

IEA PVPS Task 9 Optimal Integration of Photovoltaics in Micro-Grids that are dominated by Diesel Power Plants





Report IEA-PVPS T9-19:2019

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

# Optimal integration of Photovoltaic in Micro-grids that are dominated by diesel power-plants

Recommendations for utilities and consulting engineers

IEA PVPS Task 9 Report IEA-PVPS T9-19:2019 June 2019

ISBN: 978-3-906042-85-5

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# 1 Foreword

This document is a joint publication of the IEA PVPS (International Energy Agency's Photovoltaic Power Systems Programme) Task 9 and the Fraunhofer-Institute for Solar Energy Systems (ISE).

## **The IEA PVPS Programme**

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Co-operation and Development (OECD). Among its 30 member countries the IEA carries out a number of so called Technology cooperation programmes (TCPs). One of these is the IEA Photovoltaic Power Systems Programme (IEA-PVPS).

Inside PVPS several tasks are defined that are addressing different fields that are of high interest for the further development of the photovoltaic technology. Each programme is headed by an executive committee that is composed of one representative from each participating country or organization. The management of the individual Tasks (research projects / activity areas) is the responsibility of the Operating Agents.

At the beginning of 2018 there were 32 members (27 countries and 5 organizations) involved in the ongoing tasks. Since the existence of the PVPS programme 17 tasks were defined from which 8 are still ongoing. These are:

- Task 1: Strategic PV Analysis & Outreach
- Task 9: Deploying PV Services for Regional Development
- Task 12: PV Sustainability
- Task 13: Performance, Operation and Reliability of Photovoltaic Systems
- Task 14: High Penetration of PV Systems in Electricity Grids
- Task 15: Enabling Framework for the Development of BIPV
- Task 16: Solar Resource for High Penetration and Large Scale Applications
- Task 17: PV for Transport

Information about the active and completed Tasks can be found on the IEA-PVPS website <u>www.iea-pvps.org</u>.

This paper was written in the framework of the Task 9 that addresses the use of PV as a means to enhance regional development – both for rural electrification applications and more broadly in the urban environment. The Task achieves this by developing partnerships with appropriate regional and national organizations plus funding agencies, and carrying out work on specific applications of interest and relevant business models.

## 2 Acknowledgements

This report received valuable contributions from several international experts and studies.

Special thanks are due, in particular to Alexander Schies (SMA Sunbelt Energy GmbH), Johannes Wüllner (Fraunhofer ISE), Georg Bopp (Fraunhofer ISE) and Lluis Millet Biosca (Fraunhofer ISE).

## 3 Executive summary

In this report the effects of PV integration into diesel driven micro-grids was investigated. The focus was set to the fuel saving potential due to the PV integration and the resulting economics for the system.

The report starts with a summary of the most relevant technical aspects that need to be considered for the integration of PV in a diesel driven micro-grid.

Then the report analyzed the different types of systems that are of interest for the integration of PV. From this analysis three case studies with quite different electric demand profiles were identified for which a detailed simulation was performed. The focus was on the effects of varying PV penetrations and the corresponding fuel saving potential and thus the economics of the system. The systems under investigation were typical diesel driven micro grid use cases, a Hospital complex in Haiti, a rural village in Nepal and a mine in South-Africa. To get comparable results for all systems the same specific component costs were assumed.

The simulations showed a reduction of fuel consumption and the levelized costs of electricity (LCOE) for all systems and all PV penetration levels based on peak power except for very high PV penetrations (> 150%) for the case of the rural village in Nepal. The benefits were particularly high for the Hospital case in Haiti where the demand fitted very well the PV production curve and the mine case in South-African where the load was extremely constant on a high level.

Concerning the minimum value of the LCOE the PV penetration levels for the three case studies were very different. For the hospital in Haiti a PV penetration level of 110% was found as optimum leading to a fuel saving of about 30% and a cost reduction of about 6 cents. For the rural village in Nepal the minimum was found at a penetration level of about 65% resulting in only about 12% of fuel saving and two cent price reduction. For the mine in South-Africa a minimum LCOE value was simulated for a PV penetration of 135% and a fuel saving reduction of about 27% and a LCOE reduction of about five cents.

By adding a battery to a PV diesel system, the LCOE remains the same or even decreases slightly in the case of the rural village were the demand does not fit well with the PV production curve, but allows for higher PV penetration and a higher overall share of renewable energy. As a rule of thumb, a battery capacity of 30% of the maximum load value could be assumed to be reasonable, depending on the battery system cost that was estimated with a conservative value of 800 Euro/ kWh.

