developing the system's feasibility study (Greancen et al 2007). This becomes later the base case scenario for the own simulation exercise. The second study is taken from the flagship publication on hybrid mini-grids of the Allianz for Rural Electrification (ARE 2011), and showcases that hybrid mini-grids are in most cases, the least-cost, long-term option for rural electrification. Building the case for a model village in Ecuador, the analysis tests a range of hybrid solutions to prove that at current capital costs and with adequate natural conditions, hybrid solutions with high renewable energy fractions are competitive with diesel-only systems. This analysis is later contrasted with the results of the own HOMER simulation exercise.

The second part of this chapter comprises a range of simulation exercises conducted by the author of this thesis. The first optimization exercise uses adjusted cost inputs for the different components as presented in Graencen et al (2007). The original study was produced in 2007 and cost inputs are outdated. Instead, cost inputs for the different generation technologies are taken from the publication ARE 2011 and own research. This is done in order to assess whether the optimal system configuration designed by Graencen et al in 2007 for the hybrid mini-grid in the village Bahn Koh Pu would look different today based on adjusted cost variables, including the sensitivity analysis for future demand fluctuations. The second optimization exercise includes variations in wind speed and solar radiation as an additional variable. It aims to assess how the system configuration would change at wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day (which are inputs for local natural conditions used in ARE 2011, assumed to be typical local conditions in many developing countries). The third optimization exercise aims to assess costs for higher levels of renewable energy fraction. It builds upon the new base case scenario (with the adjusted prices) and the second modeling exercise for wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day. The second generator is erased here as option in the system configuration, and capacity for generator #1 is kept constant (as already available in the system). The fourth optimization exercise aims to assess costs for higher levels of renewable energy fraction. It builds upon the new base case scenario and the second modeling exercise for wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day. The second generator is erased as option in the system configuration, as well as generator #1. A 10 kW diesel generator is added to serve as back up and for covering peaks. Finally, a capital investment cost subsidy of 40% and its impact on the LCOE is simulated and consequences for tariff setting discussed. The different outcomes of the simulation exercises are compared at the end and results interpreted.

The sixth chapter moves away from assessments of technical and economical feasibility towards a focus on practical implementability. The first part describes the four ownership and business model options for implementing hybrid-mini grid projects: the Utility Model, the Community-based Organization Model (including cooperatives), the Private Sector Model and the Hybrid Model (ARE 2012). Then the emphasis is turned to tariff schemes. Determining appropriate tariff schemes is at the core of successful business model. The chapter highlights that cost-recovery and cost-based tariffs are an important prerequisite for private sector involvement. At the same time full cost recovery is often not feasible because of the low ability to pay in rural areas. Therefore smart subsidy schemes for hybrid mini-grid projects exist in order to assure affordability. Tariffs must always be set in relation to the affordability and willingness to pay, as well as existing subsidy schemes. Then the chapter moves to one of the biggest barriers for the implementation of hybrid mini-grid systems: financing. High initial capital investment requirements, paired with limited local financing options, pose a threat to many technical and economical feasible hybrid mini-grid projects. The chapter describes the various sources of capital required by mini-utilities during an investment cycle. The chapter concludes with other important success factors for hybrid mini-grid projects, such as ensuring adequate demand of electricity, developing the right operational model and ensuring sufficient management expertise for scaling-up successful pilots.

The seventh chapter describes several ecosystem conditions which need to be in place for mini-utilities to operate successfully. The first one is that mini-utilities need to be allowed to operate legally, which is by no means a given starting point considering that electricity distribution was treated as a natural monopoly throughout recent history. Furthermore, complicated mini-utility licensing and permitting barriers can prevent enterprises to enter the mini-utility market. One of the areas where over-regulation can hamper the development of mini-grids are tariffs, which are sometimes set at the same level as the prices charged by large utilities. Connection and capital cost subsidies which help closing the "viability gap" (the shortfall between revenues that customers are able to contribute and those needed for enterprises to be financially workable) can be an important enabling factor (IFC 2012). Some countries set-up strategic planning frameworks for rural electrification with associated local delivery mechanisms (in form of e.g. rural electrification agencies). They can boost the deployment of hybrid mini-grids by tendering concessions, generating market intelligence, mapping resources or raising the awareness of local communities and entrepreneurs about the benefits of renewable energies.

1.5 Description of method and approach to calculate the case study

The micropower optimization model HOMER was used to calculate the hybrid mini-grid case study presented in this thesis (see chapter 5). HOMER was developed by the National Renewable Energy Laboratory of the U.S. Department of Energy. It is an internationally recognized tool for energy system modeling and used by energy system planners across the globe. HOMER evaluates designs of both off-grid and grid-connected power systems for a variety of applications. It helps to determine the kind of components that need to be included into the system design as well as the number and sizes of components to be used. Based on provided input data, HOMER simulates the annual performance of a variety of possible system designs in order to find a configuration that satisfies technical constraints at the lowest life-cycle costs. The outcome of the simulation is a list of the possible systems in the order of life-cycle costs (IEA PVPS 2011, page 20). “HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, HOMER compares the electric and thermal demand in the hour to the energy that the system can supply in that hour, and calculates the flows of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides for each hour how to operate the generators and whether to charge or discharge the batteries” (NREL 2011, page 4). Then it performs this analysis for each considered system configuration and determines whether a configuration is feasible, i.e. whether it can meet the electric demand under the specified conditions, as well as estimates the cost of installing and operating the system over the lifetime of the project (NREL 2011, page 4). HOMER includes an optimization function, which allows comparing different system design options and can perform sensitivity analysis for system configuration variables, such as stronger wind speeds or escalating fuel prices. Chapter five describes in detail how HOMER was used for the purpose of modeling the case study presented in this thesis.

2 Market Potentials for Hybrid Mini-Grids for Rural Electrification in Developing Countries

The aim of this chapter is to characterize the market potential for hybrid mini-grid systems for rural electrification in developing countries. The theoretical market potential is framed by a renowned and frequently quoted IEA analysis, which indicates that an average annual investment of 30 billion USD is needed to achieve universal access to electricity by 2030 (IEA 2012). From the approximately 1,3 billion people lacking access to modern electricity provision today, around 600 million people will be electrified via mini-grids by 2030 (IEA 2012, page 539). The theoretical market potential is contrasted with the immediate addressable market potential for hybrid mini-grids, which is estimated by the IFC at investments of 4 billion USD per year for mini-grids. This estimate is based upon the current cash expenditure patterns of bottom of the pyramid (BOP) energy consumers (IFC 2012, page 32). In addition, the chapter highlights the hidden market potential of retrofitting already established diesel mini grids, e.g. in the rural telecom operators market, and its benefits for rural electrification. The chapter concludes that research priorities currently shift from a focus on technologies to a focus on enabling market conditions.

2.1 The Theoretical Market Potential for Hybrid-Mini Grids for Rural Electrification in Developing Countries

Energy access is becoming a key pillar of the international development agenda. Thus, conducive frameworks are in the making to enable large scale deployment of off-grid, mini-grid and grid electrification technologies in developing countries. Consequently, markets for rural electrification technologies will evolve more rapidly in the future. This will create enormous investment and business opportunities. The IEA estimates that a total investment of 979 billion USD would be required to achieve universal energy access by 2030, which accounts to an average of 49 billion USD per year from 2011 to 2030 (see IEA 2012, page 538). Projecting current trends of global spending and commitment towards achieving universal energy access for all (under the "New Policy Scenario" this amounts to 296 billion USD cumulative investment from 2010 to 2030, or 14 billion USD annually), the IEA estimates that there will be a shortfall of 678 billion USD by 2030. This equals an average of 34 billion USD per year of investment deficit to achieve universal access to energy by 2030 (see IEA 2012, page 538; see also IFC 2012, page 22).[1]

The largest portion of the total investments is needed for providing universal electricity access. Here the gap alone will amount to a total investment deficit of 602 billion USD by 2030, an average of 30 billion USD per year (IEA 2012, page 539). As the following table indicates (see Table 1), this lack of investments - together with an increasing global demography - will keep still 1 billion people without electricity in 2030. There are even worsening trends expected for Sub-Sahara Africa.

[1] For this analysis, the IEA defined modern energy access as "a household having reliable and affordable access to clean cooking facilities, a first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average" (IEA 2011, page 12). The initial level of electricity consumption for rural households is assumed here to be 250 kWh per year and for urban households 500 kWh. Here, electricity consumption is assumed to rise gradually over time, attaining the average regional consumption level after five years. The average level of electricity consumption of newly connected households will be 800 kWh in 2030 according to the IEA analysis (EIA 2011, page 12). Here access to modern energy services is defined at the household level. Electricity access to business or public buildings such as schools or hospitals is excluded. It indicates that incremental investments are required to provide sufficient energy for productive usage. In contrast to this working definition, the UN Secretary-General's Advisory Group on Energy and Climate Change defined in its summary report "Energy for a Sustainable Future" (2010), universal energy access as "access to clean, reliable and affordable energy services for cooking and heating, lightning, communications and productive uses" (AGECC 2010, page 9). This broad definition was adopted as energy for productive uses is needed to drive sustainable local economic development in the poorest countries, a prerequisite for income generation and the end user's ability to pay for energy services (AGECC 2010, page 13). These varying definitions reveal that there is no universally-adopted and agreed definition of modern energy access, a fact that complicates the comparison of data.

	2009			2030		
	Rural	Urban	Share of population	Rural	Urban	Share of population
Africa	466	121	58%	539	107	42%
Sub-Saharan Africa	*465*	*121*	*69%*	*538*	*107*	*49%*
Developing Asia	595	81	19%	327	49	9%
China	*8*	*0*	*1%*	*0*	*0*	*0%*
India	*268*	*21*	*25%*	*145*	*9*	*10%*
Rest of developing Asia	*319*	*60*	*36%*	*181*	*40*	*16%*
Latin America	26	4	7%	8	2	2%
Middle East	19	2	11%	5	0	2%
Developing countries	1 106	208	25%	879	157	16%
World	**1 109**	**208**	**19%**	**879**	**157**	**12%**

Table 1: Number of People without excess to electricity by region in the new polices scenario (million). Source: IEA 2011, page 16.

The practical constrains and inherent necessities of the access gap together with complex geographies will require the application of centralized and decentralized energy technologies and systems for electricity provision, i.e. grid extension, mini-grid access and off-grid access. Grid extension is seen by the IEA as the most suitable option for all urban zones and approximately 30% of rural areas in proximity to urban centers. The remaining 70% of rural areas will need to be connected via mini-grids and small, stand-alone off-grid solutions. According to IEA, mini-grids will play the overwhelming role in these remote rural areas with a share of 65%, leaving a 35% share for stand-alone off-grid solutions (EIA 2011, page 21). Mini-grids are seen as a competitive solution for rural areas which enable future demand growth for income generating activities.[2] As 1,3 billion people lack access to electricity today, this analysis projects that 591,5 Million people would have access to electricity via mini-grids by 2030.

As the following table indicates (see Table 2), the total additional investment need to achieve universal access to electricity is estimated by the IEA to be around 640 USD billion between 2010 and 2030 (in comparison to the IEA business as usual scenario). But alone 60% of the additional investments (related to the IEA business

[2] This assumption is based on an assessment of regional cost per MWh in relation to available technology options, regional cost structures and population density. Off grid stand-alone systems have in consequence higher costs per MWh as mini-grids according to this analysis (EIA 2011).

as usual scenario) need to go to Sub-Saharan Africa. Here reliance on mini-grids and isolated off-grid solutions is projected to be even more significant (EIA 2011, page 21).

	2010-2020	2021-2030	Total
Africa	119	271	390
Sub-Saharan Africa	*118*	*271*	*389*
Developing Asia	119	122	241
India	*62*	*73*	*135*
Rest of developing Asia	*58*	*49*	*107*
Latin America	3	3	6
Developing Countries*	243	398	641
World	**243**	**398**	**641**

*Developing countries total includes Middle East countries.

Table 2: Additional Investment required to achieve universal access to electricity in the Energy for All Case (billion in year-2010 Dollars). Source: IEA 2011, page 22.

As indicated in the figure below (see Figure 1), mini-grid and off grid solutions account for the greater part of the needed additional investments, amounting to 20 billion USD annually from 2010 to 2015 (connecting 25 million people annually), with an increase over time, reaching 55 billion USD per year towards 2030 (connecting 80 million people annually plus covering the higher level of consumption expected from earlier connected households) (EIA 2011, page 22).

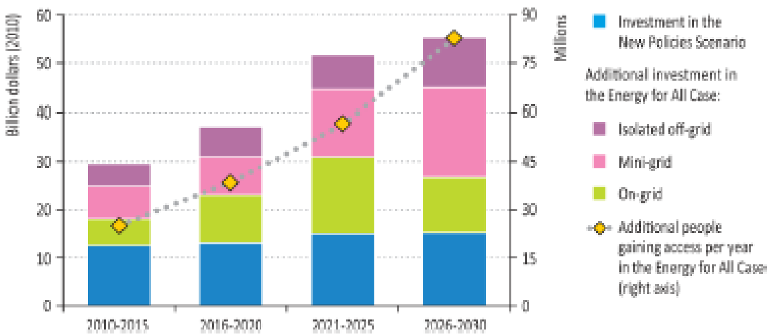


Figure 1: Average Annual Investment in Access to Electricity by type and number of people connected in the Energy for All Case. Source: IEA 2011, page 22.

To achieve universal access to electricity by 2030, a total incremental electricity output of around 840 TWh, and additional power generation capacity of around 220 GW is required. Universal access by 2030 will require 379 TWh of grid electricity, 399 TWh for mini-grids and 171 TWh for off-grid electrification (IEA 2011). This results in an increase in global electricity generation of only 2,5% and an increase of global CO2 emissions of 0,7% (EIA 2011, page 26). As indicated in the below figure (see Figure 2), for mini-grids and off grid stand alone solutions, it is expected that more than 90% of electricity will be provided by renewables. In comparison, it is projected that 63% of on-grid electricity generation will be based on fossil fuels.

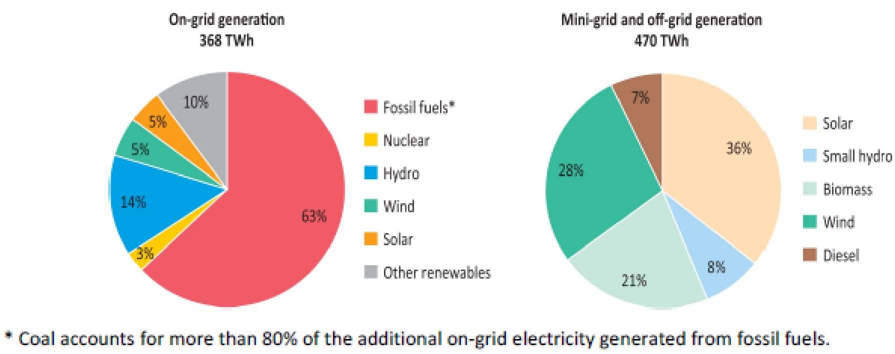


Figure 2: Additional electricity generation by grid solution and fuel in the Energy for All Case 2030. Source: EIA 2011a, page 26.

The needs for financing the universal access to energy are significant. EIA estimates that from 2010 to 2030 18 billion USD of investments per year needs to come from multilateral banks and Official Development Assistance (ODA). This requires a restructuring of development priorities (as currently under way through the UN Sustainable Energy for All Initiative). 15 billion USD per year needs to be invested by governments of developing countries and another 15 billion USD per year by the private sector. This requires the development commercially viable business models at significant scale (IEA 2011, page 29), good governance and an enabling regulatory framework.

According to the EIA, 12 billion USD of investments per year is required for mini-grid electrification to connect in average 19 million people with electricity annually (EIA 2011, page 31). The majority of these investments need to be shouldered by governmental budgets and the private sector, supported by bilateral and multilateral development assistance (in form of technical assistance, grants, concessional loans, investment guarantees and carbon finance). Developing country government sources include the balance sheet of state-owned utilities, subsidies provided by the government, grants and loans offered by developing country national development banks, and specialized national institutions and funds, such as rural energy agencies (EIA 2011, page 40). Private sector financing is assumed to come from international banks, local banks and microfinance institutions, international and domestic project developers, concessionaires, contractors and risk capital providers such as venture capital funds, private equity and pension funds (see EIA 2011, page 41). The following figure (see Figure 3) summarizes the annual investment needs and sources of financing.[3]

	Annual Investment ($ billion)	People gaining access annually (million)	Level of household energy expenditure	Main source of financing	Other sources of financing
On-grid	11.0	20	Higher	Private sector	Developing country utilities
			Lower	Government budget	Developing country utilities
Mini-grid	12.2	19	Higher	Government budget, Private sector	Multilateral and bilateral guarantees
			Lower	Government budget	Multilateral and bilateral concessional loans
Off-grid	7.4	10	Higher	Multilateral and bilateral guarantees and concessional loans	Private sector, Government budget
			Lower	Multilateral and bilateral concessional loans and grants	Government budget

Figure 3: Additional financing for electricity access in the Energy For All Case compared with the New Policy Scenario. Source: EIA 2011, page 31.

2.2 The Addressable Market for Hybrid Mini-Grids for Rural Electrification in Developing Countries

To frame the energy access gap as a market opportunity for the private sector and not only as a development challenge is a rather new phenomenon and progressively promoted by multilateral financial institutions such as the International Finance Corporation (IFC). The 4 billion poor people living of less than 1,500 USD annually, the so called "bottom of the pyramid" (BOP), have long been invisible to the

[3] The most important enabler for increasing private sector investments is the prospective rate of return. A sufficient level of financial returns can be enabled through specific forms of governmental support. According to Lamech and Saeed (2003), important factors for private investors in the power sector typically include a legal framework; consumer payment ability, discipline and enforcement; credit enhancement or guarantees; and an independent regulatory process (see more in a later chapter).

corporate sector. Since more than a decade they slowly moved into the center of attention of corporations, social entrepreneurs and impact investors. Developing business models that include poor people into value chains as consumers and producers and building commercial infrastructure at the bottom of the pyramid through creating buying power, shaping aspirations, designing local solutions and improving access has opened the door to a yet largely untapped market (Prahalad and Hart 2002). Policymakers and donors have started redirecting their efforts in order to catalyze private sector action and to help the private sector to size these markets.

This is also true for the energy market, where a growing number of entrepreneurs are demonstrating that profitable ventures can be created in low-income markets that extend energy access to the poor (even for those earning less than 2 USD a day). The IFC (2012) has calculated that there is already an addressable market for modern energy solutions, i.e. that many poor could afford to switch to modern energy technologies as they currently pay more for traditional lightning and heating solutions. It requires innovative business models to capture this immediately addressable market, which could be furthermore accelerate by eliminating market barriers, improving regulations and policies or providing access to adequate financing options.

The IFC calculated that the poor spend 37 billion USD annually on poor-quality energy solutions to meet their lightning and cooking needs. This represents a largely untapped market opportunity for the private sector (IFC 2012). IFC estimates that the BOP currently spends 18 billion USD annually on lightning and charging services for small appliances, while 19 billion USD is spend on wood and charcoal for cooking and heating on inefficient stoves and fireplaces (in total up to 10% of monthly income). IFC argues that an estimated 90% of poor people already spend so much on kerosene lamps, candles, disposable batteries and battery-charging services to meet lightning needs that they could afford to purchase better options (IFC 2012, page 12). Modern energy solutions – such as devices, mini-grids or central utilities – have therefore the potential to replace spending on traditional lightning and small electricity expenditures.

This indicates that there is a market for "lightning plus", which can be split into solar and rechargeable lanterns, solar kits and modern electrification solutions such as solar home systems, or power supplied by mini-grids or central utilities (IFC 2012, page 29). IFC reckons that, based on current spending patterns and the cost of modern alternatives, about 256 million households could afford improved "lightning plus" services. This constitutes the theoretically "addressable market", which is the number of households that could afford now to pay the full commercial price of a service based on current spending patterns for traditional energy supply. According to IFC analysis, this results in a potential addressable market of 31 billion USD for devices, 4 billion USD for mini-grids and 2 billion USD for central grid connection annually, which is based upon the current cash expenditure patterns of BOP energy consumers (IFC 2012, page 32). Changing income levels, technological developments, supportive policies and regulations or consumer awareness and willingness to pay could substantially expand these markets. IFC concludes that where good business models meet appropriate financing and enlightened policy, rapid penetration of the market is possible despite the inherent challenges of BOP markets (page 36). The following figure (see Figure 4) shows the theoretically addressable BOP market for electricity and heating as per IFC analysis.

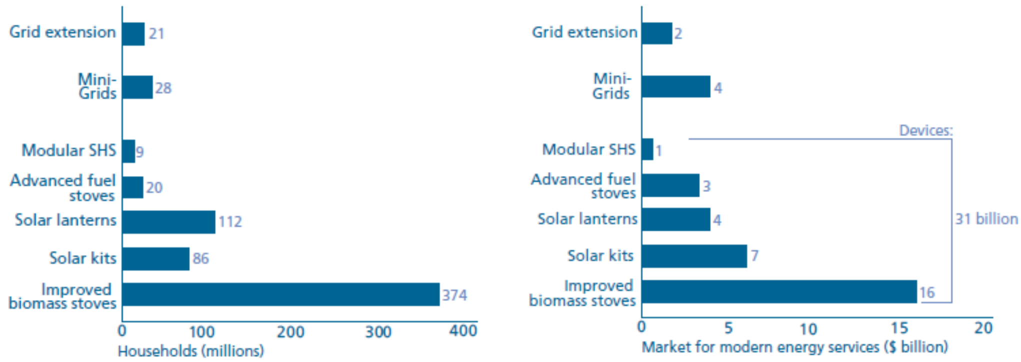


Figure 4: Theoretically addressable market by technology category. Source: IFC 2012, page 32.

The addressable market can be further segmented based on the purchasing power of costumers. According to the IFC, electricity options at 8,50 USD per month and above constitutes the addressable market for rooftop solar home systems, mini utilities and central utilities (a total of 58 million households, or 7 billion annually). Electricity options between 5,50 and 8,50 USD a month constitutes the addressable market for small and rooftop solar home systems (a total of 86 million households, or

7 billion annually) and electricity options between 1,25 and 5,50 USD a month constitutes the market for solar lanterns (a total of 112 million households, or 4,2 billion USD annually). IFC reckons that 10% of the households without access to modern energy solutions cannot be commercially addressed at all (IFC 2012, page 32). The following figure (see Figure 5) shows the market segmentation and size for the addressable market for "lightning plus" energy services.

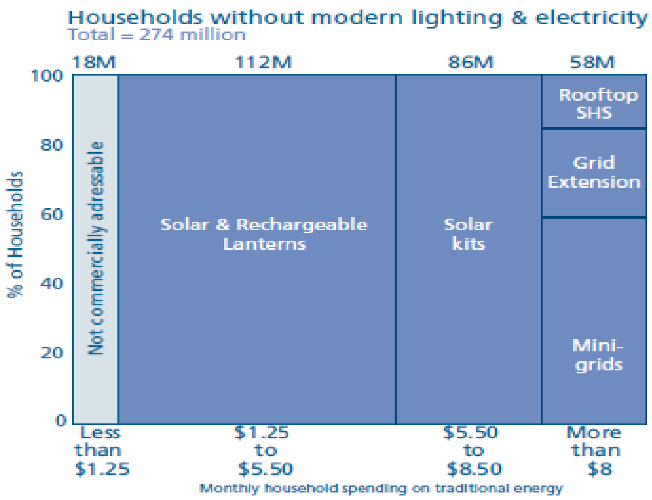


Figure 5: Theoretically addressable market for "lightning plus". Source: IFC 2012, page 30.

IFC highlights that mini-utilities provide electricity for household needs and productive uses often for much less than what is currently spend. According to IFC, they deliver electricity at 0,20 USD to 0,50 USD per kWh[4], allowing households to meet basic electricity needs for less than 10 USD per month. IFC reckons that 58 million households without access to modern energy spend around 8,50 USD or more per month on traditional lighting and electricity (which equals to a total of 7 billion USD annually). But costs and expenditures are not enough for defining the market. As already discussed, geographies play a big role too. Mini-grids will be best suited for densely populated villages far away from a grid, leaving solar home systems as fall back option when neither central grid nor mini-grid is feasible. IFC builds upon the estimates of the previously mentioned IEA studies (2012 and 2011) to classify these market segments. According to the IEA, it is projected that 30% of rural population will be connected to the central grid, and from the remaining 70%, 65-75% will be connected to a mini-grid, indicating a theoretical market potential of

[4] A critical discussion about these cost estimates will be presented in a later chapter.

totally 591,5 million people. Applying this perspective on the 58 million households that could currently afford to pay for this prize segment of modern electricity supply, 29 million households could be currently serviced by mini-grids on a commercial basis, which amount to 145 million people in total (estimating 5 people per household). This represents 24,5% of the estimated total market potential for mini-grids for rural electrification in developing countries. It constitutes an annual purchase power of 4 billion USD (see IFC 2012, page 149). The following figure (see Figure 6) summarizes the addressable market for modern energy products and services in developing countries.

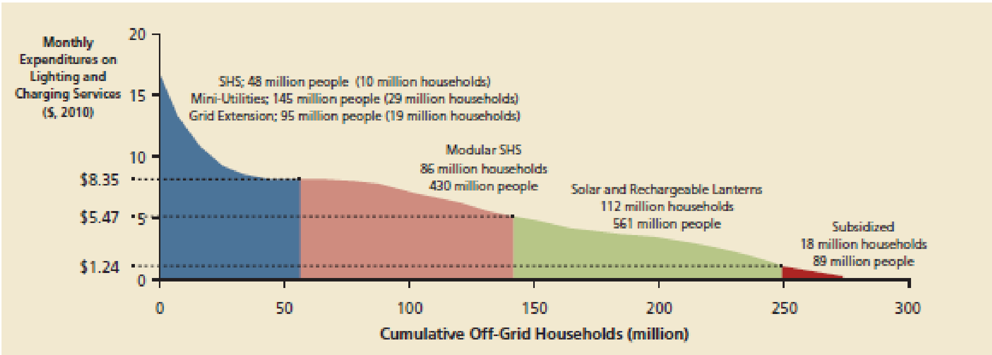


Figure 6: Addressable Market for modern energy products and services. Source: IFC 2012, page 147.

2.3 New Vs. Old Markets for Hybrid Mini-Grids for Rural Electrification in Developing Countries

Beside the establishment of new village mini-grids for rural electrification, there is a considerable market for integrating renewable energy technologies into existing diesel mini-grids (see IEA/PVPS Task 11 2009). They are in use around the world to supply remote villages, industries or small islands. Supplementing these diesel generators with renewables such as PV reduce fuel costs, improve reliability and availability of power, and achieve CO2 reductions and environmental benefits (IEA/PVPS Task 11, page 3). ARE (2011) points out that hundreds of gigawatt of diesel based isolated grids have the potential to become retrofitted with renewable energy technologies. ARE reckons that official and unofficial installed mini-grids powered by diesel gensets amount to 20-50 gigawatt in India and 3 gigawatt in Brazil. According to ARE Mali counts 43 private operators of this kind, Cambodia and Madagascar have hundreds of diesel powered mini-grids, and Nigeria runs more diesel gensets than generation supplying the national grid (ARE 2011a). Another example presents the rural telecom operators market. GSMA research points out that there are worldwide 600,000 GSM base stations powered by diesel gensets. Alone in Ghana and Nigeria, GSMA estimates that a total of 10,890 sites could be retrofitted through renewable energy technologies. 56% of these sites are off-grid and 44% are unreliable grid sites. This represents a market potential for Energy Service Companies (ESCOs) of 405 million USD per annum by 2015 at a power purchase agreement (PPA) rate of 0,6$/kWh, excluding the market opportunity for associated community power (GSMA Research 2013). Benefits for community power can potentially arise from such hybrid mini-grids for GSM base stations, as the GSM base station represents the anchor client which guarantees financial viability of the mini-grid project, while additional capacities can be easily installed to connect nearby village households.

2.4 Enabling Markets for Hybrid Mini-Grids for Rural Electrification in Developing Countries

The IFC analysis reveals that purchasing power (expressed in relation to current expenditures for traditional energy supply) gives an important indication for the ability to pay for a specific technological solution, and thus, for the overall affordability of the system. Installing mini-grids in areas where people have previously paid much less for traditional energy services impacts the viability of hybrid mini-grid projects. Support programs for mini-grids need to facture income level differences and energy expenditure patterns into their tariff and subsidy structure, especially when expanding mini-grids to areas that can currently not afford the full levelized commercial cost of the system. These limits of the theoretically addressable market for mini-grids together with the progressive goal of providing universal energy access to all by 2030 also highlights that energy access business models in this field will vary depending on the location and encountered circumstances between commercial enterprise-based (fully or nearly financial viable), quasi-commercial (partially subsidized), non-commercial (primarily publicly funded) (IFC 2012, page 39). Despite these variations, the IFC analysis represents an imperative to size this addressable market now, to find ways of scaling and replicating pioneering business models, and to foster an enabling ecosystem so that these innovations can flourish.

In order to fully size these market potentials, market mechanisms need to be simultaneously developed. An ecosystem is needed that enables the deployment of a wide range of instruments and approaches, such as technical know-how transfer, replication of business models, credit for rural households and entrepreneurs, regulatory frameworks and financing for private power developers, market facilitation organizations, targeted donor assistance, smarter subsidies, and greater attention to social benefits and income generation (see Martinot et al 2002). Changing actor landscapes, global commitments to achieve universal energy access by 2030 and shifting investment patterns require new approaches for securing large scale deployment and up-take of renewable energy systems in the developing world. There is the need to move away from an only technology focused approach towards embracing market orientation and enabling frameworks. As already discussed and explained in depth later, the technologies are ready. Now there is the need to develop and pilot market mechanisms that allow long-term sustainability and growth.

Therefore, there is also the increased need to direct research to social conditions, demand for products or services, sales potentials, financing options, business models, regulatory frameworks and public policies, as well as the interface with rural and private sector development. Through the rise of BOP, impact investing and social and rural entrepreneurship, financing and business viability became a new trend, which was long time neglected in the literature as well as a missing part in support programmes on renewable energy in developing countries (Morinot et al 2002, page 332). Tens of thousands of rural enterprises offering renewable-energy services and products would be required to meet the needs of the 1,5 billion people lacking energy access (Morinot et al 2002). Sizing these markets will require increased technical know-how and business skills in developing countries, including local capabilities to adapt, install, operate, and maintain technologies, to build local distribution and manufacturing industries, as well us to develop and run viable businesses (Morinot et al 2002, page 339). As Marinot et al reckon, especially systems that allow for local socio-economic development (i.e. productive uses), such as mini-grids build around income generating micro-enterprises, will gain of importance in the mid-term. This constitutes a large development challenge. A review conducted for this thesis of current mini-grid support programs in developing countries has indicated that such integrated approaches are being taken-up progressively. They already become institutionalized and mainstreamed in support structures across the globe. The following figure (see Figure 7) indicates the changing paradigms of research on renewable energies in developing countries. This thesis was written in this light. It aimed to transcend a mere economical, technological and environmental assessment of hybrid mini-grids, and enrich the discussion through an ecosystem-centered socio-political perspective.

Old paradigm		New paradigm
Technology assessment	➔	Market assessment
Equipment supply focus	➔	Application, value-added, and user focus
Economic viability	➔	Policy, financing, institutional, and social needs and solutions
Technical demonstrations	➔	Demonstrations of business, financing, institutional and social models
Donor gifts of equipment	➔	Donors sharing the risks and costs of building sustainable markets
Programs and intentions	➔	Experience, results, and lessons

Figure 7: Renewable Energy: From technologies to markets. Source: Martinot et al 2002, page 311.

