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Mini-Grids Go Green: An Economic Viability Assessment of Integrating Renewable Energy into Off-Grid Diesel Power Systems in Cambodia - a Case Study on Koh Rong Island

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

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Affidavit

I, **BETTINA RÖTHLIN, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "MINI-GRIDS GO GREEN: AN ECONOMIC VIABILITY ASSESSMENT OF INTEGRATING RENEWABLE ENERGY INTO OFF-GRID DIESEL POWER SYSTEMS IN CAMBODIA - A CASE STUDY ON KOH RONG ISLAND", 56 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Diesel-fuelled mini-grids have become one of the main tools of supplying electricity to rural or off-grid areas in many African and South-Asian countries due to their ease of installation and the low initial investment required. However, these systems often bear high long term and large environmental costs. This thesis therefore assesses, by means of a case study on the Cambodian island of Koh Rong, whether it is economically viable to hybridize existing diesel-powered mini-grids with renewable energy technology, in particular solar photovoltaic, and if hybridization could lead to a reduction in cost of electricity. Moreover, it discusses whether such a hybridization project could offer an attractive investment opportunity for private investors. For this purpose, a levelized cost of electricity (LCOE) analysis is carried out, comparing the electricity generating costs of the existing diesel-powered mini-grid with those of a diesel-PV hybrid system for two ownership structures, namely a tax-exempted public utility and a tax-paying independent power producer. First, an overview of the Cambodian electricity sector is provided and the appropriate technologies regarding diesel and hybrid mini-grids are reviewed. Further, an introduction to LCOE analysis, on which this work is based, is given and the input variables required for the LCOE calculations are discussed. Finally, the calculation results are presented and eventual barriers for the deployment of renewable energy in Cambodia are identified. It is found that hybridizing existing diesel mini-grids on Koh Rong island can lead to electricity generation cost reductions of up to 9.9% and hybridization projects can present attractive investment opportunities for equity investors. However, despite the economic viability of hybrid mini-grids, non-economic barriers, such as the lack of a profound regulatory framework, might inhibit the larger deployment of renewable energy technologies in Cambodia.

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List of Abbreviations

CapEx	Capital Expenditure
EAC	Electricity Authority of Cambodia
EDC	Electricité du Cambodge
EHS	Energy Home Systems
EIA	U.S. Energy Information Administration
GHI	Global Horizontal Irradiation
ha	hectares
HFO	Heavy fuel oil
IEA	International Energy Agency
IPP	Independent Power Producers
kVA	kilovolt-ampere
kW	kilowatt
kWh	kilowatt hour
kW_p	kilowatt peak
LCOE	Levelized Cost of Electricity
MME	Ministry of Mines and Energy
O&M	Operation and maintenance (costs)
PR	Performance Ratio
PrV	Present Value
PV	Solar photovoltaic
PVGIS	Photovoltaic Geographical Information Service
RE	Renewable energy
REF	Rural Electrification Fund
RETs	Renewable energy technologies
RPO	Rated power output
SREP	Sustainable Rural Electrification Plans
STC	Standard testing conditions
TLCC	Total life-cycle cost
UNFCCC	United Nations Framework Convention on Climate Change
V	volt
W	watt
W_p	watt peak
WACC	Weighted Average Cost of Capital
WTP	Willingness to pay

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1 Introduction

Reliable access to energy and electricity is considered to be a basic precondition for economic growth, the successful establishment and enhancement of healthcare and educational systems, and the general improvement of quality of life of people living in rural or remote areas. Whether one considers the creation of jobs, climate change or food production, access to energy plays a vital role and is one of the main drivers of increased welfare in developing countries.
During recent decades, rural electrification efforts have achieved an increase in the global electrification rate from 71% of the population in 1990 to 87% in 2016 (The World Bank, n.d.a). Ensuring access to affordable, reliable, sustainable and modern energy for all continues to be one of the most central development goals of our time as part of the United Nations Agenda 2030.

As communities living with non-reliable or no access to electricity are often characterized by living in remote areas or island settings with very low population densities, electrification via the extension of the national grid is often inefficient, uneconomical or technically not possible. Hence, decentralised electricity generation systems on local levels via the creation of mini-grids or Energy Home Systems (EHS) have in most cases become the main tool of supplying electricity to rural or off-grid areas. In 2016, an estimated 133 million people were served by off-grid technology with numbers set to increase further during the next decade. Mini-grids provide a reliable and economically competitive electrification option to increase connection rates in remote areas of developing countries all around the world. Due to their modularity, their installation and usage is simple and does not require advanced levels of technical expertise, making these systems even more suitable for the developing world. Moreover, as opposed to EHS systems, they can cover non-domestic energy demands in addition to domestic needs, allowing for the creation of income-generating possibilities and thus the improvement of quality of life of communities. The International Energy Agency (IEA) has estimated that in order to achieve the goal of universal electrification by 2030, mini-grids and other off-grid solutions will have to deliver electricity for 70% of rural areas, in the proportion of 65:35, as grid extension will only provide a cost effective option for the remaining 30% of cases (International Energy Agency 2011, 21). Hence the implementation of mini-grids in rural settings will continue to play a vital role in global electrification efforts in future years, with their popularity likely to increase around the globe.

1.1 Motivation

Regarding the history of mini-grids and the beginning of larger scale mini-grid implementation for rural and off-grid electrification in many African and South-Asian developing countries, mini-grids fuelled by diesel have largely been considered the easiest electrification solution due to their relatively low short term investment costs and ease of installation. As a result, diesel remains the prevalent source of mini-grid operations in many developing countries with up to 90% of mini-grids running on diesel. Yet, due to high volatility and an increase in fuel prices, they often bear higher long term as well as immense environmental costs.

The energy sector has been estimated to account for around 60% of the total global greenhouse gas emissions (United Nations, n.d.) and has been recognized as the dominant contributor to climate change. With fossil fuels, such as coal, oil, and gas continuing to play a prominent role in our global energy system, all members of the United Nations Framework Convention on Climate Change (UNFCCC) determined that the reduction of carbon emissions from fossil fuels is indispensable for combatting climate change and achieving the internationally accepted goal of limiting global warming to 2º Celsius. A change in energy sources away from fossil fuels and towards renewable energy (RE) is therefore necessary and a transformation in energy generation is indispensable in reducing carbon emissions by 80% until 2050.

With technological advancements in efficiency and reliability of renewable energy technologies (RETs) and decreasing costs of RE components, RE electricity generation has become more and more popular during the past decades. Thereby, RETs have also started to be implemented in mini-grid configurations all around the world. The resulting RE- or hybrid mini-grids not only constitute an environmentally more viable option than solely diesel generated assets, but have, in some cases, even become the more cost-competitive alternative. Many locations for which mini-grid electrification is considered the most effective electrification option provide optimal natural conditions for the use of RETs such as solar photovoltaic (PV), small hydro power, or wind. Thus, integrating these technologies into existing diesel mini-grids can lead to more feasible electricity generation, not only in terms of cost savings but also with regards to the socio-economic and environmental impact.

1.2 Objectives

This thesis focusses on these locations for which mini-grid electrification is the only or most suitable electrification solution, with a particular focus being set on island regions. Its aim is to assess whether the RE-based hybridization of existing diesel mini-grids presents a viable alternative to pure diesel energy generation. To this end, this work will investigate the economic feasibility of hybridizing a diesel mini-grid with one of the most important RETs, namely PV, on the island of Koh Rong in Cambodia.

The purpose of this thesis is to provide the groundwork and a preliminary analysis of the potential of PV for the alteration of electricity generation in island or rural settings in Cambodia. In order to do so, the objectives of this thesis and sub-questions to be discussed have been set as follows:

- Determine whether the hybridization of existing diesel mini-grids with a PV system can lead to a reduction in the cost of electricity on the island of Koh Rong, representative for rural and island settings in Cambodia
    - Identify if the WTP for electricity is sufficiently high on Koh Rong for the economically sustainable implementation of PV hybridization from a "societal perspective".
- Discuss if a hybridization project offers an attractive investment opportunity for Independent Power Producers (IPP).
- Identify possible non-economic barriers to the wider deployment of PV systems and other RETs on mini-grids in Cambodia.

1.3 Methodology

This master thesis uses a combination of different methodologies in order to cover the objectives outlined in the previous section as best as possible.

The first part of the work lays the theoretical foundations for the discussion of the research chapters that will follow thereafter and consists of a literature review of textbooks, journal articles as well as official government publications. It seeks to provide a comprehensive overview of Cambodia's electricity sector and discusses the current technological state of the art of mini-grids, diesel generators and solar photovoltaic technology. It also gives a brief introduction to the concept of levelized cost of electricity (LCOE) analysis, the main analytical tool used in this thesis.

The second and third part of the thesis is of qualitative nature and will consist of a case study based on the conditions currently prevailing on the Cambodian island of Koh Rong.

Thereby, the impact of hybridisation of the existing diesel mini-grid on average electricity generation costs, namely the levelized cost of electricity, will be assessed and compared to the current diesel LCOE. The aim of the case study is to present a realistic scenario of a hybridization project applicable to Cambodia as well as to other countries with similar starting conditions. As some of the data required to undertake a detailed LCOE analysis has never been documented and is as such not available, assumptions had to be made in order to carry out calculations. These were, one the one hand, based on specialised literature in form of previously published analyses of similar nature, as well as on reports. On the other hand, assumptions were also drawn from observations made and information obtained directly at the project site, of Koh Rong island. The resulting input variables chosen for calculations are discussed in detail in part II of the work.

In the third part of the thesis, the case study results will be presented and discussed. Moreover, eventual non-economic barriers to the wider deployment of RET in Cambodia will be identified and discussed. Whilst partly consisting of a literature review, this part will also be based on information and indicators received during interviews conducted in the Kingdom of Cambodia.

1.4 Case Study: Koh Rong – Cambodia

The island of Koh Rong in the Kingdom of Cambodia has been chosen as a basis for the case study conducted in part II and III of this thesis. Koh Rong offers optimal conditions for the implementation of PV systems and the analysis of hybridisation of the currently existing diesel mini-grids. Despite the island being a very popular tourist destination with more than 100 holiday resorts already existing on the island and several more being in construction, diesel generators continue to remain the only source of electricity. These have all been privately purchased either by resorts for private use or by a private entrepreneur who supplies the generated electricity to several customers along the southern coast of Koh Rong island via a power line.

This case study presents ample opportunity to analyse whether the LCOE on Koh Rong, and more specifically along Long Set Beach, can be lowered by building a PV power plant that covers a portion of the electricity demand for peak solar penetration hours, during which diesel assets can be switched off, as compared to the LCOE of generating all electric demand by the existing diesel generators. In order to do so, the case analysed has been based on an existing PV power plant project on the island of Koh Rong which is set to start construction in the summer months of 2019.

2 Part I: Background and Theoretical Foundations

2.1 The Cambodian Electricity Sector

Whilst the Cambodian Electricity sector had mainly operated under *de facto* laissez-faire conditions since the time of the country's civil war from 1967 to 1975 and during Vietnamese occupation until 1991, Cambodia's government began to exert control over the sector in the late 1990s. Nowadays, the Cambodian power sector is regulated by the Electricity Law promulgated in February 2001 which defines its main actors as well as their individual responsibilities and the relationship between them (ESMAP 2017, 5).

2.1.1 The Main Actors

The most important institutions acting in the Cambodian power sector are the Ministry of Mines and Energy, the regulator Electricity Authority of Cambodia, the state-owned power utility Electricité du Cambodge and Independent Power Producers (ESMAP 2017, 10).

Ministry of Mines and Energy (MME)

The MME is responsible for planning and implementing new policies regarding the electricity industry as well as for setting new industry standards. It is hence the primary policy-making institution in the Cambodian power sector and also monitors the country's electricity supply and demand balance (Derbyshire 2015, 17).

Electricity Authority of Cambodia (EAC)

The EAC was established as a legal entity in 2001 under the Electricity Law and has a regulatory as well as a monitoring and compliance enforcing function. It is an autonomous agency exclusively funded though licence fees paid by licensees and, by law, has a clearly separated role from that of the MME.

The EAC is responsible for granting licenses to electricity enterprises, reviewing costs and approving tariffs, and for settling disputes amongst licensees or licensees and customers (Derbyshire 2015, 18).

Electricité du Cambodge (EDC)

As already mentioned above, EDC is the state-owned power utility in Cambodia and is responsible for the "generation, purchase, transmission and distribution of the electricity throughout the country" (Derbyshire 2015, 18). Due to historical reasons, EDC's service area initially only covered the area of Phnom Penh before gaining responsibility for the nation-wide electricity supply.

EDC is owned by the MME as well as the Ministry of Economy and Finance and acts as a single buyer in the electricity market, receiving electricity from IPPs, its own power plants, and imports from neighbouring countries (ESMAP 2017, 11).

Other Actors

Other actors in Cambodia's power sector include:

- IPPs, who generate a large proportion of Cambodia's electricity. Electricity generated by IPPs is sold to power suppliers such as the EDC via power purchase agreements. IPPs must be licensed by the EAC to generate electricity.
- The Rural Electrification Fund (REF), who is responsible for subsidising and funding mini-grid operations. It is a non-profit department within EDC (ESMAP 2017, 12).

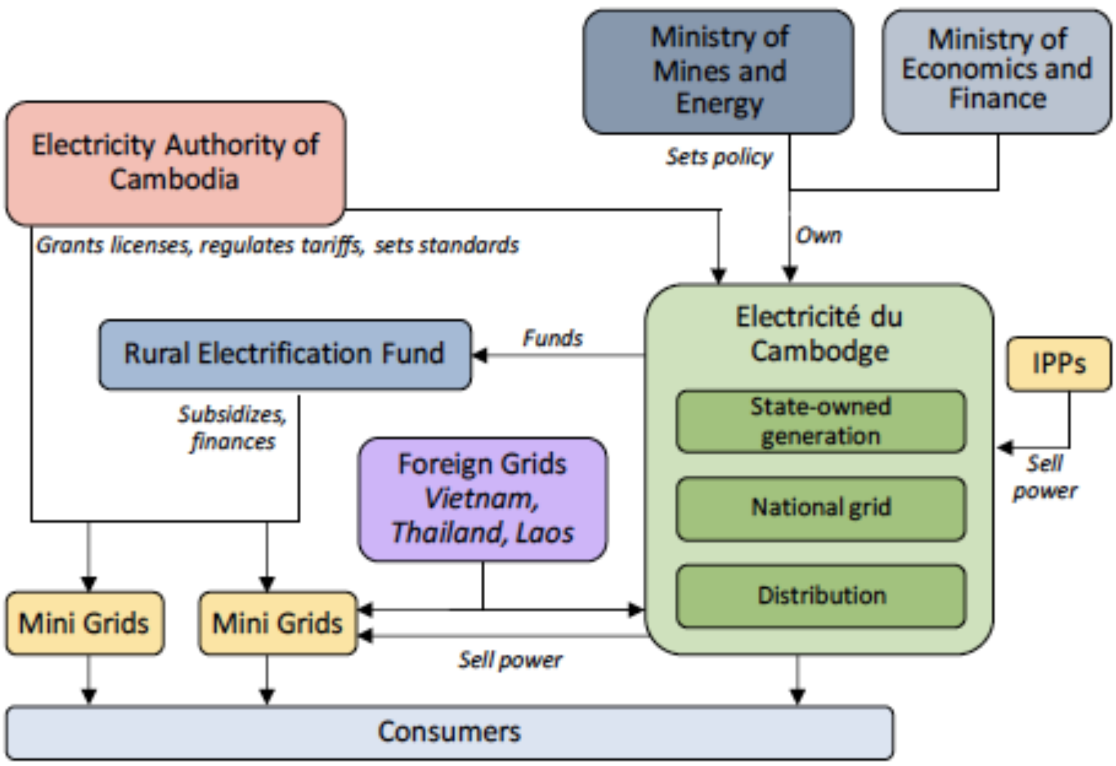

Figure 1. Power sector structure of Cambodia (ESMAP 2017, 10)

2.1.2 Overall Situation

Cambodia's electricity sector has experienced significant growth over the last decade and has undergone a drastic transformation as a result of the government's efforts to increase access to energy, reduce energy cost and to increase the country's energy security. Cambodia's peak electricity demand has skyrocketed during the past ten years with electricity consumption having quintupled from 1.5 GWh in 2007 to 8.2 GWh in 2017 (Beam Exchange 2018). Cambodia's installed capacity has also increased considerably and reached a total of 1.88 GW in 2017 (Electricity Authority of Cambodia [EAC] 2018, 76). Yet, the country's power sector continues to be small by regional standards, especially when compared to those of its neighbouring countries Thailand, Lao and Vietnam, whose installed capacity per capita exceeds that of Cambodia five times over (ESMAP 2017, 13).