For use-cases where the load is not well fitting the PV production, the integration of a storage system can be of even higher interest. Particularly if the battery prices are further reducing and the diesel prices are remaining on high levels.

## **4** Introduction

Concerning the integration of photovoltaics into diesel micro-grids there are five major fields that influence this process. These fields are the economics of the installation and operation of the system, the political framework that influences the decisions, the involvement of the customers/community members that are using the system and the technical aspects that need to be considered. The fifth field is the sustainability including the protection of the environment and the responsible exploitation of resources. These fields of influence are depicted in Figure 1.



Figure 1: Fields of influence on the realization of a PV-diesel micro-grid

None of the above mentioned fields is independent but they strongly interact and influence eachother. Decision-makers such as politicians and investors need to take this fact into account. That is the reason why all these different aspects are partly analyzed in this study.

There is a very high number of technical systems and villages that are not connected to the national electricity grid. The main reason for this is that the costs for the integration are too high for the institutions or companies in charge. The size in terms of nominal generator power goes from very small (< 10 kW) up to very large systems (multi MW scale). While the small systems generally include only one generator, the large ones have multiple generators (cascade) that are operated in parallel. This paper is focusing on larger systems (so called micro-grids) and will provide one possible form to categorize the systems of interest in terms of nominal power (section 6.1). Another categorization scheme is given in section 1 were different use-cases are identified.

This paper is focusing on the integration of PV in those systems that until now retrieved their electricity mainly from diesel generators and those that are planned to be realized as combined PV and diesel systems. There are several reasons why it could be of interest to include PV into an existing or planed micro-grid. The most important of these reasons are listed in Table 1.

Reduction of LCOE		
Reduction of greenhouse gases and		
other atmospheric emissions		
Reduction of noise emission		
Reduction of dependency on fuel		
supply		
Reduced water and soil pollution		

# Table 1: Possible reasons for the integrationof PV into diesel micro-grids

While for most investors and customers the reduction of the levelized costs of electricity (LCOE) might be the main reason, for other actors such as politicians and NGOs the reduction of greenhouse gases and other atmospheric emissions like soot will be of high importance. The reduction of the electricity costs and the greenhouse gas emission is due to the fact that fuel can be saved if a share of the electricity demand can be provided by the PV-system. Here it is important to realize that the specific fuel costs and specific emission are not only determined by the national fuel prices but also need to include the transport expenses of the fuel to the site where the generators are installed.

The economic analysis of the integration of PV into a diesel micro-grid thus also strongly depends on the location of the system. In section 8 we present a technical as well as an economic analysis of three typical use-cases that give a deep inside into the aspects that need to be considered for the PV integration in such systems.

For most of the systems that are in the scope of this paper it is meaningful to analyze if the integration of a battery storage is of interest. Not only that it can potentially increase the fuel save potential of the PV-system but it can supply further services such as increasing grid stability and the reduction of blackouts in the micro-grid. The analysis for the integration of battery storage in a PV diesel system will be given for three use-cases in section 9.

The paper will conclude with a section that collects all the important aspects that are of relevance for the integration of PV in diesel micro-grids.

# 5 Collection of helpful literature and internet sources on the topic

This report is not capable of describing all the details that are of interest for the integration of PV into existing diesel micro-grids. Many detailed studies were performed before that cover some of these additional aspects or that complement the work presented here. Many of the important details can be taken from PVPS reports that were written in the framework of Task 11. The most interesting literature is listed in Table 2.