3 Hybrid Mini-Grid System Configurations

This chapter assesses available hybrid mini-grid system configuration options. A range of physical and technological components are described that form the backbone of mini-grid configurations. Each physical and technological component offers a variety of options that need to be assessed and chosen in the design and planning process of mini grids in order to assure technological feasibility, cost-effectiveness (hence affordability), and quality of supply. The following section provides an overview for the most important components and associated optimizations considerations. First of all, hybrid mini-grids can be AC or DC coupled power systems. The selection of the AC/DC bus bars depends on the technologies used in the system and on the energy management strategy. Village mini-grids tend to be AC coupled systems. More specifically, there are four options how AC power sources in the mini-grid perform the "grid forming" function to control the mini-grid frequency and voltage (IEA/PVPS Task 11 2012). According to IEA/PVPS Task 11 these are "single fixed master" mini-grid architectures, "multi-master inverter" dominated mini-grid, "multi-master rotating machine" dominated mini-grid and "singled switched master" mini-grid architectures.

Options for distribution line configuration encompass the single phase supply and the three-phase supply, each of them split in two sub-options. Together they form the four basic distribution line configurations for a village mini-grid. Attributes of each configuration and corresponding conductor characteristics need to be assessed to determine which configuration is the most cost-effective. This is a key issue for the optimization of mini-grids systems.

For the purpose of this thesis, only the above summarized components of a hybrid-mini grid configuration have been discussed. They constitute the backbone of the system, are crucial for the system optimization and frequently referred to in this thesis. They contain key input parameter for simulating mini-grid distribution village networks. The other components necessary for designing and installing a mini-grid have not been analyzed in depth because of their minor relevance for this thesis and overall system optimization. These are poles, poletop hardware and connectors, guys and anchors, as well as safety and precaution measures. The ESMAP "Mini-Grid Manual" (2000) provides a solid assessment of these components and can be used for further analysis. A discussion about the importance of service connection and metering for the overall system design and management can be found in the Annex.

The chapter concludes with a technical and economic assessment of power delivery. It characterizes the costs caused by the power delivery loss rate, which later on allows a more complete perspective of the total system costs of hybrid mini-grid systems.

3.1 AC/DC Configuration Models for Hybrid Mini-Grids

According to the Alliance for Rural Electrification (ARE 2011b) a mini-grid typically uses low AC voltage (220 or 380V) with centralized production and storage and has an installed capacity of between 5 and 300kW. A hybrid mini-grid power system uses renewable energy as a primary source and a genset (most of the time diesel fed but potentially with gasoline and LPG) as a backup resource (ARE 2011b, page 27). ARE (2011b) points out two distinguished features of mini-grid systems. First, they can be easily scaled up in case of demand growth due to the modularity of generation components. Second, they can be potentially connected to the national grid and serve as additional generation capacity.

ARE distinguished mini grids according to the type of voltage they primarily use and the type of bus line that link the different components together. The first technological configuration connects all electricity generating components to an AC bus line (ARE 2011b, page 28) (see Figure 8). AC generating components (e.g. diesel generator, wind or small hydro power) can be either directly connected to the AC bus line or via an AC/AC converter for stable coupling of the components (i.e. with a charge controller function). A bidirectional master inverter controls the energy supply for the AC loads and the battery charging (ARE 2011b). DC electricity generating components (e.g. PV) can be connected to the AC bus line via a DC/AC inverter and DC loads can be optionally supplied by the battery (ARE 2011b). The following figure shows an AC coupled hybrid power system.

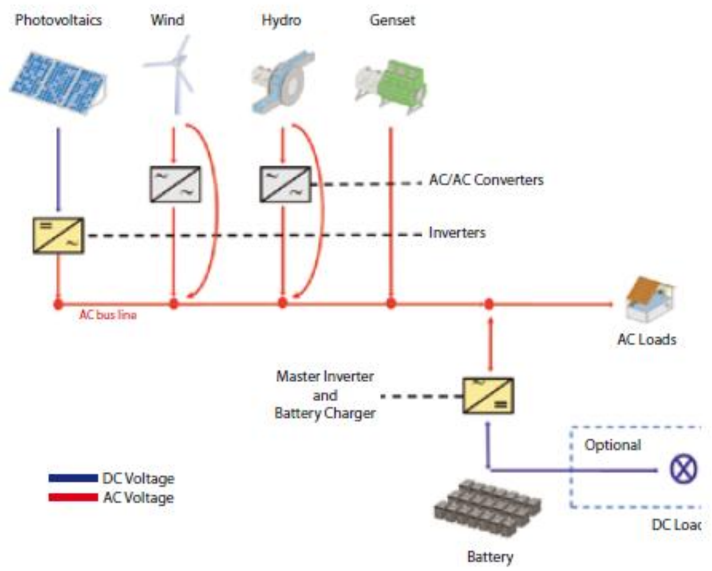


Figure 8: AC coupled hybrid power system. Source: ARE 2011b, page 28.

The second technological configuration connects all electricity generating components to a DC bus line (ARE 2011b, page 29) (see Figure 9). Hereby the battery is controlled and protected from overcharge and discharge by a charge controller and supplies power to the AC load through the DC/AC inverter. DC loads can be connected directly to the DC bus bar. The following figure shows a DC coupled power system.

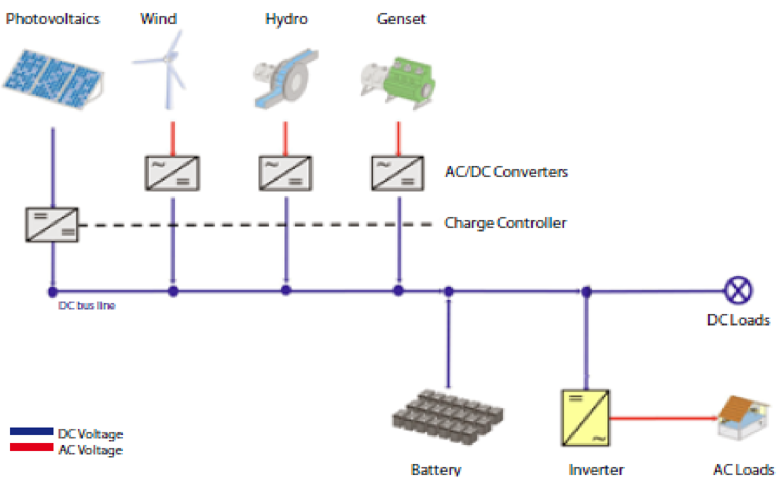


Figure 9: DC coupled power system. Source: ARE 2011, page 29.

The third technological configuration connects AC and DC electricity generating components at both sides to a master converter, which controls the energy supply of the AC loads (ARE 2011, page 29) (see Figure 10). Hereby, DC loads can be optionally supplied by the battery. The following figure shows a DC/AC coupled hybrid power system.

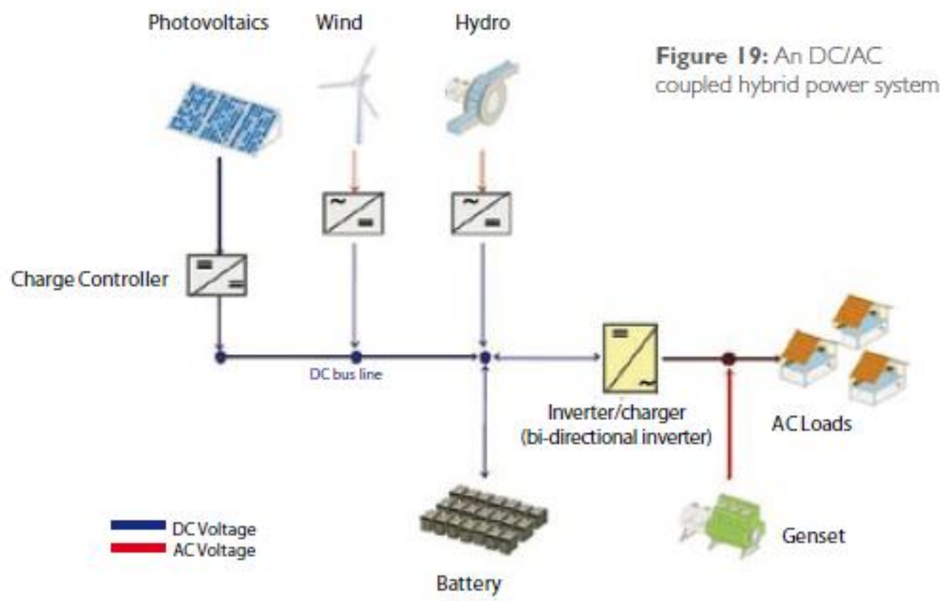


Figure 10: DC/AC coupled hybrid power system. Source: ARE 2011b, page 29.

The IEA/PVPS Task 11 (2012) classifies PV hybrid mini-grid systems into four categories according to which AC power sources in the mini-grid perform the "grid forming" function to control the mini-grid frequency and voltage. In Figure 11 – the single fixed master mini-grid architecture – only PV inverters are connected to the mini-grid and therefore do the grid forming. Figure 12 shows the singled switched master mini-grid architecture. It has multiple AC sources connected to the mini-grid, but only one source (i.e. PV inverter) supplies AC to the mini grid at any time and leads the grid forming. As the IEA/PVPS Task 11 (2012) points out, these architectures are typical in village micro-grids.

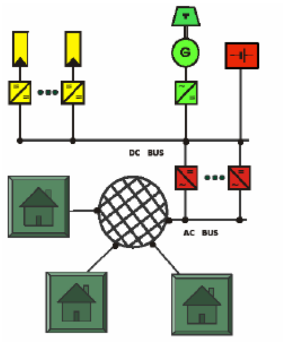


Fig. 1 Single fixed master mini-grid

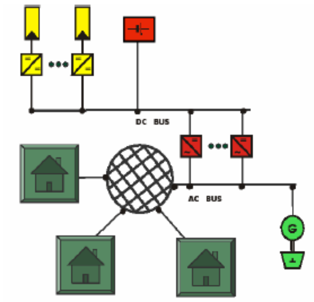


Fig. 2 Single switched master mini-grid

Figure 11: Single fixed master mini-grid. | Figure 12: Single switched master mini/grid. Source: IEA/PVPS Task 11 2012, page 19.

Figure 13 – the multi-master rotating machine dominated mini-grid – is the typical configuration of diesel mini-grids, with multiple AC sources connected to the mini grid and simultaneously supplying power. Gensets do the grid forming and PV inverters follow the mini-grid voltage and frequency. Figure 14 shows the multi-master inverter dominated mini-grid. It has multiple AC sources connected to the mini-grid simultaneously supplying power. Here several inverters participate in the grid forming along with the gensets. IEA/PVPS Task 11 points out that this approach is well suited for mini-grids with many generators distributed throughout the network (2012, page 76).

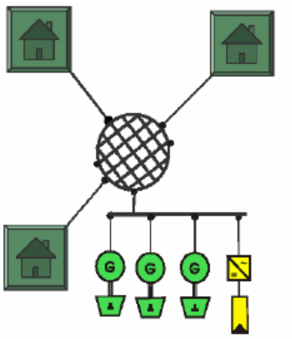


Fig. 3 Multi-master rotating machine dominated mini-grid

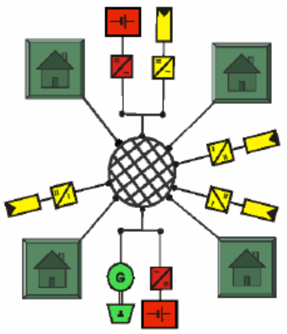


Fig. 4 Multi-master inverter dominated mini-grid

Figure 13: Multi-master rotating machine dominated mini-grid. | Figure 14: Multi-master inverter dominated mini-grid. Source: IEA/PVPS Task 11 2012, page 20.

The selection of the bus bars depends on the technologies used in the system and on the energy management strategy (ARE 2011, page 56). PV and batteries run on DC and electro-mechanic technologies such as gensets, small wind and small hydro in general produce AC power. When the battery is the central component of a hybrid mini-grid system, the use of AC bus bars is more common. Then a bidirectional master inverter can be used to control the energy supply between AC loads and battery component. "Village mini-grids often rely on an AC bus bar since the efficiency is higher, the losses lower and the system is more flexible and expandable, although the wiring is more complex. Regarding costs, the difference between both types of installation is negligible" (ARE 2011, page 56).

These different system architectures reveal that grid forming control techniques and techniques to ensure stability of voltage and frequency, as well as power sharing among AC and DC sources are important issues to consider in the system architecture design. They depend on as well as determine the configuration of the energy management system.

3.2 Distribution Line Configurations for Mini-Grids

Options for line configuration encompass the single phase supply and the three-phase supply. ARE 2011 points out that single-phase distribution grids are cheaper than three-phase but can also allow productive uses, and are therefore often the preferred option for basic distribution line configurations. Three-phase grids allow larger uses and the possibility for the future connection to the national grid (ARE 2011, page 58). Single-phase and three-phase distribution configurations can be split in two sub-options (ESMAP 2000). Together they form the four basic distribution line configurations for a village mini-grid. Attributes of each configuration and corresponding conductor characteristics need to be assessed to determine which configuration is the most cost-effective. This is one of the key issues for the optimization of mini-grids systems.

For the two-wire single phase configuration, two conductors leaving the power house serve the entire community at a voltage that is usually set at 120 or 230 V (ESMAP

2000, page 54). The pair of conductors passes by each consumer and the service drop simply taps both of these lines. The overall goal of the system is to achieve balanced loads while providing a single-phase service (e.g. 120 V or 230 V).[5] According to ESMAP (2000), the two-wire single phase configuration is the simplest option to design and therefore the most commonly used for mini-grids. The single phase configuration using three conductors is primarily used with systems operated at a nominal consumer voltage of 120 V, which are mainly countries which were historically influence by the US (such as Latin America). Here a generator is connected to generate twice the nominal voltage (240 V instead of 120 V) and a neutral conductor runs in between the two-phase conductors. The neutral conductor always taps one of the two phase conductors serving a consumer, which can be linked to the other phase conductor in case of higher load requirements. This improves efficiency and enables cost savings as smaller or greater loads can be served with a smaller voltage drop and line loss. In other words: smaller single-phase loads are only affected by the voltage drop along one conductor instead of two and greater single-phase loads (e.g. twice the voltage), which means that only half the current is required to serve the same load. Reduced voltage drop and power loss allow configurations that use one quarter the area (i.e. four times the resistance), thus these conductors are smaller and less costly, but increase the design and planning burden (ESMAP 2000, page 56/57).

The three-phase configuration also provides – in addition to a single-phase service – a three phase service for consumers who need larger quantities of power to run large motors or other industrial processes, which means 208/120 V wye or 120 V delta and 400/230 V wye or 230 V delta, respectively (ESMAP 2000, page 59). There are some disadvantages compared to single-phase distribution systems, such as higher pole, more poletop hardware requirements and additional care to balance peak-time loads on the different phase conductors. Three phase generators can be connected in two different configurations, either as four-wire delta or as three-wire wye (or star). The former configuration is commonly used for low-voltage three phase distribution networks designed by national electric utilities, while the latter is less frequently used for electricity distribution (ESMAP 2000, page 60). The following figure (see Figure

[5] Balancing loads means "… that loads are connected to each phase conductor in such a way that the currents in these conductors are as close to equal as possible" (ESMAP 2000, page 55).

15) shows the four basic distribution line configurations that may have application for a village mini-grid.

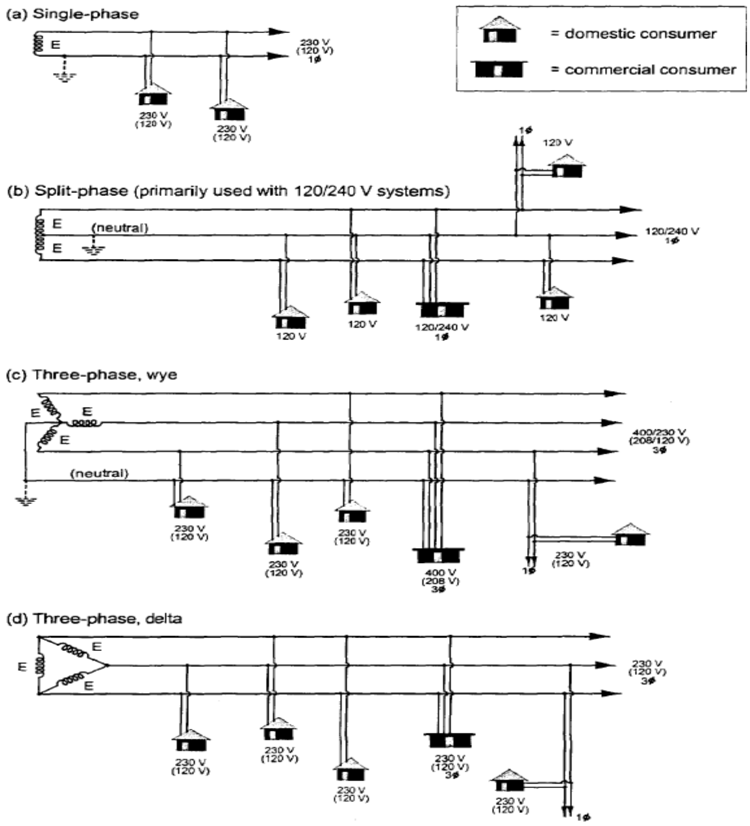


Figure 15: The four basic distribution line configurations that may have application for a village mini-grid. E represents the commonly used voltage in the country (generally 120 V or 230 V). Source: ESMAP 2000, page 55.

Conductors and poles are the costliest elements for most mini grids. Aluminum and copper are in general used as conductors. Aluminum is preferred to copper in many cases because its smaller weight-to-strength ratio permits longer spans and potentially fewer poles. To increase the strength of aluminum, aluminum strands can be wrapped around a steel core to obtain a steel-reinforced aluminum conductor (called ACSR). This is the most widely used conductor for lines constructed by conventional utilities (ESMAP 2000, page 64). The basic conductor types used in mini-grids with conventional low-voltage distribution systems are bare conductors, single insulated conductor (commonly use for housewiring), non-metallic-sheathed multi-conductor, multiplex and aerial bundled cable (called ABC) (specifically designed for distribution lines) and concentric neutral conductors (more commonly used as a service drop). For conventional low-voltage distribution lines, two, three or four separate bare ACSR conductors are typically used for distribution lines (ESMAP 2000, page 65). Multiplex with one, two, or three conductors wrapped around the messenger is called duplex, triplex, and quadruplex, respectively. They are typically used as the conductor for the service drop (ESMAP 2000, page 68).

Using the right conductor size is important for assuring cost-effectiveness and quality of supply. "In the process of transmitting electricity, resistance in the conductor leads to a drop in voltage along the line and to an associated loss of power. Reducing conductor size can result in 1) poor quality of power at the consumer end of the line (low voltage and more pronounced voltage fluctuations) and 2) loss of power (due to resistive losses in the conductor)" (ESMAP 2000, page 70). Low voltage can result in poor service, and the need for extra power to be generated. The size and type of conductor as well as the power factor determine the voltage level. For calculating the required conductor size a correct load assessment, geographical system layout and the defined line configuration are needed.[6]

3.3 Technical and Economic Assessment of Power Delivery

The World Bank (2007) undertook the important exercise to assess the costs for energy distribution and delivery. This is important cost information that allows a complete perspective of the total system costs of hybrid mini-grids. The focus of most literature on hybrid mini-grids is put on the generation costs, thus not including an important part of the costs into the analysis and associated interpretation of results. Power generation technologies discussed in this thesis are deployed as part of an electrically-isolated mini-grid, where the grid serves to transport the electric power from the generator to the costumer via low-voltage distribution networks (WB 2007). Power delivery requirements and associated costs derive from the specific power system configuration. The following table (see Table 3) summarizes the power delivery requirements and indicative associated levelized costs, including capital costs, operation and maintenance costs and technical losses for four power generation configurations that were considered in the World Bank study (WB 2007).

[6] Dimensioning, load management and system layout is discussed in the Annex. For further information on calculating the conductor size see ESMAP 2000.

	Grid-connected			
	Large	*Small*	*Mini-grid*	*Off-grid*
Typical Generator Size (kW)	50-300 MW	5-50 MW	5 kW-250 kW	0.3-5.0 kW
Annual Output	1,000 GWh	35 GWh	1 GWh	0.005 GWh
Transmission Costs	~US¢0.25/kWh (100 km circuit)	~US¢0.5/kWh (20 km circuit)	None	None
Distribution Costs	None	None	~US¢1-7/kWh	None

Table 3: Power Delivery Requirements According to Generation Configuration. Source: World Bank 2007, page 39.

Transmission and distribution equipment requires regular maintenance, and may include repair of damage caused by storms or accidents. According to the World Bank report, a good rule of thumb is that O&M costs for a power delivery system should run between 1/8 and 1/30 of capital costs on an annual basis. The lifetime of a grid is 20 to 30 years for depreciation purposes, but can be more than 50 years with proper maintenance (WB 2007, page 41). Losses in electrical power output from generator to customer can vary between 10 and 25% or even more, depending on design and maintenance. Comparing a range of power delivery loss rates in selected countries, the report indicates an average power delivery loss of 17,2% (see Table 4). In general, distribution losses amount to two-third of the total power delivery losses. As distribution technology is very mature, cost reduction or performance improvements cannot be expected in the near future (WB 2007).

Country or Region	*T&D Loss (%)*	*Fiscal Year*	*Source*
Cambodia	22.6	1998	EDC
Chubu Region (Japan)	4.9	2003	CEPCO Annual Report
India	31.42	1999	Indian Power Planning Committee Annual Report (2001/2002)
Karnataka State (India)	31.69	2002-03	KPTCL Data http://www.kerc.org/english/index.html
Kenya	16.2	1997	Overseas Japan Electric Power Investigation Committee (2000)
Lao PDR	24	2000	Overseas Japan Electric Power Investigation Committee (2000)
Malawi	14.8	1999	ESCOM Annual Report (1999/2000)
Philippines	14.4	2001	NPC Annual Report MERALCO Annual Report
Tanzania	11.9	1996	ESKOM Statistical Yearbook
Tunisia	11.2	1998	STEG
Vietnam	14.5	2000	Fifth Electric Power Master Plan (EVN)
Zimbabwe	10.8	1997	Annual Report
Average	**17.2**	–	–

Note: "–" means no cost needed.

Table 4: Power Delivery Loss Rates in Selected Countries. Source: World Bank 2007, page 41.

The capital cost of distribution facilities is proportional to both the circuit-kilometer of distribution conductor and the rated output of the generation source (WB 2007, page 42). A low-voltage distribution network is needed when the power station output is less than 60 kW, as loss reductions will be nominal unless the distribution circuit kilometers are very large (WB 2007, page 42). A power station output above 100 kW might need a higher voltage network with transformers, which depends on customer density and the size of the mini-grid.

In the World Bank report a distribution capital cost calculation for each power generation technology configured to serve a mini-grid is performed, whereby the capital costs of the distribution facilities are converted into a levelized cost (USD/kWh) over the lifespan of equipment and the volume of power delivered. In the assessment distribution costs typical for Indian rural electrification programs were used, which average to 3,500 USD/circuit-km for low voltage reticulation (0,2 kV), along with 3,500 USD per MV/LV transformer. Costs for operation and maintenance amount to 2% of the capital cost annually and losses are decrementing the net delivered electricity by 12 percent (WB 2007, page 42/43). The results of the assessment are presented in the table below and indicate that there is a "separate and distinct cost” associated with power delivery in mini-grids that, if added to generation cost, would be a significant component of overall cost of electricity (WB 2007, page 44). The World Bank points out that it is up to the system designer to include these costs in evaluating an electrification alternative. As also discussed later, most of the literature does not include nor consider these extra cost or the need to install stronger generators in order to balance the power delivery loss. Most of the literature reviewed did not even include the distribution infrastructure cost. The World Bank did deliberately not include these power delivery costs in the comparisons of different generating costs by generation technology and configuration. The following table (see Table 5) shows the distribution capital cost calculation for each power generation technology configured to serve a mini-grid (WB 2007).

Generating-types			*Mini-grid*					
	Rated Output	*CF* (%)	*US¢/kWh* 2005	2010	2015	*US$/kW* 2005	2010	2015
Solar-PV	25 kW	20	7.42	6.71	6.14	56	56	56
Wind	100 kW	25	3.80	3.61	3.49	193	193	193
PV-wind Hybrids	100 kW	30	5.09	4.72	4.42	193	193	193
Geothermal	200 kW	70	2.53	2.38	2.34	193	193	193
Biomass Gasifier	100 kW	80	1.58	1.51	1.48	193	193	193
Biogas	60 kW	80	1.03	0.99	0.99	56	56	56
Microhydro	100 kW	30	2.43	2.36	2.36	193	193	193
Diesel/Gasoline	100 kW	80	3.08	2.94	2.97	193	193	193
Microturbines	150 kW	80	4.69	4.54	4.54	193	193	193
Fuel Cells	200 kW	80	3.99	3.72	3.58	193	193	193

Table 5: Power Delivery Costs Associated with Mini-Grid Configurations. Source: World Bank 2007, page 44.

4 Renewable Energy Technology Generation Options for Hybrid Mini-Grids: Technological and Economic Assessment of PV and Wind Power

The fourth chapter describes the renewable energy technology generation options for hybrid mini-grids. An in depth technological and economical assessment of PV and wind power in the context of hybrid mini-grid deployment is conducted. Several examples of PV micro-grids and hybrid PV/diesel mini-grids are discussed, highlightening the important role of island inverters, as well as the correlation between generation and load profiles in rural areas in developing countries. System costs for hybrid mini-grids are assessed based on an in-depth literature review.[7] The second part of this chapter makes a technological and economical assessment of Small and Medium Wind Energy (SMWE) in the context of hybrid mini-grid deployment. The assessment starts with a short market overview about SMWE technologies before analyzing in depth the available SMWE technologies, the multiple factors determining the wind energy output, as well as the costs of off-the-shelf SMWE technologies and wind electricity generation. The chapter concludes with a technological cost comparison of renewable energy generation technologies and hybrid mini-grid systems.

4.1 Solar Photovoltaic for Hybrid Mini-Grids

4.1.1 PV Generation and Load Profiles for Rural Villages in Developing Countries

The following figure shows the typical load profile for a rural village (IEA PVPS Task 9/CLUB-ER 2013) (see Figure 16). It consists of a prominent peak in the evening corresponding to lighting use, a morning/midday peak and a very low base

[7] A detailed discussion about the PV technology, describing the multiple factors influencing the power output of PV systems, as well as the market segmentation for hybrid mini-grids can be found in the Annex.

load during night, often not covered by diesel-genset-only generation because of high generation costs and engine degradation.

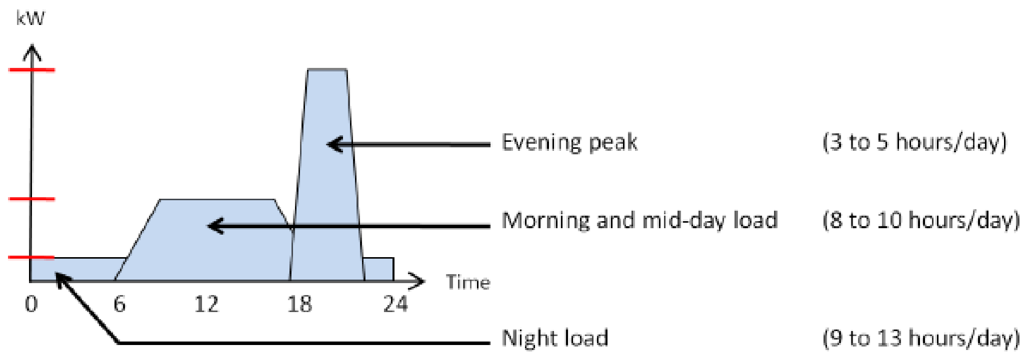


Figure 16: Typical load profile in rural areas. Source: IEV PVPS Task 9/CLUB-ER 2013, page 8.

The "hybridization with PV and a battery bank" allows here to fully cover the morning and mid-day load and to utilize the stored energy in the battery bank to run the system for low loads overnight (IEA PVPS Task 9/CLUB-ER 2013, page 8). The diesel generator is mainly used to cover the evening peak and to complement battery charging when required.

IEA PVPS Task 9/CLUB-ER (2013) describes two representative cases of PV hybrid mini grids and corresponding load curves, solar output, battery and genset use. The following figure (see Figure 17) shows a genset power plant of 55 kVA to which a 16 kWp PV system was added with a 150 kWh battery supplying the village of Ain Ehel in Mauritania (daily demand of 140kWh). The yearly PV penetration rate achieves 35%[8], which reduces fuel consumption, improves genset performance (because genset hours running on low load are reduced) and lifespan (IEA PVPS/CLUB-ER 2013, page 9).

[8] PV penetration rate is calculated by dividing the amount of energy produced by the PV system by the total amount of energy delivered by the hybrid power plant over a year (IEA PVPS/CLUB-ER 2013 page 9).

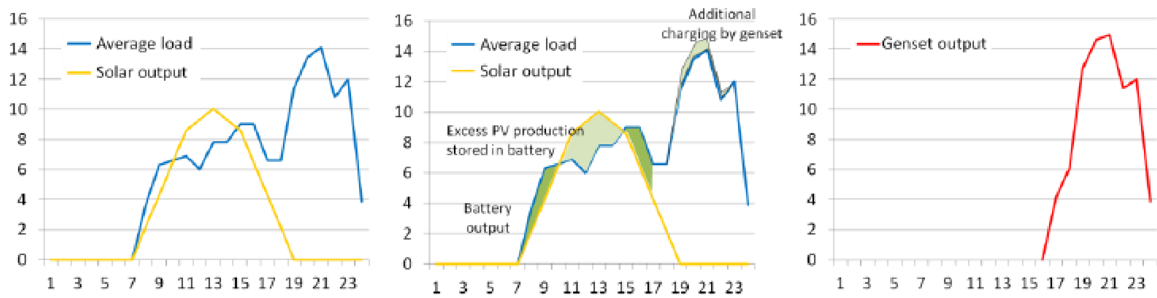


Figure 17: 16 kWp hybrid system in Mauretania: average daily load curve, solar output, battery and genset use (values in kW). Source: IEA PVPS Task 9/CLUB-ER 2013, page 9.

The other case demonstrated in the figure below shows a hybrid mini-grid powered by a 70 kWp PV system with a 600 kWh battery and a diesel plant consisting of three diesel gensets (73, 125 and 175 kVA) in Cambodia (see Figure 18). PV penetration rate achieves here 45%, which enables the base load to be covered by the battery bank, replacing the originally used small diesel genset.

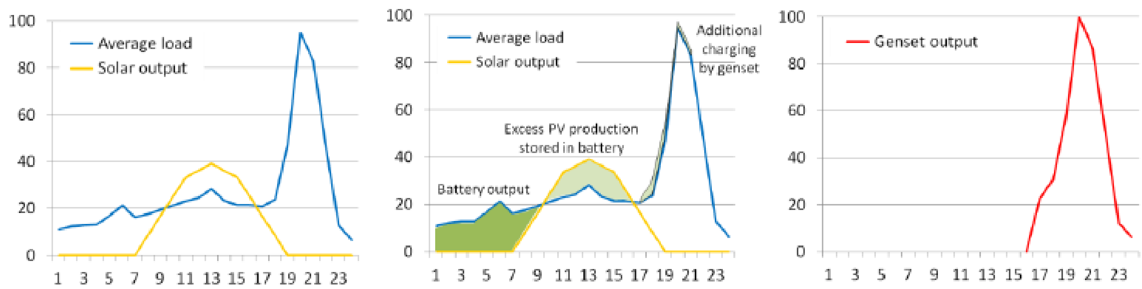


Figure 18: 70 kWp hybrid system in Cambodia: average daily load curve, solar output, battery and genset use (values in kW). Source: IEA PVPS Task 9/CLUB-ER 2013, page 9.