Whilst the country was mainly supplied by mini-grids using diesel and heavy fuel oil (HFO) in 2007, accounting for around 85% of the total electricity supplied, Cambodia succeeded in diversifying its energy recourses in recent years and is now using a mix of hydro (34% of supply), coal (44%), diesel and HFO (3%), biomass (1%) and imports (18%) for generation based on 2017 levels (EAC 2018, 75-77).
Despite energy generation in Cambodia having covered 82% of energy supplied in 2017, the country continues to remain heavily dependent on energy imports from its neighbours, mainly Vietnam. Especially during the dry season, domestic generation resources are not sufficient to meet demand due to shortfalls in hydro production which then have to be covered by imports. The country is also largely dependent on IPPs as they cover 98.5% domestic generation while the state-owned utility EDC only generates 0.6% of supplied electricity (EAC 2018, 76).

2.1.3 Access to Electricity: Grid and Off-Grid Electrification

The sharp increase in energy demand and consumption mentioned in the previous section is closely linked to a significant progress in electrification levels over the same time period. While only around 21% of Cambodia's population had access to electricity in 2005, levels reached almost 50% of the population in 2016 and are estimated to lie around 60% in 2019 (The World Bank, n.d.a). However, there still exists a large discrepancy between electrification rates in urban and rural areas where 77% of the population live, with rates being at 100% and 36%, respectively (The World Bank, n.d.b, n.d.c, n.d.d). Moreover, electrification levels continue to lie far below the regional average, with neighbouring countries Vietnam and Thailand having 100% access and Lao having an access rate of 87% (The World Bank, n.d.a).

The bulk of the expansion during the 1990s was achieved through local private sector-led development of several hundred diesel-fired mini-grids with the result that in 2015, approximately 60% of the population with an electricity connection were served by mini-grids rather than the main electricity grid. Currently, around 350 privately operated mini-grids connect over 1 million households, with the number of connections growing from year to year (ESMAP 2017, 18).

During recent years, the EAC has increased its efforts to integrate mini-grids into the main grid, with the aim of lowering electricity prices and increasing reliability of energy supply. Upon the arrival of the main electricity grid, most mini-grid operators hence opted for transforming their distribution network into gird-connected distribution franchises over the past years. As a result, average power tariffs for mini-grids connected to the main grid have dropped from an average USD 0.50/kWh in 2003 to USD 0.25/kWh, and 24 hours of service or electrify supply increased from a previous 42% of licensees to 98% (IRENA 2018, 53).
However, the problem of low supply availability and reliability as well as high power tariffs around USD 0.45/kWh remain for isolated mini-grid locations in areas where no national grid extension is foreseen, such as remote or island settings. There, diesel remains the most prevalent generation source and operators are allowed to charge full cost-recovery tariffs without government subsidies providing any financial support.

2.2 Mini-Grid Technology for Island and Rural Electrification

2.2.1 Mini-Grid Definition

Mini-grids can generally be defined as a collection of electricity generating units, sometimes in combination with an energy storage system, connected to a small scale distribution network that supplies energy to a limited amount of customers living in surrounding areas. They differ in power architecture from Energy Home Systems or single consumer systems, such as for example Solar home systems (SHS), which are designed to provide electricity to isolated, non-connected households and hence do not entail a transmission grid. Mini-grids also differ from centralized grid systems; while the latter produce electricity in a de-centralized manner and transmit it over long distances to meet the energy demand of a large dispersed group of customers, mini-grid generation occurs on a local level and supplies electricity to a localized group of customers (Energypedia, n.d.).

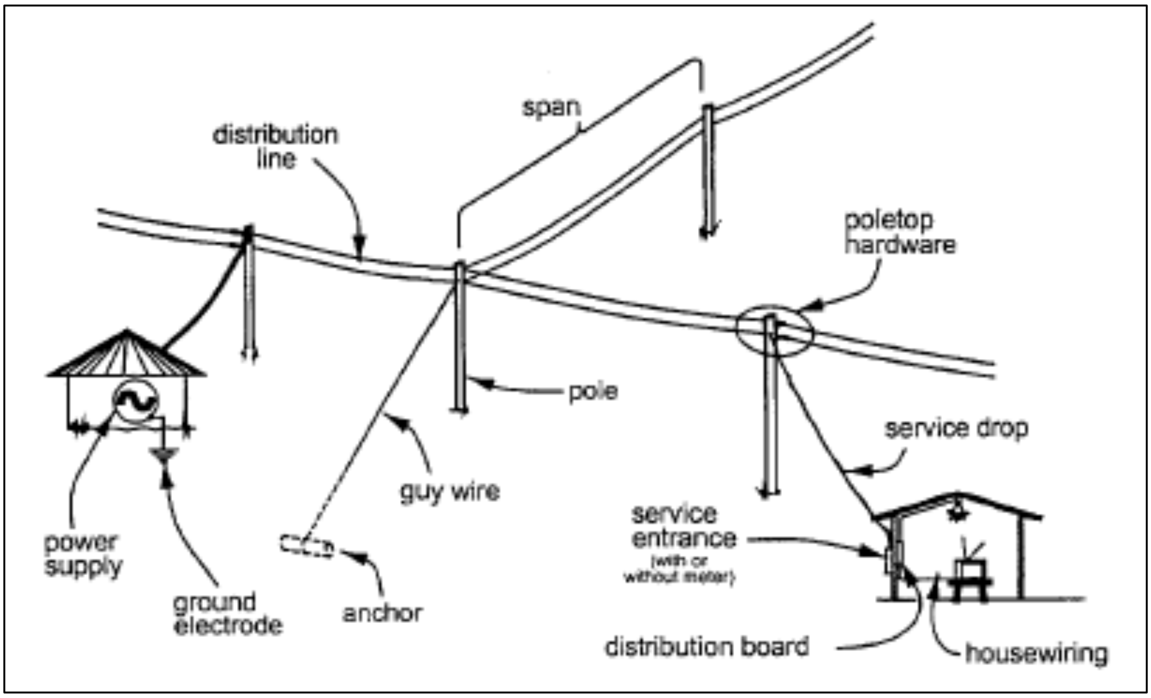

Figure 2. General set-up of typical off-grid mini-grid system (ESMAP 2000, vii)

Mini-grids have the unique feature of being capable of functioning autonomously and in isolation from national power transmission grids. It is due to this feature that they provide an optimal solution for rural electrification purposes, as they can supply electricity to remote areas for which a connection to the national grid is not possible. Nevertheless, mini-grids may be designed in a flexible manner to allow for an immediate interconnection with a centralized distribution network or for a later integration in a national grid, in case a grid extension becomes feasible in the future. Once part of a centralized grid, the mini-grid will generally operate as an integral part of the main grid, however, in exceptional circumstances, such as central grid failure, it may still be disconnected and provide a separate, local source of electricity (Energypedia, n.d.).

With regards to the generating capacity, definitions for mini-grids often vary but generally cover a range of small-scale electricity generation from around 50kW up to 10MW. It is thereby larger in size than a micro-grid, which usually only covers a generation capacity of up to 50kW, and a nano-grid which generally defines a grid serving a single customer or building (Rycroft 2016). In this study, the mini-grid application concerns an isolated network along one of the beaches on the island of Koh Rong with an estimated load of 1200kW.

2.2.2 Mini-Grid vs. Grid Extension

In the context of rural electrification efforts, it is important to mention that the extension of the national grid of a country may always be a feasible option for bringing access to electricity to remote areas, and should therefore always be considered as such. However, depending on the distance between different locations to already existing transmission lines and the characteristics of the terrain lying in between, the costs of extending transmission lines can become too high to be supportable by developing countries, rendering such projects economically unfeasible. Moreover, in order for a grid expansion project to become viable, a critical mass of consumers with sufficient demand is required, which often does not exist in remote areas or island settings of developing countries. It must hence be carefully determined whether the extension of the national grid or an off-grid electrification system in form of a mini-grid presents the more cost-effective electrification option (Alliance for Rural Electrification [ARE], 10).

With regards to this study's project site, Koh Rong island, none of the national grid extension scenarios currently envisaged by the MME of Cambodia include the island in their range. Moreover, despite not being nationally funded, there already exist privately funded off-grid electrification systems on the island in form of diesel generators. Koh Rong island is hence classified as an area for which mini-grid electrification has already been identified as the most suitable electrification option. As outlined in section 1.2, it is precisely these locations that this thesis is aiming to address. An analysis of whether grid extension efforts could lower the LCOE on Koh Rong lies outside the scope of this thesis and is therefore not conducted in this work.

2.2.3 Types of Mini-Grid Power Systems

In general, mini-grid power systems can be grouped into three different types of mini-grids, namely diesel generator set or genset power systems, renewable energy generated systems and hybrid power systems. Whilst diesel mini-grids and RE mini-grids completely rely on either diesel fuel, in case of the former, or renewable energy, in case of the latter, as their sole source of power, hybrid mini-grids combine at least two types of power generating technologies.

Diesel Mini-Grids

Fossil fuel based gensets and, in particular, diesel systems remain the most common electricity generation method for rural areas all across the Global South. They have the big advantage of being readily available in almost all countries and their low-cost of transportation as well as ease of installation make them an attractive electrification option, especially in the developing world. Moreover, due to their application and manufacturing being very widespread, the initial capital costs of diesel genset power systems are very low compared to those of RETs. Other advantages include a high reliability even in rough operating environments, a low specialised skills and knowledge requirement for operation and maintenance of the system, and short installation, start and loading times (ARE, 12; ESMAP 2000, 18).

However, several disadvantages of diesel mini-grids must also be taken into consideration. Although diesel gensets are generally promptly obtainable, the same must not be true for the fuel required to run the generator. It is often uncertain whether the availability of fuel can be guaranteed throughout the year in light of the political situation of a country and the accessibility conditions prevailing in rural areas during all seasons of the year (e.g. during the rainy season). Also, regarding the cost structure of diesel powered systems, initial capital investments advantages over RETs are often offset by significantly higher running costs resulting from high operation and maintenance (O&M) as well as fuel costs. In this regard, the volatility of crude oil and diesel fuel prices play an important role as unforeseen price increases might diminish fuel supply and increase costs significantly. Another matter of concern are local environmental impacts stemming from pollution commonly associated with internal combustion engines such as noise, exhaust emissions and the disposal of spent fuel. These are often not adequately addressed in remote settings of developing countries, resulting in negative effects on the local population, flora and fauna (ARE, 12; ESMAP 2000, 18).

Renewable Energy and Solar PV Mini-grids

Renewable energy powered mini-grids, including Solar PV systems, present an alternative electrification option to diesel mini-grids and have become increasingly important in establishing and expanding electricity access around the globe. Not only have costs of RETs decreased significantly in recent years, but technological improvements have also increased their efficiency and reliability. Hence, over the past decade, the number of renewable mini-grids as well as the number of people being connected to these grids have grown steadily with at least 9 million people being connected to a RE mini-grid in 2016. Whilst small-hydro mini-grids continue to connect the largest amount of end-users, the most rapid growth in deployment was experienced by solar PV, from 11 MW of capacity in 2008 to 308 MW connecting 2.1 million people in 2017 (IRENA 2018, 5-6). Solar energy has the advantage of being more evenly distributed around world than any other renewable power source. Moreover, the amount of solar energy, namely the insolation, in a specific location is known with a greater certainty than that of, for example, wind, making predictions about energy yields from PV solar systems more accurate (ESMAP 2000, 22).

RE power systems generally have very low O&M costs and the fact that they are additionally linked to practically no generating costs can result in a cost advantage over diesel based systems. Moreover, due to usually replacing the use of diesel or HFO, they have high environmental and social benefits by decreasing greenhouse gas emissions and providing a healthier environment for the local population. Despite the high daily and seasonal variability in renewable energy sources, energy production can usually be predicted with good accuracy. Yet, the coupling of the system with battery energy storage is indispensable to secure supply of electricity during times when no renewable source is available (ARE,12-13).

However, RE mini-grids also have certain disadvantages. Whilst diesel power generating systems have very low initial investment costs, the opposite is the case for RE power systems. Also, in order to avoid blackouts and to provide a reliable source of energy, RE systems need to be designed with bigger generation capacities than fossil-fuel or hybrid power systems in order to produce an excess of electricity for storage. This can eliminate any cost advantage over diesel fuelled mini-grids or hybrid mini-grids and can lead to higher energy prices (ARE,12-13).

Hybrid Power Systems

Hybrid power systems combine the technologies of the above two types of mini-grid systems and are hence powered by a mix of RE sources and a fossil fuel genset, conventionally supplied by diesel. They emerged in response to the high initial investment costs of pure PV systems and the extensive O&M and fuel costs of purely diesel powered mini-grids, and are usually the most competitive technical electrification solution. For many rural communities, the combination of the two different energy sources has proved to be the least-cost solution due to both technologies complementing each other and increasing their benefits and advantages. For example, one of the main advantages of renewable systems is that they essentially operate fuel free and are therefore not affected by the volatility of prices or supply of fuels. However, these systems are non-dispatchable, meaning that they cannot be used on demand but are instead dependent on the availability of a certain RE source at a specific time. Diesel gensets, on the other hand, are dispatchable and can supply electricity according to market needs. When these two power sources are now combined, fuel supply shortages can be counterbalanced by renewable energy and a lack of RE source can, in turn, be compensated by diesel generated electricity. In this way, the supply of electricity is more flexible and various shifting load profiles can be served. For similar reasons as the above, it is often also advisable to consider the combination of various renewable sources in hybrid mini-grids if more than one RE source is available at a specific location. A resources mix can accommodate seasonal or daily resource fluctuations, such as a lack of water during the dry season or the lack of sunshine during night-time. Energy storage systems in form of batteries can further add stability to such systems (ARE, 12).

Although most existing mini-grids are still being supplied by fossil fuel based gensets rather than being RE or hybrid systems, the significant reduction in price of RE power systems and growing environmental concerns have led to the rising trend of hybridizing existing diesel mini-grids with a RE system, especially with solar PV. The overarching objective of this is "to achieve diesel fuel savings, to reduce on-going operational costs and [to reduce] diesel fuel price exposure" (Power and Water Corporation, 28). By incorporating RE into existing diesel mini-grids, the amount of electricity being produced by diesel generators can be reduced, thus leading to savings in diesel fuel and, in turn, to lower operating and electricity costs. Moreover, the reliability and stability of electric supply can be increased due to lower exposure to fuel price volatility and associated financial risks of diesel fuel generation. Another benefit includes the reduction of greenhouse gas emissions as well as health and environmental benefits for local communities and biodiversity (Power and Water Corporation, 28).

In most hybridization projects, the PV modules are added to supply a part of the electric demand during the daytime, whilst diesel based systems continue to make up the larger fraction of the overall power system. Depending on load characteristics, PV systems without storage capacity may cover around 20% to 30% of the annual electric demand, with the remaining amount being fuelled by diesel. With a certain level of storage capacity, this yield may be increased up to between 50% and 80%. However, previous studies have shown that a PV share over 30% in combination with batteries only becomes a feasible solution in highly remote areas with very high diesel prices, while the combination of one third PV and two thirds diesel generation resulted in optimized LCOE for most of the cases (Cader et al. 2016, 20).

2.3 Diesel Based Electricity Generation

2.3.1 Diesel Generator Definition and Working Principle

A diesel based electricity generator, also referred to as a diesel generator set or diesel genset, couples a conventional diesel engine with an electric generator, often an alternator, to produce electricity. It utilizes the mechanical rotary power of the engine to create a varying magnetic field in the generator which produces a current and hence creates electric energy output. Thus, it initially converts fuel energy into mechanical energy by means of the engine and subsequently the mechanical energy into electric energy via the generator.

2.3.2 Technical Details

Diesel gensets exist in a large range of sizes specified by the electrical load and typically range from 20kW to 2000kW real power, or alternatively 25kVA to 2500kVA apparent power (real power plus reactive power). The ratio between real power given in kilowatts (kW) and apparent power given in kilovolt-ampere (kVA) is defined as the power factor of a generator and is typically assumed to be 0.8, unless specifically known (Diesel Service and Supply, n.d.).

The fuel consumption of a diesel generator set depends on various factors, such as the efficiency of the genset, and increases with size and the load at which it is operating. The load factor of an engine is the ratio of current output of the generator to its rated capacity. In order to avoid damage of a genset and to ensure optimal life and generation, it is recommended to run generators at at least 50% of maximum load or higher, with 30% often being the minimum load unless stated otherwise by manufacturers. The optimal load factor is often said to lie between 60% and 80% of the generator’s prime power rating (Power and Water Corporation, 26). The efficiency of a diesel generator can generally be defined as the power still available for work at the generator output, given as a percentage of total power supplied to the generator in form of fuel. It is thus the percentage of total power that is not lost as heat. Although increasing with load, the efficiency of diesel power generation is generally low with peak efficiencies ranging from 35% to 40%.