Published by:	Title	Year	Source
IEA Task 9:	PV Injection in Isolated Diesel Grids	2007	(IEA-PVPS 2007)
	Rural Electrification with PV Hybrid Systems	2014	(Léna Grégoire 2014)
	A user guide to simple monitoring and sustainable operation of PV-diesel hybrid systems	2015	(Bastholm 2015)
IEA Task 11:	World-wide Overview of Design and Simulation Tools for Hybrid PV Systems	2011	(Arribas et al. 2011)
	The Role of Energy Storage for Mini-grid Stabilization	2011	(Espinar and Mayer 2011)
	Sustainability Conditions for PV Hybrid Systems	2011	(Yumoto 2011)
	Communication between Components in Mini-grids	2011	(Steca et al. 2011)
	Social, Economic and Organizational Framework for Sustainable Operation of PV Hybrid Systems within Mini-Grids	2011	(Jacquin et al. 2011)
	Design and Operational Recommendations on Grid Connection of PV Hybrid Mini-grids	2011	(Araki 2011)
	PV Hybrid Mini-Grids: Applicable Control Methods for Various Situations	2012	(Lopes 2012)
	Overview of Supervisory Control Strategies including a MATLAB <sup>®</sup> Simulink <sup>®</sup> Simulation Tool	2012	(Vandenbergh et al. 2012)
GIZ	What size shall it be?	2016	(Blechinger et al. 2016)
PowerWater	Solar/Diesel Mini-Grid Handbook	2013	(Power and Water Corporation 2013)
USAID	Mini-Grids support toolkit	2018	(USAID 2019a)

Table 2: Overview on the most important contributions for the integration of PV into diesel driven micro-grids

# 6 Definitions and technical conditions

Talking about the integration of PV into diesel driven micro-grids one is confronted with many technical terms that are not clearly defined. This lack of clear definition stems among others from the fact that several different technical fields are involved in the research and the realization of photovoltaic integration into micro-grids. In the following sections we will provide the reader with some definitions and technical specifications concerning the different aspects that are of importance for the integration of PV into diesel driven micro-grids.

## 6.1 Micro-grids

There is not one common definition for what a micro-grid is but several different depending on the field of research, politics or industry the definition is taken from. That is the reason why we don't want to add another definition here but want to set a framework in that we are performing this analysis for.

As the notion of a micro-grid needs to be differentiated from a "standard" grid, it is meaningful to find a parameter that is avoiding to include grids that are too large. This can be achieved if we restrict the voltage level of a micro-grid to the Low-Voltage (LV) level as it is also done by the EU research project on micro-grids. The International Electrotechnical Commission (IEC) defines supply system low voltage as voltage in the range 50 to 1000 V AC or 120 to 1500 V DC.

To differentiate a micro-grid from smaller systems is a difficult task. As some of these systems consist of the same elements as small micro-grids (PV, generator, battery) it is not clear where the lower threshold can be set. So we leave this lower threshold variable and define that a micro-grid begins where the system is not anymore a Solar-Home-System (SHS).

## 6.2 Diesel power-plant

A Diesel generator is the combination of a diesel engine with an electrical generator. The generator is producing electrical power from the mechanical torque that is obtained from the diesel engine. It controls the output voltage and the reactive power flow to the system. By far most of the generators are operated as synchronous machines.

The mechanical torque of the engine is controlled by the fuel injection. It is organized by device called the speed-governor control unit, which effectively controls the frequency and real power flow of the system.

Diesel generators are the most common electricity generation method used in remote micro-grids. Listed below are the key characteristics and advantages of diesel engines for remote power generation relative to larger power stations.

- Low capital costs due to their widespread application and manufacturing.
- High reliability Diesel engines are robust, proven, sturdy machines, well suited to harsh operating environments. Engine maintenance is based on run hours and is therefore fairly predictable.
- Quick start and loading Diesel engines can be brought online quickly if required and require minimal warm-up time before being able to accept load
- Good load following capabilities Diesel engines are responsive to load fluctuations

- Servicing skills are common Diesel engine operation and maintenance (O&M) does not require highly specialized skills due to the prevalence and long history of diesel engine operation.
- High energy density of fuel a low energy density would mean that higher volumes of fuel would be required to generate the same amount of electricity, increasing the fuel delivery and fuel storage requirements.
- Quick installation Diesel engines are relatively easy to install.

## 6.2.1 Minimum load factor (MLF)

The generator efficiency curve in Figure 2 shows that the diesel generators are the most efficient from 80% rated power and above. Although, the efficiency is not linear to the output power, it is very low at low load condition, typically below 30% of rated power.



Figure 2: Diesel generator and its typical fuel efficiency curve

Moreover, diesel generators can run at low loads only for limited durations with negligible effects. On-going operation at low loads can result in engine damage including cylinder 'glazing' and increased 'blow-by' (Power and Water Corporation 2013). Operating at low load means less fuel is burned, this means reduced cylinder pressure during combustion and reduced energy dissipated. Lower cylinder pressure means the cylinder rings are not forced out to seal the cylinder as effectively. This allows greater 'blow-by' of combustion products into the oil sump. This also means that more oil remains on the cylinder surface. Over time this oil carbonizes and the grooved cylinder lining surface becomes clogged with carbon.