4.1.2 AC PV Micro-Grid Example

A good example for a simple AC PV micro-grid system powering a rural boarding school complex in the village of Bulyansungwe, Uganda, is presented by Brandt (2005). Electricity is supplied by a 3,6 kW PV array, connected to the micro-grid through two SMA Sunny Boy 1700E inverters, and stored in a 21,6 kWh battery bank. The battery bank is connected to the micro-grid through a 3,3 KW SMA Sunny Island Inverter, which also performs the control and balance function (Brandt 2005, page 53). There are plans to extend the system by supplying a DC water pumping and purification system in the future. This will require the installation of another small PV generator, which can be connected anywhere to the grid through a standard grid-tied inverter. If the system growth further, a modular multi-master operation system can be built by adding installed capacity, using additional sunny island inverters and later, connecting them to a multi-cluster box (see URL 4). This modular system technology enables the evolvement of a modular built power plant and mini-grid system in relation to increased demand by adding additional producers over time.

4.1.3 Hybrid PV/Diesel Mini-Grids

Hybrid PV/diesel mini-grids have attracted increased attention for rural electrification because of the relative installation and maintenance simplicity (i.e. availability of off-the-shelve turnkey systems and components), smaller investment costs as compared to wind and micro-hydro and universal energy resource availability (see Figure 19).[9] Especially advantages to diesel-only generation systems have made it to an interesting opportunity. Diesel and PV generation systems have both limitations that can be partially offset by combining these sources. Diesel genset options are sensitive to fuel prices and transportation costs and inefficient when running at low load factors. Solar energy is an intermittent energy source, which requires storage and high up-front investment costs (IEV PVPS Task 9/CLUB-ER 2013, page 7). IEV PVPS Task 9/CLUB-ER (2013) define a hybrid generation system as following: "A hybrid generation system is a system combining two (or more) energy sources, operated jointly, including (but not necessarily) a storage unit and connected to a local AC distribution network (mini-grid). As PV power output is DC and mini-grids operate in AC, at the heart of the hybrid system are the multifunctional inverter devices able to convert DC and AC currents, control the generation and storage systems and set up the voltage and frequency of the mini-grid" (IEA PVPS Task 9/CLUB-ER 2013, page 7).

[9] This is for example reflected in the IEA, which commissioned a Photovoltaic Power Systems Programme (PVPS) with a proper task force working on "PV hybrid systems within mini-grids" (Task 11) and another one focused on "deploying PV services for regional development" (Task 9). Both published a number of groundbreaking publications on the topic.

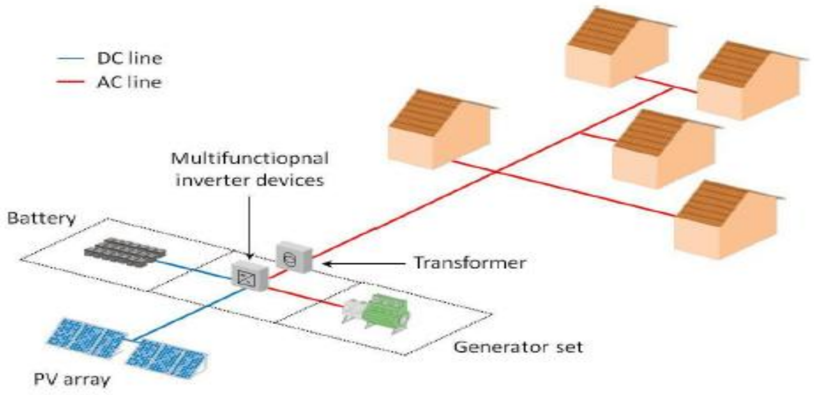


Figure 19: Schematic view of a PV/diesel hybrid system for rural electrification. Souce: IEA PVPS Task 09/CLUB-ER 2013, page 7.

4.1.4 Inverters

Power conditioning units (inverters) play a key role in the energy efficiency and reliability of PV systems, as the energy produced by the PV module also depends on the operating point of the module. Therefore, the PV module requires a power conditioning component (i.e. a maximum power point tracker) which can optimize the delivered power based on the operation conditions. The DC power generated by PV modules is inverted into alternating current (AC) of the desired voltage and frequency (e.g. 230 V and 50 Hz) (Fechner 2012b, page 1). For stand-alone systems, a battery system is necessary, which requires also the installation of a charge controller. It controls battery overcharging and deep discharging thus protecting it and guaranteeing long battery life (ARE 2011, page 40).

According to IEA PVPS Task 09/CLUB-ER, inverters have the following functionalities, which can be split between several units or combined in a central unit component (2013, page 13):

- Controlling the operating point of the PV array and optimizing its output
- Inverting DV current into AC and rectifying the AC current into DC to charge the battery
- Controlling the charging process of the battery to extend its lifespan

These multifunctional inverters in hybrid mini-grids "… are designed to form the mini-grid, i.e. they set the voltage and frequency of the mini-grid. They are referred to as grid-forming inverters or islanding inverters" (IEA PVPS Task 09/CLUB-ER 2013, page 13).

4.1.5 Costs for PV Hybrid Mini-Grid Systems

Investment costs for PV installations are determined by the costs of the PV panels, the cost of the storage component and specific inverters for mini-grids. IEA PVPS Task 09/CLUB-ER (2013) estimates that the typical real installed cost of a complete PV/diesel hybrid system in Africa and Asia currently costs between 5,500 and 9,000 EUR/kWp with variations according to system size and location (IEA PVPS Task 09/CLUB-ER 2013, page 14). The cost structure follows the breakdown structure in the below tables (see Table 6).

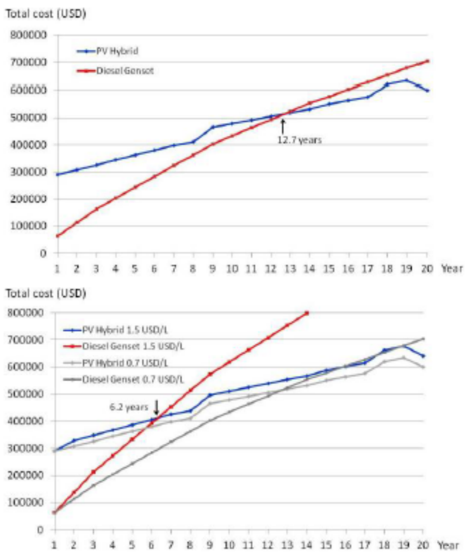
Location	**Senegal**	**Cambodia**
PV array capacity	**30 kWp**	**70.8 kWp**
PV panels and support structure	56 600 €	141 700 €
Inverters	42 700 €	93 600 €
Battery bank	29 800 €	122 600 €
Genset	21 400 €	84 600 €
BOS (including civil works)*	24 000 €	98 400 €
Total	**174 500 €**	**540 900 €**
Total / kWp PV	**5 820 €**	**7 640 €**

*Cost does not include any MV or LV grid. Sources: GIZ, IED

Table 6: Cost structure of two hybrid systems in Senegal and Cambodia. Source: IEA PVPS Task 09/CLUB-ER 2013, page 14.

According to the IEA PVPS Task 11/CLUB-ER (2013, page 14), the typical cost structure of a PV/diesel hybrid mini-grid system in developing countries is set at 15-20% for costs of installation and balance of system (BOS), 30% for costs of PV panels, 20% for costs of inverters, 20% for costs of batteries, and 10-15% for the diesel genset. Reduction of fuel consumption is a crucial argument for adding a solar PV component to an isolated diesel power plant. The payback time for the PV system compensated by fuel savings is the parameter for the investment decision. The following simulation for a 60 kWh hybrid system with a solar energy penetration of

93% indicates a payback period of 12,7 years, with the assumption of a constant fuel cost of 0,7 USD/L (see Figure 20). The levelized cost of energy is reduced by 15% compared to a simple genset solution (0,46 USD/kWh compared to 0,54 USD/kWh). Fuel costs of 1,5 L would reduce the payback time even to only 6,2 years (IEA PVPS Task 09/CLUB-ER 2013, page 15; ARE 2011).



Energy data	
Solar resource	6 kWh / m² / day
Energy demand	266 kWh / day
Peak load	26 kW
Fuel cost (constant)	0.7 USD / L
Cost of components	
Genset 30 kVA	400 USD / kW
PV 60 kWp	2 822 USD / kWp
Battery	225 USD / kWh
Converter	1 445 USD / kW
Lifespan of components	
Genset	25 000 hours
Battery	8 years
Break-even point	**12.7 years**

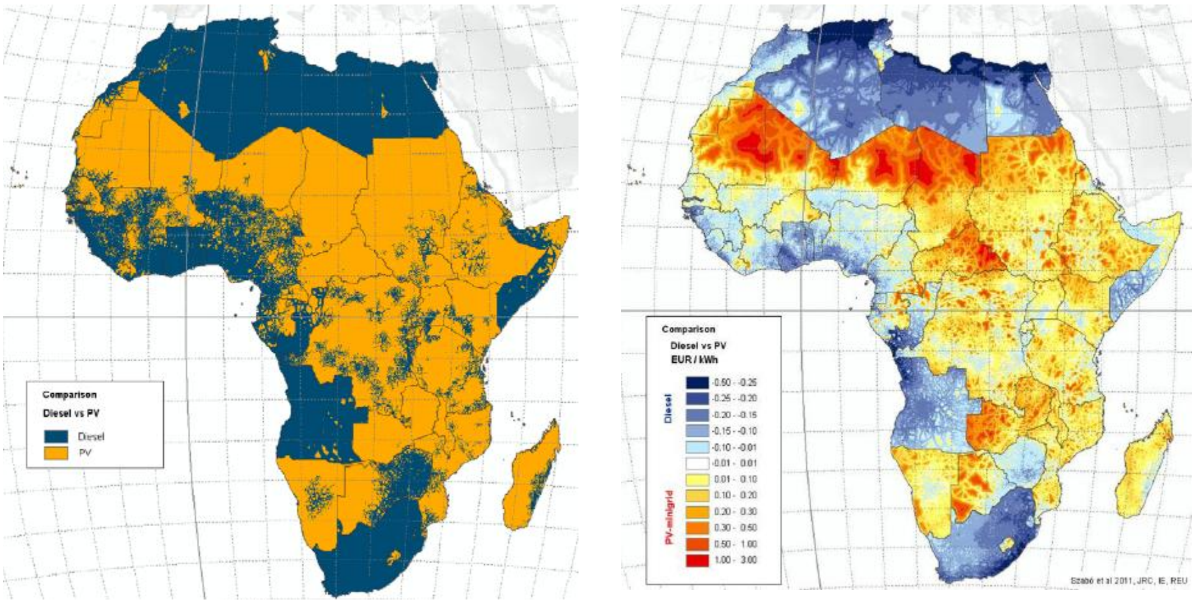
Source: [2]

Impact of higher fuel cost	
Fuel cost (constant)	1.5 USD / L
Break-even point	**6.2 years**

Adapted from [2]

Figure 20: Example of 60 kWp PV/diesel hybrid system in Ecuador: simulation of total accumulated costs over 20 years. Source: IEA PVPS Task 09/CLUB-ER 2013, page 15 (taken from ARE 2011).

Szabo et al 2011 undertook an economic comparison of PV and diesel off-grid systems and identified the most economic viable option by geography, which is illustrated in the map below (see Map 1). The color blue shows the location where diesel is more economically viable and the color orange shows where PV is cheaper (Szabo et al 2011, page 5). The other map estimates the levelized cost of kWh delivered by a diesel generator and by a PV system with a mini-grid in Africa (Szabo et al 2011). It shows that PV based mini-grid systems are already a competitive alternative to diesel only systems in good parts of Africa.



Map 1: PV/diesel cost comparison for Africa. Source: Szabo et al 2011, page 5.

4.2 Wind Power Technology for Hybrid Mini-Grids

Small and Medium Wind Energy (SMWE) for rural off-grid electrification is an emerging technology. According to the American Wind Association (AWEA 2010) the global market for SMWE grew in 2008 alone by 10% with an additional installed capacity of 42,5 MW of 21,000 sold units amounting to 189 million USD in sales. With more than 250 manufacturers worldwide, and two thirds of all small wind systems sold by US manufacturers, the market is still concentrated on the developed world. Manufactures are based in 26 countries, many of them in the start-up phase (AWEA, 2010, page 19). Sales growth alone for the US market is predicted to reach one gigawatt of cumulative installed small wind capacity by 2015 (AEWA 2010, page 7). Several factors have spurred these growth rates, such as enabling state policies and inventive schemes, increased investments in research and development, transparent installer and equipment certification standards, eased permitting procedures, improved resource assessment technologies, improved distribution networks, the emergence of hybrid mini-grid technologies, increased electricity prices, raised awareness or human capabilities (AEWA 2010, page 9). As ARE points out, growth will not end in the developed world, but most likely spillover to developing countries. For example, China already started to use SMWE for rural electrification in the early 1980ies and had more than 400,000 systems installed in 2010 (ARE 2012, page 1).

4.2.1 SMWE Technology

According to ARE, turbines used for microgeneration with a diameter of less than 15m and a power output below 50kW are classified as small (ARE 2012, page 1). However, the average small wind turbine has a diameter of 7 m or less (see also URL 5) and produces electricity at a rate of 0,3 and 10 kW. Medium size wind systems have a maximum output of 250 kW and a rotor diameter of 15-30 m (ARE 2012). The majority of installed small wind turbines are horizontal axis wind turbines, usually placed on a pole or tower-mounted, preferable higher than 15 meter (ARE 2012). Small wind turbines usually rely on a permanent magnet generator which produces AC power that is in turn rectified to DC and used in conjunction with a battery bank (UNDP 2005, page 19). They use a vane to point into the wind, and rely on dynamic braking to regulate the speed by dumping access energy (URL 5). In-battery-charging systems include a charge controller to prevent the battery from overcharging and grid-connected systems use inverters to control the SMWT and for supplying electricity to grid voltage and grid frequency (ARE 2012). The following figure (see Figure 21) shows an off-grid wind system set-up.

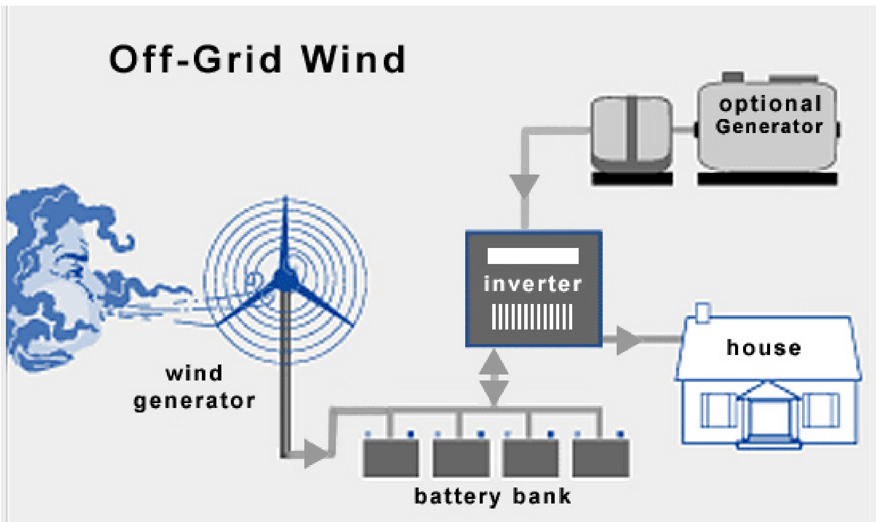


Figure 21: Off-Grid Wind System. Source: URL 6.

Medium size AC wind turbines use mostly induction generators and have a gearbox. The use of gears becomes necessary in order to obtain the required generator rotational speed (1,200 – 1,800 r/min) (Krenn 2012, page 5). According to ARE, these turbines are better suited for feeding into mini-grids rather than charging batteries directly (ARE 2012, page 2), though for rural electrification, smaller DC based permanent magnet turbines are often the first choice (UNDP 2005).
Small wind turbines can be integrated into hybrid mini-grids in a similar manner as solar PV panels explained in the previous chapter. Especially designed wind-inverters, developed based on solar inverter technology, are used as system interface and control organ. Small wind systems can be complementary with solar systems, as wind energy harvest is higher in colder months and solar harvest in warmer month. Similar to solar mini-grids, diesel gensets are used as back-up or in conjunction with small wind systems.

4.2.2 Location and Energy Output

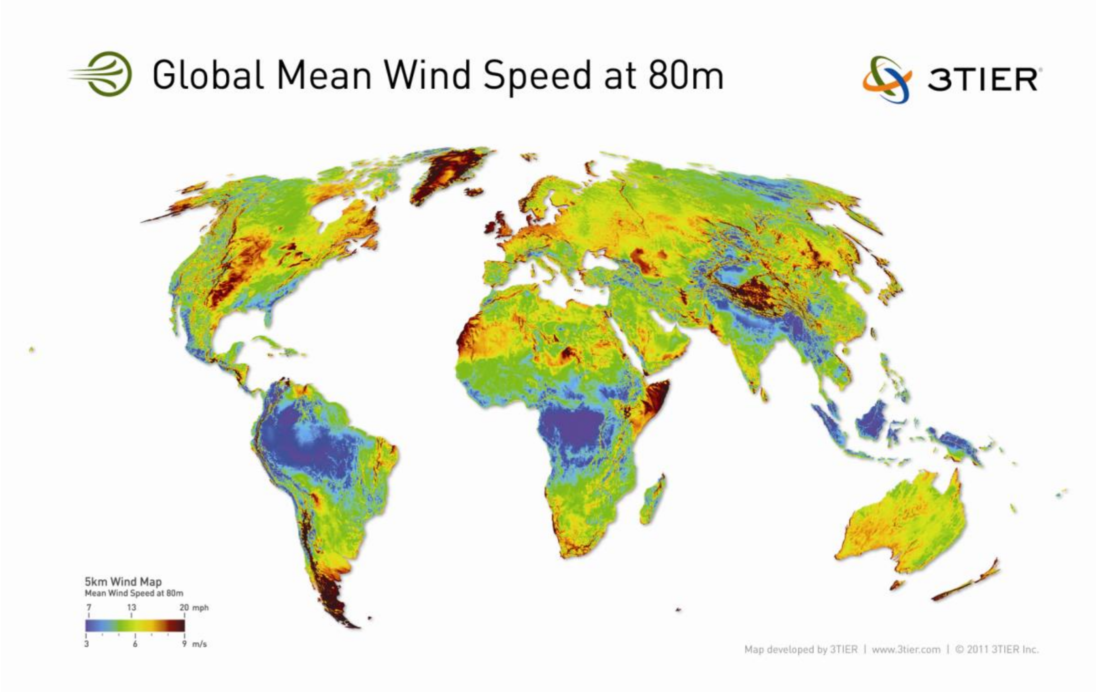
"The purpose of a wind energy plant is to collect the energy contained in the shifting air mass as efficiently as possible by means of wind turbines, before converting it into mechanical and ultimately into electrical energy" (Krenn 2012, page 4).
Wind speed is the determining factor for calculating the amount of energy produced by wind energy systems. Ideally, anemometers or special equipment such as SODAR (sound detection and ranging) or LIDAR (light detection and ranging) are for short-term measurements and the measurement of special wind characteristics (such as vertical wind profile, wind distribution, wind direction, daily and seasonal wind cycles, strong winds and turbulences, affects of roughness). This is then contrasted with information of long-term wind conditions produced by meteorological stations to get an impression about possible annual variations (going back to at least 10 years). Determining the annual average wind speed as well as specific time periods (e.g. monthly average wind speed) or frequency of different wind speed classes are important outputs of the measurement process. These data sets help to dimension and design the wind system as well as to efficiently integrate it into hybrid mini-grids. The key determent for evaluating the suitability of locations for wind energy projects is the annual specific energy output of the wind turbine per square meter of

vertical surface at hub height (kWh/m2/year), and simply expressed as mean specific power (W/m2) (Krenn 2012, page 4).

If these specific measurement instruments are not available or economically feasible, benchmarking and approximation can be used instead. However, this will result in weaker generation forecasts affecting e.g. the accurate design of hybrid mini-grid systems. A rough assessment can be undertaken by analyzing wind resource maps and the wind atlas, utilizing already existing wind measurement data from meteorological stations, examining production data from nearby wind power plants, interviewing local people on wind characteristics or relying on expert judgment (Neubauer 2012, page 7). Available computer programs can help extrapolate the needed wind resource information from existing data sets (URL 7).

In general, most commentators share the opinion that an annual average wind speed of 5 m/s is the benchmark for economic viability of small wind systems, which justify the installation of wind turbines without the need for a detailed wind resource study (URL 8). At this speed a SMWS produces 350 kWh per square meter rotor surface annually and a 5 kW system with a rotor diameter of 5 meter (20m2 rotor swept area) generates around 6,000 kWh per annum (ARE 2012, page 3). With an annual average wind speed of 6 m/s, the same turbine would produce 8,500 kWh because wind speed is added to the energy calculation in form of its third power. This means that in general the doubling of wind leads to an energy production increase of eight times, and quadrupling of wind speed produces 64 times the energy (Krenn 2012, page 5).

Wind resource maps are slowly emerging in many developing countries. They are a prerequisite for wind energy planning and therefore part of many wind support programmes currently under implementation. For example, South Africa recently launched a large scale resolution wind resource map, which was supported by the UNDP-GEF South Africa Wind Support Programme (URL 9). The Global Atlas for Solar and Wind of the International Renewable Energy Agency (IRENA) is another information platform on the potential of renewable energy globally. “It provides resource maps from leading technical institutes worldwide and tools for evaluating the technical potential of renewable energies. It can function as a catalyst for policy development and energy planning, and can support investors in entering renewable energy markets" (URL 10). According to ARE, countries like Morocco, Egypt, Kenya, Ethiopia and Madagascar have very suitable regions for small wind (ARE 2012, page 3). ARE recons that SMWE should be mainstreamed into the national energy mix, as in such conditions small wind is competitive with any other energy source. The following map (see Map 2) shows the global mean wind speed at 80m height.



Map 2: Global Mean Wind Speed at 80 m. Source: URL 11.

4.2.3 Cost of wind energy

There are wide price ranges for wind energy, as many factors influence the final costs of a kWh of wind energy. The most important are availability and quality of state incentives; average annual wind speed; costs of conventional electricity supply (the higher the better); cost of equipment, installation, operation and maintenance (averages 0,01 – 0,05 USD per kWh, or roughly 1 % of retail costs of installation annually); taxes; financing and permitting costs (AWEA 2011, page 17). AWEA estimates the costs of a well sited small wind turbine between 3 and 6 USD per watt, and 0,15 – 0,20 USD per kWh (AEWA 2011, page 17). ARE places the costs of a small wind turbine between 2,500 and 7,500 EUR per kW installed (ARE 2012, page

3). The REN21 Global Status Report 2013 puts the costs of small wind turbines in the US between 3,000 and 6,000 USD per kW installed and the levelized costs of energy between 0,15 to 0,20 USD per kWh (2013, page 55). Geography and its impact on production costs play an important role. REN21 estimates the price for small wind turbines in China at 1,580 USD per kW installed. Nevertheless, annual levelized costs between 0,15 and 0,35 USD per kWh makes SMWE a competitive renewable energy source for rural electrification, far cheaper than conventional energy (such as diesel or kerosene), and can even be lower than the costs for small-scale rural off-grid solar and hydropower (ARE 2012, page 4). As SMWE is still an emerging market, economies of scale and research innovation will most probably lead to a decrease in costs in the mid-term. R&D proprieties for the future include improved blade efficiencies from approximately 32% to 45% and improved efficiencies of alternators from 65-80% to 90-92% (AWEA 2012, page 20). Beside the wind turbine, battery replacement costs are the second major cost component, especially as batteries have to be changed in average every 6-8 years (UNDP 2005, page 20).

4.3 Technological Cost Comparison

Ren21 provides an overview about capital costs and levelized cost of energy for several renewable energy technologies, including small-scale off-grid technologies. As can be seen in the figure below (see Figure 22), small wind, hydro and solar are competitive with traditional energy sources, ranging from 0,5-0,40 USD/kWh for off-grid rural hydropower with plant sizes from 0,1 to 1,000 kW and 0,15-0,20 USD/kWh for small wind turbines with turbine sizes up to 100 kW.

Technology	Typical Characteristics	Capital Costs (USD/kW)	Typical Energy Costs (LCOE – U.S. cents/kWh)
Power Generation			
Bioenergy combustion: Boiler/steam turbine Co-fire; Organic MSW	Plant size: 25–200 MW Conversion efficiency: 25–35% Capacity factor: 50–90%	800–4,500 Co-fire: 200–800	5.5–20 Co-fire: 4–12
Bioenergy gasification	Plant size: 1–10 MW Conversion efficiency: 30–40% Capacity factor: 40–80%	2,050–5,500	6–24
Bioenergy anaerobic digestion	Plant size: 1–20 MW Conversion efficiency: 25–40% Capacity factor: 50–90%	Biogas: 500–6,500 Landfill gas: 1,900–2,200	Biogas: 6–19 Landfill gas: 4–6.5
Geothermal power	Plant size: 1–100 MW Capacity factor: 60–90%	Condensing flash: 2,100–4,200 Binary: 2,470–6,100	Condensing flash: 6–13 Binary: 7–14
Hydropower: Grid-based	Plant size: 1 MW–18,000+ MW Plant type: reservoir, run-of-river Capacity factor: 30–60%	Projects >300 MW: <2,000 Projects <300 MW: 2,000–4,000	2–12
Hydropower: Off-grid/rural	Plant capacity: 0.1–1,000 kW Plant type: run-of-river, hydrokinetic, diurnal storage	1,175–3,500	5–40
Ocean power: Tidal range	Plant size: <1 to >250 MW Capacity factor: 23–29%	5,290–5,870	21–28
Solar PV: Rooftop	Peak capacity: 3–5 kW (residential); 100 kW (commercial); 500 kW (industrial) Capacity factor: 10–25% (fixed tilt)	2,275 (Germany; average residential) 4,300–5,000 (USA) 3,700–4,300 (Japan) 1,500–2,600 (Industrial)	20–46 (OECD) 28–55 (non-OECD) 16–38 (Europe)
Solar PV: Ground-mounted utility-scale	Peak capacity: 2.5–250 MW Capacity factor: 10–25% (fixed tilt) Conversion efficiency: 10–30% (high end is CPV)	1,300–1,950 (Typical global) Averages: 2,270 (USA); 2,760 (Japan); 2,200 (China); 1,700 (India)	12–38 (OECD) 9–40 (non-OECD) 14–34 (Europe)
Concentrating solar thermal power (CSP)	Types: parabolic trough, Fresnel, tower, dish Plant size: 50–250 MW (trough); 20–250 MW (tower); 10–100 MW (Fresnel) Capacity factor: 20–40% (no storage); 35–75% (with storage)	Trough, no storage: 4,000–7,300 (OECD); 3,100–4,050 (non-OECD) Trough, 6 hours storage: 7,100–9,800 Tower, 6–15 hours storage: 6,300–10,500	Trough and Fresnel: 19–38 (no storage); 17–37 (6 h. storage) Tower: 20–29 (6–7 hours storage); 12–15 (12–15 hours storage)
Wind: Onshore	Turbine size: 1.5–3.5 MW Capacity factor: 25–40%	1,750–1,770 925–1,470 (China and India)	5–16 (OECD) 4–16 (non-OECD)
Wind: Offshore	Turbine size: 1.5–7.5 MW Capacity factor: 35–45%	3,000–4,500	15–23
Wind: Small-scale	Turbine size: up to 100 kW	3,000–6,000 (USA); 1,580 (China)	15–20 (USA)

Figure 22: Status of Renewable Energy Technologies: Characteristics and Costs. Source: REN21 2013, page 54.

In a 2007 publication, the World Bank made a rigorous technical and economic assessment of off-grid, mini-grid, and grid electrification technologies, based on 2005 values (see Figures 23 and 24). Already at that point in time, the assessment concluded that renewable energy is more economical than conventional generation for off-grid applications (less than 5 kW) and that many renewable energy technologies are potentially the least-cost option for mini-grid generation technologies. In addition, the report gives a 2015 forecast about the capital cost developments for off-grid generation technologies, and the electricity generating costs for mini-grids based on a range of off-grid technologies. The following figure sets the 2015 projected off-grid capital costs for solar energy in the range of 4,200 to 7,000 USD per kW installed. The 2015 projected off-grid capital costs for SMWE are set in the range 3,500 and 5,000 USD per kW installed, and the 2015 projected off-grid capital costs for hybrid wind-solar installations are set in the range of 3,900 to 6,000 USD per kW installed.

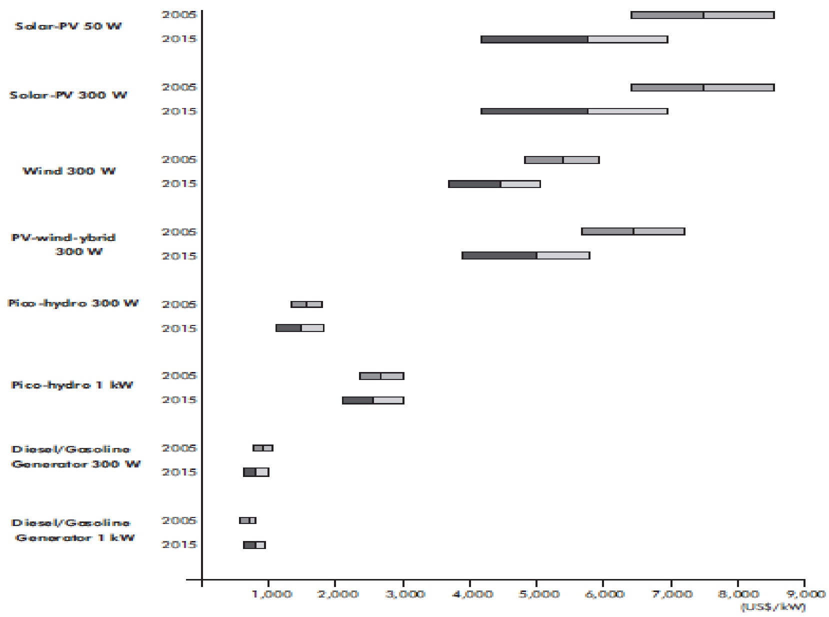


Figure 23: Off-grid forecast capital costs. Source: WB 2007, page 251.

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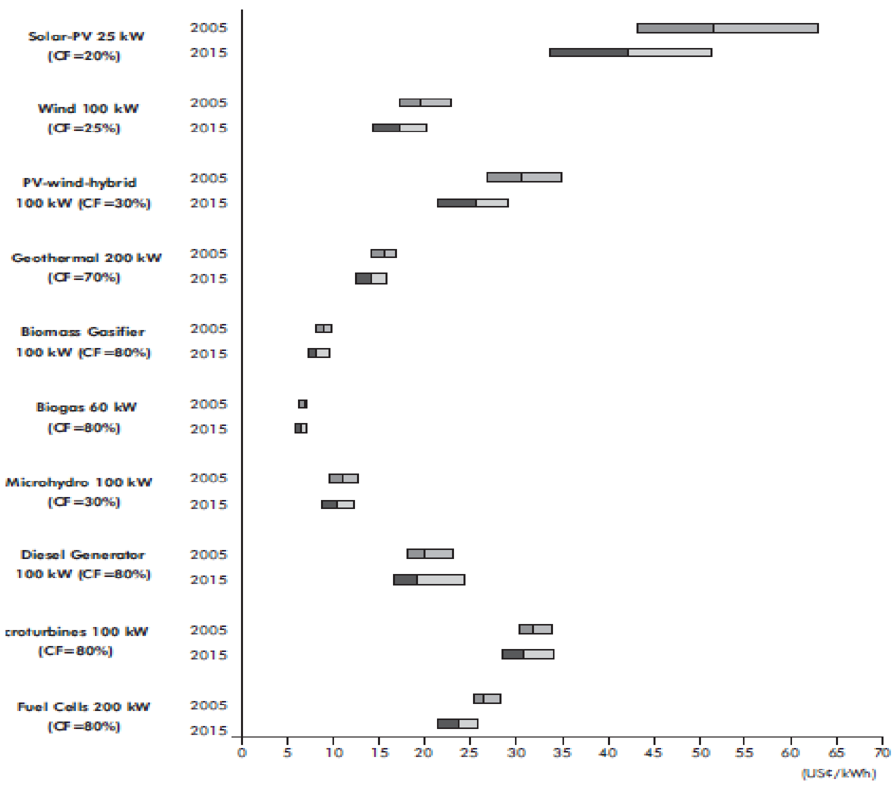

Figure 24: Mini-Grid Forecast Generating Cost. Source WB 2007, page 256.