The lifetime of a generator is usually specified in hours rather than in years, unlike that of most energy or RE components. This is due to it largely being dependent on the hours of operation instead of the age of the genset. For diesel generators in the size range of

7 to 10,000 kW estimations lie between 20,000 to 80,000 hours. However, it is difficult give a precise estimate of the lifetime as it depends on factors such as fuel quality, maintenance frequency and operating conditions (HOMER Energy, n.d.).

2.4 Solar Energy and Photovoltaic Technology

Solar Photovoltaic (PV) describes a technology that generates electricity by directly converting sunlight, or more precisely solar radiation, into a flow of electrons via the use of PV cells. It is one of the four main solar-power technologies and is the third most important renewable energy source in terms of globally installed capacity, after hydro and wind power. With solar being the planet's most evenly distributed as well as the most abundant renewable energy source, having a potential high enough to cover all global primary energy demand, solar PV technology plays a key role in transforming global generation and in moving away from fossil fuels.

Photovoltaics have their origins in the discovery of the photovoltaic effect, also known as the Becquerel effect, in 1839 by French physicist Alexandre Edmond Becquerel. In an experiment involving a solid electrode in a conductive solution, he observed the creation of electric potential and electric current in certain materials upon their exposure to light. The first solar generator, based on selenium and gold and with an efficiency of 1%, followed 45 years later, in 1883, and was developed by the New Yorker inventor Charles Fritts (Wesselak et al. 2017, 195).

The theoretical basis of today's modern photovoltaic systems was laid in the middle of the 20th century with the concept of p-n junctions and first conventional photovoltaic cells, with efficiencies of 6% to 7%, started being produced in the late 1950s. Whilst research and development during the following decades was mainly concerned with the improvement of efficiency levels of photovoltaic cells, the focus shifted in the 1990s towards material and cost savings with the result of prices of PV modules having dropped by 99% percent over the last four decades (Chandler 2018).

2.4.1 The Working Principle of Photovoltaic Cells

Photovoltaic cells convert solar energy directly into electricity using the photovoltaic effect in semiconductor materials. When sunlight strikes a solar cell, the materials of the cell absorb part of the incident light. This causes electrons to be released and creates the flow of an electrical charge through the material.

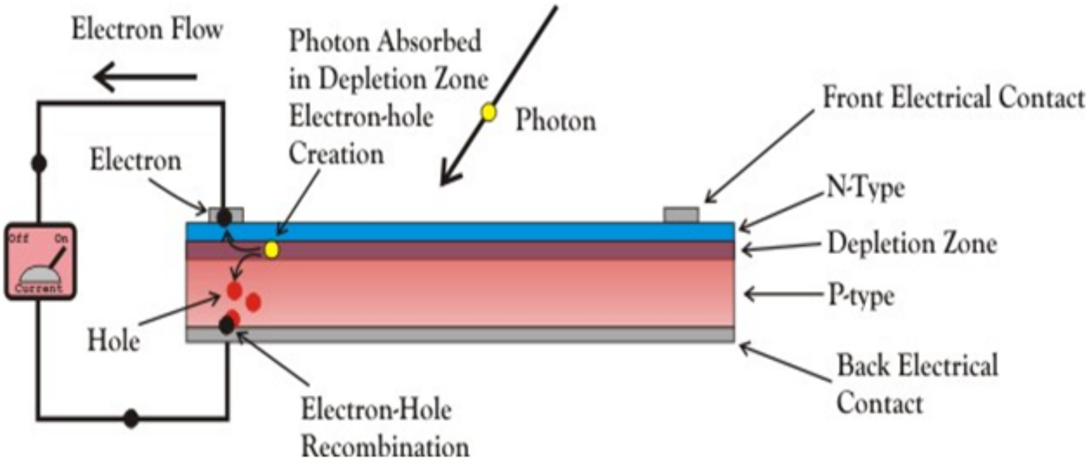

Figure 3. Working principle of a solar cell (Electrical4U 2018)

PV cells consist of two layers of semiconductors - a thin layer of negative or n-type semiconductor on top and a thick layer of positive or p-type semiconductor at the bottom. P- and n-type semiconductors are the result of doping a conventional semiconductor, often crystalline silicon, with a material that either creates an excess of free movable electrons (n-type region) or with elements that create deficiencies of valence electrons and hence leave electron holes (p-type region). When joined together, these two types of semiconductors form a p-n junction and electrons migrate from the n-side to the p-side, creating a depletion region between them with no free electrons and holes. As a result of this electron migration, the n-side boundary becomes slightly positively charged and the p-side becomes negatively charged, forming an electric field (Konstantin 2017, 217).

When sunlight now strikes the surface of the PV cell, it passes through the n-region of the solar cell and penetrates the depletion zone. There, the energy contained in the light in form of photons is transferred onto the electrons of the atoms and causes them to break free. As a result, electron-hole pairs are formed (Schabbach and Leibbrandt 2014, 23).
The slightly positive charge of the n-type layer now attracts the electrons and drives them out of the depletion region into the layer. Similarly, the positive charge of the p-side attracts the holes. Therefore, electron concentrations in the n-region and hole concentrations in the p-region increase and cause a potential difference between the two layers. Connecting the two layers through an outside circuit will now lead to the excess electrons in the top layer moving towards the bottom layer with excess holes, where the two reconnect. In this way, a direct current is produced and electricity is generated

(Electrical4U, 2018). This electricity can then either be used directly to power an electrical device or it can be exported to the grid as an alternating current after passing through an interposed DC/AC inverter.

There exist several types of solar cells which are generally grouped into crystalline silicon PV cells and thin film solar cells. Silicon crystalline cells, named after the semiconducting material they are made out of, form the first generation of cells, also referred to as conventional cells. These cells are the commercially predominant type of cell with silicon being one of the most-studied photoactive materials yielding some of the highest performances. Thin film solar cells build the second cell generation. These cells are characterized by containing only a very thin layer of active material, in the range of tens of micrometers. The semiconductor materials in these types of cells are very efficient in absorbing energy contained in sunlight and hence already create efficient devices with thin films (Konstantin 2017, 218-219).

2.4.2 From Solar Cell to PV System

The electrical power output produced by a single solar cell usually lies between 2 watt (W) to 7 W at a voltage of 0.5 volt (V), which is too low for its use in technical applications. Several solar cells are therefore connected and packaged to form a photovoltaic module. They are usually connected in series to achieve output voltages high enough for the use in PV system operation. In a series circuit the total voltage equals the sum of the individual voltages of each solar cell whilst the current flowing through each cell remains the same. In a parallel circuit the opposite is the case; the voltage remains constant whilst the current intensity of the connected cells is cumulative. The interconnected cells are then sealed in a protective laminate, framed with aluminium or stainless steel and covered with a glass front (Konstantin 2017, 220).

Several modules can be interconnected to form a string, and several strings are connected to form arrays of PV modules. Whether the connections in each of the steps are in series or in parallel depends on the output voltage and current required for a particular project and PV system. The same applies for the size of the array. Arrays can consist of any number of modules depending on the power required from the PV system, and their size is theoretically only limited by the amount of space available at a project site (Häberlin 2012, 149-152).

Arrays, in the end, form the core of each photovoltaic system. The PV system describes the entire power system that converts solar energy into usable electricity by means of photovoltaics, with all its components. Depending on the type of system, it consists of several parts, the most important of which are the arrays of PV modules. Other components can include power control systems, such as inverters or system balance instruments, power storage in form of batteries, cabling and other electrical parts required for the working of a system in a particular application (ESMAP 2007, 10).

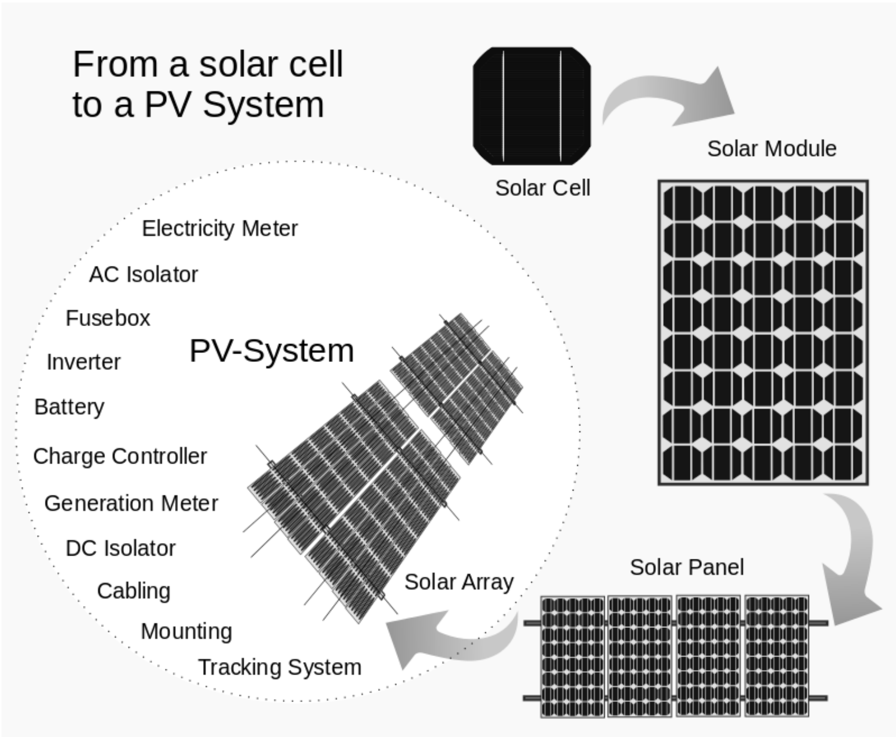

Figure 4. From Solar Cell to PV System (Rfassbind 2014)

2.4.3 Power and Energy Output of PV modules

When evaluating the power of photovoltaic panels, it is important to differentiate between their rated power output (RPO) of PV modules and their actual power output. The rated electrical power output of a PV module, also referred to as peak power, is given in watt peak (W_p) or kilowatt peak (kW_p) and is determined by the producer of the panel. It describes the power output achieved by a module under standard testing conditions (STC) and is hence a theoretical maximum power output. The standard test conditions are an industry-wide standard specifying a solar irradiance of 1000 W/m^2 with an air mass of 1.5 and a cell temperature of 25ºC, and are comparable to conditions prevailing on a clear day. The rated power output of an array of PV modules is simply calculated

by adding the rated outputs of all modules in the array and will give its installed capacity (Konstantin 2017, 224).
In practice, however, the actual average power output of a PV panel lies below the rated one, as it is dependent on the actual solar irradiance at a project site and a variety of other factors. Whilst the RPO will provide an approximation of the power of the system and can help in estimating the number of PV modules needed for a project, it is important to use a more accurate measure of average output when successfully designing a PV system, especially when tailoring a project to a specific load.

One such measure is given by the potential annual energy output, E_p, in kWh which is estimated the following way:

$$E_p = A * \eta * PR * H \qquad (1)$$

E_p … Energy output (in kWh)
A … Total panel area (in m^2)
η … Conversion rate of panel or efficiency (in %)
PR … Performance ratio
H … Annual average solar irradiation (in kWh/m^2)

The *conversion rate* or *efficiency of a solar panel, η,* is defined as the ratio of useful electrical energy output of a panel to incoming solar radiation under STC and hence measures the portion of energy of sunlight that is converted into electricity by the PV panel. It ranges from approximately 7% up to 23%, depending on the cell material of the panel and is usually given by the manufacturer. The efficiency has an influence on the area requirement of a PV panel – the higher the efficiency, the lower the area required (Konstantin 2017, 219). As an example, if 100% solar panel efficiency was assumed, 1 m^2 panel area would produce 1 kW at STC; with an efficiency of 20%, the same area would only produce 200 W at STC. Hence, in the latter case, five times the amount of space would be required to achieve the same power output as in the first case. This link between efficiency, area and installed capacity can be used to estimate the solar panel area requirement for a PV system or the power that can be installed on a certain area of land. The nominal peak solar generator power at STC is simply the area of the generator field multiplied by the module efficiency (Häberlin 2012, 17). Is the exact conversion rate unknown at the beginning of a project, it is usually assumed to lie around 10%, meaning that 1 kW_p requires an area of 10 m^2.

The *performance ratio, PR,* is an indicator for the performance of a plant defined as the actual output of the system, the final yield divided by the reference yield, that is the theoretically possible energy output of an ideally installed, power-loss free PV installation (Häberlin 2012, 488-490). In formula 1, it hence represents a coefficient accounting for all the losses in the PV system, such as those resulting from varying irradiation intensities and incident angles, losses due to shading, inverter losses, cable losses, and temperature losses, among others. The PR is independent of location and usually ranges from around 0.7 to 0.85 for stand-alone PV systems, with often 0.8 being chosen as the default value (Konstantin 2017, 224).

The *annual average solar irradiation, H,* gives the sum of global annual radiation incident on the solar panel at a specific location in kWh per square meter. It varies greatly around the world ranging from 400 kWh/m^2 in regions close to the Arctic up to 2200 kWh/m^2 in regions close to the equator in Africa and the Orient as well as the Australian dessert. Apart from geographical variations, irradiation and hence energy yield from solar panels also differs considerably with seasons and time of day. Irradiance on a solar generator can be influenced and increased by tilting the generator towards the sun and orienting it such that it captures most of the sun. In order to size a PV system, it is generally sufficient to use site-specific data on the irradiation on the horizontal plane, namely the Global Horizontal Irradiation (GHI), which can nowadays be obtained from a majority of data sets available online.

An alternative way of estimating the potential annual energy output, E_p, of a PV system is via the specific annual energy yield, Y_a, of a system and its installed peak capacity at STC, P_{STC} (Häberlin 2012, 15).

$$E_p = Y_a * P_{STC} \qquad (2)$$

The *specific annual energy yield, Y_a,* gives the yearly energy production per peak installed generator power and is defined in kWh per kW_p. As with the annual average solar irradiation, there exist estimations of this parameter in global data sets. Alternatively, regional recommended values can be used or reference values can be drawn from already existing plants in the region.

2.4.4 The Solar Energy Resource in Cambodia and on Koh Rong Island

Cambodia benefits from a high degree of solar irradiation with annual GHI ranging from 1450 to over 1950 kWh/m^2. It is estimated that 65% of the country benefits from GHI levels of 1800 kWh/m^2 or more, making it a country with an enormous solar resource and potential for solar energy. With regards to the country's suitability for PV development, about 75% of the country's land area, corresponding to 134,500 km^2, have been identified to meet the slope and elevation requirements and could hence theoretically be equipped with PV technology (Asian Development Bank [ADB] 2015, 15).