This is the reason why most of the generator manufacturers recommend not the run the generator beneath a certain loading threshold. In the literature a typical value for this minimum load factor (MLF) that is given is a threshold of 40% of the name plate rating (Power and Water Corporation 2013). The MLF has been subject of some studies as it is assumed that a lower MLF value may significantly increase the fuel saving potential when photovoltaic is integrated into a diesel driven micro-grid. This is also the reason why some manufacturers offer dedicated low load units (LLU) that allow the operation of the generator way below a load factor of 30% (e.g. Danvest<sup>®</sup>). One of the concepts to reduce the minimum load factor is to cut off individual cylinders of the machine. At the same time this cylinder cut-off concept leads to an overall reduction in fuel consumption.

In Figure 3 an example for an off-grid village in Nepal is given where the MLF is varied between 0 and 40%. It can be seen that the levelized costs of electricity (LCOE) can be reduced by more than 1 cent for high PV penetrations if the MLF is reduced from 40% to 0%. A detailed description on the overall simulation and the calculation of the LCOE is given in section 8.1.



Figure 3: Influence of the minimum load factor (MLF) for the fuel reduction potential of a diesel driven micro-grid for the example of a village in Nepal.

#### 6.2.2 Fuel consumption

The fuel consumption characteristics of a diesel generator are described by its specific consumption in relation to time [I/h] and to produced energy [I/kWh]. The typical specific consumption per time of a diesel generator can be considered linear - the higher the load the higher the fuel consumption. The specific consumption in terms of energy is typically non-linear and increases exponentially at low loads. In Figure 4 the specific consumption curves of a 365 kW generator is exemplary shown. Three measurement points are sufficient to find a linear fit from that the specific consumption in terms of energy can be calculated. Here it was assumed that the specific consumption curves are linearly dependent on the nominal power of the generator. That is why this curve was used to simulate the consumption for much larger and much smaller systems.



Figure 4: Example Diesel consumption of a 365 kW diesel generator

#### 6.2.3 Generator control units

Both the diesel engine and the synchronous generator are equipped with several controllers and protection devices to perform the tasks of engine start-up, generator voltage/speed adjustment, frequency stabilization, and/or automatic synchronization. In addition, a supervisory control unit is normally used for dispatch functions such as adjusting active/reactive power generation of the diesel generator for operation in parallel with other units and to control load transfer from one unit to another. This is mainly achieved by a Master-Slave control strategy. Most often all generators except for one are feeding in at a constant power while only one is supplying the fluctuating loads. To control the amount of power that a generator can feed into the grid the exiting voltage and the frequency of the engine are controlled in the corresponding way. This control strategy is also referred to as droop control<sup>1</sup>.

An overall block diagram of the control units and interconnection signals for a three-phase generator is shown in Figure 5. The principal objective of the speed-governor control is to respond to load variations and ultimately adjust the power frequency of the generator by controlling the fuel injection. The voltage regulator controls the excitation of the synchronous generator to power the field winding and regulate the terminal voltage.

There are only few companies dominating the market offering supervising control units with an extensive functionality required for a micro-grid control, for example Woodward, ComAp and Deif.

<sup>&</sup>lt;sup>1</sup> We don't want to go deeper into the electro-technical background here. A more detailed analysis of the technical details is given in (Lopes 2012).



Figure 5: Schematic diagram of a diesel generator with governor and excitation systems and supervisory controls (Lopes 2011)

#### 6.2.4 Fuel save controller

The fuel save controller is a supplementary device or a part of the supervisory control. By measuring the output power of the generator it protects the diesel generator from running below the minimum load factor by curtailing the excess PV power output from the inverters by data communication. In emergency case it protects the diesel generator from reverse power scenario by shutting down the PV inverter or disconnect the grid e.g. in case of sudden load change. In other words the fuel save controller is in combination with the supervisory control the energy management system (EMS) of the micro-grid which includes the above described functions and sometimes additional functions, like control of switchable loads if available.

#### 6.2.5 Spinning reserve

The definition for spinning reserve in this report is taken from the definition used by the Australian PowerWater company (Power and Water Corporation 2013). According to this definition spinning reserve refers to the amount of spare diesel generator capacity that is online and available to instantaneously service additional load. Spinning reserve is carried in order to manage normal community load fluctuations.