5 Economic Assessment, System Design and Optimization of Hybrid Mini-Grids

Cost optimization is key for the success of hybrid mini-grids for rural electrification. Only the least cost optimum mini-grid system will allow consumers to pay for the service and the private sector to profitably install and operate the system in the long-term. Previous chapters have already explained in detail the importance of adequately sizing mini-grid configurations, so that supply matches demand while allowing extra capacity for future load growth, as well as of assessing local resource availability to most efficiently employ relevant renewable energy generation technologies. This chapter will look at available planning tools that exist to help determine the least cost option for village grid systems. A case study is implemented using the simulation tool HOMER developed by the US National Renewable Energy Laboratory (NREL). HOMER is widely used and acknowledged to be one of the main instruments in rural electrification planning (ARE 2011, page 15).
The IEA Photovoltaic Power Systems Program (PVPS) developed a world-wide overview of design and simulation tools for hybrid PV systems in 2011. Complexity at the dimensioning stage make software simulation tools an important planning aid. For the purposes of this thesis, two software tools were considered, one dimensioning tool (HOMER) which can calculate the system dimensions on the basis of input data and one mini-grid design tool (VIPOR) which assists with the design of the mini-grid electrical distribution network. They are both open source, easily downloadable at no cost and have suitable application areas. While HOMER is fully developed, recognized and used internationally, VIPOR is still in the development phase, with an online available pre-release version (IEA PVPS 2011, page 22). HOMER and VIPOR are both developed by NREL and can work in conjunction. After the initial review of both software tools, it was decided to only deploy HOMER for the purpose of this thesis.

5.1 HOMER – Hybrid Optimization Model for Electric Renewables

HOMER evaluates designs of both off-grid and grid-connected power systems for a variety of applications. It helps to determine the kind of components that need to be included into the system design as well as the number and sizes of components to be used. Based on provided input data, HOMER simulates the annual performance of a variety of possible system designs in order to find a configuration that satisfies technical constraints at the lowest life-cycle costs. The outcome of the simulation is a list of the possible systems in the order of life-cycle costs (IEA PVPS 2011, page 20). "HOMER simulates the operation of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, HOMER compares the electric and thermal demand in the hour to the energy that the system can supply in that hour, and calculates the flows of energy to and from each component of the system. For systems that include batteries or fuel-powered generators, HOMER also decides for each hour how to operate the generators and whether to charge or discharge the batteries" (NREL 2011, page 4). Then it performs this analysis for each considered system configuration and determines whether a configuration is feasible, i.e. whether it can meet the electric demand under the specified conditions, as well as estimates the cost of installing and operating the system over the lifetime of the project (NREL 2011, page 4). HOMER includes an optimization function, which allows comparing different system design options and can perform sensitivity analysis for system configuration variables, such as stronger wind speeds or escalating fuel prices.

5.2 HOMER Reference Case Studies

HOMER is used by hybrid mini-grid system planners and researchers internationally. Several studies can be found in the internet. Two examples of how HOMER is used for mini-grid system planning are presented below in order to create a reference framework for the thesis case study. The first one presents a real case taken from the Andaman Islands of Thailand. The publication is called "Renewable Energy Options on Islands in the Andaman Sea - A feasibility study for hybrid renewable energy/diesel systems in two Tsunami impacted communities" (Greancen et al 2007). It offers transparent access to the data sets and simulation exercise conducted in the energy simulation software HOMER. The feasibility study for the village Bahn Koh Pu on a remote island in Southern Thailand presented in this publication served as the base case scenario for the own HOMER simulation exercises. It is the most transparent and accessible publication of a HOMER simulation exercise on a hybrid mini-grid system encountered in the research and literature review for this thesis.

The second study is taken from the flagship publication on hybrid mini-grids of the Allianz for Rural Electrification (ARE 2011), and showcases that hybrid mini-grids are in most cases, the least-cost, long-term option for rural electrification. Building the case for a model village in Ecuador, the analysis tests a range of hybrid solutions to prove that at current capital costs and with adequate natural conditions, hybrid solutions with high renewable energy fractions are competitive with diesel-only systems. This analysis is later contrasted with the results of the own HOMER simulation exercise.

5.2.1 HOMER Reference Case Study 1

The first reference case study presents a real case taken from the Andaman Islands of Thailand and is taken from the publication called "Renewable Energy Options on Islands in the Andaman Sea - A feasibility study for hybrid renewable energy/diesel systems in two Tsunami impacted communities" (Greancen et al 2007). It shows how existing scattered energy infrastructure of an island village can be integrated in a hybrid mini-grid system, utilizing HOMER to calculate the least cost option for the system configuration and developing the system's feasibility study (Greancen et al 2007).

The island of Koh Pu is approximately 10 km (north to south) by 4,5 km (east to west), located 3 km west of the mainland Krabi province in the Southern part of Thailand, and counts three villages with approximately 500 houses in total. Village 2, called "Bahn Koh Pu", was taken for the study, as it appeared the most organized and most able to operate a mini-grid project in the long term (Greancen et al 2007). It has approximately 150 houses with a population of 1,160 people. 85% earn their living through fishery, 10% are small shop owners and 5% own small rubber plantations. Tourism is not yet developed. One of the main reasons is the lack of electricity, and grid extension is not in sight due to the current low electricity demand on the island.

Power supply for Bahn Koh Pu comes from three sources: two diesel generators (each 30 kVA), 128 Solar Home Systems (120 W) and a dozen of small diesel generators. Generator #1 serves 40 houses and the mosque, and is used in general 4 hours per night (6.30 pm to 10.30 pm), and SHS are mostly used to meet the daytime load. The Bahn Koh Pu school has a 5kWp solar electric system. Each SHS system comprises a 120Wp PV panel, a 150W inverter/charge controller, a 125-Ah 12-volt battery, and two 10-watt fluorescent lights (Greancen et al 2007). Total solar production of the SHS is about 350 to 450 wH/d and maximum power output is limited to inverters capacity of 150 watts. Of the 128 SHS systems installed, 26 have failed, mostly due to failures in the inverter/charge controller, and 1/3 were installed in shaded locations. It is estimated that 95% of the SHS solar panels are technically fit to be re-used in a hybrid mini-grid system.

The current distribution system in Bahn Koh Pu used two conductor 2,5 mm copper wires, with indoor-rated insulation. They are assessed to be inappropriate for such distribution systems, which means that an entirely new distribution system in necessary for Bahn Koh Pu adhering to at least minimum quality standards found elsewhere in Thailand. At the time of the assessment, **diesel fuel costs** were at 33 baht/liter (approximately 1 USD), considerable higher than on the mainland. Generator #1 uses approximately 0,47 liter per kWh (15 liters per day for a daily production of 32 kWh). A typical value of 0,08 liters/hr-kW rated output or 2,4 liters for the 30kVA generator was assumed. As 40 households are connected to the generator #1, this implies a monthly “fuel cost” per household of about 340 baht (10,5 USD).

The electricity tariff is 25 Baht per kWh (0,77 USD), which is sufficient to cover the diesel fuel costs but not the depreciation of the generator. Funds are not collected to address future needs of equipment replacement and repair. As meters have difficulties reading demands below 1 kWh, houses with only few appliances pay 100 Baht per light monthly (approx. 3 USD). Fees are collected by the village committee.

SHS is used free of charge. The rest of the houses are not connected to the diesel generator, and use SHS or small diesel generators. Generator #2 is mostly used to power woodworking tools (drills, planers, saws, grinders) in a boat yard for fisher boat repairs, including for some houses in the vicinity of the boat yard.

An estimation of energy demand for all 150 houses is 160 kWh per day with the peak demand at 40kW. Typical appliances used in the houses are two to five fluorescent lamps, a color TV, a VCD Player and a fan. A few houses have in addition stereos and washing machines. Generator #1 has a constant demand between 8 and 10 kW between 6.30 and 10.30 pm, slightly decreasing in the later hours. To estimate future demand growth, villagers were interviewed and benchmarking was done through a reference project on a neighboring island. The results suggested a future demand of 419kWh per day. For hybrid modeling purposes, three scenarios of future demand are considered, the "base case" with 410 kWh/d, and a low and a high scenario of 75% and 125% of base case demand respectively.

Goals of the hybrid mini-grid are to increase the electricity service quality available to villagers and to enable future load growth, to lower the costs to villagers through using existing energy infrastructure more efficiently while adding new renewables, and to build local capacities. Important determinants for optimized hybrid systems include the village electricity load; location specific solar (kWh/m2/d) and wind resources (monthly averages); physical characteristics of batteries, diesel genset, solar panels and wind turbines; diesel fuel price; and investment, O&M and replacement costs of all components.

Several questions where posed by Greancen et al 2007 to lead the HOMER simulation. Which components does it make sense to include in the system design? How many and of what size each component should be used? What will be the total costs involved? What will be the least cost option?

The systems modeled in the study are AC bus systems, especially because of its modular character for future system expansion. Generator #1 and #2, PV and wind are the potential generating sources in the simulation. The following figure (see

Figure 25) shows the HOMER system layout, which indicate that the AC bus system has renewable sources directly connected to AC lines that go throughout the village.

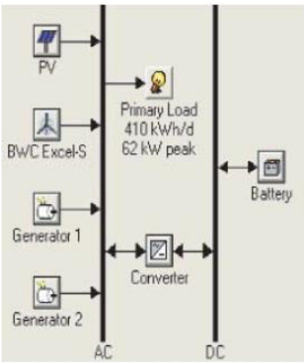

Figure 25: AC bus system has renewable sources directly connected to AC lines that go throughout the village. Source: Graencen et al 2007, page 16.

Input assumptions for the simulation are summarized in the tables below (see Table 7 and 8).

Variable	Value	Data source	Notes
Interest rate	6%		
Fixed costs	Fixed O&M $4,500 per year. Fixed capital cost $ 81,250	Koh Jig experience	(technician salary + power house, transmission line, installation fee)
PV cost	20 kW for $16,280 30 kW for $63,890, with linear increase for subsequent PV	PV cost estimated at $3.9 per watt (Leonics Jun06) + cost includes cost of Sunny Boy inverter (SMA quote).	First 20 kW recycled, and need only grid-intertie inverter.
Solar resource	5.04 kWh/m2/day	NREL dataset	
Wind turbine cost	10 kW for $66,000	Koh Jig installation	Uses Excel BWC S power curve (XLS)
Wind resource	Annual average 3.67 m/s with monthly variations	E for E study – data for Satun Province	Should be considered a rough estimate only.
Generator #1	30 kW initial cost $0.		Existing generator

Table 7: Input Assumptions for HOMER Simulation. Source: Graecen et al 2007, page 16.

Generator #2	Sell existing 30 kW for 80,000 baht. Subsequent purchase of 60 kW for $15,800. Linear interpolation for other sizes	Bangkok IVECO representative estimates	Generator #1 and #2 cannot operate simultaneously
Diesel cost	$0.86/liter (33 baht/liter)	Village interview	
Converter (inverter)	13.5 kW for $14,666. Other size costs by linear interpolation	SMA quote for three 4.5 kW "Sunny Island" units	Note – same inverter in Koh Jig costs $21,050 including tax and shipping
Battery	Hoppecke 12 OPzS. 30 cells cost $19,452. Other sizes determined by linear interpolation.	SMA quote.	Each cell is 2 volt, 1200 Ah. In actual practice the installation will need batteries in multiples of 30 (because it is a nominal 60 volt system) and therefore may need sizes other than 1200 Ah.

Table 8: Input Assumptions for HOMER Simulation. Source: Graencen et al 2007, page 17.

Fixed costs occur due to the need of building a new distribution system, a power house, and other minor costs that are independent of the generation and storage equipment. Also fixed O&M costs are required, which consists of the labor of one technician (4500 USD per year). These fixed costs were estimated in the study based on a reference hybrid project in a neighboring island.

Costs for PV are non-linear. The first 20kW are supplied by the existing 15kW SHS and 5kW by the solar electric school system. Additional expenditures for inverters and mounting structures were estimated to amount in total 16,000 USD. Additional PV units are available at a market price of 3,900 USD per kW. In the standard setting, HOMER assumes that the cost and generator size are related linearly. But non-linear cost curves can be indicated to account for discounts, economies of scale or as in this case, already existing infrastructure (NREL 2011). The figure below (see Figure 26) shows the non-linear cost curve for installed PV in Bahn Koh Pu.

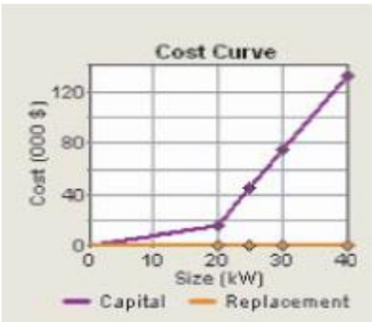

Figure 26: Cost curve for installed PV in Bahn Koh Pu. Replacement cost is irrelevant as no PV is replaced in the time period covered in the analysis (PV life and project life are both set at 20 years). Source: Graencen et al 2007, page 19.

For wind, turbines less than 10kW are considered to guarantee smooth erection and installation. The model Bergey BWC Excel-S 10 kW wind turbine is considered at a cost of 66,000 USD per installed turbine. These numbers are based on a reference hybrid project on a neighboring island.

There are two 30kVA **diesel generators** currently available in the village. The expected future peak load exceeds what one of those generators can generate. The best options from a fuel-savings perspective are that either one generator is sold and a larger one purchases (keeping the old one as a back-up), or both generators run simultaneously but need to be synchronized (at a substantial cost of 7,000 USD). A 60 kW generator would cost 15,790 USD, and the existing generator could be sold at

2,100 USD. O&M costs are estimated at 1USD/hour for a 30kW generator and 1,5USD/hour for a 60kW generator. Generator lifetime is 15,000 hours.

Batteries considered are large two-volt industrial lead –acid batteries manufactured by Hoppecke, with costs at 19,452 USD for thirty two-volt cells, each 1200 Ah (42,1 kWh) of storage. Costs are assumed linear with increasing kWh storage.

As seen in the figure below (see Figure 27), in order to simulate a wide spectrum of configuration options, a range of sizes und numbers were indicated for the different generation source. The existing generator #1 capacity is fixed at 30kW, and generator #2 capacity is choose by HOMER. Data is inserted so that both generators are not allowed to run in parallel (because of high synchronization costs).

PV Array (kW)	XLS (Quantity)	Gen1 (kW)	Gen2 (kW)	Batteries (Quantity)	Converter (kW)
0.000	0	30.00	0.00	0	0.00
20.000	1		30.00	40	10.00
25.000	2		40.00	50	13.50
30.000			50.00	60	17.00
40.000			60.00	70	20.00
50.000			70.00	80	
				90	
				100	
				110	

Figure 27: sizes considered for components in Bahn Koh Pu HOMER model run. XLS refers to the wind turbine. Source: Graencen et al 2007, page 17.

The figure below (see Figure 28) shows the results of the HOMER modeling exercise. The system with the least cost of energy is the one highest on the list. The first six columns show graphic icons representing which components are present in the optimized system. The other columns show the optimized capacity of each component, the initial capital costs, the total net present cost, the cost of energy (USD/kWh), renewable energy faction, total liter of diesel consumed per year, and number of hours each generator is operating (Greancen et al 2007).

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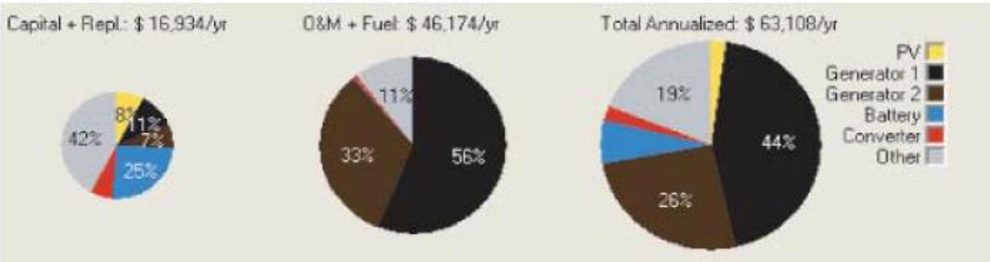
PV (kW)	XLS	Gen1 (kW)	Gen2 (kW)	Batt.	Conv. (kW)	Disp. Stgy	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)
20		30	50	40	10.0	CC	$ 145,379	$ 723,848	0.422	0.19	41,523	3,734	1,030
20	1	30	50	40	10.0	CC	$ 211,379	$ 787,471	0.459	0.22	40,094	3,670	990
		30	50	40	10.0	CC	$ 129,099	$ 837,862	0.488	0.00	51,111	5,143	1,051
20		30	60			CC	$ 111,210	$ 885,428	0.516	0.17	56,203	6,016	2,036
	1	30	50	40	10.0	CC	$ 195,099	$ 897,075	0.523	0.03	49,328	5,011	1,009
		30	60			CC	$ 94,930	$ 924,063	0.538	0.00	60,444	6,720	2,040
20	1	30	60			CC	$ 177,210	$ 956,431	0.557	0.20	55,265	5,949	2,018
	1	30	60			CC	$ 160,930	$ 998,250	0.582	0.04	59,564	6,734	2,026

Figure 28: Results for HOMER modeling for Bahn Koh Pu under the base-case assumption. Source: Graencen et al 2007, page 24.

Based on these results, the optimal system is a hybrid solar/diesel system (no wind power), with 20kW of solar, a 50kW diesel generator #2, 96kWh of batteries, and 10kW bi-directional inverter. This system uses 19% renewable energy, and cost of electricity is at 0,422 USD/kWh, including depreciation of capital and O&M costs. Initial capital costs for the system is 145,379 USD. In comparison, a diesel-only solution would lead to a cost of energy of 0,538 kW/h. Both is cheaper than what is currently paid.

The distribution system and power house are the single largest cost (indicated as "other" in the Figure 29). Net present costs are largely dominated by generator costs (72% of total costs).



Component	Initial Capital ($)	Annualized Capital ($/yr)	Annualized Replacement ($/yr)	Annual O&M ($/yr)	Annual Fuel ($/yr)	Total Annualized ($/yr)
PV Array	16,280	1,419	0	10	0	1,429
Generator 1	0	0	1,803	3,734	22,297	27,835
Generator 2	11,049	963	267	1,717	13,412	16,359
Battery	25,936	2,261	1,991	133	0	4,385
Converter	10,864	947	198	370	0	1,516
Other	81,250	7,084	0	4,500	0	11,584
Totals	145,379	12,675	4,259	10,464	35,710	63,108

Figure 29: Cost breakdown of optimized Koh Pu system. Source: Graencen et al 2007, page 25.

The sensitivity analysis encompassed diesel fuel price escalation and future demand fluctuations. In the above base case assessment, a diesel fuel price of 0,86 USD per liter was assumed. In the sensitivity analysis, additional fuel prices were set at 134%, 163% and 259% relative to the base-case diesel fuel price (see Figure 30). The modeling revealed that higher diesel prices encourage higher renewable energy system fractions. As shown in the figure below, wind is in no scenarios a good investment.

Diesel ($/L)	PV (kW)	XLS	Gen1 (kW)	Gen2 (kW)	Batt.	Conv. (kW)	Disp. Strgy	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)
0.860	20		30	50	40	10.0	CC	$ 145,379	$ 723,848	0.422	0.19	41,523	3,734	1,030
1.150	20		30	50	40	10.0	CC	$ 145,379	$ 862,104	0.502	0.19	41,528	3,735	1,030
1.400	30		30	50	80	13.5	CC	$ 222,727	$ 968,605	0.564	0.27	36,799	2,996	797
2.230	40		30	50	100	13.5	CC	$ 283,305	$ 1,309,664	0.763	0.34	34,499	2,880	720

Figure 30: Fuel price sensitivity results Bahn Koh Pu. Source: Graencen et al 2007, page 26.

The sensitivity analysis looks at different demand growth scenarios and includes a low (75%) and a high (125%) scenario relative to the base case of 410kWh/day. In the low load scenario, a 40 kW generator is sufficient, and in the high scenario a 60kW generator is required. Renewable energy fraction is higher in low load scenarios. The figure below (see Figure 31) shows the forecast sensitivity results in Bahn Koh Pu.

Pri. Load (kWh/d)	PV (kW)	XLS	Gen1 (kW)	Gen2 (kW)	Batt.	Conv. (kW)	Disp. Strgy	Initial Capital	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)
410.000	20		30	50	40	10.0	CC	$ 145,379	$ 723,848	0.422	0.19	41,523	3,734	1,030
307.000	20		30	40	50	10.0	CC	$ 149,232	$ 566,344	0.441	0.24	28,161	3,562	177
512.500	20		30	60	40	13.5	CC	$ 151,812	$ 887,854	0.414	0.15	54,115	3,118	1,691

Figure 31: Load forecast sensitivity results in Bahn Koh Pu. Source: Graencen et al 2007, page 29.

5.2.2 HOMER Reference Case Study 2

The case study is done on the island of Bellavista located at the Jambeli Archipielago, El Oro province, Ecuador (ARE 2011). It simulates various hybrid configurations and associated cost structures in comparison to a diesel-only system. ARE (2011) emphasis that the results can be exemplary for other location, especially as the local conditions simulated in the study are typical for many locations in developing countries.

The village has an average daily energy demand of 266 kWh, a peak power demand of 26 kW, and the system serves 24 hours electricity a day to 52 users including a school and a naval station. The local natural conditions and the costs of the components are presented in the tables below (see Table 9 and 10).

Local natural conditions	
Solar insolation	6 kWh/m²/day
Average wind speed	5 m/s
Hydro resources[9]	80 L/s
Oil price	US$ 0.70/L

Table 9: Natural Conditions of Test Site. Source: ARE 2011, page 15

Cost of components	
Genset	US$ 400/kW
Small wind turbine[10]	US$ 2,120/kW
PV	US$ 2,822/kW
Small hydro	US$ 1,790/kW
Battery	US$ 225/kW
Converter	US$ 1,445/kW

Table 10: Costs of Components. Source ARE 2011, page 15.

Under these conditions the total accumulated costs of the systems is shown in the figure below (see Figure 32).

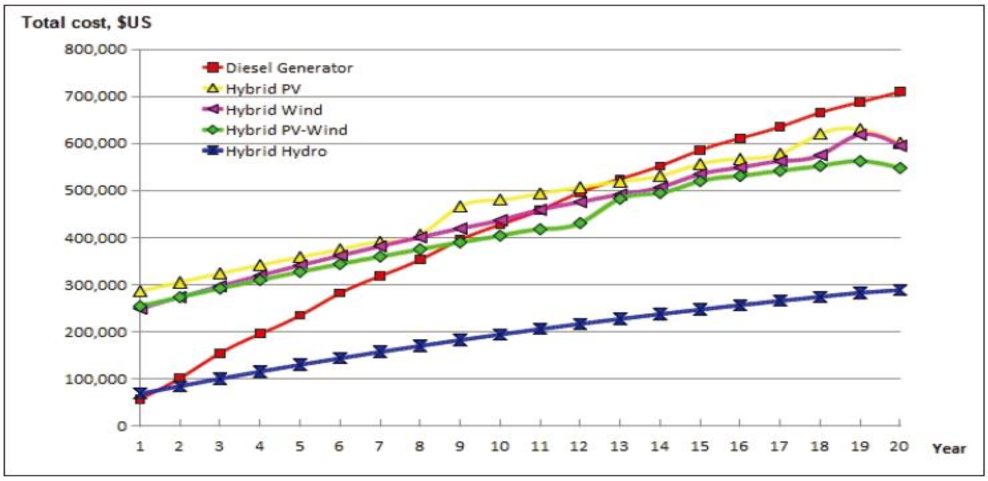


Figure 32: Total cost through the lifetime of the project. Source: ARE 2011, page 16.

The diesel based mini-grid powered by a 30 kV genset is the most expensive solution over the lifetime of the project. Fuel costs and replacement costs of the genset every 3-4 years (after 25,000 operating hours) clearly offset the low initial investment costs.

The cheapest option is the hybrid hydro-diesel option, which breaks even with the diesel-only system already after one and a half years. PV-diesel hybrid and small wind-diesel hybrid have similar costs, both being still cheaper than the diesel-only solution. Although wind technologies are in general cheaper than PV, in this case the higher solar insulation offsets this cost advantage. Operating costs are higher for the wind-hybrid system as it relies more on diesel (17%) than the PV hybrid system (8%). The battery replacement costs are higher in the PV system, where it needs to be changed twice as frequently as in the wind power scenario, after 8 and 16 years. Break even points with diesel-only system are after 12,7 and 11,2 years respectively, with 16% less total costs.

Beside the hydro hybrid system, a hybrid power system combining PV, small wind, and a diesel genset is the least cost option (see Table 11). Diesel fraction is only 9%, which keeps operating costs low, and battery has a prolonged lifetime of 13 years. The system breaks event with the diesel-only system after 8,7 years, with 23% less total costs.

	Genset Capacity	RET Capacity	RE Share	LCOE* (US$/kWh)	Break-even point
100% diesel	30 KVA	-	0%	0.538	-
Hybrid PV	20 KVA	60 kW	93%	0.456	12.7 years
Hybrid Small Wind	20 KVA	60 kW	83%	0.451	11.2 years
Hybrid PV-Small Wind	10 KVA	PV - 35 kW SW - 20 kW	91%	0.420	8.7 years
Hybrid Small Hydro	10 KVA	26.8 kW	97%	0.219	1.5 years

Table 11: Outcome of Model Configurations. Source: ARE 2011, page 17.

A sensitivity analysis regarding changing natural conditions was conducted. It showcases that hybrid PV-wind-diesel systems become competitive in comparison to a diesel-only system at wind conditions of 3,4 m/s, or with an insulation of 4,1 kWh/m2/day. The following figure (see Figure 33) visualizes the sensitivity analysis. The case study situation is marked as a small white circle.

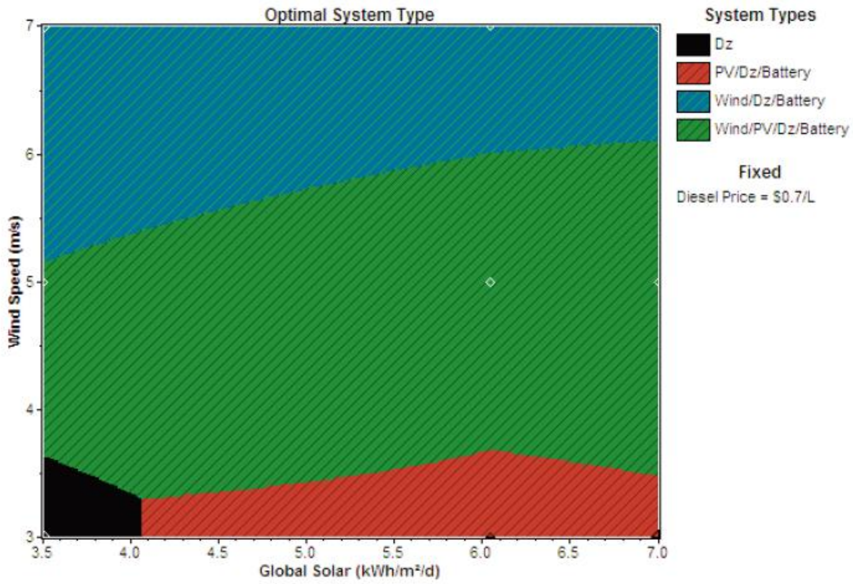


Figure 33: Optimal system type at different natural conditions with fixed oil price of 0,70 USD per liter. Source: ARE 2011, page 17.

The next sensitivity analysis integrates escalating diesel fuel prices (see Figure 34). It demonstrates that at a diesel fuel price of 1,30 USD – a price not unusual for remote areas – a diesel-only system is never cost competitive with hybrid solutions.

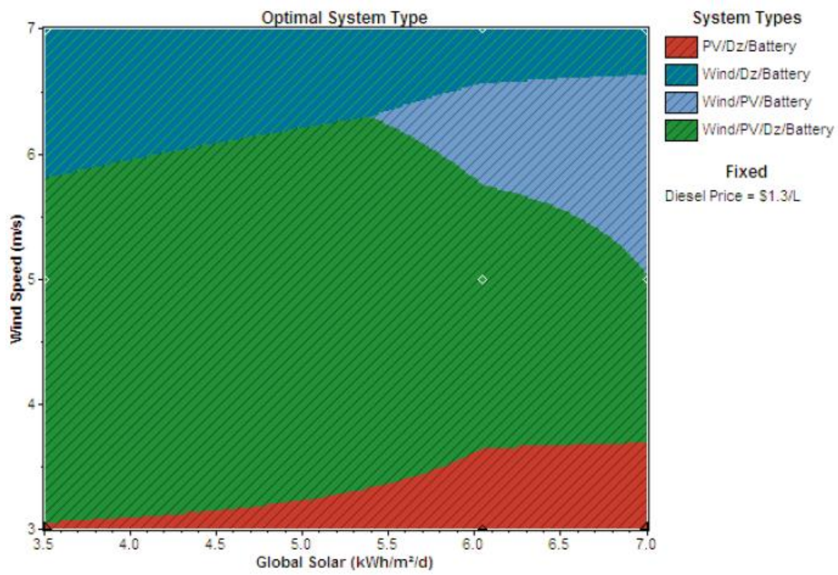


Figure 34: Optimal system type at different natural conditions with a fixed oil price at 1,30 USD per liter. Source: ARE 2011, page 18.

The next table (see Table 12) shows how expensive the diesel-only system gets when the fuel price increases from 0,70 USD to 1,50 USD per liter. At a diesel price of 1,50 USD per liter, the levelized cost of energy (LCOE) is almost twice as much as for a hybrid PV-wind system.

	LCOE (US$c/kWh)	Break-even point
Hybrid PV-wind	42.0	-
Diesel generator – US$0.70/L	53.8	8.7 years
Diesel generator – US$1.00/L	63.9	6.4 years
Diesel generator – US$1.50/L	80.8	4.4 years

Table 12: Sensitivity Analysis with Escalating Diesel Prices. Source: ARE 2011, page 19.

5.3 HOMER Optimization Simulation for a Hybrid Mini-Grid System

The HOMER optimization study for this thesis is based on the Graencen et al (2007) case study for a village hybrid-mini grid on the island Thai Koh Pu. There are three villages with approximately 500 houses in total on the village. Village 2, called "Bahn Koh Pu", was taken for the study. It has approximately 150 houses with a population of 1,160 people (see previous sub-chapter for details). The original HOMER simulation model, including the used input data – as explained in detail in the previous sub-chapter – was available and accessed via URL 12. It presents the base case scenario for the following optimization exercise.

The first optimization exercise uses adjusted cost inputs for the different components as presented in Graencen et al (2007). The original study was produced in 2007 and cost inputs are outdated. Instead, cost inputs for the different generation technologies are taken from the publication ARE 2011 and own research. This is done in order to assess whether the optimal system configuration designed by Graencen et al in 2007 for the hybrid mini-grid in the village Bahn Koh Pu would look different today based on adjusted cost variables, including the sensitivity analysis for future demand fluctuations. It would raise the same questions to lead the HOMER simulation exercise as originally pointed out by Graencen et al (2007):

- Which components does it make sense to include in the system design? How many and of what size each component should be used? What will be the total costs involved?

The second optimization exercise includes a sensitivity analysis for new variable determents. It includes variations in wind speed and solar radiation as a third variable. The question addressed here is the following:

- How would the system configuration change at wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day (which are inputs for local natural conditions used in ARE 2011, assumed to be typical local conditions in many developing countries)?

The third optimization exercise aims to assess costs for higher levels of renewable energy fraction. It builds upon the new base case scenario (with the adjusted prices) and the second modeling exercise for wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day. The second generator is erased as option in the system configuration, and capacity for generator #1 is kept constant (as already available in the system).