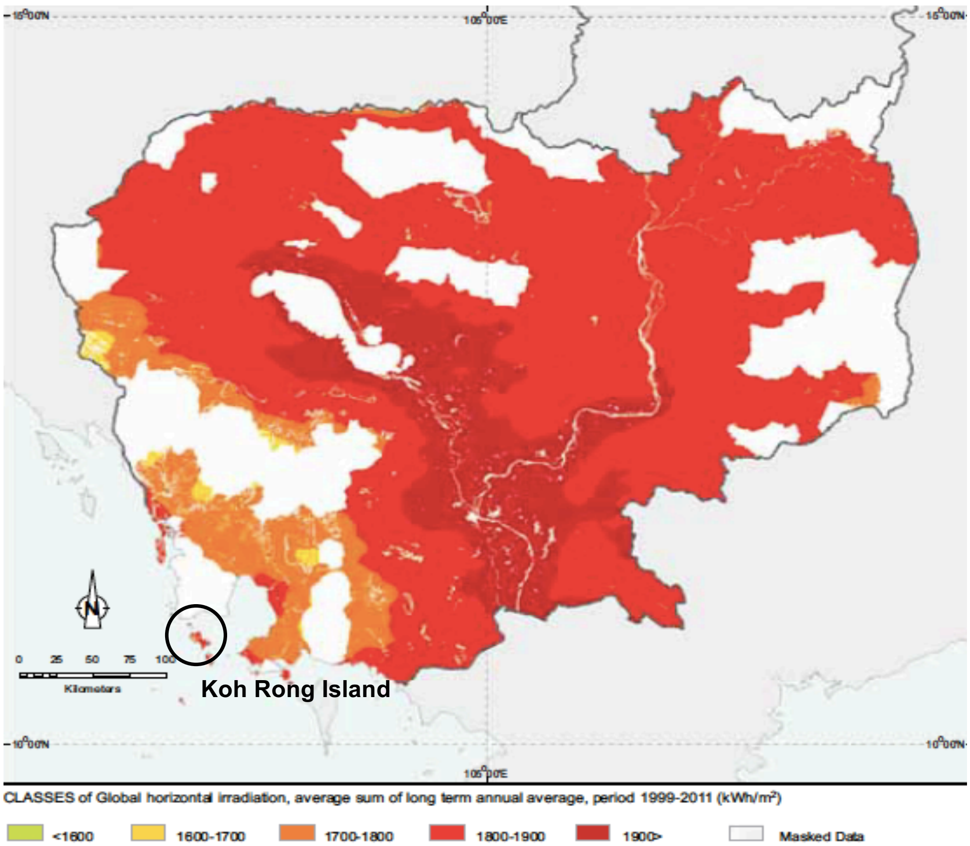

Figure 5. Global horizontal irradiation map Cambodia (ADB 2015, 16)

Koh Rong island is situated in the South West of Cambodia about 25km off the coast of Sihanoukville in the Gulf of Thailand and is the country's second largest island. It has an area of approximately 78km^2 and an estimated population of 1100 inhabitants (WorldAtlas, n.d.). Koh Rong benefits from a high degree of solar irraditation, similarly to large other parts of the country. According to data obtained from the Photovoltaic Geographical Information System (PVGIS) of the European Commission Joint Research Centre (European Commission n.d.), Koh Rong island has an annual GHI of 1850 kWh/m^2 and a specific annual energy yield of 1390 kWh/kW$_p$. Based on this data, the annual energy output of a PV installation on Koh Rong island will be estimated in part II and III of this thesis, building the basis of the case study calculations that will follow. The detailed PVGIS report on Koh Rong is attached in Annex 1.

2.5 Levelized Cost of Electricity

The economic model applied for determining the effects of the hybridization of existing diesel mini-grids with a PV system on the generation cost of electricity on the island of Koh Rong, is based on the measure of levelized cost of electricity (LCOE). The LCOE is used for the comparison of different electricity generation technologies and is defined as a unit cost of electricity, usually per kWh. It is calculated by dividing the total life-cycle cost of building and operating an energy system by the total life-cycle energy production and determines the minimum unit price of electricity that must be charged in order for the project to break even. The life-cycle of an energy system can generally be defined as the expected economic life-time of those components bearing the largest share of capital investment.

$$LCOE = \frac{Total\ Life - Cycle\ Cost\ [in\ currency]}{Total\ life - cycle\ energy\ production\ [in\ kWh]} \qquad (3)$$

In this manner, the LCOE generated will be determined in the quantitative part II and III of the thesis for two separate cases. First for a public utility company representing the no-tax case and secondly for a profit oriented independent power producer (IPP).

2.5.1 Present Value Calculation and Discount Rates

Present value analysis is used to evaluate today's worth of a future transaction in order to take changing currency valuations into account. The present value (PrV) is hence a measure of the present-day value of costs or revenues incurred in the future as a result of future money being worth less than money received in the present. It is calculated by discounting a cash flow occurring n years in the future, CF_n, back to the present by multiplying it with a present value discount factor, DF_n, with discount rate, r (Formula 4).

$$PrV = CF_n * DF_n = \frac{CF_n}{(1+r)^n} \quad ,where \quad DF_n = \frac{1}{(1+r)^n} \qquad (4)$$

In the same manner, the present value of a series of cash flows from now until some point in the future can be calculated, by summing up the present values of each future year's cash flow (Formula 5).

$$PrV = \sum_{n=1}^{N} \frac{CF_n}{(1+r)^n} \quad (5)$$

For an annuity, that is for a series of equally sized future cash flows, CF, occurring at equal intervals for N years, the PrV is calculated as follows:

$$PrV = CF * \frac{[(1+r)^N - 1]}{[r\,(1+r)^N]} \quad (6)$$

The PrV analysis can be performed using either nominal currency values, also referred to as current values, or constant values, as long as the choice of cash flow value is consistent with the discount rate used. Whilst nominal values are not adjusted for inflation and include its effect, constant or real values exclude inflationary effects and thus enable a comparison of quantities as if inflation had not changed prices over time. The same applies to nominal and real discount rates; nominal discount rates include inflation whereas real discount rates exclude inflation. Thus, when nominal cash flows are used, nominal discount rates have to be applied, whereas constant dollar analyses require the use of real discount rates (Short, Packey, and Holt 1995, 6).

2.5.2 Total Life-Cycle Cost

The total life-cycle cost (TLCC) is the total of all costs incurred through owning an asset over the asset's expected life span and hence represents the PrV of all costs involved in a project. It is calculated by taking into account all significant costs over the asset's expected economic life-time and discounting them via present value analysis to a base year. When considering costs related to renewable energy projects, they generally consist of the initial investment or capital expenditure (CapEx), operation and maintenance costs excluding the cost of fuel (O&M), and fuel costs, F. Depending on whether an investment is made by a tax-paying for-profit organisation, or by a tax-exempted entity, such as governments or non-profit organisations, taxes must be included into TLCC calculations or not.

In the no-tax ownership case, the TLCC is given as

$$TLCC = CapEx + \sum_{n=0}^{N} \frac{O\&M_n}{(1+r)^n} + \sum_{n=0}^{N} \frac{F_n}{(1+r)^n}$$
$$= CapEx + PVOM + PVF \qquad (7)$$

$O\&M_n$ … operation and maintenance costs n years from base year

F_n … fuel costs n years from base year

In the case of a for-profit investor, the TLCC represent the before-tax revenue required in order for the business to cover all after-tax costs as well as its cost of capital.

$$TLCC = \frac{CapEx + (1 - Tx)[PVOM + PVF] - (Tx * PVDEP)}{(1 - Tx)} \qquad (8)$$

Where PVOM and PVF is as above, Tx is the tax rate paid by the IPP, DEP is the depreciation of the asset and PVDEP is the present value of accumulated depreciation defined by

$$PVDEP = \sum_{n=0}^{N} \frac{DEP_n}{(1+r)^n} \qquad (9)$$

As with PrV analysis, it is important to apply the correct discount rate, r, in the above TLCC calculations, which has to be in accordance with the form in which the cash flow values are given (Short, Packey, and Holt 1995, 42-45).

2.5.3 Real LCOE

The LCOE calculations in this work will be carried out in real terms, that is, real discount rates and real cash flow values are applied, which implies that inflationary effects are not included. Whilst both nominal LCOE and real LCOE are acceptable measures, the choice of which one is used is often linked to the type of organisation or business undertaking the calculations. Real LCOE tend to be used by governments and policy makers, whereas project owners and developers normally opt for nominal LCOE owing to inflationary corrections in O&M costs and fuel costs yielding a higher level of financial detail. However, for long-term analyses, it is often preferred to use real LCOE due to the inclusion of predictions of inflation trends introducing a high level of uncertainty to the model.

As mentioned above, the LCOE can be interpreted as the PrV of the cost of producing one unit of electricity. It calculated in the following way:

$$LCOE = \frac{TLCC}{\sum_{n=1}^{N} \frac{E_n * (1 - Lf)^n}{(1 + r)^n}} \qquad (10)$$

E_n … Energy produced in year n (excluding loss factor)
Lf … Annual loss factor (rate of system efficiency degradation)
N … economic life-time of generation system

The denominator in the above formula represents the discounted value of the annual energy production over the project life-time, N. Depending on which ownership structure is considered, the TLCC in formula 10 will represent the no-tax case or the before-tax revenue required as discussed in section 2.5.2 (Short, Packey, and Holt 1995, 48).

3 PART II: Case Study – Koh Rong, Cambodia

In the following chapter, the basis for calculating the impact of hybridizing an existing diesel mini-grid with PV technology on the generation cost of electricity will be laid. To this end, this part discusses the input variables required for the calculation of the LCOE of the existing diesel mini-grids at the study site Koh Rong island, and for the LCOE calculations of a hybridized system. It also presents the base-case scenario chosen for the initial comparison of pure diesel LCOE and hybrid LCOE. Due to Cambodia's large dependence on IPPs in domestic electricity generation (see section 2.1.2), two separate ownership structures will be considered for both LCOE scenarios:

- The first case is referred to as the no-tax case and assumes that the tax exempted public utility, EDC, is realising the hybridization project with all capital allocation from the public sector.

- In the second scenario, an IPP or a private investor are assumed to build and operate the power plant with certain return expectations. This case hence represents a profit-oriented and tax-paying ownership structure and is therefore referred to as the for-profit case.

The focus on solar PV as hybridizing technology stems from the fact that solar energy has been identified as having the largest potential on Koh Rong island compared to other renewable energy sources, such as wind energy or biomass. Cambodia generally suffers from low wind resources in most parts of the country. Although mean wind speeds are higher in southern regions around Koh Rong island, the resource availability in terms of relative abundance of solar radiation compared to wind result in the former being favoured. Moreover, while reliable data on solar irradiance at the project site is readily available, the same is not the case for long term wind resource measurements or biomass availability. However, there is no general advantage of PV as hybridizing technology compared to other RE technologies and, though not in the scope of this thesis, the hybridization with other RE sources should generally always be considered as alternatives to PV.

Please note:

- *It was assumed that all existing generators are replaced with a new set of generators with the same generation capacity in year 0 of the project period. This is done to ensure comparability between the diesel and hybrid system configurations.*
- *All calculations are based on 2019 U.S. Dollars and carried out in real terms, that is, inflationary effects are not included.*

Calculations of this chapter are attached in Annex 2.

3.1 Site Study

The LCOE estimations in this chapter will be based on existing conditions on Koh Rong island, and in particular, on a renewable energy project currently being developed in the area of Long Set Beach, also referred to as 4K Beach, in the southern part of the island. There, a local land owner is in the process of developing his plot of land and has decided to reserve approximately 2.5 hectares (ha) of land for the installation of a PV system, operated and maintained by an external party. The PV park is aimed to supply electricity to some of the existing holiday resorts along Long Set Beach which are, at the moment, all powered by electricity stemming from diesel generators.

In the scope of this thesis, it will thus be assessed which impact the above mentioned planned hybridization of electricity source will have on the cost of electricity for the customers along Long Set Beach. To this end, it is assumed that the number of customers of the hybridization project is limited to six holiday resorts. Due to no data existing regarding the exact energy demand of these resorts, it is assumed that the energy demand is the same for all six resorts with the daily load patterns, elaborated on below, being constant throughout the year, that is, seasonal variability has not been taken into account.

The energy demand of a resort is dependent on several factors, some of which include the number of rooms available, whether these rooms are air conditioned or not, other appliances available in the rooms, the facilities the resorts provides, such as a restaurant, a shop, and many more. The following schematic daily average load profile represents a rather luxurious resort and is based on estimates received on the island of Koh Rong:

Table 1. Daily average electricity demand of single holiday resort

Time of day	*Load (kW)*	*Average daily demand (kWh)*
00:00 – 07:00 (night-time demand)	100	700
07:00 – 18:00 (day-time demand)	160	1,760
18:00 – 24:00 (peak demand)	250	1,500

Load variations during the different daily periods stem from increased use of cooling systems, shower facilities and the kitchen during the evening hours - when resort guests return to their rooms after a day at the beach - and a low use of facilities during the night.

3.2 General Assumptions

While the cost assumptions regarding CapEx, operation and maintenance costs, and fuel costs will be different in the diesel mini-grid case and in the hybrid mini-grid system, which will be discussed separately in section 3.3 and 3.4, there are general project assumptions which apply to both system configurations. These are discussed below.

3.2.1 Project and System Lifetimes

In order to effectively compare the LCOE of both power generating systems, the project lifetimes of both the diesel mini-grid as well as the hybrid mini-grid system have been set to 25 years, which are based on the useful life of a PV system. While this time period represents the lifetime of a PV system (Schabbach and Leibbrandt 2014, 13), the life span of a diesel generator lies far below that. As mentioned in section 2.3.2, the lifetime of a generator is difficult to estimate and can range from two up to nine years at constant operation, depending on the size of the generator and a number of other factors. In this work, the life span of a diesel generator is assumed to be 7 years in the case of the pure diesel system, and 10 years in the hybrid case. Reinvestment in new diesel generators will therefore be required in several project years to extend the diesel system's lifetime to 25 years. The reason for the longer life span in the hybrid configuration is to reflect the fact that due to the PV system generating electricity during the day, some generators can be switched off during that time. This leads to fewer daily hours of operation and extends the generator's lifetime in years.

3.2.2 Discount Rates and Real Cost Escalation

At the most basic level, the discount rate is the rate at which future cash flows are discounted in order to determine their present value. It greatly influences the outcome of economic evaluations and is hence often considered the most important factor in life-cycle cost analyses. The discount rate represents the opportunity cost of capital, that is, the rate of return forgone by investing the money in one asset rather than committing it to an alternative investment with equal risk. The rate chosen by an investor is largely dependent on the characteristics of a project, and particularly on the risk involved in the investment undertaken. It must be at least as high as the rate of return that could be achieved by a risk-free investment, such as by putting the money into a bank account, and is hence composed of the risk-free rate as well as the required rate of return of a project. The higher the risk of an investment, the higher the demand of return will be and in turn, the discount rate.

In this work, two different discount rates will be used for the no-tax public utility case and the for-profit IPP investment case. While for the former a 'social' discount rate will be applied, reflecting pure time preference return expectations of a public utility and thus a social perspective, the latter discount rate is chosen to reflect the return and risk expectations of a private sector investor (Steinbach and Staniaszek 2015, 1).
Discount rates in the energy sector are often based on a utility's Weighted Average Cost of Capital (WACC). However, this work will assume that the capital structure in both ownership scenarios consists of 100% common equity and no debt or other capital distributions. The discount rate chosen can hence be interpreted as the desired rate of return on common equity. On the basis of the Sustainable Rural Electrification Plans (SREP) for Cambodia undertaken by IED Innovation Energy Development (n.d., 73), the real social discount rate is set at 6%. In the case of the IPP, a discount rate of 13% will be used which is representative of market conditions in the private sector, albeit being quite a conservative estimate given the risk related to RE projects.

Although the calculations in this Master thesis are undertaken in real terms and hence exclude inflation, an annual real cost escalation rate of 1% will be applied to the O&M cost components discussed below, to reflects cost increases above general inflation.

3.2.3 Tax Rate and Depreciation

As discussed in section 2.5.2, the TLCC calculations used in the levelized cost of electricity analysis must be adjusted for income tax when the investment is made by a tax-paying for-profit organisation. In this case, the TLCC represent the before-tax revenue required by a company to cover all after-tax costs. In Cambodia, the standard corporate income tax rate for companies with an annual turnover above USD 175,000 is 20% (Pricewaterhouse Coopers, n.d.). Thus, a tax rate of 20% will be applied to the for-profit case in both the diesel mini-grid as well as the hybrid mini-grid LCOE calculations.

In addition to tax rate, the TLCC calculations in the for-profit also include the present value of depreciation. Depreciation is a convention in accounting that allows a company to recover the cost of an asset through income tax deductions by writing off its value over time. It is done by allocating the cost of the property against net income over its useful lifetime, rather than writing off the entire cost in year one. Country specific rules govern which depreciation tax deductions are allowed to be included in a company's balance sheet.
In the case of Cambodia, "if the life of the intangible asset cannot be determined, a tax depreciation rate of 10% based on the straight line method is used" (KPMG 2017, 22). Hence in the following LCOE calculations, a depreciation rate of 10% will be applied to the depreciable asset costs, resulting in a depreciation period of 10 years according to the straight line method. It is assumed that the resale value of the mini-grids at the end of their useful economic life, that is, their salvage value, will be equal to zero. As a result, the depreciable asset costs will equal the initial investment costs or capital expenditure, CapEx.

3.2.4 Diesel Price Assumptions

For the calculation of the annual fuel costs for both mini-grid cases, diesel price developments for Koh Rong island are based on the real diesel fuel price forecasts of the U.S. Energy Information Administration (EIA) published in the Petroleum and Other Liquids Prices Table of the Annual Energy Outlook 2019 (2019). Of the three separate price scenarios given by the EIA – namely low oil price, reference case, and high oil price – the reference case scenario was chosen for the base case calculations of the LCOEs in this chapter.