In the case of PV-diesel hybrid systems, additional spinning reserve may be required in order to service any unmet load in the event of a reduction in solar output (such as during a cloud event).

To the extent fluctuation can be regulated depends on the degree of grid stability that one wants to achieve. If the grid stability is of very high importance the total peak power of the photovoltaic system needs to be kept available from one or several diesel generators. This will severely impair the profitability of the investment.

Adding battery storage into the system can help to reduce the affordable spinning reserve of the diesel generators and thus increase the fuel saving potential of the project.

#### 6.2.6 Sizing of the generator-plant

Generally the sizing of the generator-plant strongly depends on the use case it is designed for. As a rule of thumb the total power of the generator plant needs to be capable to serve the maximum load peak that occurs over a year. If the demand for electricity will most probably increase after the initial

operation of the plant a projection for the next 5 years needs to be done and the maximum peak load in year 5 is taken as reference for the generator sizing (Blechinger et al. 2016).

If several generators need to be installed, there are two common approaches to realize the system. One strategy is to realize the plant with ascending power ratings. The sizes need to be chosen such that only one generator is running at a time. So if the load is increasing and the next larger sized generator is taking over it should not run beneath the minimum load level. The smaller generator should have enough power capacity left to serve the spinning reserve. A more detailed description for the dimensioning of such a system can be found in (Power and Water Corporation 2013).

The second possibility to size a generator plant is to choose the same type of generators. The advantages of this approach is that the spare parts for only one generator type need to be stored, the runtime of the individual machines can be equalized and additional redundancy is given. Potential disadvantages are that several generators need to run in parallel such that the fuel reduction potential is reduced and that the investment costs are potentially higher (Power and Water Corporation 2013).

## 6.3 The photovoltaic technology and degree of its penetration

The photovoltaic technology for the transformation of solar into electrical energy developed in an unforeseen velocity over the past years. The increasing number of installed capacity is driven by a rapidly decreasing system price that mainly stems from the large production capacities that are builtup in china and some other Asian countries. Because of the low prices more and more projects can be realized achieving attractive Levelized Cost of Electricity (LCOE).

The low LCOE is also the driving force for the integration of PV into diesel-driven micro-grids.

Without going too deep into the technical details of PV systems the main components shall be named here. A certain number of PV modules are connected in series to achieve voltages that are high enough to achieve acceptable efficiencies (low cable losses and high inverter efficiencies). Several of such "strings" that are giving DC voltage can be connected in parallel to increase the overall power that can be achieved by the solar field. If the energy system includes battery storage two major configurations can be applied: AC- or DC-coupling.

For the AC-coupling configuration one or several inverters are needed that transform the DC current into an AC current that can be fed into the AC grid. If no electricity storage is included into the system only the AC-coupling configuration is applicable. The DC-coupling configuration does not need an inverter but one or several DC/DC converters. The voltage is transformed to a voltage level that is capable of loading the battery included in the system. The DC-coupled system is mainly applied in smaller systems. One of the advantages of such a system is a solar charging is still possible even if the energy of the batteries got so low that the AC-grid was switched of. Most of the micro-grids this report is focusing on will be realized in the form of AC-coupling.

Concerning the integration of PV into micro grids one technical advantage compared to other fluctuating RES such as wind energy needs to be emphasized. This is that the power output of the inverter can be regulated with help of the Maximum Power Point (MPP)-tracker. For the integration of wind energy a dump load is needed to get rid of power that cannot be consumed by the loads.

In the literature a categorization of the systems with PV integration can be found that is based on the penetration level of PV (Lopes 2012; Power and Water Corporation 2013). The penetration level either refers to the instantaneous peak power, to average power or to the annual average energy. Low, medium and high penetration classes are distinguished. As there is no common definition and the details can be found in the dedicated literature we will not discuss the topic in depth here. But qualitatively it can be said that the complexity and thus the technical effort is increasing the higher the penetration level is becoming. Additional measures need to be taken to guarantee the stability of the grid if for example clouds are passing resulting in highly fluctuating solar energy. The penetration level in the following chapters and examples refer to instantaneous peak power.