The fourth optimization exercise aims to assess costs for higher levels of renewable energy fraction. It builds upon the new base case scenario and the second modeling exercise for wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day. The second generator is erased as option in the system configuration, as well as generator #1. A 10 kW diesel generator is added to serve as back up and for covering peaks. Finally, an investment capital cost subsidy of 40% and its impact on the LCOE is simulated, as well discussed in relation to setting appropriate tariff schemes.

The demand for all optimization exercises is set at 410 kWh/day. The different outcomes of the simulation exercises are compared at the end and results interpreted.

5.3.1 HOMER Optimization Exercise 1

5.3.1.1. Cost Adjustments

Costs for PV: In the original base case scenario according to Graencen et al (2007) additional costs for existing PV include the costs of Sunnyboy inverters (since PV is directly connected to AC bus) as well as rack and wire. 3.8 kW Sunnyboy inverters are taken, each with a cost of 1867 EUR, resulting in existing PV costs per kW of 614 USD/kW. Rack and wire costs additional 200 USD per kW. This results in a total of 814 USD per kW, and for the existing 20 kW of SHS extracted PV modules a total of 16280 USD. Additional 10 kW of PV capacity costs 3950 USD per kW plus 814 USD per kW for inverter, wires and rack. Total costs for 30 kW PV capacity thus costs 63890 USD (4761*10+16280 = 63890).

A 3,8 kW SMA Sunny Boy inverter is available today at a price of 1722 USD (URL 13), thus costs per kW amount to 453 USD. Rack and wire costs need to be included, for which 200 USD per kW are calculated. Prices for rack and wire are considered to be constant relative to the base case scenario. This amounts to 653 USD per kW or 13,060 USD for 20 kW (compared to 16,220 USD in the base case).

According to ARE 2011, 2822 USD per kW PV component cost is assumed for the new optimization exercise, plus the above calculated 653 USD per kW for inverters, wires and rack. This amounts to a total costs of 3,475 USD per kW newly installed PV, or 34,750 USD for 10 kW newly installed PV. Thus, 30 kW PV (20 kW recycled from the SHS and solar school system and 10 newly installed kW) make a total cost of 47,810 USD (compared to 63,890 USD in the base case).

Costs for Wind Turbines: In the base case scenario two Bergey Excel 5 wind turbines (URL 14) were used and the price was estimated at 66,000 USD, not specifying whether this included costs of the tower, controller, inverter, wiring, installation and labor.

In the new base case scenario the Alize Wind Turbine manufactured by Fortis Wind Energy is used. The reason for choosing the Alize Wind Turbine is because it was used for benchmarking the wind component costs per kW in the ARE 2011 publication. The Alize wind turbine has a maximum output of 10 kW, a rotor diameter of 7 meter, an annual yield at 6 m/s of 22 MWh, and is mounted on a pole between 18-36 m height. Blades are made of Fibreglass reinforced epoxy. The generator is a synchronous, 3 phase permanent magnet one (URL 15). It comes in different voltages, so it can be connected at 120Vdc, 240 Vdc, single phase grid or 3 phase grid applications. Safety system includes a hinged vane which will gradually turn the rotor out of the wind and a short circuit system for the generator. Fortis Wind Energy gives a 5 years guarantee and the average lifetime of the system is given at 20 years. It is a maintenance free system (URL 15).

The wind component costs is rated in ARE 2011 at 2,120 USD/kW, but this seems not yet to include costs for the tower, controller, inverter, wiring, installation and labor.

In the new base case scenario, costs for an Alize wind turbine type grid connection 1 phase 230V/50Hz amounts to 40,191 USD. It is a package price offered by Fortis Wind Energy and includes the Alize wind turbine (14,371 USD), an unimex voltage controller with dump load (4,143 USD), SMA Windy Boy inverter (3x3300 or 2x5000) (7,381 USD), and a guyed wire mast of 18 meter height (URL 16). The kW costs for a Alize 10 kW small wind system thus amount to 4,019 USD, which is significantly higher than the 2,120 USD indicated by ARE 2011, but substantially lower than the 6,600 USD of the base case scenario (Graencen et al 2007). Also the power curve increased substantially through replacing the two Bergey 5 kW turbines with the Alize 10 kW turbine (Fortis 2008). In addition, as the average lifetime of the Alize wind system is 20 years, no replacement costs were included in the HOMER simulation (in contrary to the base case scenario, where the Bergey wind turbines were projected to be replaced after 15 years). The table below (see Table 13) shows the different power outputs at wind speeds of 3, 4, 5 and 6 meters. Both adjustments – power curve and replacement costs – were added into the HOMER simulation.

Wind Speed (m/s)	Power Output (kW)	
	Bergey	Alize
3	0,046	0,024
4	0,247	0,359
5	0,584	1,176
6	1,028	2,224

Table 13: Power Output Comparison per m/s wind speed for Bergey and Alize Wind Turbines. Source: Own Table.

Costs for Diesel Generators: In the base case scenario, the price of a 60 kW diesel generator is rated at 15,800 USD, and the replacement costs for generator#1, a 30 kW generator, are set at 9,000 USD. Interestingly, ARE (2011) puts the price per kW of a diesel genset at 400 USD, far more than the diesel genset costs placed by Graencen et al (2007). Research for this thesis has indicated cost estimates for a 60 kW diesel generator at approximately 12,000 USD (e.g. URL 17) and for a 30 kW at approximately 8,000 USD. These numbers were used as input data for the new base case simulation. For operation and maintenance costs, numbers of Graencen et al (2007) were used.

Costs for Inverters: The base case simulation assumes three SMA "Sunny Island" inverters a 4,5 kVA, which are assumed to be 90% efficient in changing electricity from AC to DC, or from DC to AC. Costs for three Sunny Island inverters of 4,5 kW are estimated at 13,666 USD, plus 1000 USD for integration, monitoring and metering equipment costs, resulting in 14,666 USD. This puts one Sunny Island at approximately 4,500 USD, which correlates with the research findings for this thesis. Thus, the same numbers were applied for the new base case scenario. Only the inverter efficiency was upgraded from 90% to 95%.

Costs for Batteries: The batteries considered in the base case scenario are large two-volt industrial lead-acid batteries manufactured by Hoppecke (Graencen et al 2007). Costs are estimated to be 19,452 USD for thirty 2-volt cells, each 1,200 Ah of storage. Thus, one 2-volt cell amounts to 648,4 USD. Costs are assumed to be linear with increasing kWh storage. This is consistent with the research for this thesis and therefore the same numbers are applied in the new base case scenario. Lead-based batteries are the most commercially viable technology in the off-grid renewable energy market, and therefore also considered in the new based case scenario (ARE 2013).
One 2-volt cell a 1,200 Ah has a potential (nominal) storage capacity of 2,4 kWh, but as discharge should ideally not go below 30 to 50%, storage capacity is reduced in reality. Graencen et al (2007) stipulates the usable nominal storage capacity of thirty 2-volt cells, each 1,200 Ah at 42.1 kWh (compared to 72 kWh nominal storage capacity). This amounts to 476 USD per kWh of usable nominal storage capacity, and 270 USD per kWh of nominal storage capacity. This is slightly higher than ARE

2011 and ARE 2013 numbers. ARE (2011) puts the costs for the battery component at 225 USD/kWh. ARE (2013) puts the costs per kWh installed between 120 and 200 EUR. Nevertheless, ARE 2011 is not indicating whether the costs occur for usable nominal storage capacity or storage capacity, which can lead to underestimating the real costs per kWh of installed battery storage capacity.

ARE 2013 puts the cost per kWh electricity throughput between 0,1 and 0,15 EUR per kWh Levelised Cost of Electricity (LCOE) for battery only. In the base case scenario (Graencen et al 2007), HOMER results for the optimized system configuration put the battery wear costs on 0,169 USD/kWh, the cost per kWh of throughput resulting from the shortening of the battery lifetime by cycling energy through the battery bank (HOMER 2010), which is consistent with the aforementioned ARE 2013 numbers.[10]

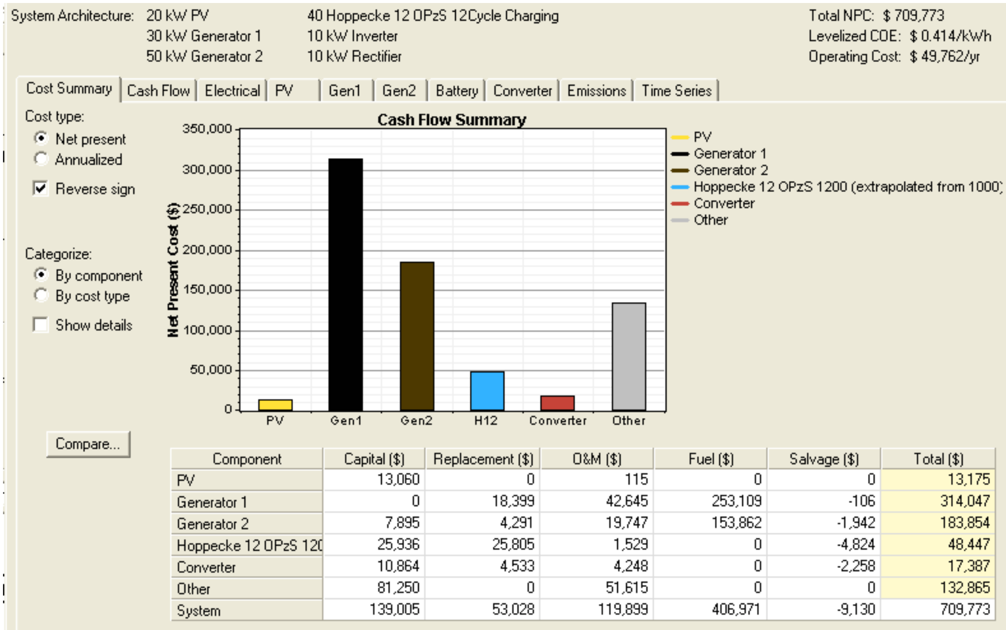
Fixed Costs: Building a hybrid system on Koh Pu requires a new distribution system, a power house, and other costs that are roughly independent of the electricity generation and storage equipment chosen, and are estimated in the base case scenario at 81,250 USD (Graencen et al 2007). In addition, the project incurs fixed O&M costs, which is labour for one technician at 4,500 USD per year. These figures were also used in the new base case scenario.

5.3.1.2. Results for the Optimization Exercise 1

As expected, the results are similar to the base case scenario (Graencen et al 2007). According the new base case scenario, the optimal system for Koh Pu is a hybrid solar/diesel system (no wind power), with 20 kW of solar, a 30 kW Generator #1, a 50 kW diesel generator #2, 96 kWh of batteries, and 10 kW bi-directional inverter. This “optimal” system uses 13% renewable energy, and the cost of electricity is 0,414 USD/kWh (as compared to 0.422 USD/kWh in the base case scenario of Graencen et al 2007) including depreciation on capital and levelized O&M costs. The

[10] In the base case scenario (Graencen et al 2007), HOMER results for the optimized system configuration put the average energy costs at 0,198 USD/kWh, which is the average cost that the system has incurred for deliberately charging the battery bank. The price of battery power is the sum of the battery wear cost and the battery energy cost. This means that the total cost of battery power in the base case simulation is 0,367 USD/kWh.

initial capital cost for this system is estimated to be 139,000 USD (as compared to 145,379 USD in the base case scenario) with the “other” (distribution system and power house) being the single largest cost at this stage. Diesel expenditures over the project’s 20 year lifetime mean that the net present cost is largely dominated by generator costs. The figure below (see Figure 35) shows the HOMER results for optimal hybrid system configuration in Optimization Exercise 1.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	13,060	0	115	0	0	13,175
Generator 1	0	18,399	42,645	253,109	-106	314,047
Generator 2	7,895	4,291	19,747	153,862	-1,942	183,854
Hoppecke 12 OPzS 12(	25,936	25,805	1,529	0	-4,824	48,447
Converter	10,864	4,533	4,248	0	-2,258	17,387
Other	81,250	0	51,615	0	0	132,865
System	139,005	53,028	119,899	406,971	-9,130	709,773

Figure 35: HOMER results for optimal hybrid system configuration in Optimization Exercise 1. Source: Own results.

According the new base case scenario, the second optimal system for Koh Pu is a hybrid solar/wind/diesel system, with 20 kW of solar, one 10 kW Alize wind turbine, one 30 kW Generator#1, one 50 kW diesel generator #2, 96 kWh of batteries, and 10 kW bi-directional inverter. This “second optimal” system uses 16% renewable energy, and the cost of electricity is 0,433 USD/kWh (as compared to 0,414 USD/kWh for the PV/diesel hybrid system in the new base case scenario) including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 179,196 USD (as compared to 139,000 USD for the PV/diesel hybrid system).

According to the new base case scenario, the third optimal system for Koh Pu is a diesel-only system, with a 30 kW Generator#1, a 50 kW diesel generator #2, 96 kWh of batteries, and 10 kW bi-directional inverter. This "third optimal" system uses 0% renewable energy, but battery banks and inverters, and the cost of electricity is 0,480 USD/kWh, including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 125,945 USD (as compared to 179,196 USD for the wind/PV/diesel hybrid and 139,000 USD for the PV/diesel hybrid system). CO2 emissions are 133,609 kg/yr as compared to 106,687 kg/yr for the wind/PV/diesel hybrid and 108,645 kg/yr for the PV/diesel hybrid system.

The following figure (see Figure 36) shows the monthly average electric production according to generating sources for the optimal hybrid system configuration. The overall production is 159,226 kWh per year. 19%, or 29,681kWh are produced by PV panels (with a capacity factor of 20,2%). The 30 kW generator #1 produces 53%, or 83,680 kWh (with a capacity factor of 31,8%), and the 50 kW generator #2 produces 29%, or 45,864 kWh (with a capacity factor of 10,5%). There is some excess electricity. It amounts to 1,899 kWh per year, or 1,19%.

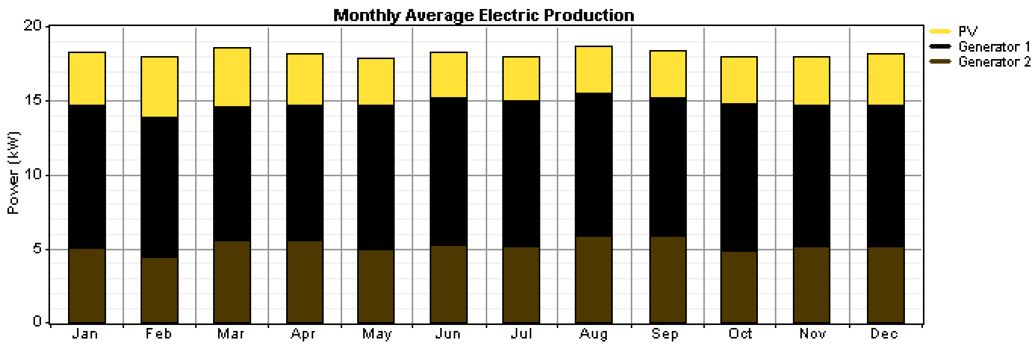


Figure 36: Monthly Average Electric Production for optimal hybrid system configuration in Optimization Exercise 1. Source: Own results.

5.3.1.3. Sensitivity of optimized system design to changing load forecasts

The base case load is forecast to be 410 kWh per day with a peak load of 63 kW. The sensitivity analysis considers an additional high and low scenario of 125% (512 kWh/d) and 75% (307 kWh/d) of base-case forecast (Graencen et al 2007).

The optimal solution for the low demand scenario (307 kWh/d) is a hybrid PV/diesel system consisting of 30 kW PV, a 30 kW diesel generator, 120 kWh nominal battery storage capacity and a 13,5 kW inverter. This system uses 26%

renewable energy, and the cost of electricity is 0,430 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 125,945 USD. CO2 emissions amount to 63,047 kg/yr.

In comparison, the optimal solution for the base case low demand scenario is a hybrid PV/diesel system consisting of 20 kW PV, a 30 kW diesel generator, a 40 kW diesel generator, 120 kWh nominal battery storage capacity and a 10 kW inverter. This system uses 24% renewable energy, and the cost of electricity is 0,441 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 149,232 USD. CO2 emissions amount to 74,283 kg/yr.

The optimal solution for the high demand scenario (512 kWh/d) is a hybrid PV/diesel system consisting of 25 kW PV, a 30 kW diesel generator, a 60 kW diesel generator, 96 kWh nominal battery storage capacity and a 13,5 kW inverter. This system uses 13% renewable energy, and the cost of electricity is 0,403 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 162,182 USD.

In comparison, the optimal solution for the base case high demand scenario is a hybrid PV/diesel system consisting of 20 kW PV, a 30 kW diesel generator, a 60 kW diesel generator, 96 kWh nominal battery storage capacity and a 13,5 kW inverter. This system uses 15% renewable energy, and the cost of electricity is 0,414 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 151,812 USD. The figure below (see Figure 37) shows the decreasing levelized costs of energy in correlation with increasing demands.

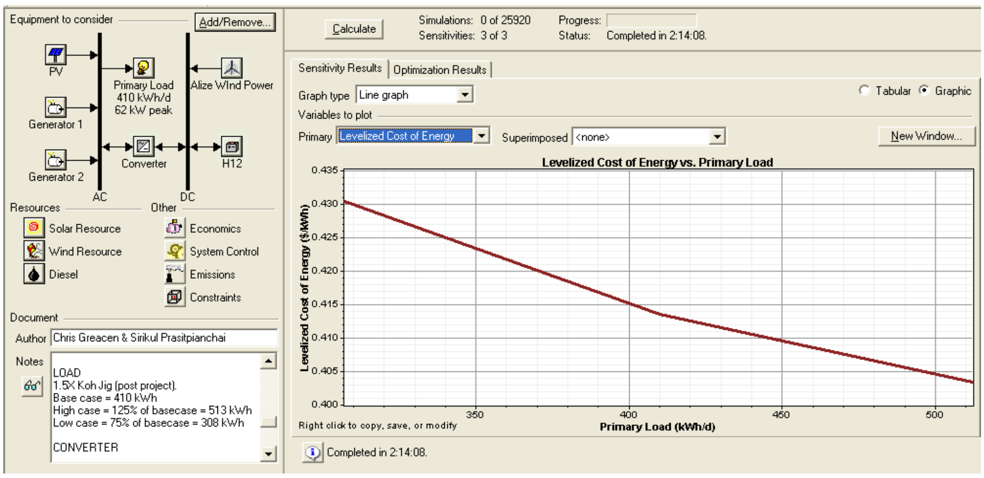


Figure 37: Decreasing levelized costs of energy in correlation with increasing demands. HOMER results for Optimization Exercise 1. Source: Own results.

5.3.2 HOMER Optimization Exercise 2

The second optimization exercise includes a sensitivity analysis for a set of new variable determinants. It encompasses variations in wind speed and solar radiation as new variables. The question addressed here is the following:

- How would the system configuration change at wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day (which are inputs for local natural conditions used in ARE 2011, assumed to be typical local conditions in many developing countries)?

Results for this optimization exercise are shown in the below figure. The optimal solution for the new base case scenario with natural conditions of 4,94 m/s wind speed and 6 kWh/m2/day is a PV/diesel hybrid mini-grid consisting of 25 kV PV, a 30 kV diesel genset, a 50 kV diesel genset, a battery bank of 168 kWh nominal storage capacity and 13,5 kV inverter. This system uses 20% renewable energy, and the cost of electricity is 0,399 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 179,634 USD. CO2 emissions are 94,768 kg/yr.

The "second" optimal solution for the new base case scenario with natural conditions of 4,94 m/s wind speed and 6 kWh/m2/day is a PV/wind/diesel hybrid mini-grid consisting of 25 kV PV, one 10 kV Alize wind turbine, a 30 kV diesel genset, a 50 kV diesel genset, a battery bank of 168 kWh nominal storage capacity and 13,5 kV inverter. This system uses 22% renewable energy, and the cost of electricity is 0,417 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 219,825 USD. CO2 emissions are 92,416 kg/yr. The figure below (see Figure 38) shows the HOMER results for Optimization Exercise 2.

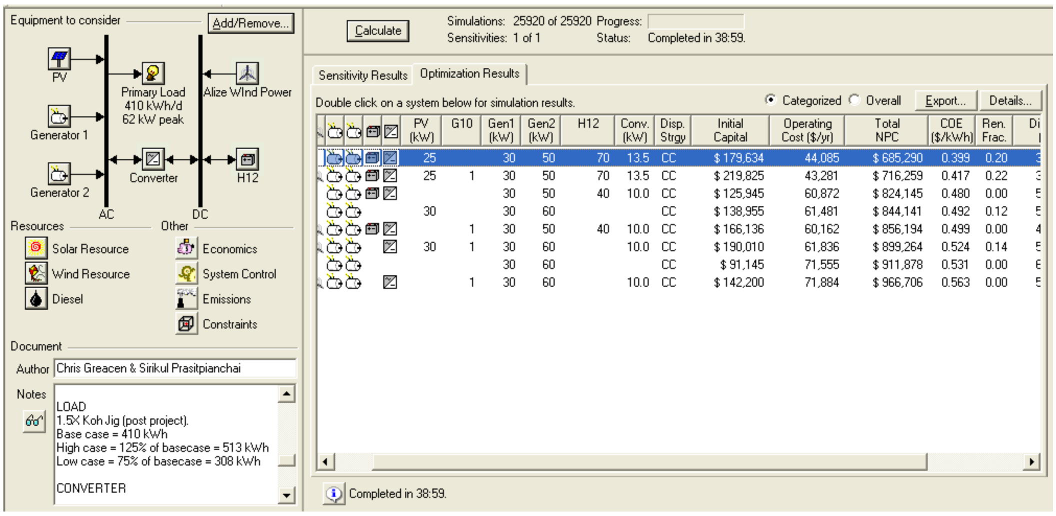


Figure 38: HOMER results for Optimization Exercise 2. Source: Own results.

The following figure (see Figure 39) shows the monthly average electric production according to generating sources for the optimal solution. 163,642 kWh are produced per year. 27%, or 44,154 kWh are produced by PV panels (with a capacity factor of 20,2%). The 30 kW generator #1 produces 49%, or 80,953 kWh (with a capacity factor of 30,8%), and the 50 kW generator #2 produces 24%, or 38,538 kWh (with a capacity factor of 8,8%). There is some excess electricity. It amounts to 2,870 kWh per year, or 1,75%.

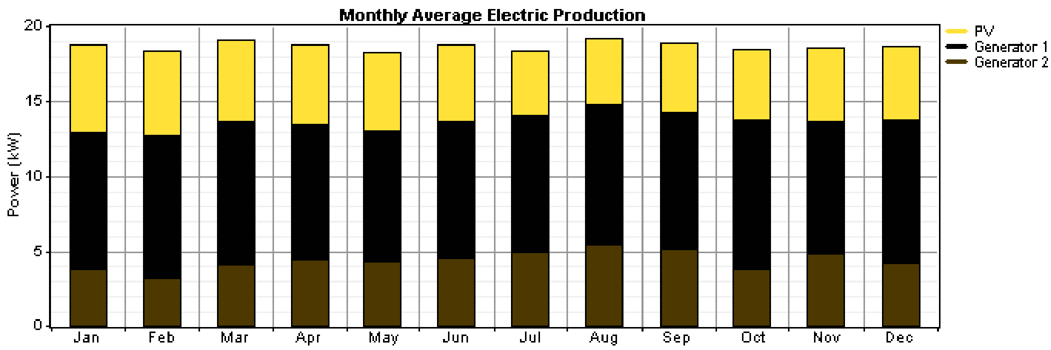


Figure 39: Monthly Average Electric Production for optimal hybrid system configuration in Optimization Exercise 2. Source: Own results.

5.3.3 HOMER Optimization Exercise 3

The third optimization exercise aims to assess costs for higher levels of renewable energy fraction. It builds upon the new base case scenario and the second modeling exercise for wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day. The second generator is erased as option in the system configuration, and the 30 kV generator #1 is optional.

The optimal solution for the new base case scenario with natural conditions of 4,94 m/s wind speed and 6 kWh/m2/day (including one fixed 30 kV diesel generator) is a PV/diesel hybrid mini-grid consisting of 30 kV PV, a 30 kV diesel genset, a battery bank of 384 kWh nominal storage capacity and 27 kV inverters. This system uses 24,5 % renewable energy, and the cost of electricity is 0,426 USD/kWh including depreciation on capital and levelized O&M costs. The initial capital cost for this system is 262,136 USD. CO2 emissions are 83,363 kg/yr. The figure below (see Figure 40) shows the HOMER results for Optimization Exercise 3.

PV (kW)	G10	Gen1 (kW)	H12	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Dies (L)
30		30	160	27.0	CC	$ 262,136	40,847	$ 730,642	0.426	0.24	31,
30	1	30	190	27.0	CC	$ 321,779	38,882	$ 767,755	0.447	0.27	30,
		30	150	27.0	CC	$ 207,842	58,753	$ 881,739	0.514	0.00	47,
	1	30	150	27.0	CC	$ 248,033	57,898	$ 912,115	0.532	0.00	46,

Figure 40: HOMER results for Optimization Exercise 3. Source: Own results.

The following figure (see Figure 41) shows the monthly average electric production according to generating sources. 165,988 kWh are produced per year. 32%, or 52,985 kWh are produced by PV panels (with a capacity factor of 20.2%), and 68%, or 113,303 kWh are produced by the 30 kW diesel generator (with a capacity factor of 43%). There is hardly any excess electricity. It amounts to 86 kWh per year, or 0,0518%.

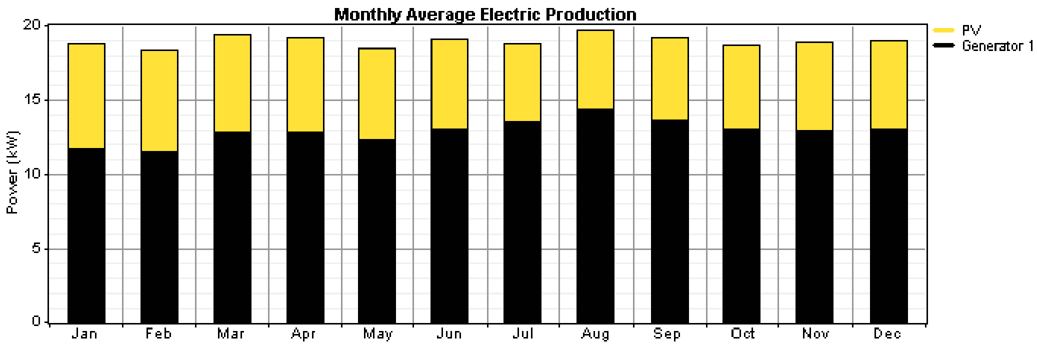


Figure 41: Monthly Average Electric Production for optimal hybrid system configuration in Optimization Exercise 3. Source: Own results.

5.3.4 HOMER Optimization Exercise 4 – The 100% Renewables Solution

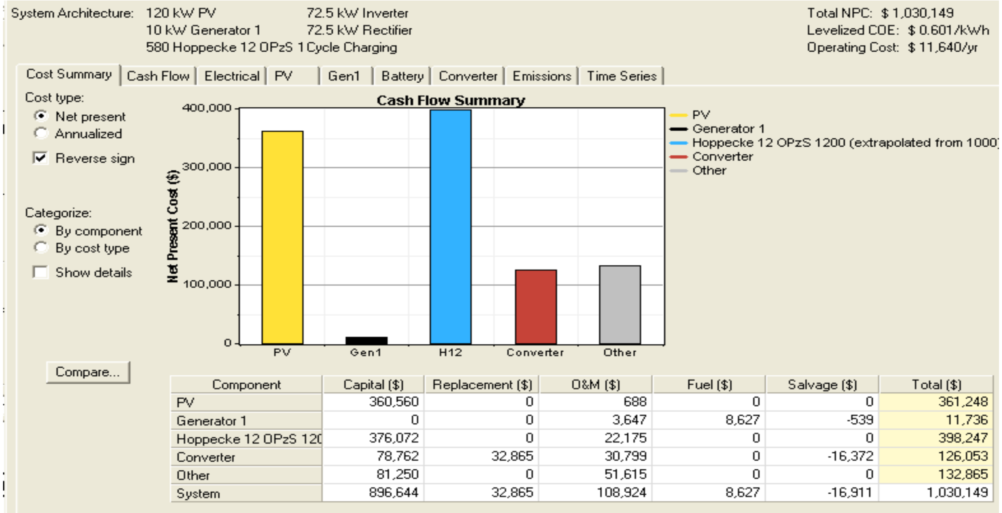
The fourth optimization exercise aims to assess costs for higher levels of renewable energy fraction. It builds upon the new base case scenario and the second modeling exercise for wind speeds of 4,94 m/s and solar radiation of 6 kWh/m2/day. The second generator is erased as option in the system configuration, as well as generator #1. Instead a 10 kW diesel generator serves as back up and for covering peaks in the simulation. The 10 kW diesel genset is fully financed by selling the other two generators. Therefore no initial investment costs occur.

According to the HOMER simulation results, the optimal solution for a 100% renewables configuration with natural conditions of 4,94 m/s wind speed and 6 kWh/m2/day is a PV/diesel hybrid mini-grid consisting of 120 kW PV, a 10 kW diesel genset, a battery bank of 1,392 kWh nominal storage capacity and 72,5 kW inverters. This system uses 98% renewable energy, and the cost of electricity is 0,601 USD/kWh including depreciation on capital and levelized O&M costs (see Figure 42). The initial capital cost for this system is 896,644 USD. CO2 emissions are 2,203 kg/yr.

PV (kW)	G10	Gen1 (kW)	H12	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Dies (L)
120		10	580	72.5	CC	$ 896,644	11,640	$ 1,030,149	0.601	0.98	
110	1	10	580	77.0	CC	$ 906,974	13,548	$ 1,062,372	0.619	0.95	2,
140			620	72.5	CC	$ 992,080	10,760	$ 1,115,493	0.650	1.00	
140	1		620	63.5	CC	$ 1,022,494	10,448	$ 1,142,330	0.666	1.00	

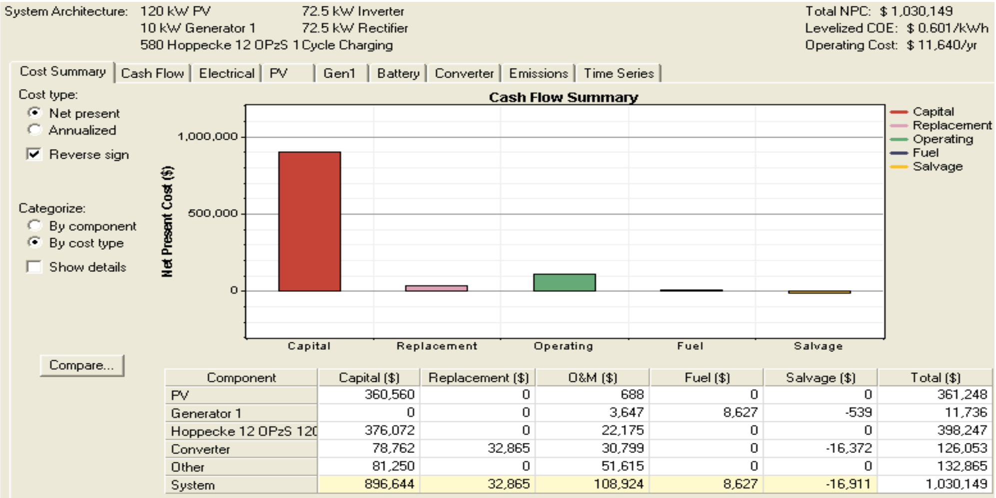
Figure 42: HOMER results for Optimization Exercise 4 – The 100% Renewables Solution. Source: Own results.