3.3 LCOE estimation of Diesel Mini-Grid

It is assumed that in order to cover the peak load demand of the six resorts on Long Set Beach of 1500 kW in the evening hours, as well as the lower electricity demand during the night time and during the day, five 450 kVA prime power rated power generators and one 250 kVA generator are required to supply electricity to the resorts. To arrive at this estimate, a power factor of 0.8 was used to convert the 1500kW real power required into an 1875 kVA apparent power requirement. Moreover, the diesel generators were sized to run at an optimal load factor of approximately 75%, and definitely within the optimal load range outlined in section 2.3.2. With the above specified set of generators, the night time demand can be covered by using only two of the five 450 kVA generators and the smaller generator at an average load of 65%, while the day time demand is met by running three 450 kVA generators and the 250 kVA generator at 75% load. Hence, the total assumed size of the diesel generator set is 2500 kVa or 2000 kW installed capacity. The calculations of the sizing of the diesel mini-grid are attached in Annex 2.

Table 2. Total diesel mini-grid size

Amount of generators	*Size kVA*	*Size kW*
5	450	360
1	250	200
Total diesel grid capacity	**2500**	**2000**

3.3.1 Diesel Capital Expenditures

For the diesel mini-grid, the investment in year zero of the analysis will consist of three cost components. Firstly, all generators will be replaced with a set of new generators with the same generation capacity, resulting in generator set expenditures. According to the SREP for Cambodia (n.d., 72), unit costs of diesel gensets vary between 115 USD and 450 USD per kW installed capacity and will be set at 300 USD/kW. Moreover, a contingency of 5% of the cost of the generator sets will be included in order to ensure the availability of capital reserves in the case of equipment cost overruns (Al-Hammad et al. 2015, 45). Lastly, a non-refundable import tax and VAT of 18% on the sum of generator costs and contingency will be accounted for.

Table 3. CapEx diesel mini-grid

Investment Type	CapEx [USD]
(1) Generator Set	600,000.00
(2) Contingencies (capital reserves for cost overrun), 5%	30,000.00
(3) Import Tax and VAT, non-refundable 18%	113,400.00
CAPEX Diesel	**743,400.00**

3.3.2 Diesel Operation and Maintenance Costs

While initial investment costs are relatively low for diesel powered electricity systems, operation and maintenance costs comprise one of the largest cost components of diesel powered mini-grids, and together with fuel costs, contribute to the often very high running costs of such grids. Several factors must be taken into account when calculating annual O&M costs. These include maintenance and repair costs, costs for insurance purposes as well as costs related to the administration of the system and the servicing of the power system by personnel.

Maintenance and repair costs are the most expensive of these components and are expected to amount to an annual cost of 15% of CapEx. This is due to the fact that regular oil and filter changes are required to ensure the smooth operation of diesel generators. In addition, the gensets must be decarbonized and parts might need replacement. Insurance costs for the system are set to 1% of CapEx per year and the annual administration and servicing costs are expected to lie around 0.8% of the initial investment.

Table 4. Annual diesel mini-grid O&M costs

O&M Costs	Annual rate	Cost escalation
(1) Maintenance	15% of CapEx	1%
(2) Insurance	1% of Capex	1%
(3) Administration, service and personnel	0.8% of Capex	1%
Annual Diesel O&M	**16.8% of Capex**	**1%**

In addition to the above O&M costs, annual land lease costs can also be considered in the calculations. However, the land required for the six diesel generators including storage space for maintenance equipment and fuel reserves lies at around 70m^2. Due to this small land requirement, land lease costs are not accounted for in the diesel LCOE calculations.

3.3.3 Fuel Consumption and Costs

The annual fuel costs of the diesel mini-grid are dependent on the diesel fuel prices on Koh Rong island, as well as on the annual fuel consumption of the generators. While the fuel consumption of the diesel generators is dependent on various factors previously mentioned, it has been assumed that, at 75% load, it lies on average at 75 litres per hour of running time for the 450 kVA generator and at 41 litres per hour for the 250 kVA generator. These estimates are based on information regarding fuel consumption of generators received by resorts on the island of Koh Rong. Hence, the annual fuel consumption and in turn the annual fuel costs are dependent on the total running hours of the generators, which are summarized in table 5.

Table 5. Running hours of diesel generators in pure diesel mini-grid

Day Period	*Hours per day period*	*Amount of 450 kVA generators in use*	*Amount of 250 kVA generators in use*
Night Time	7	2	1
Day Time	11	3	1
Peak Demand	6	5	1
Total daily hours of running time of 450 kVA			77
Total daily hours of running time of 250 kVA			24
Total annual hours of running time 450 kVA			**28,105**
Total annual hours of running time 250 kVA			**8,760**

With the above specifications, the annual fuel consumption of the purely diesel powered mini-grid amounts to 2,410,825 litres (Table 6).

Table 6. Annual fuel consumption diesel mini-grid

Generator Size in kVA	*Fuel consumption (in litres/h)*	*Annual Fuel Consumption (in litres)*
450	73	2,051,665
250	41	359,160
Total Annual Fuel Consumption		**2,410,825**

From the above annual fuel consumption, the diesel fuel cost for each project year is determined according to the specific real diesel price projected by the EIA.

3.3.4 Annual Energy Output

The annual active electric energy production of the diesel generators in kWh is calculated from their installed capacity, the load factor of approximately 75% at which the system is running, and the total annual running time of the generators in hours, as specified in table 5. There is no annual loss factor with regards to diesel gensets and is hence assumed to be zero. This implies that the denominator in the LCOE calculation in formula 10 in the diesel case is reduced to the PrV of the energy produced in year n, E_n, whereby E_n is the same in every year. The annual active electricity produced thus lies at 8,902,350 kWh.

Table 7. Annual energy production of diesel mini-grid

Diesel Generator Size (in kW)	*Load Factor*	*Annual Running Time (in h)*	*Electricity Output (in kWh)*
360	0.75	28105	7,588,350
200	0.75	8760	1,314,000
		Total Annual Electricity Output	**8,902,350**

3.3.5 Base-case scenario for Diesel LCOE calculations

Based on the discussions in section 3.2. and 3.3., the following base-case scenario for the LCOE calculations of the purely diesel powered mini-grid can be established. These assumptions form the basis of the calculations determining the diesel LCOE and will serve as a comparison scenario to the hybrid LCOE base case.

Table 8. LCOE base case assumptions diesel mini-grid

LCOE Input Variable	*Diesel Mini-Grid Base Case*
Project lifetime (in years)	25
Generator lifetime (in years)	7
Installed capacity (in kW)	2000
Load factor	75%

CapEx (in USD)	743,400
Annual O&M Costs (% of CapEx)	16.8%
Annual O&M Cost escalation (in %)	1%
Annual Fuel Consumption (in litres)	2,410,825
Annual Electricity Production (in kWh)	8,902,350
Discount Rate	6% (no-tax case) 13% (for-profit case)
Depreciation	Over 10 years (for-profit case)
Corporate Tax Rate	20% (for-profit case)

3.4 LCOE estimation of Diesel-PV Hybrid System

In the diesel-PV hybrid system case, the electricity generation cost, that is, the LCOE will be a combination of the diesel LCOE and the pure PV system LCOE. More specifically, the hybrid LOCE is the result of adding the diesel and the PV LCOE, both weighted by their respective share of total electricity production. This is due to the fact that in the hybrid system, a large share of the electricity demand will still be covered by purely diesel generated electricity. Hence, the cost of generating electricity stemming from the diesel system is still the pure diesel LCOE, whereas cost for the electricity resulting from the PV system is equal to the pure PV LCOE. Thus, the average electricity generation cost for the hybrid system is a weighted combination of diesel and PV LCOE.

For the following estimations of the diesel-PV hybrid system, it is assumed that around half of the land provided for PV by the land owner on Koh Rong will be covered with PV panels, that is, the total panel area will amount to 1.2 ha or 12,000m^2. Assuming a conversion rate of 10%, which implies that the installation of 1 kW$_p$ requires an area of 10 m^2 (see section 2.4.3), this land area allows the installation of 1,200 kW or 1.2 MW peak installed capacity. This hybrid system will not include a battery storage system and for simplicity it is assumed that all the electricity produced by the PV system will also be used.

Due to the hybrid system not being equipped with a battery storage system and the PV system only generating electricity during the daylight hours on Koh Rong, the night time demand and peak electricity demand of the holiday resorts will still have to be fully covered by diesel generated electricity. Thus, the same amount of diesel generators as in the pure diesel mini-grid case will also be required after hybridizing the energy system. However, the amount of diesel generators running during the day time and thus the overall annual hours of running time will be reduced. This will not only prolong the generator lifetime but will also reduce fuel costs as well as total diesel energy production.

3.4.1 Hybrid Capital Expenditures

Capital expenditures of the Photovoltaic system are more comprehensive than those of the diesel generator set. They include the PV system costs, costs for the installation of the system, costs of the grid cable extension to the PV field, and a contingency for the module costs as well as income tax and VAT expenses.
The PV system costs have been estimated at 900 USD per kW peak installed capacity. This estimate includes not only the cost for the PV modules, but also the costs associated with the Balance of Systems (BoS), that is, the cables required for connection of the PV arrays, the mounting structures, grid connection, costs for inverters and transformers, among others (Vartiainen, Masson and Breyer 2017, 10). For the installation of the PV system, an engineering fee of 7% of the PV system costs are included in the calculations and the grid extension costs are estimated at 10,000 USD per 100 m of medium voltage cable. The area reserved for the installation of the PV modules is located inland, about 1 km from the beach and the grid line. Hence, 1000m of cable will be required for the connection of the PV system to the grid. As in the pure diesel mini-grid case, a contingency of 5% on the above listed costs is included and the calculations account for an import tax and VAT of 18% on the sum of the overall PV system and contingency.

Table 9. CapEx PV system

Investment Type	*CapEx [USD]*
(1) PV System	1,080,000.00
(2) Engineering, 7%	75,600.00
(3) Grid Extension Cable costs	100,000.00
(4) Contingency (Capital reserves for cost overrun), 5%	62,780.00
(6) Import Tax and VAT, non-refundable 18%	237,308.40
CAPEX PV	**1,555,688.40**

The capital expenditures for the diesel gensets remain the same as for the pure diesel case and are listed in table 3.

3.4.2 Hybrid Operation and Maintenance Costs

In contrast to diesel genset or other electricity generation systems, PV generation systems have very low maintenance costs. These merely include the cost for the occasional cleaning of the panels as well as the replacement of the capacitor of the inverter. As a result, maintenance costs have been found to lie in an annual range of 0.5% to 1.5% of capital expenditures, whereby an annual factor of 0.5% is chosen in the base case scenario of the hybrid calculation (Ringbeck and Sutterlueti 2013).

As in the case of the purely diesel powered electricity generation system, insurance costs as well as costs related to the administration and servicing of the system have to be accounted for with 1% and 0.3% of CapEx, respectively.

Whilst omitted in the diesel case, land lease costs have to be taken into account in the diesel-PV hybrid system, due to the large area requirement of the PV modules. According to the land owner on Koh Rong island, the price charged for one hectare of land amounts to 3,000 USD per month. Hence, the annual land lease costs for the PV system are 43,200 USD.

Table 10. Annual PV system O&M costs

O&M Costs	*Annual rate and costs*	*Cost escalation*
(1) Maintenance	0.5% of CapEx	1%
(2) Insurance	1% of Capex	1%
(3) Administration, Service and Personnel	0.3% of Capex	1%
(4) Land Lease Costs	43,200 USD	n/a
Annual PV O&M	**1.8% of Capex** **43,200 USD**	**1%** **n/a**

Operation and maintenance costs of the diesel genset incorporated in the hybrid system remain the same as outlined in section 3.3.2.

3.4.3 Diesel Generator and PV System Energy Output

The annual electricity production of the PV system will be calculated according to formula 2 and with a specific annual energy yield of 1360 kWh/kW_p on Koh Rong island, both described in section 2.4. Following this approach, the PV module with 1200 kW_p installed capacity will generate 1,668,000 kWh of electricity in the initial year of the installation. However, due to the performance of PV systems declining over time, a system degradation factor of 0.5% is taken into account over the 25-year system lifetime (Jordan and Kurtz 2013).

For simplicity, it is assumed that the daily electricity production of the PV system is constant throughout the year and in total amounts to the above mentioned annual yield. Thus, a daily electricity production of 4570 kWh during the day time hours of the initial production year is estimated.

Table 11. Annual PV energy production in hybrid mini-grid (excluding degradation)

Installed PV capacity (in kW_p)	1,200
Annual Energy Yield (in kWh/kW_p)	1,390
Annual Energy Production (in kWh)	**1,668,000**

As the electricity production of the PV panel only occurs during the day time hours and the electricity generated only covers part of the day time electricity demand, the remaining day time demand as well as the night- and peak energy demand will be covered by diesel generated electricity. Under the simplification that the PV electricity production is constant during the day, the remaining electricity demand can be covered by two 450 kVA diesel generators. This is still the case in the 25^{th} project year when the PV system output will have decreased owing to declining system performance. Thus only two generators, rather than the four generators in the pure diesel case, will be required to run during the day. As a result, the annual running hours of both the 450 kVA and the 250 kVA generators will be reduced, which, in turn, lowers annual fuel consumption as well as annual diesel powered electricity production. The same assumptions regarding the fuel consumption of the diesel generators as outlined in section 3.3.3 will be used and applied to the adjusted annual running hours summarized in table 12.

Table 12. Annual diesel energy production in hybrid mini-grid

Diesel Generator size (in kW)	*Load Factor*	*Annual Running time (in h)*	*Electricity Output (in kWh)*
360	0.75	24090	6,504,300
200	0.75	4745	711,750
Total Annual Electricity Output			**7,216,050**

3.4.4 Base-case scenario for Hybrid LCOE calculations

Based on the discussions from section 3.2. and section 3.4., the base-case assumptions applied to the LCOE calculations of the diesel-PV hybrid mini-grid are summarized below in table 13. As for the purely diesel powered system, these assumptions form the basis of the diesel-PV hybrid LCOE, which will subsequently be compared to the base-case diesel LCOE. In the hybrid system, 18% of the total electricity production over the 25-year project lifetime will be generated by the PV system from solar energy. The remaining 82% will continue to be generated by diesel generator sets.

Table 13. LCOE base case assumptions hybrid mini-grid

LCOE Input Variable	*Diesel Genset*	*PV System*
Project lifetime (in years)	25	25
System lifetime (in years)	10	25
Peak installed capacity (in kW)	2000	1200
CapEx (in USD)	743,400.00	1,555,688.40
Annual O&M Costs (% of CapEx)	16.8%	1.8%
Land Lease (in USD)	n/a	43,200.00
Annual O&M Cost escalation (in %)	1%	1%
Annual Fuel Consumption (in litres)	1,953,115	n/a
Annual Electricity Production excluding degradation (in kWh)	7,216,050	1,668,000
System Degradation factor	n/a	0.5%
Discount Rate	6% (no-tax case) 13% (for-profit case)	
Depreciation	Over 10 years (for-profit case)	
Corporate Tax Rate	20% (for-profit case)	

4 PART III: Key Findings and Discussion

4.1 Presentation and Comparison of Results

Following the financial model approach presented in section 2.5. and applying the base-case scenario assumptions for the purely diesel powered electricity system as well as the diesel-PV hybrid system, outlined in table 8 and 13 respectively, the results of the LCOE calculations for both the no-tax case and the for-profit case are summarized in table 14. The detailed LCOE calculations (Microsoft Excel) have been attached in Annex 3.

Table 14. LCOE calculation results

System Type	*LCOE Public Utility [$/kWh]*	*LCOE Private Sector [$/kWh]*
Diesel Generator System	$0.301	$0.315
Diesel-PV Hybrid System	$0.271	$0.295

From the above presented results it can be seen that hybridizing the existing diesel powered electricity system on Koh Rong island will lead to a decrease in LCOE for both ownership scenarios, in the public utility no-tax case as well as in the IPP for-profit case. Thus, the average generation costs of the hybridized system will lie below the current costs for electricity generation. This clearly indicates that the hybridization of diesel powered electricity generation with a photovoltaic system has the potential to lower the costs for electricity on Koh Rong island.

In the case of the public utility owning and operating the electricity generation system, the analysis in this thesis has shown that hybridizing the existing diesel mini-grid reduces the LCOE from 30.1 to 27.1 USDc per kWh at EIA reference case diesel price projections and at a 6% social discount rate. This represents a decrease in electricity generating costs of 9.9%. Whilst the hybridization overall results in higher capital expenditures per kWh produced electricity as well as higher operation and maintenance costs, excluding the cost of fuel, the overall reduction in LCOE stems from savings in fuel costs of 17.9%.