## 6.4 Battery storage

The electrochemical battery energy storage is the most widely used storage technology for rural/remote electrification applications, and has been implemented globally in off-grid and some micro-grid installations (Espinar 2011). It enables the continuity of power to the load in the event of power failure or, for PV generator sites, when there is no solar resource available e.g. in the event of cloud and at night. Depending on the size and design, it also protects the generator from inefficient operational mode. Lead-acid, Ni-Cd and Lithium-ion batteries are in use in PV systems depending on system requirements. For example Ni-Cd batteries are very suitable for cold climates like Canada. Along with the storage, a load and/or battery management system is necessary to control the power flow in and out of the battery within its acceptable power and voltage thresholds. This is essential to ensure reliable operation and to guarantee the expected lifetime of the battery. The battery management system can usually communicate with the system management in order to ensure that the battery operates within its buffer range.

The capacity of the battery is specified by manufacturers in Ah under a certain discharge rate and cell temperature. If energy stored in a battery is C25=100 Ah then it can provide a current of 4 Amps for 25 hours. Energy in Kilowatt Hours (kWh) = Ah x V / 1000, in which V is the battery voltage.

Because lead acid batteries are the most used storages in PV hybrid systems and Li-Ion starts to replace them, only these two storage technologies will be described a little bit in detail.

## a) Lead-acid batteries

Lead acid batteries are the most widely used electrochemical system globally, with proven safety, performance and low cost. Currently, still a high share of industrial stationary and motive applications are covered by lead acid batteries. Lead acid batteries are already prevalent as a "low Total Cost of Ownership<sup>2</sup>" component in existing small to large-sized rural electrification applications. They have the following advantages:

- Low cost/kWh
- Proven technology in stationary applications
- Robust design
- High resource efficiency and recyclability

Lead-based batteries comprise a wide range of types and capacities (1 up to 1000s Ah). This allows for flexible scalability in rural projects depending on system requirements. A typical stationary lead acid battery system can be seen in Figure 5.

<sup>&</sup>lt;sup>2</sup> The purchase price of an asset, plus the costs of operation, plus cost of decommissioning.



Figure 5: Stationary lead acid battery for rural electrification

Both vented/flooded and sealed maintenance-free Valve Regulated Lead-Acid (VRLA) batteries can be used in rural and remote applications, although VRLA remain the most prevalent due to their limited maintenance requirements and excellent performance. However, lead acid batteries have a limited cycle life and a reduced calendar life at low state of the charge.

The lifetime of lead acid batteries (its number of cycles) is strongly depending on the discharge depth that is applied to them as can be seen in Figure 6.



Figure 6: Typical lifespan of a stationary lead acid battery according to depth of discharge (Léna Grégoire 2014)

## b) Lithium-ion batteries

Lithium-ion batteries are a well-established technology for Consumer portable electronics, and are the technology of choice for use in Electric Vehicles. Since 2000, they have begun to enter industrial markets, where they feature:

- High energy density
- High energy efficiency
- Maintenance-free design
- Lighter weight
- Excellent charge acceptance
- Low state of charge do not limit the lifetime in comparison to lead acid batteries

For rural electrification systems, these characteristics make Li-ion batteries most competitive when volume, weight, cycling performance, energy efficiency and remote monitoring are more of a driving factor than initial cost.

In this research, the dynamic simulation of the battery has not been used because of the lack of research time. However, a static battery model with a fixed battery power has been used to show the effect of storage systems in PV-diesel micro-grids.

# 7 Identifying typical use-cases

As pointed out in section 6.1 there is no clear definition concerning the difference between small offgrid-systems and micro-grids. Such small systems can be extended in size and thus become microgrids. Examples for such systems that can be extended to the size of small micro-grids are:

- Mountain huts
- Antenna systems
- Weather stations and comparable data logging stations
- Farms
- Oil platforms
- Temporary events such as markets and festivals

On the other hand there are systems that mostly exceed a minimal size and thus are operated as micro-grids. The most important of these systems are presented beneath.

## 7.1 Rural villages

Many people living in rural areas in the poorer countries of the world don't have access to electricity. But the overall situation got better. The number of people without access to electricity fell below 1 billion in 2017 for the first time. But it is still a long way to go especially for some African countries as can be seen from Figure 7. The overall proportion of the population with access to electricity is at 43% for all of Sub-Saharan Africa.



Figure 7: Proportion of rural population with access to electricity (IEA data 2017)

Thus many villages don't have electricity access due to their remoteness and in many of those that have electricity, the energy is provided by diesel generators.