The figures below (see Figure 43 and 44) show that the investment costs for PV panels and battery banks represent more than 70% of the total system costs over the lifetime of 20 years. Once the initial investment costs are stemmed, operating and maintenance costs are negligible. Interestingly, no replacement costs for battery banks were calculated, as simulations indicated an expected lifetime of 20 years under the optimal scenario.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	360,560	0	688	0	0	361,248
Generator 1	0	0	3,647	8,627	-539	11,736
Hoppecke 12 OPzS 120	376,072	0	22,175	0	0	398,247
Converter	78,762	32,865	30,799	0	-16,372	126,053
Other	81,250	0	51,615	0	0	132,865
System	896,644	32,865	108,924	8,627	-16,911	1,030,149

Figure 43: Initial Capital Costs per system component for the 100% renewables solution. Source: Own results.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	360,560	0	688	0	0	361,248
Generator 1	0	0	3,647	8,627	-539	11,736
Hoppecke 12 OPzS 120	376,072	0	22,175	0	0	398,247
Converter	78,762	32,865	30,799	0	-16,372	126,053
Other	81,250	0	51,615	0	0	132,865
System	896,644	32,865	108,924	8,627	-16,911	1,030,149

Figure 44: Comparison between cost elements (initial capital costs, replacement costs, operating costs, fuel costs) for the 100% renewables solution. Source: Own results.

The following figure (see Figure 45) shows the monthly average electric production according to generating sources. 215,041 kWh are produced per year. 99%, or 211,940 kWh are produced by PV panels (with a capacity factor of 20,2%), and 1%, or 3,101 kWh are produced by the 10 kW diesel generator (with a capacity factor of 3,54%). There is considerable excess electricity. It amounts to 19,908 kWh per year, or 9,26%. Based on the LCOE of 0,601 USD/kWh, monetized excess energy amounts to 11,964 USD per year, or 239,294 over 20 years, which is approximately 1/5 of total system costs over the lifetime of 20 years. Being able to put this excess energy in value will be an important factor for stabilizing the electricity cost at 0,601 USD/kWh, and needs to be considered in the business plan.[11]

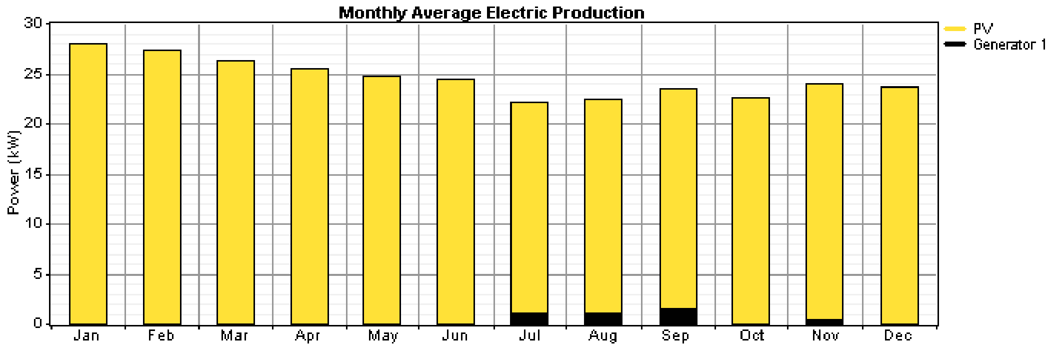


Figure 45: Monthly Average Electric Production for optimal hybrid system configuration in Optimization Exercise 4. Source: Own Results.

5.4 Conclusions and Interpretation of Results

A summary of the results of all 4 simulation exercises are presented in the table below (see Table 14).

HOMER Optimal Results (410kW/ day, 63 kW peak)	**Base Case Scenario**	**New Base Case Scenario - Optimization Exercise 1** (adjusted costs)	**Optimization Exercise 2** (wind speed 4,94 m/s, 6 kWh/m2/day solar radiation)	**Optimization Exercise 3** (only one optional 30 kV diesel genset in the system)	**Optimization Exercise 4** (only one optional 10 kV diesel genset in the system)
System Configuration	20kW of solar, a 30 kW a diesel genset, a 50kW diesel genset, 96kWh of	20 kW of solar, a 30 kW diesel genset, a 50 kW diesel genset, 96 kWh of batteries,	25 kV PV, a 30 kV diesel genset, a 50 kV diesel genset, a battery bank of 168 kWh nominal	30 kV PV, a 30 kV diesel genset, a battery bank of 384 kWh nominal storage capacity and	120 kV PV, a 10 kV diesel genset, a battery bank of 1,392 kWh nominal

[11] It would be an interesting additional simulation to model this scenario with lower solar radiation per m2, e.g. 5kW/m2/day and its impact on installed capacity and generation potential.

	batteries, and 10kW bi-directional inverter	and 10 kW bi-directional inverter	storage capacity and 13,5 kV inverter	27 kV inverters	storage capacity and 72,5 kV inverters
Renewable Energy Fraction	0,19%	0,13%[12]	0,20%	0,24%	0.98%
LCOE (USD/kWh)	0.422	0,414	0,399	0,426	0,601
Initial Investment Costs (USD)	145,379	139,000	179,634	262,136	896,644
CO_2 Emissions (kg/yr)	109,435	108,648	94,768	83,363	2,203
Diesel-only LCOE Cost	0,538	0,531	0,531	0,531	0,531

Table 14: Summary of the results of all 4 HOMER simulation exercises. Own table.

Comparing the results, several interesting observation can be noted:

1. The cost adjustments undertaken in the "new base case scenario" compared to the "base case scenario" (Graencen et al 2007) do not have a compelling positive impact on the overall system costs nor LCOE. As optimization exercise 1 shows, LCOE goes down from 0,422 to 0,414 USD/kWh, and initial investment costs

[12] Note: HOMER calculated that the solar fraction is reduced from 19% to 13%. Nevertheless, in the base case scenario, out of the produced 160,454 kWh/yr, 18% is produced by PV panels, 53% by generator#1 and 29% by generator#2. And in the "new base case scenario", out of the 159,226 kWh/yr produce, 19% is produced by PV panels, 53% by generator#1 and 29% by generator#2. As this is nearly identical, it seems to indicate an error in the HOMER calculation for solar fraction.

from 145,379 to 139,000 USD. A reduced LCOE of 0,008 USD/kWh will lead to 25,600 USD cost savings over the life time of the system.

2. Reduced costs and increased solar production in more conducive natural environments (as modeled in the optimization exercise 2), will reduce LCOE from 0,422 (base case scenario) to 0,399 USD/kWh. Based on an average annual production of 160,000 kWh, this difference in LCOE leads to cost savings of 3,650 USD per year, which amounts to savings of 73,600 USD over the lifetime of the system (20 years). This represents more than 10% of total system costs.

Research and HOMER simulations done for this MSc thesis have shown that the cost per unit of generating source indicated in ARE 2011 are to a certain extend misleading, as they e.g. seem not to include costs for additional equipment (e.g. inverters), and therefore distort a systemic perspectives on the LCOE. In addition, ARE 2011 does not reflect costs for setting up the distribution infrastructure, i.e. the capital or levelized costs of power delivery. It is a merely generation-technology focused cost indication, which has its shortfalls when analyzing total hybrid-mini grid system costs.

This is a general issue not addressed probably in the reviewed literature. Many generic cost information used in the literature are referenced to a study done by the World Bank in 2007 called "Technical and Economic Assessment of Grid, Mini-Grid, and Off-Grid Electrification Technologies". The report gives a forecast about the capital cost developments of off-grid generation technologies, the capital costs of mini-grids based on a range of off-grid generation technologies as well as the electricity generating costs by mini-grids based on a range of off-grid technologies (see also previous chapter). But this publication does not include the capital cost or levelized cost of power delivery in the comparison of generation technology alternative (see also previous chapter). This is apparent when looking at the flagship publication of the International Finance Cooperation called "From Gap to Opportunity: Business Models for Scaling Up Energy Access" (2013). This report estimates that at least 30 million households could be served profitably by mini-utilities, representing a market of up to 4 billion USD. These estimates are based on levelized costs of electricity generation from hybrid mini-grids ranging from about 0,20 USD/kWh for a biomass gasifer or micro-hydro plant to 0,30 USD/kWh for a small-scale wind or solar PV plant to 0,40 kW/h for a diesel generator (see below table for details). These are very optimistic assumptions. In comparison, ARE (2011) modeled the average levelized costs of electricity generation for hybrid PV mini-grids at 0,456 USD/kWh (with a 0,93 RES fraction), for hybrid small wind mini-grids at 0,451 USD/kWh (0,83 RES fraction) and for hybrid PV-small wind at 0,420 USD/kWh (0,91 RES fraction), and for diesel-only mini-grids at 0,538 USD/kWh. Only the LCOE of small hydro mini-grids are consistent with the IFC assumptions, and is put at 0,219 USD/kWh. The below table shows the different capital cost assumptions used in ARE 2011 and IFC 2013. Interestingly, IFC 2013 uses higher capital cost assumptions compared to ARE 2011, but the levelized cost of electricity generation per technology is lower (see Table 15). This indicates again the need for more transparently displayed cost assessments in order to allow comparability of results.

Technologies	Genset	Small Wind Turbine	PV	Small Hydro
ARE 2011	400 USD/kW	2,120 USD/kW	2,822 USD/kW	1,790 USD/kW
IFC 2013	850 USD/kW	3,300 USD/kW	4,800 UDS/kW	3,000 USD/kW

Table 15: Comparison of Cost Assumptions used in ARE 2011 and IFC 2013. Source: Own table.

In general, it shows that there are tremendous differences in generic cost indications for renewable energy generation technologies in the context of mini-grids presented in the literature. These generic numbers can provide a first impression about potential opportunities or barriers, but need to be challenged, and do by no means relieve from the necessity of simulating site specific cost assessments based on local prices. At the same time, this means that when undertaking simulation exercises with HOMER, it needs to be clearly indicated whether the costs for distribution and delivery of energy as well as additional costs such as for inverters are included in the calculations or not, something hardly done in the existing literature.

3. The HOMER optimization exercise 2 shows that increasing solar radiation from 5 kW/m2/day to 6 kW/m2/day reduces the LCOE in comparison to the “new base case scenario” by 0,015 USD/kWh. In the new base case scenario, out of the total energy production of 159,226 kWh per year, 19%, or 29,681kWh are produced by PV panels (0,13% solar fraction). In the optimal scenario of “optimization exercise 2” out of 163,642 kWh/yr, 27% or 44,154 kWh/yr are produced by PV panels (0,20% solar fraction). The reduced LCOE due to better natural conditions will lead to annual savings of approximately 2,400 USD in comparison to the “new base case scenario”, which results in overall savings of approximately 49,000 USD over the lifetime of the system (20 years).

4. The HOMER simulation calculates that a 100% renewables configuration is possible through a PV mini-grid, using a 10 kW diesel genset as backup to cover month of lower solar energy output. LCOE for this solution amounts to 0,601 USD/kWh. The system has a significant amount of excess energy, which amounts to 19,908 kWh, or 9,26% of total production (215,041 kWh). Excess energy in terms of annual costs amount to 11,964 USD, or 239,294 USD over the lifetime of the project (20 years). This is significant, but need to be analyzed in the context of energy distribution delivery costs. Energy distribution delivery costs are related to electrical losses that occur in the process of transporting electricity from the generation source to the end consumer. This “power distribution loss rate”, as explained in a previous chapter, averages 17% of net production. These losses and associated costs are often not included in generation technology cost information, not even in the HOMER simulation exercises presented here. According to the World Bank (URL 18), Thailand has a power distribution loss rate of 6 %. Balancing these 6 % with the excess energy in the HOMER simulation would reduce the excess energy to 3,36%, or 7,225 kWh/yr, which is an acceptable level providing space for slight demand growth. While this suggests unexpected blessing in disguise, the occurred costs related to excess energy and power distribution losses are still not factored into the system design.

5. A 100% renewable hybrid mini grid demands a dramatic increase in initial investment costs. Its four times higher than the system having a 0,24% renewable

fraction (optimization exercise 3), and increases from 262,136 USD (optimization exercise 3) initial investment costs to 896,644 USD (optimization exercise 4). This showcases the need for innovative financing methods to overcome this barrier.

6. Cost per kW installed for the PV/diesel hybrid mini-grid with 0,98% of solar fraction is 7,924 USD. This is in-line with IEA PVPS Task 11/CLUB-ER estimates (2013, page 14), which puts the typical real installed cost of a complete PV/diesel hybrid system in Africa and Asia currently between 5,500 and 9,000 EUR/kWp with variations according to system size and location. It is also consistent with WB 2007 estimates, but on the upper end of cost estimates (see previous chapter).

7. The 100% renewables hybrid mini-grid emits 44,060 kg CO2 over the lifetime of the project (20 years) compared to 3,183,400 kg CO2 in the diesel-only configuration of the "new base case scenario". Thus, the 100% renewables solution saves in total 3,139,340 kg CO2 compared to the 100% diesel solution. This is a distinctive adventure for accessing carbon finance, e.g. under the Clean Development Mechanism of the UN Framework Convention on Climate Change.

8. Wind was not assessed competitive with PV/diesel hybrid mini-grids throughout all simulations conducted. But at a wind speed of averaging 5 m/s, wind turbines became part of the energy mix in the "second" or "third" optimal solutions in most optimization exercises conducted. These PV/wind/diesel hybrid mini-grid configurations achieved lower LCOE as the diesel-only system in optimization exercise 2 and 3.

9. As the electricity tariff in Bahn Koh Pu is set at 25 Baht per kWh (0,650 USD), which is already seen as the upper level of ability and willingness to pay, all above options are better than doing business as usual.

10. The LCOE for the 100% renewables hybrid mini-grid solution amounts to 0,601 USD/kWh. A break-even-tariff, designed so that the system generates enough revenues to cover all its operating costs, could be set at this LCOE level.

Nevertheless, the currently 0,650 USD/kWh paid by the villages for a service that does not yet include the depreciation of equipment, and which at the same time indicates the maximum level of ability and willingness to pay, creates a possible profitable window of 0,049 USD/kWh (0,650 minus 0,601). A financially-viable-tariff that allows full cost recovery and sufficient return on investment to attract investors could amount to the same electricity price as paid previously, which would create an additional annual profit of 10,537 USD (0,049 USD x 215,041 kWh total annual production), and 210,740 USD over the lifetime of the project (20 years).

11. A final simulation done was to assess the impact of capital expenditure subsidies on the LCOE. It is a general practice in many countries, and especially in the context of specialized mini-grid support programs to subsidize a portion of the initial capital investment costs (between 20% and 80%). In addition, the community can contribute to the establishment of a hybrid mini-grid though labor, in-kind, and financial contributions, which can amount between 10% – 20% of the initial capital costs. As discussed in a later chapter, subsidies are often important to enable affordability of electricity provision from hybrid mini-grids. In this context, Graencen et al 2007 did another hybrid mini-grid feasibility study on the village of neighboring island called Koh Po. In Koh Po's current electricity price amounts to 0,390 USD/kWh (not including depreciation costs of equipment), and the hybrid mini-grid system modeled by Graencen et al (2007), with a solar fraction of only 20%, would increase the LCOE to 0,484 USD/kWh. Let's assume for the purpose of this simulation exercise, that Bahn Koh Pu's currently paid electricity price is at the same level as Koh Po's, i.e. 0,390 USD, and that the ability and willingness of the villagers to pay for electricity is set at a maximum level of 0,450 USD/kWh. At the same time, the village contributes with 10% of the initial capital investment costs, and governmental subsidies amount to another 30%. Thus, 40% of the initial capital investment costs are subsidized. As total initial capital costs amount to 896,644 USD, 40% of that equals 358,657 USD, and reduced the overall system costs from 1,030,149 USD to approximately 671,492 USD. The simulation calculated a new levelized cost of electricity of 0,390 USD/kWh. If it was decided to take a break-even-tariff, this would amount to the same electricity price as paid before. With a potential

ability and willingness to pay at a level of 0,450 USD/kWh, this would leave some room to define an appropriate commercially-viable tariff.

12. The simulations have been done assuming a constant diesel price of 0,86 USD/liter. This is a rather conservative assumption, as diesel price is expected to increase over the years. An additional optimization exercise simulating at which diesel price the 100% renewables option would become competitive, could provide interesting insights into the advantages of 100% renewable mini-grids. As seen, 100% renewable mini-grid solutions have high initial investment costs, but hardly operation, maintenance and replacement costs (in optimal configured systems), which keeps the LCOE cost constant over the years. Diesel dominated hybrid mini-grids in comparison depend on the price fluctuations of the international fossil fuel market. In that respect, Graencen et al (2007) conducted a simulation for increased diesel prize in the base case scenario presented above. At a diesel price of 1,15 USD/l, the LCOE in the base case scenario increases to 0,50 USD/kWh (with a solar fraction of 20%), and the LCOE of a diesel-only mini-grid to 0,66 USD/l. This indicates roughly that the 100% renewables mini-grid solution presented above would already be competitive to diesel-only systems at a diesel price of 1,1 to 1,15 USD/l.

These results are confirmed by the following example. An interesting real example of an escalating diesel price and its impact on consumer tariffs is provided by Suwannakum et al 2009, a paper that reflects on the results of four years monitoring of a hybrid PV/wind/diesel mini-grid on a remote island in Thailand. This system consists of 7.5 kWp PV, 2x5 kW wind turbines, 65 kVA diesel generator, 252 kWh battery storage, 3x2.5 kW PV inverter, 4x2.5 kW wind turbine inverter, 3x4.5 kW bi-directional inverter data acquisition system and the 3-phase 4 wire transmission system (Suwannakum et al 2009). The daily energy demand is 265 kWh and the peak demand is 37,5 kW. The ability to pay for electricity in the village is 17,56 Baht/kWh. Price for electricity for the PV/diesel mini-grid at the start of the project was 9,75 Baht/kWh, and when two 5 kW wind turbines were added, it increased to 12,43 Baht/kWh. A cost recovery tariff was established, with a fixed tariff put at 12 Baht/kWh (0,374 USD/kWh). Reacting on increasing diesel prices, the Electricity Committee decided to change the electricity tariff six times in the consequent years, to 15 Baht/kWh (0,468 USD/kWh) on October 2005, 20 Baht/kWh (0,624 USD/kWh) on June 2006, reduced to 15 Baht/kWh on January 2007, 18 Baht/kWh (0,562 USD/kWh) on October 2007, and increased to 20 Baht/kWh before changing the tariff to a step rate on April 2008 (Suwannakum et al 2009).

6 Hybrid Mini-Grid Business Models

The sixth chapter moves away from assessments of technical and economical feasibility towards a focus on practical implementability. In order to make a hybrid mini-grid project implementable, an appropriate institutional arrangement and business plan is needed, which determines who invests, builds, owns, and operates the system (ARE 2011, page 21). The first part describes the four ownership and business model options for implementing hybrid-mini grid projects: the Utility Model, the Community-based Organization Model (including cooperatives), the Private Sector Model and the Hybrid Model.[13] Then the emphasis is turned to tariff schemes. Determining appropriate tariff schemes is at the core of successful business model. The chapter highlights that cost-recovery and cost-based tariffs are an important prerequisite for private sector involvement. At the same time full cost recovery is often not feasible because of the low ability to pay in rural areas. Therefore smart subsidy schemes for hybrid mini-grid projects exist in order to assure affordability. Tariffs must always be set in relation to the affordability and willingness to pay, as well as existing subsidy schemes. Then the chapter moves to one of the biggest barriers for the implementation of hybrid mini-grid systems: financing. High initial capital investment requirements, paired with limited local financing options, pose a threat to many technical and economical feasible hybrid mini-grid projects. The chapter describes the various sources of capital required by mini-utilities during an investment cycle. The chapter concludes with other important success factors for hybrid mini-grid projects, such as ensuring adequate demand of electricity, developing the right operational model and ensuring sufficient management expertise for scaling-up successful pilots.

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[13] Operations and maintenance management options are not discussed in detail here. ARE (2011) acknowledges four types of management and operation contract models: a) An authorization arrangement when the system is globally managed by a public authority, utility, or private company that appoints some individuals to operate and maintain the system on a daily basis; b) A contracted operation when the system owner contracts the operation of the system to an individual or enterprise that assumes full O&M responsibility, and may even collect revenues and pay for fuel and other consumables; c) A leasing contract where the tangible assets of the system are leased to the system operator, who can be an individual, a community or an enterprise. The system operator takes on a greater degree of responsibility for medium-term system maintenance and recovers its investment through the fees collected; d) Full ownership transfer to the system operator or the community (ARE 2011).

6.1 The Four Types of Ownership

Existing literature distinguishes in general four business models and types of ownership for renewable energy mini-grids: the Utility Model, the Community-based Organization Model (including cooperatives), the Private Sector Model and the Hybrid Model (WB 2008, WB 2008a, ARE 2011, IFC 2013).[14]

6.1.1 The Community-based Organization Model

In remote areas, where interest from private sector is limited, and strong village structures exist, community-based organizations are often the preferred option for renewable energy mini-grids. According to WB (2008), it is the most common business model to develop renewable energy mini-grid systems. In this case the community becomes the owner and operator, providing maintenance, tariff collection, and management services (WB 2008a, page 14).

Rural electric cooperatives, one form of community-based organizations, are consumer owned systems that distribute electricity to their members, for example by operating an independent mini-grid system with its own generating sources (WB 2008, page 115). The US has extensively used this model for its rural electrification efforts since the 1930s, and in the EU it becomes a new phenomenon in the context of freshly liberalized energy markets and the emergence of the "energy autonomy"

[14] The IFC report (2013) differentiates between "commercial-enterprise based" (fully or nearly financial viable; might receive subsidies to cover a portion of the capital costs or connection costs to end users; revenue model based on product sales or fee for service), quasi commercial" (partially subsidized, using PPP or CSR approaches), and "non commercial" (primarily publicly funded through government or donors) approaches for serving the energy access market (page 39). Mini-utilities have been instrumental in providing energy access to remote areas in recent years, emerging strongly in Cambodia, India, Nepal, Bolivia, Brazil, Colombia, Peru, across the Philippines and in many parts of Mali and Nigeria. In Cambodia alone 42% of electrified households outside the capital city are served by decentralized mini-grid systems (IFC 2013, page 76). IFC estimates the mini-utility market for commercially viable business models at 4 billion USD and highlights that currently many mini-utilities are simply doing business on their own by seizing existing market opportunities. They develop simple and standardized systems for loads that allow efficiently sized hybrid mini-grid configurations, with reported profits of 10 to 30%, and a rate on equity of 20 to 25% (IFC 2013, page 77).

movement.[15] Based on the US experience, Bangladesh piloted the rural electric cooperative model, where the community regulates the tariff, and a subsidy comes from a rural electrification fund for the renewable energy component. In Sri Lanka, a community cooperative model is used to help local communities own and operate mini-hydropower systems. The tariff is negotiated with community members and based on their ability to pay, while GEF provides a 400 US/kW subsidy in the form of an upfront grant. Both examples are supported by international organisations and funding instruments (WB 2008, page 115). In addition, governments in general are subsidizing a portion of the capital cost, while the community covers the balance investment cost (utilizing the grant to access bank finance) and full cost for operation and maintenance (WB 2008a).

Literature agrees that this type of ownership model faces many challenges, and even more so in developing countries. Poor skills, know-how, commitment or abuse often result in technical and financial failure of community-owned hybrid mini-grids (WB 2008, page 114). Therefore, institutional support and capacity building is a critical requirement for this model, and guidance has to be available throughout the lifecycle of the project, but especially in the development and start-up phase, e.g. for developing the feasibility study and business plan, attracting finance, training operations and maintenance staff and managing the system to optimize community benefits.

6.1.2 The Utility Model or government-contracted ESCO Model

According to the WB, utilities are the most common model for rural electrification in developing countries, whereas mini-grid services are mostly based on small hydro and diesel (WB 2008). Utilities are experienced and privileged players, have access to financial resources and technical capacities to implement and manage mini-grid systems. Furthermore, utilities can generate economies of scale and the universal

[15] National Rural Electric Cooperative Association (NRECA) is the national service organization in the US for more than 900 not-for-profit rural electric cooperatives and public power districts providing retail electric service to more than 42 million consumers in 47 states and whose retail sales account for approximately 12 percent of total electricity sales in the United States (URL 19). In Europe, the goal of project "REScoop 20-20-20", funded by the Intelligent Energy Europe Fund, is to promote the renewable energy based cooperative model of local citizen involvement in RES energy. It aims to build a map of all "RESCoops" in the EU, to develop best practice cases, guidelines and lobbying material (URL 20).

presence and large stock of spare parts are conducive for efficient and reliable maintenance of mini-grid system. Nevertheless, according to ARE (2011) success from utility driven rural electrification programs based on hybrid-mini grids comes in the first place through innovative business approaches, less the aforementioned natural advantages of utilities. In this case, tariffs are regulated and in general subsidized by public sources. This model is applied in China to operate more than 700 centralized PV mini-grids, each with a 10–150 kW capacity (WB 2008a), and the Philippines has used this approach to fund isolated diesel mini-grids for years. Despite these advantages, many barriers exist for utilities to become promoters of hybrid mini-grid solutions. As ARE (2011) points out, market liberalization and the associated increased competition in developing countries has de-prioritized installing and running remote, low-revenue hybrid mini-grids. This trend seems now slowly reversed by the momentum created through the UN Energy Access Initiative and its associated support programs for developing countries, as well as the increasing recognition of bottom of the pyramid business opportunities (see previous chapter for details). Furthermore, many utilities are bankrupt and operate inefficiently. Utilities may also be driven by political agendas and have difficulties to respond to local particularities, with negative impacts on local acceptance and willingness to pay (ARE 2011).

6.1.3 The Private Sector Model

Here large private utilities or small rural energy service companies develop, own and operate mini-grid systems. There are many advantages associated with this model, and most rural electrification programs nowadays stimulate private sector involvement and investments into the provision of electricity to marginalized populations. In general, the private sector model is seen as the most efficient, adaptable and fast-moving approach for rural electrification. Literature agrees that it needs an enabling environment for the private sector to unfold its potentials (ARE 2011, WB 2008). Public policy support schemes, such as subsidies or regional concessions, are often needed to catalyze larger involvement of the private sector into rural electrification efforts. As the WB (2008a) points out, it is sound practice for the government to subsidize a portion of the capital cost, while the community or investor covers the balance investment cost and full cost of operation and maintenance (WB 2008a, page 14). Nevertheless, and as highlighted by the IFC (2013), local entrepreneurs have so far established rural energy service companies just because of recognizing and seizing existing market opportunities, and not relying on any subsidy scheme. There is a considerable bottom of the pyramid market for hybrid mini-grids. The IFC estimates it at currently 4 billion USD (see previous chapter), where profitable investments and affordable energy provision would already be possible without any form of subsidies. Over regulating or subsidizing these markets could furthermore have counter impacts.

As we have seen in the first chapter, going beyond the pioneering efforts of impact entrepreneurs requires the development of local markets and industries. Thousands of local energy entrepreneurs are needed to make energy access a reality by 2030. Most local small entrepreneurs today have limited technical skills and financial resources. Financing poses a considerable barrier. As the financial return may be 10 years or more, banks are not willing to lend money under such terms. They most of the time also do not understand the specifics of the hybrid mini-grid business. Seed money thus often comes from governments, international organisations, private savings or personal networks (i.e. family and friends). Even existing potentials are currently often missed out due to lack of capacity. This is true for rural electrification programs that instrumentalize mini-grids. Often there is a lack of awareness and know-how to integrate renewable energy generation into the design of hybrid-mini grids on the side the bidders for rural electrification concessions. The Philippines for example introduced a private sector participation scheme for remote power generation, were existing distribution utilities/electric cooperatives are required to source out their power generation needs to private sector companies. These "New Power Producers" are selected based on a competitive tender (i.e. the lowest proposed generation cost) and provided with a 15 year local concession based on power supply agreement with the electric cooperative. From the 41 bids received non included renewable energy generation technologies in the proposed mini-grid configuration (ARE 2011, page 26).

6.1.4 The Hybrid Business Model

As ARE (2011) and WB (2008) point out, hybrid business models are probably the most interesting, as they can combine the advantages of the three business models presented above to guarantee an effective local institutional arrangement for renewable energy mini-grids. But they are also hardest to define as they can be quite diverse with changing ownerships structures, O&M contracts, and tend to be very site specific and context driven.

One interesting example comes from the Lao's based private rural off-grid energy provider Sunlabob (URL 21), which proposes an innovative operative set-up for hybrid mini-grid systems. Here, public investors would pay for the fixed infrastructures (civil works and grid), whereby the grid ownership is consequently transferred legally to the village community. The public investor might be the village itself, a higher level public institution, or a donor agency, all in line with the Cambodian public support policies for rural electrification. Private investors pay for the movable assets (generating equipment), operated by a so called "Private Energy Provider". Thus, public infrastructure investments leverage private investments into the movable assets (Sunlabob 2006). In addition, this private provider trains and coaches the "village energy committee" (an organ mandated by the elected Village Authorities) to operate the village owned grid. It sells the energy into the village grid, and the village sells energy to households and small rural enterprises (Sunlabob 2006, URL 22). Alternatively, the private provider can directly sell the electricity to the households by employing villagers to operate the system and collect the fees. Maintenance can also be sub-contracted to the private energy provider. The village can decide to switch to another private energy provider if they are not fulfilling the contractual agreement.

In reality, Sunlabob participated in pilot program committing itself for a 25-year PPA (Public Private Partnership) with the village, at an internal rate of return of 15%. The power system installed by Sunlabob combines a 12 KW small hydro generator with a 2kWp PV system and a 15 kVA diesel generator (supposed to run on jatropha in the future). The 3-phase grid mainly operates on the hydro generator. This hybrid mini-grid feeds 105 households with a daily peak load of 8kW (ARE 2011, page 29). This initial public support was incremental to realize the project, as LCOE to recover the project costs would have been too high for the rural population. Because of no further subsidies received and a limited load factor (i.e. sold energy compared to produced energy) (and limited growth perspectives due to structural barriers for local economic development), Sunlobab aims to extend the distribution lines and connect it to the nearby grid in the future. This win-win situation would bring utilities additional generation capacity, end-users would benefit from subsidized social tariffs that exist for grid users, and Sunlabob would increase its revenues by using its full power capacity through selling excess electricity to the grid.

Another interesting example and developed solution comes from a UNDP program that enabled biomass gasification mini-grid systems in China (WB 2008). It explicitly aimed to overcome the lack of capacities and know-how present in rural villages, a key barrier for developing commercially-viable mini-grid systems in rural areas. Here, private rural energy service companies are incentivized to sell systems to villages using a co-investment approach. It would invest itself as a minority investor into the project, designing the mini-grid project, building the capacities of the village, while selling the equipment to the village, and providing long-term technical support. Income for the private provider would come from system design and installation, service fees, as well as long term economic returns from the initial investments made into the village energy supply company (for further information see UNDP 2004, URL 23).

6.2 Tariffs Schemes

Allowing cost-recovery and cost-based tariffs is an important prerequisite for local entrepreneurs and community-based organizations to implement hybrid mini-grid projects, as they have no possibilities to cross-subsidize their electricity rates and need to demonstrate financial viability to obtain financing (WB 2008, page 102). Nevertheless, in reality full cost recovery is often not feasible because of the low ability to pay in rural areas. Many countries already apply subsidy schemes for hybrid mini-grid projects in order to assure affordability, which are mostly capital cost-based (i.e. capex, subsidies on capital expenditure), or aim to reduce the mini-grid connection costs for end-users.