In the alternative private ownership scenario, the hybridization of the existing diesel mini-grid results in a reduction in LCOE from 31.5 USDc per kWh to 29.5 USDc at EIA reference case diesel price projections, implying a cost reduction of 6.3%. As in the public utility ownership case, these cost savings are linked to the overall fuel cost savings of 17.9% in the hybridized system compared to the purely diesel powered generation system. These greatly offset increases in capital expenditures and operation and maintenance costs per kWh resulting from the hybridization.

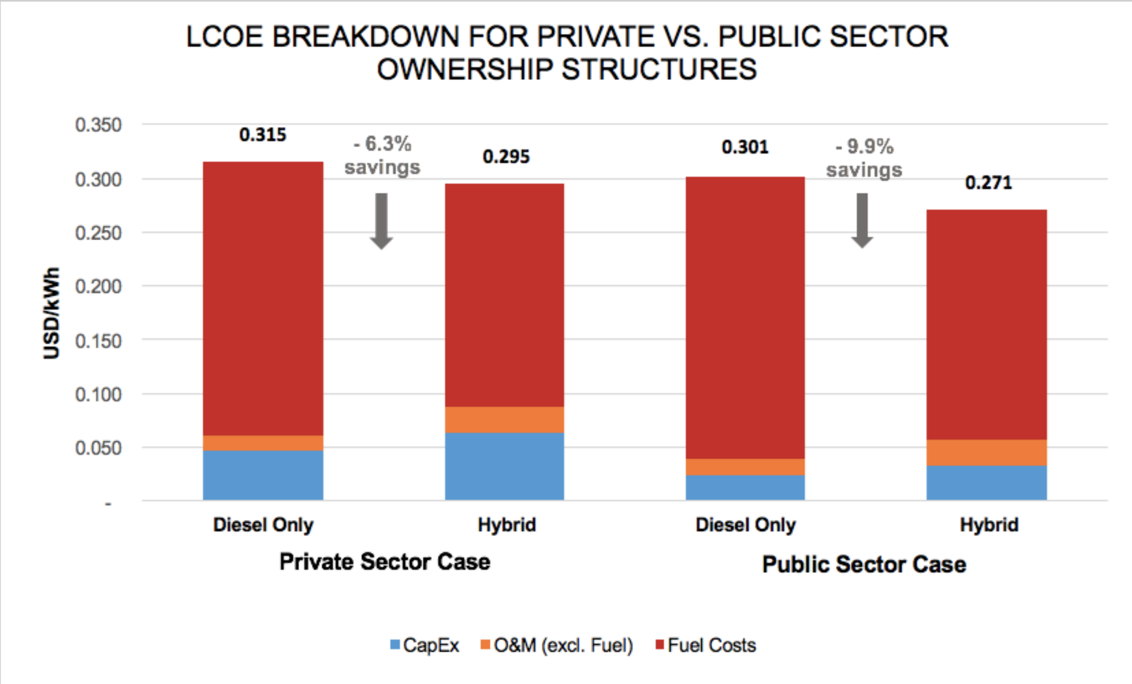

Figure 6. LCOE breakdown for private and public ownership structures

4.1.1 Sensitivity Analysis

In order to determine how variations in the assumptions made in the base-case scenario affect the outcome of the LCOE calculations, a sensitivity analysis with regards to several cost components was carried out. The sensitivity analysis compares the LCOE from the base-case scenario assumptions with the LCOE resulting from alternative fuel price development regimes, changing PV system O&M costs and different diesel generator unit costs. Due to the public sector ownership scenario having the lowest electricity generating costs, this case was chosen to be further analysed in this section.

Impact of Diesel Price Development

The development of diesel fuel prices over the next 25 years represent the most uncertain factor in the LCOE calculations undertaken in this work. Fuel price projections are generally subjected to a high level of uncertainty making them one of the main drivers of economic variability. For this reason, the LCOE of the diesel-only and the hybrid case were re-evaluated for two additional price projections, the low as well as the high oil price scenario of the EIA, with all other assumptions remaining as outlined in the base-case tables (*ceteris paribus*).

The results of the diesel price sensitivity analysis show that in all three EIA diesel price projection scenarios, the increase in diesel prices is sufficiently high enough to justify the hybridization of the diesel electricity generation system on Koh Rong island. Moreover, even in the high diesel price scenario, the generation costs of electricity from the hybrid system still lie below the WTP on the island in the case of public financing. The high diesel price scenario might by some be considered the more accurate one for the project site Koh Rong. This is due to the diesel price charged on the island being influenced by transport costs and profit margins, and generally being higher than the price charged directly at the refinery.

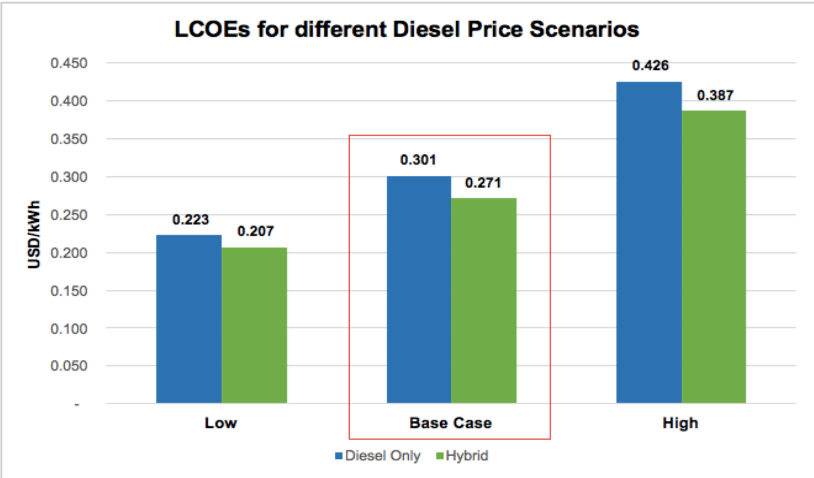

Figure 7. LCOEs from diesel price sensitivity analysis

Influence of PV O&M Costs

The maintenance costs of the PV system have been estimated to lie at an annual rate of 0.5% of capital expenditures. However, research has shown that these costs can lie in an annual range of 0.5% to 1.5% of the initial investment. Thus, the effects of an increase in maintenance costs to 1% and 1.5% have been analysed and compared to the base-case scenario.

The sensitivity analysis shows that the O&M costs, and in particular, the maintenance costs of the PV system, have very little influence on the LCOE of the hybrid generation system. In all three maintenance cost scenarios, that is in the base case scenario, the medium 1% case and the high 1.5% case, the hybrid LCOE continues to be below the pure diesel LCOE and changes only very slightly with variations in PV system O&M costs.

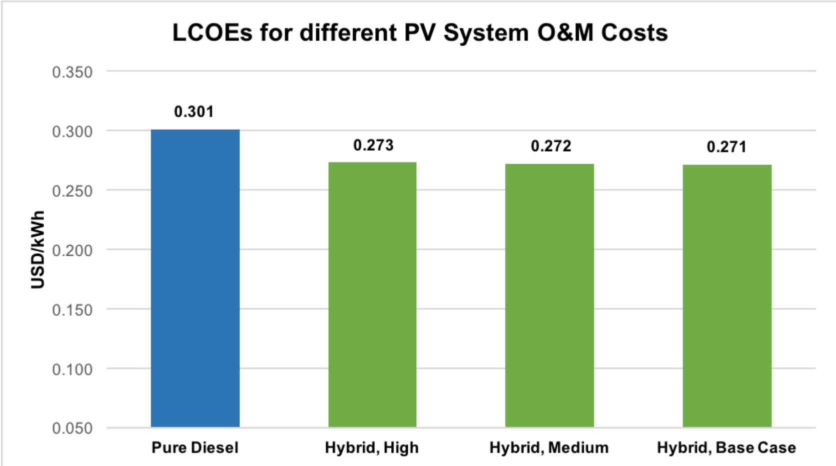

Figure 8. LCOEs from PV system O&M sensitivity analysis

Impact of Variations in Diesel Generator Unit Costs

Variations in the price of diesel generator unit costs may also affect the outcome of the LCOE calculations as they influence not only capital expenditures and replacement costs of the diesel genset, but also O&M costs and so have also been taken into consideration. Whilst the base case scenario assumes a genset cost of 300 USD per kW installed capacity, they may vary between 115 and 450 USD per kW. For this reason, the LCOE of both hybrid and diesel systems were recalculated, assuming unit costs of 150USD/kW in the low case and 450 USD/kW in the high case.

The analysis shows that the cost increases or decreases resulting from the variations in generator unit costs affect the LCOE of the purely diesel generated system and hybrid system almost equally, and do not influence the hierarchy of the electricity generating costs. That is, the hybrid system continues to have lower LCOE in all three generator unit price scenarios as compared to the LCOE of the purely diesel powered system.

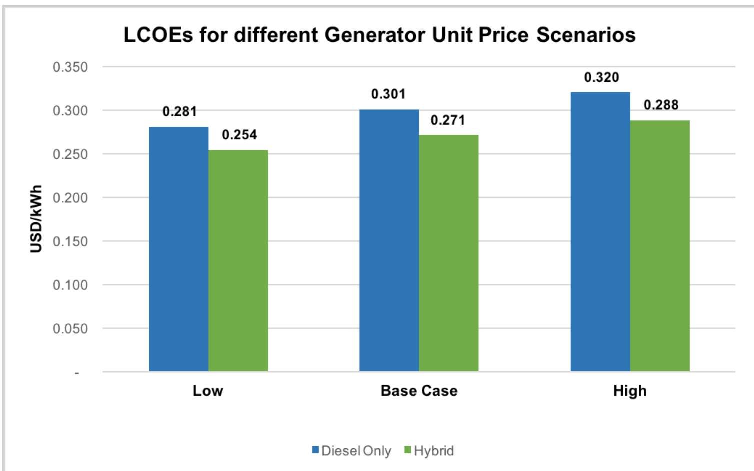

Figure 9. LCOEs from generator unit price sensitivity

4.2 Benefits of the Hybridization of Diesel Mini-Grids on Koh Rong

4.2.1 Diesel-PV Hybrid LCOE and Willingness to Pay on Koh Rong Island

The local affordability of electricity is an important factor to consider in any rural or island electrification or hybridization project, and must be taken as a reference when comparing prices for different electricity generation systems. To this end, it is crucial to determine the project site specific willingness to pay (WTP) for electricity and to compare it to the cost of electricity resulting from different generation systems.
The price for electricity currently charged on Koh Rong island lies at 0.50 $/kWh, based on price levels in February 2019. The project specific WTP for electricity has thus been identified to be equal to this value.

As mentioned above, the average base-case hybrid LCOE estimated for an annual specific solar energy yield of 1390 kWh/kW$_p$ is 0.295 USD/kWh and 0.271 USD/kWh for the IPP and public utility scenario, respectively. Comparing these generation costs to the WTP on Koh Rong island clearly shows that for both ownership structures, the LCOE of the diesel-PV hybrid system is significantly below the WTP for electricity on Koh Rong island. This implies that the willingness to pay for electricity is sufficiently high for the economically sustainable implementation of the hybridization project on the island from a societal perspective. What is more, the realization of such a project could even lead to significant electricity cost savings for local business and electricity customers.

Whilst the LCOE estimated in the for-profit case merely represents the revenue required per kWh by the business in order to cover all after-tax costs of the project and hence does not include any profit considerations, even if a profit margin of 25% was assumed, the resulting price for electricity of 0.369 $/kWh would still lie below the project site specific WTP. This indicates that the societal electricity cost benefit of a hybridization project is not only ensured when realized by the public utility but can also be maintained with private sector financing, albeit at a lower scale. Moreover, it signals that hybridizing the existing diesel mini-grid on Koh Rong might offer an attractive investment opportunity for private sector investors and independent power producers, although this is not analysed in greater detail in this work.

4.2.2 Environmental Benefits

Apart from the above mentioned societal benefits, hybridizing the purely diesel powered electricity generating system on Koh Rong island would also result in large environmental benefits. Covering part of the energy demand with solar powered electricity could lead to annual diesel savings of up to 457,710 litres per year as diesel generators can be switched off during the day time hours. This represents an annual reduction in fuel consumption of 19%. Moreover, assuming CO_2 emissions of 2.67 kg per litre of diesel burnt (Valsecchi et al. 2009, 2), the above fuel savings would translate into CO_2 emission reductions of 1,222,085 kg per year. While this reduction not only contributes to the overarching goal of reducing global greenhouse gas emissions and to tackle climate change, lowering CO_2 emissions on Koh Rong island would also contribute to a healthier environment for both the local population as well as the local biodiversity.

Table 15. Diesel savings and CO_2 emission reductions of hybridization

Total generation capacity (MW; diesel/PV)	*Total energy demand (MWh; year)*	*Avg. daily PV supply (MWh/day)*	*PV share of total production*	*Possible diesel savings (litres/year)*	*Possible CO_2 emission reductions (kg/year)*
3.2 (2.0/1.2)	8,672.4	4.57	18%	457,710	1,222,085

4.3 Limitations of Case Study

Despite its thoroughness, this case study is limited in its scope. One of the limitations of this study stems from a lack of data existing at the project site which resulted in many input variables having to be assumed and estimated based on findings in specialised literature. Especially with regards to the energy demand of the resorts on Long Set beach, a more detailed analysis of the benefits or drawbacks of a hybridization project could be undertaken if the exact energy demand patterns at the project site were known. Moreover, for reasons of simplicity, the calculations were based on the assumption that the capital structure in both project ownership scenarios consists solely of equity with no debt or other assets being deployed to cover the project costs. This scenario is highly unlikely in any public sector or private sector project financing structure and hence does not reflect real life conditions. Lastly, the scope of this thesis was limited to calculating and comparing the average electricity generation costs of a diesel powered mini-grid and a diesel-PV hybrid system without battery storage for two different ownership structures. Including further hybrid configurations or ownership structures in the analysis could have been interesting as well as undertaking a detailed profitability analysis of the hybridization project for the private sector scenarios.

4.4 Non-economic Barriers to RET Implementation in Cambodia

Despite the technological competitiveness of the hybrid power generation system in terms of security of supply and the economic viability of integrating renewable energy technology into the existing diesel mini-grid, and in terms of electricity generation cost savings, a number of political and institutional as well as other non-economic barriers may still inhibit the wider deployment of RETs, including solar PV, in mini-grids across the Kingdom of Cambodia.

4.4.1 Political and Institutional Barriers

One of the key challenges faced by potential energy project developers, both public and private, with regards to RET implementation is, on the one hand, the lack of a RE regulatory framework and, on the other hand, the inexistence of any kind of government incentives supporting the move to a more sustainable energy generation solution.

As mentioned in part I, the Cambodian electricity sector is currently managed and regulated by the Cambodian Law of Electricity of 2001. However, the law does not include any specific laws or regulations addressing electricity generation from renewable energy sources, despite the law having been revised in 2015. While a set of regulations on the installation and operation of solar PV systems was issued by the EAC in January 2018, indicating a step in the right direction from sides of Cambodian policy makers, such regulations are still lacking for other RE technologies. This leads to potential project developers often having to read up on a large number of regulations in the initial phase of project planning in order to learn about permits and licenses required for the development of RE projects. In addition to the above, it is often not clear which authority or government department could serve as a point of contact regarding questions linked to the process of obtaining necessary licenses or permits, as no single designated authority is entrusted with this task (Watson Farley & Williams, 2018).

Moreover, there are currently no financial incentives, such as tax breaks on RET or feed-in tariffs, nor any other mechanism from the side of policy makers in place supporting the investment in renewable energy generation. The implementation of such policy tools to promote the deployment and production of RE is, according to interviews conducted in Cambodia, also not envisaged in the near future. The often prevailing expectation is that electricity supply problems can and will be resolved by the extension of coal and hydropower electricity generation options in combination with energy imports from neighbouring countries. As a result, RE projects are financed either by donations or by private investors, both of which are not always easily found.

Lastly, all energy producers selling electricity to third parties require an electricity generation as well as a distribution license granted by the EAC. Although these can theoretically be obtained, most of the regions in Cambodia have already been licensed off which is why it can be very difficult, if not impossible, to receive the required licenses in certain regions, especially as a foreign project developer.

4.4.2 Other Challenges

Other key challenges obstructing the RE development in Cambodia are related to land issues as well as technology stigma.

There are several facts to consider regarding the ownership of land in Cambodia, particularly for foreign investors. Some renewable energy projects, especially solar power plants, have large area requirements, the land for which will have to be leased or acquired. In general, only 49% of land in Cambodia is legally allowed to be in foreign possession which leads to developers from abroad having to find local partners in the case that leasing land is not an option or not the intention (Watson Farley & Williams, 2018). Moreover, due to large amounts of land having recently been purchased by foreign investors, many from China, conflicts between the local population and foreign land owners have erupted in some regions of the country, such as Sihanoukville. Also, all plots of land need to have the necessary land use permits in order for them to be used for the development of a renewable energy project.