Literature agrees that subsidies should not be applied to operating costs and ongoing consumption, and that tariffs should at least recover costs of operation, maintenance and replacements to guarantee operational sustainability (IFC 2013, WB 2008, ARE 2011). In general, it is important to balance commercial viability of the service provider (sustainability) and meeting rural consumers' ability to pay (affordability). As the WB and IFC studies point out, poor people already pay 3 to 15 USD per month for low quality energy, and are in general interested and willing to pay for improved energy services that enable better education, information, entertainment and productive use (WB 2008, page 108). Nevertheless, ability (estimated at 5% of the monthly household income) and willingness to pay thresholds need to be assessed locally, and have to influence tariff schemes accordingly.
In order to recover the mini-grid lifecycle costs (i.e. capital costs; annual fuel costs; annual operation, maintenance and management cost; equipment replacement cost), rural electrification tariffs charge one-time connection fees and monthly energy fees. Connection fees are used to recover part of the initial investment costs, usually covering the costs of meters and connection from poles to households (WB 2008, page 104). They aim to ensure commitment by the user to the new rural electricity service, and need to be set in relation to the local income levels. High connection costs are considered to be a greater barrier for rural consumers than the monthly electricity bill. Monthly fees aim to assure the sustainable operation of the system. According to the WB, an adequate tariff structure should recover at least O&M costs, reflect the cost structure (O&M, fuel and partially capital investment costs), and be below the consumers' ability to pay. Communities can actively contribute to reduce the overall system costs, for example through labor, material and cash contributions, which can pay up to 10 – 20% of the capital investment of renewable energy mini-grid systems (WB 2008, page 105).

There are two broad categories of monthly tariff schemes, with different types of associated collection mechanisms. Traditional energy based tariffs quantify the monthly consumption, e.g. through meters, and users pay as they consume (USD/kWh) on a monthly basis. The second type is based on expected power consumption. Here, consumers pay monthly a specifically set maximum of power, a flat tariff which is calculated based on the electric appliances used in households. This form has multiple benefits, such as reducing administration costs, setting a limit on peak demand, preventing system overload, ensuring that all consumers have a minimum access to electricity, allowing financial forecast and this a sustainable income projections for the energy service provider (ARE 2011, page 46). Therefore, the WB reckons that a fixed monthly tariff is the more appropriate tariff scheme. Furthermore, for assuring an equitable tariff scheme, customer segmentation based on different consumption patterns and associated diversified monthly fee categories need to be established. It is important to guarantee the satisfaction of basic needs for the poorest, e.g. by enabling them to purchase a minimum block service (e.g. for two lights and a radio 3-4 hours a day, which amounts to 3kWh monthly). At the same time it is important to provide appropriate tariffs for small industries and commercial activities so as to stimulate productive uses (WB 2008, page 105/106). In reality, most village power systems charge the same per-kWh tariff to all customer types, which is not the optimal solution. Graded tariffs allow setting tariffs in proportion to the costumers' ability to pay, or to implement active location policy (e.g. through publicly subsidized fees for small businesses to spur local economic development). There are different types of tariff regimes. Highly subsidized tariffs do not pose financial burdens on the consumers but are not sufficient to cover monthly operating costs, it leads to over-consumption and providers are not incentivized to expand the customer base. Break-even-tariffs are designed so that the system generates enough revenues to cover all its operating costs. As mentioned before, a subsidy on capital costs can help to improve affordability. Financially-viable-tariffs allow full cost recovery and sufficient return on investment to attract investors (i.e. sufficient profit). In this case, involvement of private sector actors require higher tariffs or higher subsidies to improve affordability.

6.3 Financing

An important success factor for mini-grid enterprises is access to long-term debt and equity finance to support start-up and growth. Mini-utilities need to access various source of capital during an investment cycle. Start-up capital is required for project development activities, and operating capital is required to construct and operate the plant. The sources of finance can come from private, public or NGO channels. Promising programs are emerging that support rural entrepreneurs and community cooperatives with technical and business training, marketing, feasibility studies, business planning, management and financing. They can have catalytic impacts on the success of mini-utilities, especially in the project initiation stage (WB 2008, page 118). In developing countries, donor aid and impact investors often take the lead in the seed finance area. Mini-grid renewable energy projects require long-term debt for project finance, which should ideally come through loans from local banks, an option rarely available in developing countries. Public and donor funding mechanisms try to balance this shortfall through lines of credit, credit enhancement for loan provision (concessions and loan guarantees) and SME growth funds, which are funded with a mix of donor and commercial capital targeting not yet commercially financeable business expansion activities (WB 2008, page 119). Nevertheless, leveraging local financing is a prerequisite for long term success. Therefore, many support programs aim to improve the renewable energy investment capabilities of local financial institutions (see also UNEP 2008).

IFC emphasizes that this sector is ideal for impact investing because it involves the attractive combination of renewable energy, social benefits, and the base-of-the-pyramid market (IFC 2013, page 133). New venture funds are emerging and the so called “impact economy” is booming offering many new opportunities to attract finance. Marketplaces are established which aim to bring together exciting renewable energy entrepreneurs and the social finance market. These engagement platforms will most likely increase in the near future, outlining an emerging social finance infrastructure. Nevertheless, currently there seems to be a mismatch between supply and demand in the social capital market. The so called “missing middle”, investments in the range of 50,000 to 100,000 USD and 3 to 5 million USD are not yet covered sufficiently by the existing offers.

There is still the need from public, commercial and impact investors to provide more appropriate funding for each part of the business lifecycle. The figure below (see Figure 46) shows that financing is needed in three areas: to support companies in their early stage (start-up and growth capital); to support operations (working capital or trade finance); and to strengthen revenue streams. The early stages of the company life cycle often require concessional finance to cover business model development, piloting and proofing the initial concept (IFC 2013, page 135). Debt and equity are required to finance the start-up and growth capital needs of early stage energy access businesses (IFC 2013, page 136) and carbon finance has the potential to generate additional revenues (IFC 2013, page 141). In this respect, developers of off-grid electrification projects must be aware about opportunities provide by international grant-financing facilities, such as the Global Environmental Facility (GEF), the Global Partnership for Output Based Aid (GPOB), the World Bank Energy Sector Management Assistance Program (ESMAP), or the Clean Development Mechanism (CDM) under the UN Framework Convention of Climate Change (UNFCCC) and associated Kyoto Protocol (see WB 2008a, page 18).

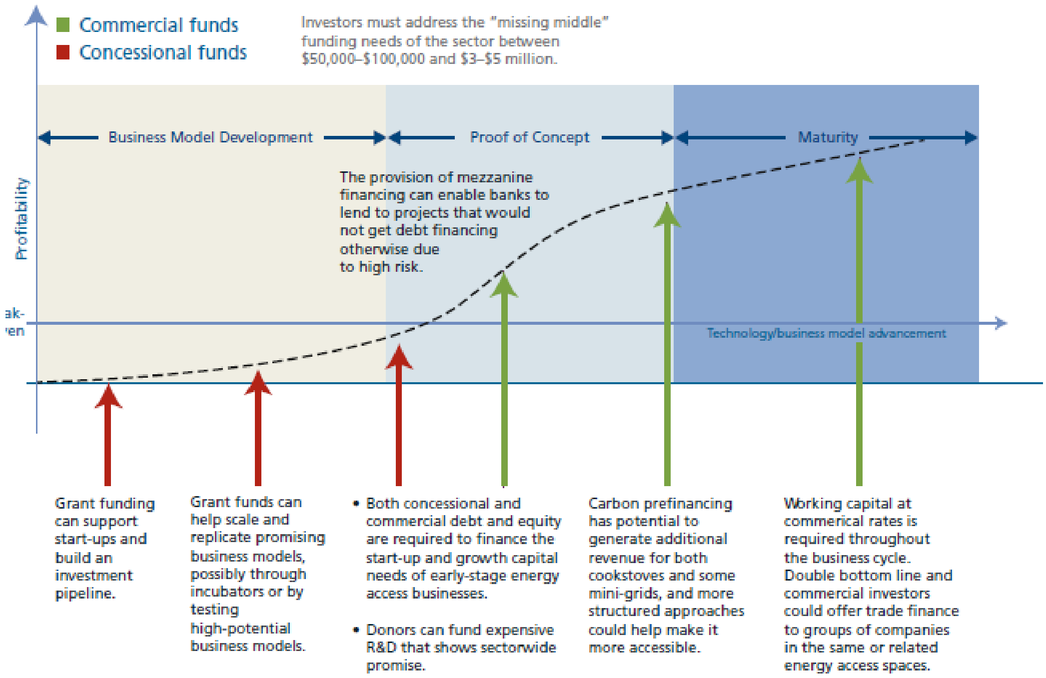


Figure 46: Financing is needed in three areas: To support companies in their early stage (start-up and growth capital), to support operations (working capital or trade finance), and to strengthen revenue streams. Source: IFC 2013, page 135.

Consumer finance mechanisms can also be leveraged to make mini-grids more affordable to the end-users. Consumer finance can enable users to cover the initial high connection costs associated with mini-grids. Consumer finance mechanisms are only possible in markets with sufficient demand to attract financial institutions to offer consumer financing. There must be sufficient existing institutional capacity in the financing market place to be able to deliver such financing offers, e.g. rural banking networks, micro-finance organizations, agricultural cooperatives or electric utilities (UNEP 2008, page 10). Such existing platforms increasingly need to react to a growing market demand and develop, test and commercialize small scale renewable energy financial products and other business lines.

For the success of financing mechanisms, it is important to accompany financing activities with technical advisory services in areas of enterprise development and business model refinement (IFC 2013, page 142). For example, there are many international awards, challenges and competitions that help identify, scale, and replicate promising energy access ventures. Incubators and business accelerators play a key role in this context, as they typically provide the needed support for local entrepreneurs to become bankable. Nevertheless, these support mechanisms are still limited, and more targeted funding for business model development activities is needed, especially in the area of mini-grid businesses (IFC 2013, page 144). Another important leverage for accelerating the mini-utility market is the provision of resource mapping, market data, consumer awareness and standard setting (IFC 2013, page 144). Governments play a key role here, which are increasingly being mobilized for this purpose, for example through the UN Energy for All Initiative (see next chapter). Developing market intelligence, assessing the availability of primary energy sources, creating industry standards, and raising the awareness of consumers are important enablers for boosting the mini-grid market.

7 The Enabling Environment: Policies, Regulations, Subsidies and Support Programmes

The seventh chapter describes several ecosystem conditions which need to be in place for mini-utilities to operate successfully (IFC 2013, page 93). The first one is that mini-utilities need to be allowed to operate legally, which is by no means a given starting point considering that electricity distribution was treated as a natural monopoly throughout recent history. Furthermore, complicated mini-utility licensing and permitting barriers can prevent enterprises to enter the mini-utility market. One of the areas where over-regulation can hamper the development of mini-grids are tariffs, which are sometimes set at the same level as the prices charged by large utilities. Connection and capital cost subsidies which help closing the “viability gap” (the shortfall between revenues that customers are able to contribute and those needed for enterprises to be financially workable) can be an important enabling factor (IFC 2012). Some countries set-up strategic planning frameworks for rural electrification with associated local delivery mechanisms (in form of e.g. rural electrification agencies). They can boost the deployment of hybrid mini-grids by tendering concessions, generating market intelligence, mapping resources or raising the awareness of local communities and entrepreneurs about the benefits of renewable energies.

7.1 Legal Recognition

The first one is that mini-utilities need to be allowed to operate legally. Historically, electricity distribution was treated as a natural monopoly and the common approach was to grant central utilities exclusive rights to specific areas for a long period of time. In geographies where central utilities were not able to perform their electrification duty, these regulations hamper mini-utilities to enter the local market (e.g. Indonesia, where the state-owned power company PLN has a constitutionally provided monopoly on power distribution). But in the last decade countries with significant areas underserved by the grid have relaxed previous legal monopoly arrangements, allowing independent rural energy power providers to operate, for example in India and Nigeria (IFC 2013, page 93). IFC concludes that exclusivity that lasts beyond a limited period of time reduces, rather than increases, energy access (IFC 2013, page 95).

7.2 Licensing and Permitting

Furthermore, complicated mini-utility licensing and permitting barriers can prevent enterprises to enter the mini-utility market. Enacted provisions that allow mini-utilities to operate in underserved areas often lack associated and adapted operational rules and procedures to become implementable. This goes typically hand in hand with institutional unpreparedness for new mini-grid regulations. In general, light handed procedures and processes allow for simplified regulatory procedures and decentralized administration for mini-grids (WB 2008, page 98). IFC highlights the positive examples of Cambodia and India, were positive regulatory frameworks increasingly lead to higher penetrations of mini-grids (IFC 2013, page 96). Government regulation should ensure fair competition for all suppliers in competing for new customers. Transparency in utility grid expansion plans is also necessary for mini-grid planning (WB 2008, page 99).

7.3 Over-regulated Tariff Schemes

One of the areas where over-regulation can hamper the development of mini-grids are tariffs (see previous chapter). Mini-utilities are in general subject to tariff regulations intended to protect the consumer. But if set too low, often at the same level as tariffs for grid electricity, it can make mini-grids unviable to exist as they are not allowed to charge cost recovery tariffs. In Nigeria for example mini-grids are legally allowed to operate but have to charge the same tariff as large distribution companies for installations above 100 kW. IFC reckons that if tariffs are set too low, mini-utilities become inviable, and that unregulated tariffs help to create a competitive price environment (IFC 2013, page 96). Regulators should also not be able to unilaterally change the tariff scheme for mini-grid operators during the regulatory contract period. Beside more liberalized tariffs, also the quality of service standards must be realistic, affordable, easily monitored and enforces (WB 2008, page 98). Standards for the national grid are technically not necessary and financially not feasible for mini-grid systems.

7.4 Connection and Capital Cost Subsidies

Connection and capital cost subsidies which help closing the "viability gap" (the shortfall between revenues that customers are able to contribute and those needed for enterprises to be financially workable) is another enabling factor (IFC 2013, page 99). Reducing the high up-front costs increases growth and profitability. In Mali for example, up to 80% of the capital costs of hydropower, solar PV, and hybrid mini-grids are paid by the national rural electrification agency (AMADAR), itself funded largely through the WB (IFC 2013, page 100). On the other side, ARE (2011) emphasizes that donations and large capital subsidies without a sustainable business plan that guarantees long-term operation destroy local renewable energy markets (ARE 2011, page 31). In general, government support should aim for allowing a solid revenue framework for mini-utilities through a combination of appropriate tariff regimes, connection subsidies, and support for handling nonpayment (IFC 2013, page 129).

7.5 Local Delivery Mechanisms

Rural electrification funds, administrated by an independent Rural Electrification Agency, manage and implement public subsidies for rural electrification in a number of countries (e.g. Philippines, Guatemala) (WB 2008, page 100). Such agencies are responsible for off-grid and grid electrification planning, technical assistance, promotion and supervision. Subsidies are typically provided for capital and connection costs, while financial sustainability for operation and maintenance must be demonstrated by the local energy provider. Subsidy schemes for hybrid mini-grids need to be responsive to local particularities and produced output. In that context, Output-Based Aid (OBA) (or results based funding) is a strategy to use explicit performance-based subsidies to support the delivery of basic services to complement or replace user-fee (WB 2008, page 101). Here, connection subsidies reimburse the service provide for part of the costs for establishing new connection, which lowers the up-front connection fee for households while providing incentives to the provider to connect more households. So called "transition subsidies" bridge the gap between the revenues collected through monthly tariffs and the costs incurred through providing the service. This subsidy scheme supports operation and maintenance for a transitional period, till system efficiency and sufficient demand is achieved that make the tariff more affordable. "Service quality subsidies" can be paid against installation and service performance targets and "indirect market development subsidies" can support promotion activities, training and technical assistance (WB 2008, page 102). It also a worldwide practice to grant consumer subsidies to underprivileged and the poorest households.

7.6 Concessions

As mini-grids are natural monopolies, there is always some kind of concession or license granted to the provider by a regulatory agency, except in the case of community owned and operated mini-grids (WB 2008, page 109). Local or regional authorities need to decide whether or not to bid out the concessions (WB 2008). They can set up concession programs that use a competitive bidding process, enter in direction negotiations with potential electricity provider or simply respond to unsolicited proposals. Under concession programs, successful bidders are granted exclusive rights to provide rural energy service to a specific service territory. In general bidders offering the most cost-effective electricity service will be granted the concession. As previously mentioned, lack of skills and awareness on the side of service providers, hamper the deployment of renewable energy generation technologies in this context. Also governments could write certain renewable energy fractions as mandatory into these concessions tenders, which is hardly happening. The WB points out that the concession approach is particularly effective when rural electrification activities are largely completed and only the remaining and very remote customers need to be served, as well as in countries which have experience with concession programs. As part of concession tender, bidders can be asked to either propose a tariff scheme to serve dispersed rural consumers or a subsidy amount (usually on a per costumer basis) that it requires from the government. Criteria for selection encompass the lowest subsidy (or fee) per connection, the

largest number of connection within a fixed budget or a combination of both. Usually concession programs are accompanied by regulatory and selection frameworks (WB 2008, page 110).
Concessions are typically implemented through energy service companies and are granted for period of at least 15 years. Concessionaires need to undertake all investments, cover all costs for operation, maintenance and replacements, and adhere to commercial service standards. The provincial regulatory agency is responsible to monitor the performance of the concessionaire, and to periodically review the tariff and subsidy structure (WB 2008, page 110). The IFC points out that policymakers should not award indefinite exclusivity in a concession, as this fosters a culture of underperformance (2013, page 128).[16]

7.7 Strategic Planning Frameworks

IFC emphasizes the need for a national energy access masterplan, which should determine market geographies and objectives for off-grid rural electrification. It should determine where commercially viable mini-grid enterprises are feasible, markets where special public support programs are needed to close viability gaps, and markets which can by no means be commercially served. This should be accompanied by specific rules and regulations that help attract investors, and an independent "delivery entity" that supports market development through resource mapping, data creation, service area definition, quality standards, product information and awareness raising (FC 2013, page 126). This approach is also promoted by the UN Secretary-General's Advisory Group on Energy and Climate Change (AGECC), manifested in its "Energy for a Sustainable Future" report (UN AGECC 2010), and taken up and spread internationally by the UN Sustainable Energy for All initiative. The second recommendation of the AGECC to the UN is that countries should develop national energy access strategies. "National strategies should create a predictable, long-term policy environment for investment and a road

[16] In Argentina for example, the Renewable Energy for Rural Markets Project (PERMER), financed by the WB and GEF, aims at providing about 35,000 remote rural households, 1,750 public services (rural schools, health posts) and 500 productive uses with electricity through "off-grid concessions" that are negotiated or bid out for minimum subsidy and regulated by independent provincial regulating agencies. About 10% of the households are served by village power-systems using hybrid mini-grids (the rest stand alone solar PV systems) (WB 2008, page 110).

map for accelerating the establishment of the required human and institutional capacity and delivery mechanisms" (UN AGECC 2010, page 10). By adhering to the UN Sustainable Energy for All Initiative, countries are required to develop national energy access action plans, which includes a stock-taking exercise to determine the country's current status with regards to the three objectives of the initiative (i.e. universal access to modern energy services, doubling the global rate of improvement in energy efficiency and doubling the share of renewable energy in the global energy mix by 2030), as well as a "a Rapid Assessment and Gap Analysis", designed to identify areas that need scaling up in action and investment (UN SEAHLG 2012). 75 countries have signed up so far and committed themselves to the UN Sustainable Energy for All objectives (with 26 from Africa).

8 Conclusions

The core objective of this thesis was to demonstrate the important role of hybrid mini-grid systems for rural electrification in developing countries, i.e. for closing the energy access gap and for providing sufficient electricity to enable local economic development. The core question that was driving this thesis is whether hybrid mini-grids (with a high degree of renewable energy fraction) for rural electrification in developing countries present a technically feasible, economically viable, and socio-politically achievable electrification alternative.

In general, the question posed by the thesis can be answered with yes. Hybrid mini-grids with a high degree of renewable energy fraction offer enormous potentials for rural electrification in developing countries, local economic development, and local socio-political resilience. The thesis shows that off the shelve technologies are available and ready for deployment, the bottom of the pyramid electricity market offers already today considerable business opportunities, market potentials and growth forecasts are enormous, and enabling regulatory frameworks are being formed in many countries. But large scale deployability is still hampered in many ways, especially by the traditional development challenges faced by developing countries. Most importantly, large scale deployment depends on the sum of local particularities, challenges and opportunities in a given territory, and is thus currently still highly contextualized and dependent on pioneering efforts of a few. Large scale deployment depends on an enabling regulatory and policy environment, political stability, functioning governance and market structures, local delivery mechanisms, capacities and awareness, local entrepreneurs and innovative business models, creative tariff structures that relate to the ability and willingness to pay, the availability of innovative financing mechanisms or the elimination of unsustainable subsidies for fossil fuels.

The thesis shows that a sole perspective on the technical and economical feasibility of hybrid mini-grid systems falls too short. To go beyond the technical and economic feasibility of a single application in a given locality, and to seize the full potential of hybrid mini-grids for rural electrification in developing countries, an integrated perspective is required that places socio-political conditions into the center of analysis, and that connects the multiple issues described above. This is also essential for developing successful business plans and assuring implementation of hybrid mini-grid projects.

The HOMER case study implemented indicates that the economic viability of a hybrid mini-grid system depends largely on the ability and willingness of the costumers to pay for energy services provided. Economic viability is strongly related to the tariff scheme proposed by the electricity provider. Starting point is the price currently paid by the local population for the available energy services. If the hybrid mini-grid is able to deliver electricity at a lower price, better quality and reliability, local responsiveness to the new energy service delivery set-up will be higher. The IFC (2012) emphasizes that there is currently a considerable seizable market for commercially viable hybrid mini-grid systems that are profitable without any form of subsidies, i.e. where local populations currently pay more for traditional electricity supply than the price for electricity from hybrid mini-grids. Nevertheless, it must be recognized that the ability to deliver basic electricity at a lower price than the traditionally available energy supply often depends on smart subsidies. While it is important to develop innovative business models that allow seizing this commercial viable bottom of the pyramid electricity market, it should not distract from the need to foster enabling ecosystems for large scale deployment of hybrid mini-grids. This thesis argues that economic viability of hybrid mini-grids depend on a range of factors, and cannot be limited to assessing the LCOE alone, like it is done in many of the literatures reviewed for this thesis. Discussions and hybrid mini-grid analysis must be challenged by the local context and a broader discussion on payable tariffs, which can be influenced by applying smart subsidies, which at the same time have the power to stimulate private sector investments. This discussion is manifested by the following example taken from the energy modeling exercises implemented in this thesis.

The LCOE for the 100% renewables hybrid mini-grid solution calculated in this thesis amounts to 0,601 USD/kWh. A break-even-tariff, designed so that the system generates enough revenues to cover all its operating costs, could be set at this LCOE level. Nevertheless, the currently 0,650 USD/kWh paid by the villages for a service that does not yet include the depreciation of equipment, and which at the same time indicates the maximum level of ability and willingness to pay, creates a possible profitable window of 0,049 USD/kWh (0,650 minus 0,601). A financially-viable-tariff that allows full cost recovery and sufficient return on investment to attract investors could amount to the same electricity price as paid previously, which would create an additional annual profit of 10,537 USD (0,049 USD x 215,041 kWh total annual production), and 210,740 USD over the lifetime of the project (20 years).

Another simulation exercises implemented in the thesis furthermore assumed that the electricity price currently paid by the villagers is only 0,390 USD, and that the ability and willingness of the villagers to pay for electricity is set at a maximum level of 0,450 USD/kWh. At the same time, the village would contribute with 10% of the initial capital investment costs for a hybrid mini-grid system, and governmental subsidies amount to another 30%. Thus, 40% of the initial capital investment costs are subsidized. As total initial capital costs amount to 896,644 USD, 40% of that equals 358,657 USD, and reduced the overall system costs from 1,030,149 USD to approximately 671,492 USD. The simulation calculated a new levelized cost of electricity of 0,390 USD/kWh. If it was decided to take a break-even-tariff, this would amount to the same electricity price as paid before. With a potential ability and willingness to pay at a level of 0,450 USD/kWh, this would leave some room to define an appropriate commercially-viable tariff attractive for private investors.

Another important shortcoming in general encountered in the existing literature is the lack of transparency, accessibility and completeness of data used in hybrid mini-grid simulation exercises and analysis. Most of the literature is based on elusive data sets and assumptions which result in partly contradictory and widely differing assessment results and outcomes. For example, desk research and HOMER simulations done for this M.Sc. thesis have shown that the cost per unit of generating source indicated in ARE 2011 are to a certain extend misleading, as they e.g. seem not to include costs for additional equipment (e.g. inverters), and therefore distort a systemic perspectives on the LCOE. In addition, ARE 2011 does not reflect costs for setting up the distribution infrastructure, i.e. the capital or levelized costs of power delivery. It is a merely generation-technology focused cost indication, which has its shortfalls when analyzing total hybrid-mini grid system costs.

Another cost hardly factored into hybrid mini-grid assessments and simulations are energy distribution delivery costs. They are related to electrical losses that occur in the process of transporting electricity from the generation source to the end consumer. This "power distribution loss rate" averages 17% of net production. These losses and associated costs are often not included in hybrid mini-grid assessments and simulations (again, which are often merely based on generation technology cost information).

In this context, it is worth to highlight that cost information used in the literature is often referenced to a study done by the World Bank in 2007 called "Technical and Economic Assessment of Grid, Mini-Grid, and Off-Grid Electrification Technologies". The report gives a forecast about the capital cost developments of off-grid generation technologies, the capital costs of mini-grids based on a range of off-grid generation technologies as well as the electricity generating costs by mini-grids based on a range of off-grid technologies. But this publication does not include the capital cost or levelized cost of power delivery in the comparison of generation technology alternative. This is apparent when looking at the flagship publication of the International Finance Cooperation called "From Gap to Opportunity: Business Models for Scaling Up Energy Access" (2012). This report estimates that at least 30 million households could be served profitably by mini-utilities, representing a market of up to 4 billion USD. These estimates are based on levelized costs of electricity generation from hybrid mini-grids ranging from about 0,20 USD/kWh for a biomass gasifer or micro-hydro plant to 0,30 USD/kWh for a small-scale wind or solar PV plant to 0,40 kW/h for a diesel generator. These are very optimistic assumptions for the LCOE of various off-grid generation technologies. In comparison, ARE (2011) modeled the average levelized costs of electricity generation for hybrid PV mini-grids at 0,456 USD/kWh (with a 0,93 RES fraction), for hybrid small wind mini-grids at 0,451 USD/kWh (0,83 RES fraction) and for hybrid PV-small wind at 0,420 USD/kWh (0,91 RES fraction), and for diesel-only mini-grids at 0,538 USD/kWh. Only the LCOE of small hydro mini-grids are consistent with the IFC estimates, and is put at 0,219 USD/kWh.

In general, it shows that there are tremendous differences in generic cost indications for renewable energy generation technologies in the context of hybrid mini-grids presented in the literature. These generic numbers can provide a first impression about potential opportunities or barriers, but need to be challenged, and do by no means relieve from the necessity of simulating site specific cost assessments based on a systemic perspective on the costs of electricity from hybrid mini-grids, based on local prices, natural conditions and development challenges. In addition, it needs to be clearly indicated whether the costs for distribution and delivery of energy and additional costs such as for inverters are included in HOMER simulation exercises and case study cost calculations, something hardly done in the existing literature.

Finally, hybrid mini-grid research and analysis needs to go beyond the isolated assessment of economic, technical and environmental feasibility of hybrid mini-grids. As technological off-the-shelf solutions are becoming commercial mainstream, research needs shift from a focus on technologies towards embracing enabling frameworks that assure large scale deployment of hybrid mini-grids in the developing world. The technologies are ready and pilots have been implemented in abundance. Now there is the need to research and design market mechanisms and locally responsive ecosystems that allow long-term sustainability and growth. Research on hybrid mini-grids will therefore increasingly focus on social conditions, demand for products or services, sales potentials, financing options, business models, regulatory frameworks and public policies, or the interface with rural and private sector development. Through the rise of BOP, impact investing and social and rural entrepreneurship, financing and business viability became a new trend, which was long time neglected in the literature and support programmes on renewable energy in developing countries (Morinot et al 2002, page 332).

The development challenge ahead is enormous. Tens of thousands of rural enterprises offering renewable-energy services and products would be required to meet the needs of the 1,5 billion people lacking energy access. Sizing the hybrid mini-grid markets will require increased technical know-how and business skills in developing countries, including local capabilities to adapt, install, operate, and maintain technologies, to build local distribution and manufacturing industries, as well us to develop and run viable businesses (Morinot et al 2002, page 339). Research for this thesis showed that current mini-grid support programs in developing countries already instrumentalize such integrated approaches. It is important that the research on hybrid mini-grids keeps path with these developments, and that a cross-disciplinary lens is applied which reflects complex socio-political and economic contexts. This thesis was written in this light. It aimed to transcend a mere economical, technological and environmental assessment of hybrid mini-grids, and enrich the discussion through an ecosystem-centered perspective. The thesis aimed to bring together all the loose ends of hybrid mini-grid research around one concrete case study and to set the floor for exploring and encouraging further cross-disciplinary and integrated research on the topic.

Annexes

Annex 1: Assessing Mini-Grid Markets

Breyer (2013) undertook a country ranking for renewable energy based mini-grids providing rural off-grid electrification based on current electrification rates, the level of political stability (WB index), the corruption perception index (Transparency International), inflation rates, the ease of doing business index (World Bank) and the current pump price for diesel fuel to identify the biggest market and investment potentials for hybrid mini-grids. Other indicators to assess the realisability of mini-grid projects would be to look at the respective regulatory environment and the country's commitment to the UN Sustainable Energy for All Initiative, the "Energy Development Index" developed by IEA (2012) or the "Human Development Index" (HDI). As discussed later, also the ability to pay or purchasing power is a crucial factor, which can be determined by current expenditures for traditional energy supply. The assessment results showcase that the largest market potentials can be found in South and East Africa. At the same time, political and financial fragile environments often correlate with large market potentials for hybrid mini-grids. This indicates that the mini-grid market is intertwined with complex development challenges. The results of this assessment are summarized in the table below (see Table 16).

Rank	Country	Electrification rate [%]	Rural population without access to electricity	Worldwide governance indicators: political stability [%]	Pump price for diesel fuel [USD/liter]	GDP per capita [USD]
1	Rwanda	5	8.5 mio	41.5	1.62	530
2	Zambia	19	8.0 mio	63.7	1.52	1,250
3	South Africa	75	8.6 mio	44.3	1.14	7,280
4	Botswana	45	0.7 mio	78.3	0.97	7,400
5	Namibia	34	1.2 mio	71.7	1.09	5,330

6	Ghana	61	9.1 mio	47.6	0.83	1,320
7	Kenya	16	29.9 mio	13.7	1.27	790
8	Uganda	9	27.8 mio	15.6	1.11	510
9	United Republic of Tanzania	14	32.3 mio	45.8	1.19	520
10	Peru	86	5.9 mio	20.3	1.10	5,400

Table 16: Results of Country Ranking based on a specific set of criteria. Source: Breyer 2013.

Annex 2: Dimensioning, Load Management and System Layout of Mini-Grids

Local demand is determining the production capacity and thus, crucial for designing cost-effective mini-grid systems (see ARE 2011, page 58). Oversizing a project increases costs and can have negative impacts of the lifetime of system components. Undersizing a project leads to unavailability of power, overstresses system components, and causes dissatisfaction of end-users. Annualized costs are therefore negatively affected. Nevertheless, experience in rural electrification shows that after installing a mini-grid system, demand gradually grows because of improved living conditions, economic activity and a gradual increase of users. This needs to be factored into the initial system design. According to the ARE (2011), 30% of extra capacity mainly in batteries and wiring should be initially installed. Generation technologies can be added at a later stage according to demand growth, as mini-grids are module energy systems.

Solid research and field work is required to determine the user's willingness to be connected, the ability to pay, and the consumption of the electricity appliances connected to the system. It is important to analyze demand fluctuations and to define the peak demand in order to configure the appropriate maximum capacity of the system (ARE 2011). In remote rural areas, electricity is most commonly used for lightning and entertainment (TV, radio and cassette/CD players) by end users. Mini-grids additionally open the door to supply motor-based applications with power thus enabling productive usages and local economic development (e.g. refrigerators, water pumping and irrigation, mechanical workshop, cereal processing, restaurants, tourist facilities, communications, etc.). Mini-grids are often developed around so called anchor clients, economic actors that require a larger bulk of electricity (such as mobile base stations), guaranteeing a minimum level of demand necessary for achieving the required return of investment. These individual loads can be larger than all the other loads and a determining factor for setting the size of power plant. Also the motor starting currents become important factors for sizing generator, conductors and designing the grid layout (ESMAP 2000, page 37). Heat-generating appliances can threaten mini-grid systems and need to be treated with caution as they can easily consume 1000 watt and more (ESMAP 2000, page 43).