Another important barrier to RE deployment is technological stigma and the general acceptance and understanding of RETs by the public. RETs are not yet prevalent in Cambodia and are not necessarily openly encouraged by policy makers. Due to the high initial investment costs, the local population, including potential local investors, can be reluctant to consider the long term cost benefits of renewable energy technology and might opt for electrification options with lower initial investment costs.

5 Conclusion

Based on a case study on Koh Rong island in the Kingdom of Cambodia, this master thesis has shown that the hybridization of diesel powered mini-grids with renewable energy technology, and in particular with a solar PV system, has the potential to reduce electricity generation costs and the thereby resulting overall costs of energy in rural and island settings in Cambodia. The WTP on the island has been identified to be sufficiently high in order to justify the implementation of a PV hybridization from a socio-economic perspective. Moreover, the comparison of generation costs with the local WTP has indicated that hybridization projects might offer an attractive investment opportunity for private sector investors willing to act as independent power producers, as even with a 15% profit margin added to electricitiy generation costs, the price for hybrid generated electricity would still lie below the current price of electricity on the island.

The current average electricity generation cost resulting from diesel powered generator sets along Long Set Beach on Koh Rong island lies around 0.31 USD/kWh produced electricity. The main drivers of this cost are high annual capital expenditures for diesel fuel amounting to between 81% and 87% of the overall costs, depending on the ownership scenario considered. By combining diesel electricity generation with electricity generated from RE energy sources, in the case of Koh Rong with solar energy, fuel expenditures can be reduced by 18% per kWh due to some diesel generators being able to be switched off during daytime hours.

At the project site, solar PV systems have been found to generate electricity at significantly lower costs than the existing diesel generators. Average generation costs range from 0.13 USD/kWh in the public utility ownership case, up to 0.20 USD/kWh in the for-profit ownership scenario when it is assumed that every kWh of electricity produced is also used. When now combining the PV LCOE with the LCOE of the purely diesel-powered system in order to receive the average generation costs of a diesel-PV hybrid mini-grid, the resulting LCOE indicates a significant reduction in electricity generation costs achieved by combining electricity generation from RE sources with diesel electricity generation.

The LCOE of a hybrid system on Koh Rong island has been estimated to range from 0.27 USD/kWh to 0.30 USD/kWh produced electricity. This presents an overall generation cost reduction of 6.3% to 9.9%, entirely stemming from reduced annual fuel costs. The higher initial investment costs of the hybridized system, as well as the higher relative O&M costs are both offset and outweighed by the large annual fuel cost savings.

In the study, the effect of the hybridization of existing mini-grids on the LCOE was analysed for two ownership scenarios, a no-tax scenario and a for-profit case. In the no-tax case, the tax exempted government or public utility was assumed to undertake the hybridization project, whereas it was undertaken by a profit oriented private IPP in the for-profit case. For both electricity generation configurations, the diesel and the hybrid system, the LCOE is generally lower under ownership and operation by the public utility, however, the economic benefit of reduced generation costs exists for both ownership scenarios. This also holds when system parameters, such as diesel price development, operation and maintenance cost assumptions, or diesel generator unit costs are adjusted to account for uncertainty in a sensitivity analysis.

Apart from the economic benefit of lower electricity generation costs, the hybridization of the existing diesel generation systems on Koh Rong could also lead to large societal as well as environmental benefits. Firstly, the lower generation costs could translate into an electricity price significantly lower than the existing price of 0.50 USD/kWh. Even with a profit margin of 15% being added to generation costs by the electricity producer, electricity prices would still lie far below the WTP for electricity on the island. In addition, with the hybridization, annual CO_2 emissions could be reduced by up to 1,222,085 kg, as a result of a lower diesel fuel consumption, benefitting not only the local population but also the local biodiversity.

Despite the good economic and societal arguments for the viability of hybrid power generation on Koh Rong island, and in general in Cambodia, there exist meaningful non-economic barriers to the broader utilization of RETs in the country. In particular, the lack of a detailed regulatory framework for RET projects as well as of an official point of contact for questions inhibit larger scale investments in renewable energy generation projects. Other barriers include land issues and the general acceptance of RETs by the public.

5.1 Future Research and Recommendations

The work in this thesis should be considered a preliminary study for the potential of integrating RETs, and in particular solar photovoltaic technology, in existing diesel mini-grids for the alteration of electricity generation in islands or rural settings in Cambodia, and could perhaps serve as an example for studies in countries with similar characteristics. While the technological review in this thesis is coherent and the case study undertaken fulfils the purpose of analysing the research question with sufficient detail, there is room for further investigation of several issues not addressed in this work. For example, whilst the case study in this thesis focusses on only one of the beaches on Koh Rong island and was based on a schematic set up, it would be interesting to conduct a similar analysis expanding the scope to the entire island and taking into account the exact demand patterns of local electricity customers. Due to this data never having been documented before and thus currently not existing as such, a data collection project would initially have to be undertaken. From a private project developer's perspective, it could also be interesting to analyse in greater detail the attractiveness of investment opportunities in hybridization projects in Cambodia and other countries.

Finally, it would be beneficial to validate the results of the underlying thesis with software operation simulations based on more detailed solar insolation data and more accurate load forecasts, in order to receive results with higher precision and lower levels of uncertainty.

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List of Tables

List of Figures

Annex

Annex 1

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

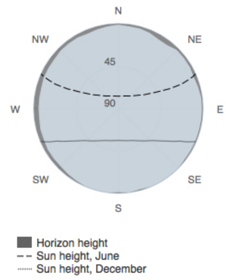
Provided inputs:

Latitude/Longitude:	10.684, 103.284
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed:	1 kWp
System loss:	14 %

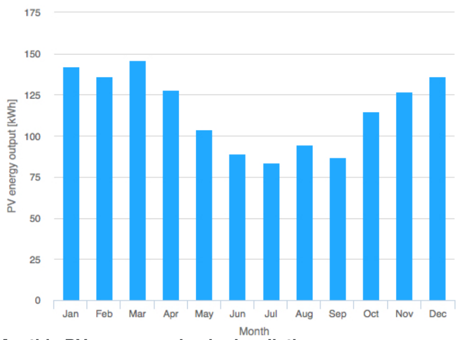
Simulation outputs

Slope angle:	16 (opt) °
Azimuth angle:	7 (opt) °
Yearly PV energy production:	1390 kWh
Yearly in-plane irradiation:	1850 kWh/m²
Year to year variability:	31.80 %
Changes in output due to:	
Angle of incidence:	-2.7 %
Spectral effects:	? (0) %
Temperature and low irradiance:	-10 %
Total loss:	-24.7 %

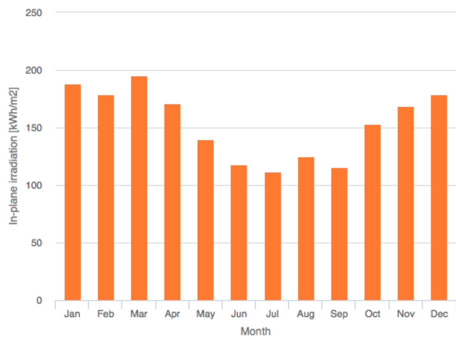
Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:



Monthly in-plane irradiation for fixed-angle:



Monthly PV energy and solar irradiation

Month	Em	Hm	SDm
January	142	188	6.12
February	136	179	10.4
March	146	195	9.57
April	128	171	10.1
May	104	140	7.73
June	88.9	118	7.33
July	83.8	112	8.46
August	94.7	125	9.63
September	87.2	116	11.2
October	115	153	13.5
November	127	169	9.58
December	136	179	9.21

Em: Average monthly electricity production from the given system [kWh].

Hm: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SDm: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Report generated on 2019/05/08

Annex 2

	A	B	C	D	E	F	G	H	I
10									
11		**PURE DIESEL GRID**							
12		**Generator sizing**							
13			*Load (kW)*		*required kVA*				
14		Night time	600		750			**Power factor**	0.8
15		Day time	960		1200				
16		Peak Demand	1500		1875				
17									
18		Prime Power Rating Generators			75% Load				
19		kVA	kW		kVA				
20		450	360		337.5				
21		250	200		187.5				
22									
23		Average load of generators with 5x450kVA und 1x250kVA sizing					**Diesel Mini Grid Size**		
24		Night time	65%					kVA	kW
25		Day time	75%				Installed capacity	2500	2000
26		Peak Demand	75%						
27									

	A	B	C	D	E	F
1						
2		**Electricity Demand Single Resort**				
3						
4		*Time of Day*	*Hours per day*	*Load (kW)*	*Average Daily Consumption (kWh)*	
5		00:00 - 07:00 Night Time	=7-0	100	=D5*C5	
6		07:00 - 18:00 Day Time	=18-7	160	=D6*C6	
7		18:00 - 24:00 Peak Deamd	=24-18	250	=D7*C7	
8			**Average Daily Consumption**		**=SUM(E5:E7)**	
9						
10						
11		**PURE DIESEL GRID**				
12		**Generator sizing**				
13			*Load (kW)*	*required kVA*		
14		Night time	=$I$5	=C14/F14	**Power factor**	0.8
15		Day time	=$I$6	=C15/F14		
16		Peak Demand	=$I$7	=C16/F14		
17						
18		Prime Power Rating Generators		75% Load		
19		kVA	kW	kVA		
20		450	=B20*F14	=B20*0.75		
21		250	=B21*F14	=B21*0.75		
22						
23		Average load of generators with 5x450kVA und 1x250kVA sizing				
24		Night time	=D14/(2*B20+B21)			
25		Day time	=D15/(3*B20+B21)			
26		Peak Demand	=D16/(5*B20+B21)			
27						

Annex 3

	B	C	D	E	F	G	H	I	J	K	L	M	N
1	**Diesel Mini-Grid: LCOE calculations**												
2	**2500 kVa / 2000 kW installed capacity**												
3	**25 year project period**												
4													
5	***LCOE Input Variable***	***Diesel Mini-Grid Base Case***											
6	Project life time (in years)	25											
7	Generator life time (in years)	7											
8	Installed capacity (in kW)	2000											
9	Load factor	75%											
10	CapEx (in USD)	743,400											
11	Annual O&M Costs (% of CapEx)	16.80%											
12	Annual O&M Cost escalation (in %)	1%											
13	Annual Fuel Consumption (in l)	2,410,825											
14	Annual Electricity Production (in kWh)	8,902,350											
15	Discount Rate	6%	no-tax case										
16		13%	for-profit case										
17	Depreciation	Over 10 years	for-profit case										
18	Corporate Tax Rate	20%	for-profit case										
19													
20	**CALCULATION**												
21	**TLCC (no-tax case), Discount Rate 6%**												
22	**Year**					2019	2020	2021	2022	2023	2024	2025	2026
23				**Cost Escalation**									
24													
25	**CAPEX**				[USD]	743,400.00							
26	**1. Replacement Costs**	every 7 years			[USD]								743,400.00
27	**PRESENT VALUE REPLACEMENT COSTS**				[USD]	1,987,117.08							
28						NPV							
29	**2. O&M**	16.80%	of CapEx	1%	[USD]	1,768,976.57	126,140.11	127,401.51	128,675.53	129,962.28	131,261.91	132,574.53	133,900.27
30	**3. Fuel Cost**				[USD]	29,723,457.54	2,118,481.87	2,125,494.48	2,107,691.97	2,130,146.84	2,174,357.28	2,207,719.23	2,223,855.04
31	**Total Annual Costs**				[USD]		2,244,621.99	2,252,896.00	2,236,367.50	2,260,109.12	2,305,619.19	2,340,293.76	2,357,755.31
32	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	31,492,434.11							
33													
34					**TLCC NO-TAX CASE (Capex + PVOM + PVF)**	**34,222,951.19**							
35													
36													
37	**TLCC (for profit case), Discount Rate 13%**												
38	**Year**					2019	2020	2021	2022	2023	2024	2025	2026
39				**Cost Escalation**									
40													
41	**CAPEX**				[USD]	743,400.00							
42	**1. Replacement Costs**	every 7 years			[USD]								743,400.00
43	**PRESENT VALUE REPLACEMENT COSTS**				[USD]	1,755,280.84							
44						NPV							
45	**2. O&M**	16.80%	of CapEx	1%	[USD]	987,671.77	126,140.11	127,401.51	128,675.53	129,962.28	131,261.91	132,574.53	133,900.27
46	**3. Fuel Cost**				[USD]	16,560,468.60	2,118,481.87	2,125,494.48	2,107,691.97	2,130,146.84	2,174,357.28	2,207,719.23	2,223,855.04
47	**Total Annual Costs**				[USD]		2,244,621.99	2,252,896.00	2,236,367.50	2,260,109.12	2,305,619.19	2,340,293.76	2,357,755.31
48	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	17,548,140.37							
49	**(1-Tx)[PVOM+PVF]**				[USD]	14,038,512.30							
50													
51	**4. Depreciation**	over 10 years			[USD]		74,340.00	74,340.00	74,340.00	74,340.00	74,340.00	74,340.00	74,340.00
52	**PRESENT VALUE OF DEPRECIATION (PVDEP)**				[USD]	422,767.20							
53	**(Tx * PVDEP)**				[USD]	84,553.44							
54													
55					**TLCC FOR-PROFIT CASE (Formula 8)**	**20,565,799.62**							
56													
57	**Energy Production**												
58	**Year**					2019	2020	2021	2022	2023	2024	2025	2026
59													
60	**Annual Energy Production**				[kWh]		8,902,350	8,902,350	8,902,350	8,902,350	8,902,350	8,902,350	8,902,350
61	**PRESENT VALUE ENERGY PRODUCTION**												
62		NO-TAX CASE, DR 6%			[kWh]	113,801,910.70							
63		FOR-PROFIT CASE, DR 13%			[kWh]	65,254,091.77							
64													
65	**LCOE RESULTS**												
66													
67	**LCOE, NO-TAX CASE**	**[USD/kWh]**	**0.301**										
68	**LCOE, FOR-PROFIT CASE**	**[USD/kWh]**	**0.315**										
69													

	A	B	C	D	E	F	G	H
1		**Diesel Mini-Grid: LCOE calculations**						
2		**2500 kVa / 2000 kW installed capacity**						
3		**25 year project period**						
4								
5		***LCOE Input Variable***	***Diesel Mini-Grid Base Case***					
6		Project life time (in years)	25					
7		Generator life time (in years)	7					
8		Installed capacity (in kW)	2000					
9		Load factor	0.75					
10		CapEx (in USD)	743400					
11		Annual O&M Costs (% of CapEx)	0.168					
12		Annual O&M Cost escalation (in %)	0.01					
13		Annual Fuel Consumption (in l)	2410825					
14		Annual Electricity Production (in kWh)	8902350					
15		Discount Rate	0.06	no-tax case				
16			0.13	for-profit case				
17		Depreciation	Over 10 years	for-profit case				
18		Corporate Tax Rate	0.2	for-profit case				
19								
20		**CALCULATION**						
21		**TLCC (no-tax case), Discount Rate 6%**						
22		**Year**					2019	2020
23					**Cost Escalation**			
24								
25		**CAPEX**				[USD]	='Assumptions Diesel'!C11	
26		**1. Replacement Costs**	every 7 years			[USD]		
27		**PRESENT VALUE REPLACEMENT COSTS**				[USD]	=NPV(C15,H26:AF26)	
28							NPV	
29		**2. O&M**	0.168	of CapEx	0.01	[USD]	=NPV(C15,H29:AF29)	=$G$25*$C$29*(1+$E$29)^(H$22-$G$22)
30		**3. Fuel Cost**				[USD]	=NPV(C15,H30:AF30)	=$C$13*'Diesel Price Projections'!H$13
31		**Total Annual Costs**				[USD]		=SUM(H29:H30)
32		**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	=NPV(C15,H31:AF31)	
33								
34						**PVOM + PVF)**	**=SUM(G25,G27,G32)**	
35								
36								
37		**TLCC (for profit case), Discount Rate 13%**						
38		**Year**					2019	2020
39					**Cost Escalation**			
40								
41		**CAPEX**				[USD]	='Assumptions Diesel'!C25	
42		**1. Replacement Costs**	every 7 years			[USD]		
43		**PRESENT VALUE REPLACEMENT COSTS**				[USD]	=NPV(C16,H42:AF42)	
44							NPV	
45		**2. O&M**	0.168	of CapEx	0.01	[USD]	=NPV(C16,H45:AF45)	=$G$25*$C$29*(1+$E$29)^(H$22-$G$22)
46		**3. Fuel Cost**				[USD]	=NPV(C16,H46:AF46)	=$C$13*'Diesel Price Projections'!H$13
47		**Total Annual Costs**				[USD]		=SUM(H45:H46)
48		**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	=NPV(C16,H47:AF47)	
49		**(1-Tx)[PVOM+PVF]**				[USD]	=(1-C18)*(G48)	
50								
51		**4. Depreciation**	over 10 years			[USD]		=$G$41/10
52		**PRESENT VALUE OF DEPRECIATION (PVDEP)**				[USD]	=NPV(C16,H51:R51)	
53		**(Tx * PVDEP)**				[USD]	=G52*C18	
54								
55						**E (Formula 8)**	**=(G41+G43+G49-G53)/(1-C18)**	
56								
57		**Energy Production**						
58		**Year**					2019	2020
59								
60		**Annual Energy Production**				[kWh]		=$C$14
61		**PRESENT VALUE ENERGY PRODUCTION**						
62			NO-TAX CASE, DR 6%			[kWh]	=NPV(C15, H60:AF60)	
63			FOR-PROFIT CASE, DR 13%			[kWh]	=NPV(C16, H60:AF60)	
64								
65		**LCOE RESULTS**						
66								
67		**LCOE, NO-TAX CASE**	**[USD/kWh]**	**=G34/G62**				
68		**LCOE, FOR-PROFIT CASE**	**[USD/kWh]**	**=G55/G63**				
69								

A		B	C	D	E	F	G	H	I	J	K
	1	**Hybrid Mini-Grid: LCOE calculations**									
	2	**PV: 1200 kWp installed capacity, no battery**									
	3	**Diesel: 2000 kW installed capacity**									
	4	**25 year project period**									
	5										
	6	***LCOE Input Variable***	***Diesel Genset***	***PV System***							
	7	Project life time (in years)	25	25							
	8	System life time (in years)	10	25							
	9	Installed capacity (in kW)	2000	1200							
	10	Load factor	75%	n/a							
	11	CapEx (in USD)	743,400	1555688.4							
	12	Annual O&M Costs	16.80%	1.80%	of CapEx						
	13	Annual O&M Cost escalation (in %)	1%	1%							
	14	Land lease costs (in USD)	n/a	43200							
	15	Annual Fuel Consumption (in l)	1,953,115	n/a							
	16	Annual Electricity Production excluding degradation(in kWh)	7,216,050	1,668,000							
	17	System degradation factor	n/a	0.5%							
	18	Discount Rate	6%		no-tax case						
	19		13%		for-profit case						
	20	Depreciation	Over 10 years		for-profit case						
	21	Corporate Tax Rate	20%		for-profit case						
	22										
	23	**DIESEL CALCULATION**									
	24	**TLCC (no-tax case), Discount Rate 6%**									
	25	**Year**					2019	2020	2021	2022	2023
	26				**Cost Escalation**						
	27										
	28	**CAPEX**				[USD]	743,400.00				
	29	**1. Replacement Costs**	every 10 years			[USD]					
	30	**PRESENT VALUE REPLACEMENT COSTS**				[USD]	1,362,944.11				
	31						NPV				
	32	**2. O&M**	16.80%	of CapEx	1%	[USD]	1,768,976.57	126,140.11	127,401.51	128,675.53	129,962.28
	33	**3. Fuel Cost**				[USD]	24,080,275.74	1,716,275.02	1,721,956.24	1,707,533.65	1,725,725.32
	34	**Total Annual Costs**				[USD]		1,842,415.13	1,849,357.75	1,836,209.18	1,855,687.60
	35	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	25,849,252.32				
	36										
	37			**TLCC NO-TAX CASE (Capex + PVOM + PVF)**			**27,955,596.42**				
	38										
	39										
	40	**TLCC (for profit case), Discount Rate 13%**									
	41	**Year**					2019	2020	2021	2022	2023
	42				**Cost Escalation**						
	43										
	44	**CAPEX**				[USD]	743,400.00				
	45	**1. Replacement Costs**	every 10 years			[USD]					
	46	**PRESENT VALUE REPLACEMENT COSTS**				[USD]	1,240,067.35				
	47						NPV				
	48	**2. O&M**	16.80%	of CapEx	1%	[USD]	987,671.77	126,140.11	127,401.51	128,675.53	129,962.28
	49	**3. Fuel Cost**				[USD]	13,416,361.47	1,716,275.02	1,721,956.24	1,707,533.65	1,725,725.32
	50	**Total Annual Costs**				[USD]		1,842,415.13	1,849,357.75	1,836,209.18	1,855,687.60
	51	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	14,404,033.23				
	52	**(1-Tx)[PVOM+PVF]**				[USD]	11,523,226.59				
	53										
	54	**4. Depreciation**	over 10 years			[USD]		74,340.00	74,340.00	74,340.00	74,340.00
	55	**PRESENT VALUE OF DEPRECIATION (PVDEP)**				[USD]	422,767.20				
	56	**(Tx * PVDEP)**				[USD]	84,553.44				
	57										
	58			**TLCC FOR-PROFIT CASE (Formula 8)**			**16,777,675.62**				
	59										
	60	**Energy Production**									
	61	**Year**					2019	2020	2021	2022	2023
	62										
	63	**Annual Energy Production**				[kWh]		7,216,050	7,216,050	7,216,050	7,216,050
	64	**PRESENT VALUE ENERGY PRODUCTION**									
	65		NO-TAX CASE, DR 6%			[kWh]	92245337.21				
	66		FOR-PROFIT CASE, DR 13%			[kWh]	52,893,538.10				
	67										
	68	**PV CALCULATION**									
	69	**TLCC (no-tax case), Discount Rate 6%**									
	70	**Year**					2019	2020	2021	2022	2023
	71				**Cost Escalation**						
	72										
	73	**CAPEX**				[USD]	1,555,688.40				
	74										
	75	**2. O&M**	1.80%	of CapEx	1%	[USD]		28,282.42	28,565.24	28,850.89	29,139.40
	76	Land Lease Costs	43,200.00	USD		[USD]	43,200.00	43,200.00	43,200.00	43,200.00	43,200.00
	77	**Total Annual Costs**				[USD]	43,200.00	71,482.42	71,765.24	72,050.89	72,339.40
	78	**PRESENT VALUE OF COSTS (PVOM)**				[USD]	992,070.80				
	79										
	80			**TLCC NO-TAX CASE (Capex + PVOM)**			**2,547,759.20**				
	81										
	82										
	83	**TLCC (for profit case), Discount Rate 13%**									
	84	**Year**					2019	2020	2021	2022	2023
	85				**Cost Escalation**						
	86										
	87	**CAPEX**				[USD]	1,555,688.40				
	88										
	89	**2. O&M**	1.80%	of CapEx	1%	[USD]		28,282.42	28,565.24	28,850.89	29,139.40
	90	Land Lease Costs	43,200.00	USD		[USD]	43,200.00	43,200.00	43,200.00	43,200.00	43,200.00
	91	**Total Annual Costs**				[USD]	43,200.00	71,482.42	71,765.24	72,050.89	72,339.40
	92	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	581,305.47				
	93	**(1-Tx)[PVOM]**				[USD]	465,044.38				
	94										
	95	**4. Depreciation**	over 10 years			[USD]		155,568.84	155,568.84	155,568.84	155,568.84
	96	**PRESENT VALUE OF DEPRECIATION (PVDEP)**				[USD]	884,710.83				
	97	**(Tx * PVDEP)**				[USD]	176,942.17				
	98										
	99			**TLCC FOR-PROFIT CASE (Formula 8)**			**2,304,738.26**				
	100										
	101	**Energy Production**									
	102	**Year**					2019	2020	2021	2022	2023
	103				**Degradation**						
	104										
	105	**Annual Diesel Energy Production**			0.5%	[kWh]		1,668,000	1,659,660	1,651,362	1,643,105
	106	**PRESENT VALUE ENERGY PRODUCTION**									
	107		NO-TAX CASE, DR 6%			[kWh]	20,386,652.48				
	108		FOR-PROFIT CASE, DR 13%			[kWh]	11,842,129.14				
	109										
	110	**LCOE RESULTS**									
	111										
	112	DIESEL LCOE, NO-TAX CASE	[USD/kWh]	0.30306			**Total Energy Production over Project Lifetime, kWh**				219,692,577
	113	DIESEL LCOE, FOR-PROFIT CASE	[USD/kWh]	0.31720				Share of Diesel			82%
	114							Share of PV			18%
	115	PV LCOE, NO-TAX CASE	[USD/kWh]	0.12497							
	116	PV LCOE, FOR-PROFIT CASE	[USD/kWh]	0.19462							
	117										
	118	**HYBRID LCOE, NO-TAX CASE**	**[USD/kWh]**	**0.271**							
	119	**HYBRID LCOE, FOR-PROFIT CASE**	**[USD/kWh]**	**0.295**							
	120										

A		B	C	D	E	F	G	H
	1	**Hybrid Mini-Grid: LCOE calculations**						
	2	**PV: 1200 kWp installed capacity, no battery**						
	3	**Diesel: 2000 kW installed capacity**						
	4	**25 year project period**						
	5							
	6	***LCOE Input Variable***	***Diesel Genset***	***PV System***				
	7	Project life time (in years)	25	25				
	8	System life time (in years)	10	25				
	9	Installed capacity (in kW)	2000	1200				
	10	Load factor	0.75	n/a				
	11	CapEx (in USD)	743400	1555688.4				
	12	Annual O&M Costs	0.168	0.018	of CapEx			
	13	Annual O&M Cost escalation (in %)	0.01	0.01				
	14	Land lease costs (in USD)	n/a	43200				
	15	Annual Fuel Consumption (in l)	1953115	n/a				
	16	Annual Electricity Production excluding degradation(in kWh)	7216050	1668000				
	17	System degradation factor	n/a	0.005				
	18	Discount Rate	0.06		no-tax case			
	19		0.13		for-profit case			
	20	Depreciation	Over 10 years		for-profit case			
	21	Corporate Tax Rate	0.2		for-profit case			
	22							
	23	**DIESEL CALCULATION**						
	24	**TLCC (no-tax case), Discount Rate 6%**						
	25	**Year**					2019	2020
	26				**Cost Escalation**			
	27							
	28	**CAPEX**				[USD]	='Assumptions Diesel'!C11	
	29	**1. Replacement Costs**	every 10 years			[USD]		
	30	**PRESENT VALUE REPLACEMENT COSTS**				[USD]	=NPV(C18,H29:AF29)	
	31						NPV	
	32	**2. O&M**	0.168	of CapEx	0.01	[USD]	=NPV($C$18,H32:AF32)	=$G$28*$C$32*(1+$E$32)^(H$25-$G$25)
	33	**3. Fuel Cost**				[USD]	=NPV($C$18,H33:AF33)	=$C$15*'Diesel Price Projections'!H$13
	34	**Total Annual Costs**				[USD]		=SUM(H32:H33)
	35	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	=NPV(C18,H34:AF34)	
	36							
	37					**VOM + PVF)**	**=SUM(G28,G30,G35)**	
	38							
	39							
	40	**TLCC (for profit case), Discount Rate 13%**						
	41	**Year**					2019	2020
	42				**Cost Escalation**			
	43							
	44	**CAPEX**				[USD]	='Assumptions Diesel'!C25	
	45	**1. Replacement Costs**	every 10 years			[USD]		
	46	**PRESENT VALUE REPLACEMENT COSTS**				[USD]	=NPV(C19,H45:AF45)	
	47						NPV	
	48	**2. O&M**	0.168	of CapEx	0.01	[USD]	=NPV($C$19,H48:AF48)	=$G$28*$C$32*(1+$E$32)^(H$25-$G$25)
	49	**3. Fuel Cost**				[USD]	=NPV($C$19,H49:AF49)	=$C$15*'Diesel Price Projections'!H$13
	50	**Total Annual Costs**				[USD]		=SUM(H48:H49)
	51	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	=NPV(C19,H50:AF50)	
	52	**(1-Tx)[PVOM+PVF]**				[USD]	=(1-C21)*(G51)	
	53							
	54	**4. Depreciation**	over 10 years			[USD]		=$G$44/10
	55	**PRESENT VALUE OF DEPRECIATION (PVDEP)**				[USD]	=NPV(C19,H54:R54)	
	56	**(Tx * PVDEP)**				[USD]	=G55*C21	
	57							
	58					**(Formula 8)**	**=(G44+G46+G52-G56)/(1-C21)**	
	59							
	60	**Energy Production**						
	61	**Year**					2019	2020
	62							
	63	**Annual Energy Production**				[kWh]		=$C$16
	64	**PRESENT VALUE ENERGY PRODUCTION**						
	65		NO-TAX CASE, DR 6%			[kWh]	=NPV(C18, H63:AF63)	
	66		FOR-PROFIT CASE, DR 13%			[kWh]	=NPV(C19, H63:AF63)	
	67							
	68	**PV CALCULATION**						
	69	**TLCC (no-tax case), Discount Rate 6%**						
	70	**Year**					2019	2020
	71				**Cost Escalation**			
	72							
	73	**CAPEX**				[USD]	='Assumptions Hybrid'!C15	
	74							
	75	**2. O&M**	='Assumptions Hybrid'!C23	of CapEx	0.01	[USD]		=$G$73*$C$75*(1+$E$75)^(H$70-$G$70)
	76	Land Lease Costs	='Assumptions Hybrid'!C24	USD		[USD]	=$C$76*(1+$E$76)^(G$70-$G$70)	=$C$76*(1+$E$76)^(H$70-$G$70)
	77	**Total Annual Costs**				[USD]	=SUM(G76:G76)	=SUM(H75:H76)
	78	**PRESENT VALUE OF COSTS (PVOM)**				[USD]	=NPV(C18,H77:AF77)+G77	
	79							
	80					**ex + PVOM)**	**=SUM(G73,G78)**	
	81							
	82							
	83	**TLCC (for profit case), Discount Rate 13%**						
	84	**Year**					2019	2020
	85				**Cost Escalation**			
	86							
	87	**CAPEX**				[USD]	='Assumptions Hybrid'!C15	
	88							
	89	**2. O&M**	='Assumptions Hybrid'!C23	of CapEx	0.01	[USD]		=$G$73*$C$75*(1+$E$75)^(H$70-$G$70)
	90	Land Lease Costs	='Assumptions Hybrid'!C24	USD		[USD]	=$C$76*(1+$E$90)^(G$84-$G$84)	=$C$76*(1+$E$90)^(H$84-$G$84)
	91	**Total Annual Costs**				[USD]	=SUM(G89:G90)	=SUM(H89:H90)
	92	**PRESENT VALUE OF COSTS (PVOM + PVF)**				[USD]	=NPV(C19,H91:AF91)+G91	
	93	**(1-Tx)[PVOM]**				[USD]	=(1-C21)*(G92)	
	94							
	95	**4. Depreciation**	over 10 years			[USD]		=$G$87/10
	96	**PRESENT VALUE OF DEPRECIATION (PVDEP)**				[USD]	=NPV(C19,H95:R95)	
	97	**(Tx * PVDEP)**				[USD]	=G96*C21	
	98							
	99					**(Formula 8)**	**=(G87+G93-G97)/(1-C21)**	
	100							
	101	**Energy Production**						
	102	**Year**					2019	2020
	103				**Degradation**			
	104							
	105	**Annual Diesel Energy Production**			0.005	[kWh]		='Sizing of Diesel and PV Plant'!$C$68
	106	**PRESENT VALUE ENERGY PRODUCTION**						
	107		NO-TAX CASE, DR 6%			[kWh]	=NPV(C18, H105:AF105)	
	108		FOR-PROFIT CASE, DR 13%			[kWh]	=NPV(C19, H105:AF105)	
	109							
	110	**LCOE RESULTS**						
	111							
	112	DIESEL LCOE, NO-TAX CASE	[USD/kWh]	=G37/G65			**Total Energy Production over Proj**	
	113	DIESEL LCOE, FOR-PROFIT CASE	[USD/kWh]	=G58/G66				Share of Diesel
	114							Share of PV
	115	PV LCOE, NO-TAX CASE	[USD/kWh]	=G80/G107				
	116	PV LCOE, FOR-PROFIT CASE	[USD/kWh]	=G99/G108				
	117							
	118	**HYBRID LCOE, NO-TAX CASE**	**[USD/kWh]**	**=D112*$I$114+D115*$I$115**				
	119	**HYBRID LCOE, FOR-PROFIT CASE**	**[USD/kWh]**	**=D113*$I$114+D116*$I$115**				
	120							