Coincident load[17] and future projections of coincident load developments are important factors to size the generator and the conductors used in the distribution system. Another important factor for assessing future demand is the estimated cost of electricity and the associated tariff system. Local demand surveys should be linked to comparative analysis of already functioning mini-grids in locations with similar features and local characteristics in order to get a better picture about expected demand developments (ESMAP 2000, page 46).

As the main goal of the system is to match available resources with the demand for energy in the most cost-effective way, load management is required to optimize the combination of different installed technologies. The use of fuels and battery banks play a crucial role here (ARE 2011, page 59). Renewables should be preferred over the usage of diesel generation as diesel fuel increases the energy prize and thus, the marginal cost of generation. Diesel gensets should therefore be the back-up option, while 50-80% capacity workload would be best to achieve maximum lifetime of the genset. At the same time, the State of Charge (SoC) of battery banks should never drop below 25%, and should be best above 45%. This means that the diesel genset should start latest when battery SoC comes close to 25% and run till the battery is fully charged again (ARE 2011).

[17] The coincident load is the sum of the loads actually on at any instant of time. This is generally different from the sum of all the individual community loads (called "connected load") because all these loads are not generally on at the same time, i.e. they do not coincide. For example, if two 1-kW motors may be used at the same time for some daytime hours and sixty 50-W bulbs are all lighted during the early evening hours, the connected load is 5 kW but the maximum coincident load that the power plant must supply is 3 kW (ESMAP 2000, page 44).

To achieve the best deployment of available generation and storage capacities, an site-depended energy management strategies need to be developed, which can run automatically, semi-automatically or manually, and can be supply or demand side focused. Supply side energy management refers to actions taken to ensure that the generation and distribution of energy are conducted efficiently. A central component for load and energy management is the control mechanism for voltage and frequency levels (IEA/PVPS Task 11 2012). As mini-grids operate independently, they cannot rely on the central grid to control line voltage and frequency and balance power supply with power consumption. Mini-grid generators often interface to the mini-grid with power electronic inverters with corresponding control characteristics. As the IEA/PVPS Task 11 (2012) puts it: "…the inherent fluctuating and intermittent power characteristics of RES and the highly variable load profile of remote communities create significant challenges for the grid forming (master) unit(s) that regulate voltage and frequency. These challenges can be addressed with suitable control strategies which should at one level, (primary control) maintain grid stability by balancing generation and consumption of power and, at the other level, (secondary, or supervisory control) optimize the generation of all sources and operation of the energy storage units." (IEA/PVPS Task 11 2012, page 6). The strategy will depend on the architecture of the mini-grid (centralized or decentralized), the generation mix (diesel dominated or high penetration of renewable sources), the economics of energy storage systems, as well as the available financial resources for installing sophisticated secondary control mechanisms and the capacities to handle them (IEA/PVPS Task 11 2012).

Demand side management gains importance because of the challenges regarding peak power output, available energy supply and fuel costs (Harper 2013). Harper distinguishes in general mini-grids that are primarily power-limited versus those that are also energy-limited. Demand management for power limited mini-grids, such as for hydro-systems, focus on equitable distribution and total demand for power, while energy-limited systems, such as wind and solar, require also regulating daily energy consumption. Demand side energy management includes more efficient appliances; commercial load scheduling, restricting residential use, dispatchable loads, price incentives or community involvement, whereas associated technologies encompass current limiters or conventional and prepaid meters (Harper 2013, page 2).

The system layout starts with mapping the location and drafting a sketch. Starting points for layouting the system are the general geographical features of the village, village infrastructure (such as roads and pathways), and ending with the placement of homes, shops and other load centers such as schools and community buildings as well as identifying potential future load demands and locations. This sketch, including all design loads to be served, is the basis for developing the layout of the distribution lines for the mini-grid and sizing the key system components (such as generator, conductor and poles) (ESMAP 2000, page 49/50). The location of power house is an important exercise at this stage. It should be placed in order to guarantee that the voltage drop at the end of each line remains within acceptable limits at minimum cost, but also depends on renewable energy resource availability (e.g. in the case of hydropower), the size and nature of end-uses (e.g. in the vicinity of high demand centers) and noise pollution (e.g. in the case of diesel gensets). In general, a shorter distribution line will minimize costs as investments in conductors and poles can be spared. Nevertheless, several factors need to be considered and weighted when designing the distribution network, such as placing lines along roads and trails or considering complicated topography and environmental impact (e.g. clearing trees) (ESMAP 2000, page 52/53).

Annex 3: Service Connection and Metering

The service connection consists of the so called service drop and the service entrance. The service drop consists of typically two (but occasionally three or four conductors) between the consumer and the distribution line, their connections to the distribution lines and their connections to the entrance of the consumer’s residence or business. The service entrance takes the electricity from the service drop to inside the user’s premises. It is comprised of the conductors and associated hardware from the service drop to the meter, the meter or the disconnecting device for controlling electricity usage (ESMAP 2000, page 145). The following figure (see Figure 47) shows the basic components delivering power from the distribution line to the user.

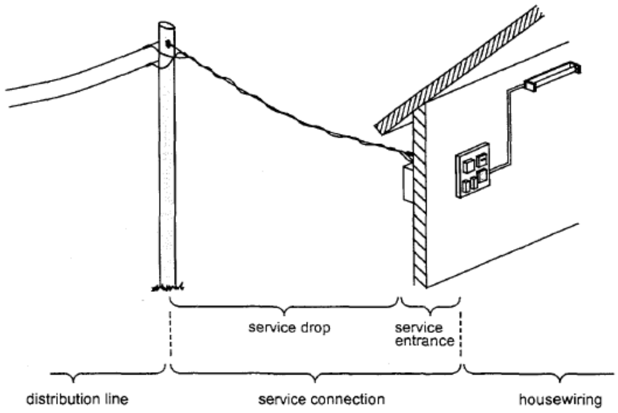


Figure 47: The basic components delivering power from the distribution line to the user. Source: ESMAP 2000, page 145.

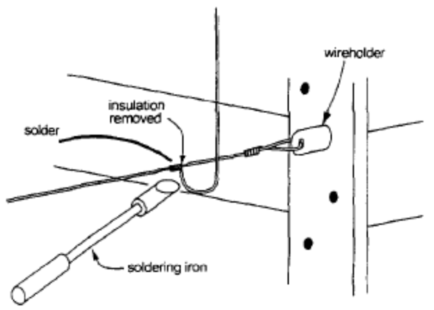
Bare conductors should not be used for service drops in mini-grids. Multiplex conductors are especially designed for service drop installation, with corresponding hardware for deadending, splicing and connections. Because of low level of consumption, small insulated, single-core copper conductors are most commonly used for service drops. They are inexpensive, easily to install, but impose safety risks and higher failure rates due to their limited physical strength characteristics which results in breaking through fatigue. Because of the low level of consumption (usually less than 5 ampere by user), sufficient carrying capacity of service drops and associated voltage drop challenges are usually not an immediate issue. A 230 V single phase service drop with a restricted voltage drop of 1 % serving loads of 30 W (one fluorescent lamp), would only require a 0,5 mm2 copper conductor for servicing four loads (i.e. houses with each one fluorescent lamp) along a 100 m length, whereas the service drop is slung from house to house. This shows that minimum size of conductor is restricted more by physical strength requirements then by its actual carrying capacity and a larger copper conductor might only be purchased because to enforce the physical strength of service drop. Often a minimum diameter of 5 mm2 for a self-supporting copper conductor is therefore recommended. For higher consumption levels, it is still useful to calculate the appropriate conductor size as voltage drop should be in general restricted to 1-3% under maximum consumer load (see Table 17). This is calculated using the same or even a simpler equation as for sizing the conductors of the main distribution lines (ESMAP 2000, page

146/147/148). The table below shows the minimum allowable size for various materials for service drops.

Size for overhead in air*	Load (A)	Voltage drop (%)	Length of run (120 V service) (meters)	Length of run (230 V service) (meters)
Aluminum (5 mm²)	5	1	22	42
	5	2	43	83
	5	3	65	125
Copper (5 mm²)	5	1	35	67
	5	2	71	133
	5	3	104	200
Copper (0.8 mm²) plus steel neutral messenger (2.0 mm²)	1	1	10	20
	1	2	21	40
	1	3	31	59

Table 17: Minimum allowable size for various materials for service drops. Source: ESMAP 2000, page 150.

In a next step, electrical connections must be made to the distribution line at one end and to the conductor used at the service entrance at the other. The figures below (see Figure 48 and 49) show the two basic ways of making a good connection, which are by using a connector or by soldering (ESMAP 2000, page 152).



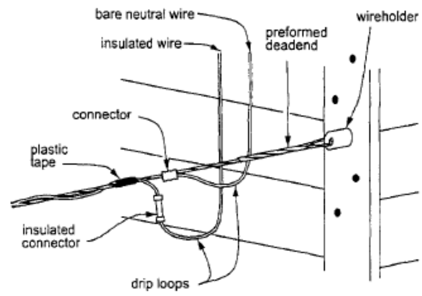


Figure 48: Soldering a twister copper to copper connection. | Figure 49: Connection between duplex service conductor and the residence. Source ESMAP 2000, page 152/153.

The essential function of the service entrance is to connect the consumer (through the housewiring) to the electric utility (through the service drop) and, may include a mechanism for monitoring or at least controlling the energy (ESMAP 2000, page 153). The main meter's function is to measure the energy used by the consumer (mostly in kWh). An energy meter should be located approximately 1,5 to 2 meters above ground level, preferably mounted on the outside of the house before bringing the line indoors, with the enclosure locked to prevent manipulation. It is checked by the meter reader and the calculated monthly amount is the basis for the consumer's bill based on a tariff schedule designed to generate the necessary revenues to cover all the costs occurred in delivering the service. As metering is expensive and associated with increased administration costs as well as the consumption of households connected to a mini-grid limited, other more cost-effective solutions are often used. Another limiting factor of meters is that they can only monitor the consumed energy. Therefore, meters are not the right instrument to assure equitable use of the available energy. Instead of billing energy consumed tariffs can be set on the basis of power consumed by household. This can take the form of tariffs based on connected loads (e.g. a household is permitted up to the use of two light lamps and one TV) or based on a subscribed maximum power input (e.g. household can use up to 40 W) (ESMAP 2000, page 155). Therefore, the second basic approach compared to metering is to limit the current to a predetermined and agreed upon level and to pay on the basis of this level. In small system, this agreement can be done verbally. For bigger systems, several technical solutions are available to limit predefined loads automatically. These load limiters are overcurrent cutout devices. The table below (see Table 18) shows the most frequently used load limiters: fuses, thermal miniature circuit breaker, magnetic miniature circuit breaker, PTC Thermistor and electronic circuit breaker (ECB). Cost and accuracy are two important factors when deciding on the load limiter. Poor accuracy could cause higher energy usage and increased costs, and thus outweigh the initial cost-savings for cheaper load limiters. Also maximum and minimum tripping currents are important to be assessed for cost optimization as they are temperature and thus site depended. Higher tripping currents will increase the overall capacity needs of the system (see ESMAP 2000, page 161/162).

Attributes	Fuse	Thermal miniature circuit breaker	Magnetic miniature circuit breaker	Thermistor	Electronic circuit breaker
Reset mechanism	Replace	Manual	Manual	Auto	Auto
Accuracy	Poor	Poor	Medium	Very Poor	Medium-Good
Short-circuit proof	Type dependent	Type dependant	Type dependant	No	Type dependant
Min. current (A)	0.04	0.05 A	0.05 A	0.01 A	0.05 A
Max. current (A)	> 50 A	>50 A	>50 A	0.7 A	5 A
Availability	Good	Good for > 6 A	Limited	Limited	Very limited
Price	Low	Low-Medium	Medium	Low	Medium-High

Table 18: Characteristics of a variety of current cut-off circuit breakers. Source: ESMAP 2000, page 157.

Annex 4: PV Technology

The photovoltaic effect refers to photons of light exciting electrons into a higher state of energy, allowing them to act as charge carriers for an electric current (URL 1). "Solar Photovoltaic systems utilize semiconductor-based materials which directly convert solar energy into electricity. These semiconductors, called solar cells, produce an electrical charge when exposed to sunlight. Solar cells are assembled together to produce solar modules. A group of solar modules connected together to produce the desired power is called a solar array" (WB 2006).

Solar cells are mostly made from crystalline silicon, sliced from ingots or castings, and grown ribbons, or thin film, deposited in thin layers on a low cost backing (Fechner 2012a, page 8). Silicon based solar PV cells are the most common solar cells in commercial use whereas Crystalline Silicon Solar Cells (both single crystalline and poly-crystalline) account for more than 90% of the world's solar cell production (WB 2006, page 2). Solar cell energy conversion efficiencies for commercially available crystalline silicon solar cells (mono and poly crystalline) are around 14-20% (Fechner 2012a, page 4). Modules are clusters of PV cells incorporated into a unit, usually by soldering them together under a sheet of glass. They are robust and reliable, often with a guaranteed performance of 20-25 years issued by the module producers (Fechner 2012a, page 8). Solar modules are the most important component of a PV system, comprising 40-50% of the total system cost (WB 2006, page 2). Several solar modules form a photovoltaic generator (Fechner 2012b, page 1).

Typical PV modules range in size from around 0,5m2 to 3m2 surface area, with peak power output of 50 to 300 watts DC. Most commercially available single and multi crystalline PV modules have 36 cells in series, and have open circuit voltages of 20-22 volts DC, which can be connected in series up to 600 volts DC. The electric load connected to a PV device determines its operating point (e.g. in case a battery is connected to a PV device, it sets the operating voltage of the PV device). In a grid connected PV system, the inverter loads the PV array at its maximum power point (which equals Vmp/Imp (ohms)) (URL 2).

The following figure (see Figure 50) shows the pricing trend of solar panels from 1985-2011. It indicates a steep technology learning curve and associated cost reductions over time. The cost of solar panels has been steadily decreasing, from 7 USD per watt in the mid 80ies to close to 1 USD per watt today, which favors the broad deployment of PV (IEA PVPS 2013).

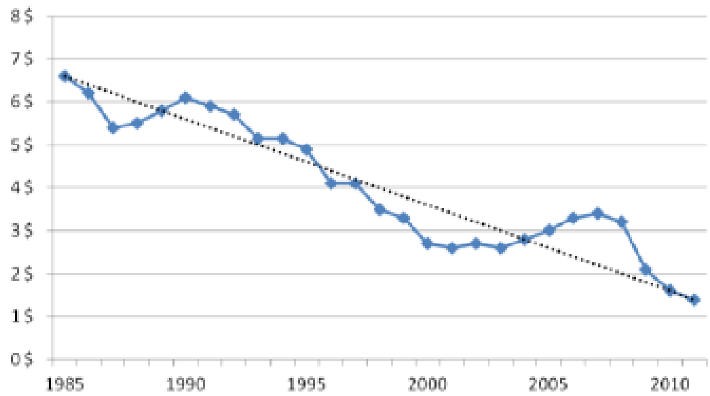
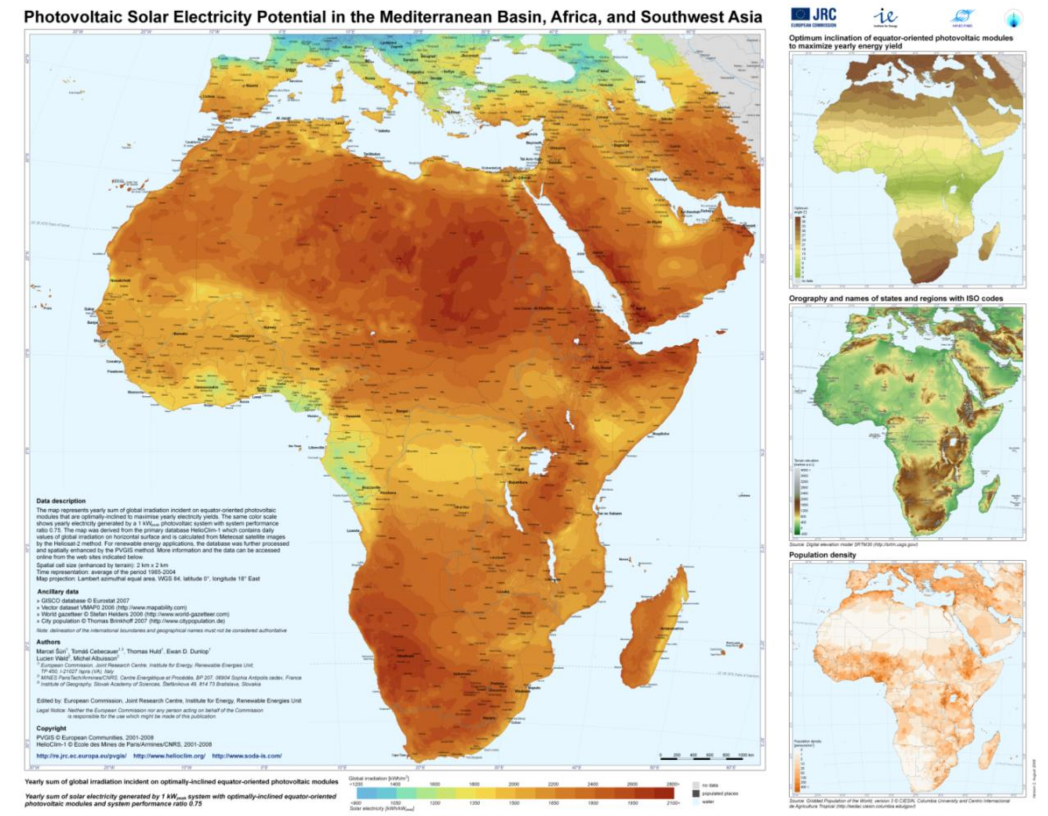


Figure 50: Pricing Trend of solar panels 1985-2011. Source: IEA PVPS Task 09/CLUB-ER 2013, page 14.

Annex 5: PV Power Output

The power output of the solar model depends on many factors, such as the size (installed capacity), efficiency of the technology, irradiation of the site, cleanliness of the surface , the power electronics and the usage of a tracking system (ARE 2011, page 39). Sunny conditions in developing countries have positive impacts on the power output of PV systems. An installed capacity of 1kWp (typically 4-6 individual modules with a total surface of approximately 8m2) can generate more than 2.000kWh annually, in contrast to e.g. Central Europe, where the same installed capacity in average reaches only have of that (ARE 2011, page 39). The following map (see Map 3) is taken from the Photovoltaic Geographical Information System (PVGIS) which provides a map-based inventory of solar energy resources and assessments of the electricity generation from photovoltaic systems in Europe, Africa, and South-West Asia (see URL 3). It shows that the yearly sum of solar electricity generated by a 1kWp system with optimally inclined equator oriented PV modules and a system performance ratio of 0,75 can yield more than 2,000 kWh in most locations, going up to 2,600 kWh in certain places.



Map 3: Photovoltaic Solar Electricity Potential in the Mediterranean Basin, Africa and Southeast Asia. Source: URL 3.

Annex 6: PV Hybrid Mini-Grid Market Segmentation

IEA PVPS Task 09/CLUB-ER (2013) divides the hybrid mini-grid market into four segments. First, micro hybrid systems below 5kWp are used for the basic electrification of institutions, such as a school, community center of health clinic (see previous example for more details). Second, the basic electrification of a small village can take place through a small hybrid system of 5 to 30kW installed capacity. Here, the low base load can be supplied by solar energy and a battery bank and PV penetration rate achieves 40-90% (see previous example for more details). Medium-size hybrid systems with installed capacities in the range of 30 to 100 kWp are suitable for the electrification of a village where productive and commercial activities use energy during the daytime. Because of the large upfront investment costs, PV penetration is typically not above 60%. Large hybrid systems (systems between 100 and 300 kWp) can supply the power needs of towns with peak loads above 150 kW, and daily consumption higher than 1000 kWh/day. The following figure (see Figure 51) shows the four market segments and its corresponding financial requirements, equipment types, as well as organizational and operational aspects.

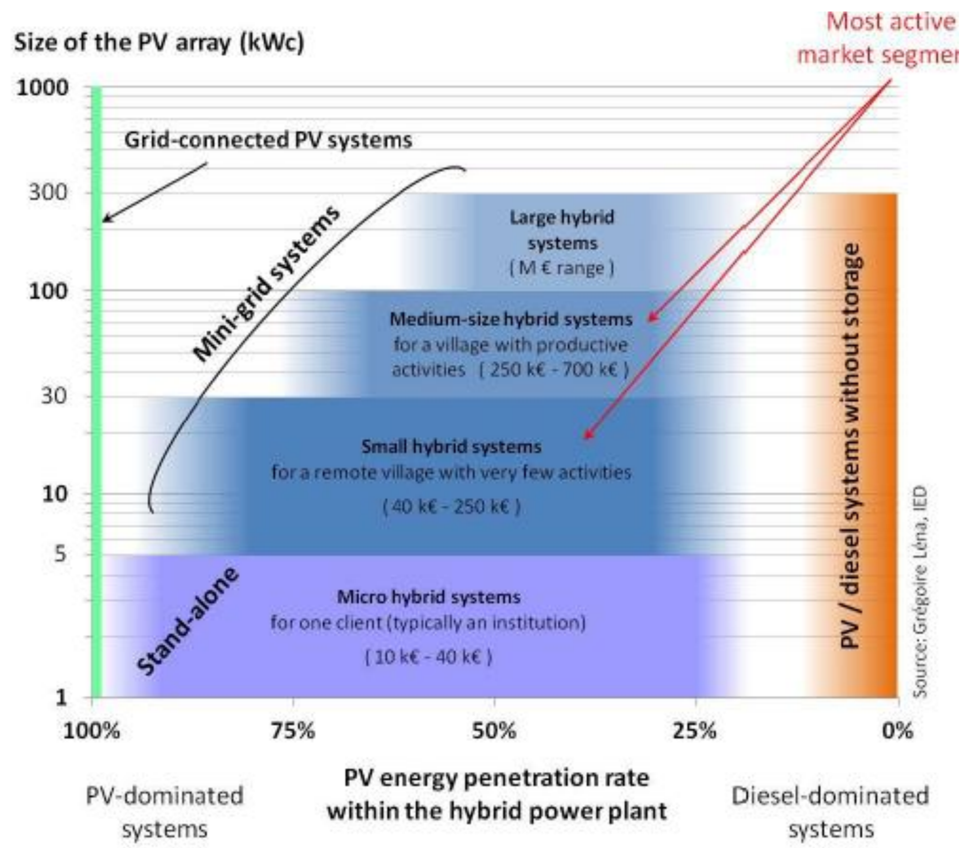


Figure 51: Market segmentation for PV/diesel hybrid systems for rural electrification in developing countries (type of system with upfront investment cost). Source: IEA PVPS Task 09/CLUB-ER 2013, page 18.

Annex 7: Other Critical Success Factors for Hybrid Mini-Grids

As already mentioned in previous chapters, one important success factor is to ensure adequate demand for electricity (IFC 2013, page 89). Sufficient population density is a key determent for the commercial feasibility of mini-grids. Larger distances between costumers and low consumption increase the cost of electricity. Income levels, i.e. the ability to pay, is another important factor, as basic energy services can

alternatively be supplied by a range of energy devices at a lower cost than mini-grids. Nevertheless, with monthly cost of 5 to 10 USD for "lightning plus" services, even very low income levels could potentially afford energy from mini-grids. In that respect, IFC distinguishes two types of mini-utilities, "lightning focused" and "total electrification types", which provide also energy for commercial and productive demand (i.e. larger base load customers) (page 89). While this increases profitability through larger sales, it also requires a greater amount of capital investments and thus, increases design, planning and operating complexity. A highly praised approach in the literature is to secure so called "anchor clients" from the start through off-agreements with industrial customers or a number of SME costumers that provide long-term demand for baseload power. Other options are to connect with the national grid, where the public utility becomes the anchor client; to partner with the municipality where public buildings and municipal enterprises need to be served; or as already mentioned, the giant market of telecom towers as anchor clients.
Another important success factor is the need to develop the right operating model – and ensuring sufficient management expertise – to scale the business beyond a handful of systems (IFC 2013, page 92). As many utilities are started by local entrepreneurs with only basic educational background, it can be assumed that a lack of formal business scales is not a major barrier. Nevertheless, mini-grids with increasing capacity lead to a level of complexity that requires new skills and know-how, a need which can be well served with focused training and capacity building. An interesting – and in the literature often quoted example – in that respect is the Indian company Husk Power Systems (HPS), which provides power to thousands of villagers through a biomass gasification technology fed by rice husks. In order to scale up beyond the 72 systems already in place, it developed a franchise model for local entrepreneurs, and an associated training program to equip them with the necessary skills to succeed, called "Husk University" (URL 24).

Bibliography

Literature

ARE 2011. Hybrid Mini-Grids for Rural Electrification. Lessons Learned.

ARE/USAID, Brussels.

ARE 2011a. PPT Presentation at Intersolar 2011. Off-Grid PV in Emerging and Developing Countries. Potential and the way to reach it.

ARE 2011b. Rural Electrification with Renewable Energy. Technologies, Quality Standards and Business Models.

ARE 2012, The Potential of Small and Medium Wind Energy in Developing Countries. A guide for energy sector decision makers.

ARE 2013. Using Batteries to ensure clean, reliable and affordable universal electricity access. A guide for energy decision-makers.

AWEA 2010. AWEA Small Wind Turbine Global Market Study.

Breyer, C. 2013. Comprehensive Country Ranking for Renewable Energy Based Mini-Grids Providing Rural Off-Grid Electrification. URL 25

Brandt, Dana 2005, The Future of Community Scale Renewable Energy, Home Power 109.

ESMAP 2000. Mini-Grid Design Manual. ESMAP Technical Paper 006. World

Bank/UNDP. Washington DC.

Fechner 2012a. TU MSc Script PV. Introduction on PV, physical basics and semiconductors.

Fechner 2012b. TU MSc Script PV. Planning, Simulation, Design and Dimensioning.

Fechner 2012c. TU MSc Script. Cost, financing of PV systems.

Fortis 2008. Summary of Test Results of Fortis Alize (10 kW) Wind Turbine.
GSMA 2013. Powering Telecoms: West Africa Market Analysis. Sizing the Potential for Green Telecoms in Nigeria and Ghana. London.

Greancen et al 2007. Renewable Energy Options on Islands in the Andaman Sea. A feasibility study for hybrid renewable energy/diesel systems in two Tsunami impacted communities. Heinrich Boell Foundation.

Harper 2013. Review of Strategies and Technologies for Demand-Side Management on Isolated Mini-Grids. Kerkeley Lab/SERC.

HOMER 2010. Battery Energy Cost. HOMER Support.

IEA 2011. Energy for All. Financing Access for the Poor. Special early excerpt of the World Economic Outlook 2011.

IEA 2012. World Energy Outlook 2013. Special Topics. Measuring progress towards energy for all. OECD/IEA 2012.

IEA/PVPS Task 11 2009: Current State of the Art in PV Hybrid Mini-Grids – Early Results from IEA PVPS Task 11.

IEA/PVPS 2011. World-wide overview of design and simulation tools for hybrid PV systems.

IEA/PVPS Task 11 2012. Control methods for PV hybrid mini-grids: Applicable control methods for various situations.

IEA/PVPS Task 09 2013. Rural Electrification with PV Hybrid Systems. Overview and Recommendations for Further Deployment.

IFC 2012. From Gap to Opportunity: Business Models for Scaling Up Energy Access. Washington DC.

Krenn 2012. TU MSc Script. Wind Power.

Lamech, Rangit/Saeed, Kazim 2003. What International Investor Look For When Investing In Developing Countries. Results from a Survey of International Investors on the Power Sector. World Bank/The Energy and Mining Sector Board.

Marinot et al 2002. Renewable Energy Markets in Developing Countries. In: Annu. Rev. Energy Environ. 2002, 309-348.

National Renewable Energy Laboratory (NREL) 2011. Getting started guide for HOMER Legacy (Version 2.68).

REN21 2013. Global Status Report 2013.

Neubauer 2012. TU MSc Script. Development of projects and planning of wind energy projects.

Prahalad, C.K./Hart, Stuart L. 2002. The Fortune at the Bottom of the Pyramid. Strategy & Business Issue 26.

Sunlabob 2006. Village electric grids for creating rural income.

Suwannakum et al 2009. Four Year's Experience on Mini-Grid System for Rural Electrification in Thailand.

Szabo et al 2011. Energy Solutions in Rural Africa: Mapping Electrification Costs of distributed solar and diesel generation versus grid extension, Environ. Res. Lett. 6.

Szabo et al 2011a, Spatial Evaluation of viable RE technologies in rural areas using GIS science, ARE Symbosium "Merging Off-Grid Research and Business".

UNDP 2004. Modernized Biomass Energy in China: Jilin, SUMMARY REPORT.

UNDP 2005. China Village Power Project Development Guidebook. A Practical Guidebook for the Development of Renewable Energy Systems for Village Power Projects.

UNEP 2008. Financing Mechanisms and Public/Private Risk Sharing Instruments for Financing Small Scale Renewable Energy Equipment and Projects.

UN AGECC 2010. Summary Report. Energy for a Sustainable Future.

UN AGECC 2012. Energy for a Sustainable Future. Report and Recommendations.

UN Secretary General's High-Level Group on Sustainable Energy For All (SEAHLG) 2012. Report of the Co-Chairs.

Volger Quaschnigg, Regenerative Energiessysteme, Carl Hanser Verlag Muenchen/Wien.

World Bank 2007. Technical and economic assessment of off-grid, mini-grid, and grid electrification technologies.

World Bank 2007a. Technical and Economic Assessment of Off-Grid, Mini-Grid and Grid Electrification Technologies – Annexes.

World Bank 2008. REToolkit Issue Note. A Resource for Renewable Energy Development.

World Bank 2008a. Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practice. Operational Guidance for World Bank Staff.

Websites

URL 1: http://en.wikipedia.org/wiki/Photovoltaics

URL 2:
http://www.pttrenenergy.upc.edu/index2.php?option=com_docman&task=doc_view&gid=213&Itemid=35

URL 3: http://re.jrc.ec.europa.eu/pvgis/

URL 4: http://www.sma-uk.com/en_UK/products/off-grid-inverters/multicluster-boxes-for-sunny-island-5048.html

URL 5: http://en.wikipedia.org/wiki/Small_wind_turbine

URL 6: http://www.wholesalesolar.com/products.folder/systems-folder/OFFGRID.html

URL 7: http://www.windustry.org/wind-basics/wind-resources

URL 8: http://www.windustry.org/home-and-farm-scale-wind/planning-small-wind-project#windresource

URL 9: http://wasadata.csir.co.za/wasa1/WASAData

URL 10: http://www.irena.org/globalatlas

URL 11: http://www.3tier.com/en/support/resource-maps

URL 12: www.palangthai.org/docs/KohPu.hmr

URL 13: http://www.civicsolar.com/product/sma-sunny-boy-3800-us

URL 14: http://bergey.com/products/wind-turbines/5kw-bergey-excel

URL 15: http://www.fortiswindenergy.com/products/wind-turbines/alize

URL 16: http://aton.lt/global/dokumentai/Fortis%20Wind%20Energy%20%20price%20list%202012-1.pdf

URL 17: http://www.centralmainediesel.com/order/Cummins-60-kW-Diesel-Generator.asp?page=6719

URL 18: http://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

URL 19: http://www.nreca.coop

URL 20: http://rescoop.eu

URL 21: http://www.sunlabob.com

URL 22: http://www.sunlabob.com/data/documents/06-01-Pilot_village_grid.pdf

URL 23: http://www.pi.energy.gov/documents/EWSLchina3.pdf

URL 24: http://www.huskpowersystems.com

URL 25: https://energypedia.info/wiki/The_Potential_of_Mini_Grids_and_Critical_Factors