It is not possible to find one load profile that fits all villages of interest because the consumption schemes strongly depend on the daily behavior of the inhabitants and if the electricity is used for employment purposes. But assuming that no special loads are in use a typical electricity load profile can be identified:

- Base load at night mainly for lightning
- o The morning and mid-day load stemming from pumps, machines
- Peak in the evening (two to five times higher than night load) by lightning and consumer electronics



Figure 8: Typical electricity load profile of a rural village (Léna Grégoire 2014)

## 7.2 Districts

Most districts of cities are connected to the regional electricity grid such that no local power sources are needed to run the micro-grid. But there are some cases in which a district is powered by a diesel power plant the whole time or for certain periods of time. The main reason for the operation of an autonomous micro-grid is the instability of the regional power grid. Thinking of industrial districts that contain companies that have a complex process that takes allot of time to be ramped up or where machinery would be destroyed if the a shortage occurs it becomes apparent how important the reliability of the electricity supply may be. Such districts are of course mainly sited in poorer countries where the grid stability is low ('Weak Grids') or no electricity supply to the industrial district is possible. The generator plants can thus often be interpreted as back-up systems that nevertheless can run during a considerable part of the year. Even though it can be expected that a considerable number of these districts exist it is hard to find reliable numbers on their exact number and the corresponding fuel saving potential.

## 7.3 Health facilities

A secure and stable electricity supply is of crucial importance for most health facilities in the world. The life of some patients is directly depending on the functioning of the machine that is keeping them alive. Some diagnostics need to be performed in a very short period of time to be able to perform the necessary operations to save a humans life. Donated blood and some medicines needs to be stored at a constant temperature what is only possible if the cooling aggregates can be supplied with electricity.

That is the reason why all hospitals have their own backup system to prevent a catastrophic situation as consequence of a black-out. In many of the poorer countries there is no regional power grid available or the number of outages is so high that a health facility needs to be supplied by an autonomous micro-grid.

The organization USAID introduced a knowledge portal named Powering Health that supplies people working on the topic with technical background information and best practice cases (USAID 2019b).

The health facilities can be categorized in three types with respect to their size. These are small, medium and large size health facilities. Medium and large facilities will generally have one or several generators and can thus be of interest for PV integration.

A particularity of health facilities is that the quality of the electricity supply needs to be of high quality as a shortage could have severe consequences for the patients that are currently under treatment or who are dependent on a machine that keeps them alive.

## 7.4 Mines

Mining and extractive industries are capital and energy intensive and large mines are mostly located in remote areas where electricity is provided by large diesel generators. The amount of electricity that is consumed depends strongly on the kind of minerals that are extracted and the processes that are applied at the mine (Votteler und Brent 2016). But most of the mines are running 24/7 to be profitable and the load (hourly energy values) is characterized by a very constant profile.

Moreover, solar radiation conditions in many of the mining regions are favorable for PV. Therefore, it can be estimated that the fuel saving potentials in mining are very high, if PV is integrated in the system.

## 7.5 Refugee camps

For 2017 the UNHCR estimated that 68.5 million people were forced to leave their homes (UNHCR 2017). Many of these refugees are living in camps that were either planned for this purpose or that resulted from self-organized settling processes (see table 3).

Accommodation	Share
Planned/ managed camp	29%
Self-settled camp	6%
Collective Centre	2%
Individual accommodation (private)	61%
Reception/ transit camp	1%

Table 3: Types of refugee camps

The camps are very different in size and may have numbers of inhabitants that are in the order of small or medium cities. A UNHCR report from 2012 states that the mean number of refugees per camp is at 11400 (UNHCR 2012).

Many of the camps evolve to permanent settlements with generations of people that lived their entire life there.

Depending on the status of the camp there are different services that are needed for the maintenance of the camp. Many of these services require electricity. The most important of these are:

- Lighting
- Water distribution
- Health services
- Camp organization

- Schools and other educational institutions
- Entertainment (music, television, radio, etc.)
- Charging mobile devices

In most of the camps the electricity production is supplied with the help of diesel engines. The costs and the environmental issues associated with the operation of these generator plants can be reduced by including renewables such as PV into the system (Ossenbrink et al. 2018).

## 7.6 Islands

A large share of the global population is living on thousands of islands. It is not possible here to give a number for the islands that are of interest for the integration of PV in diesel power plants. But it is obvious that there are many with a potentially good business case. Many islands are too far away from the next coast where they could receive a connection to the electricity grid of the mainland. The diesel plants that are supplying many of the islands are generally very costly because of the fact that the fuel needs to be shipped in by boat. There are already many projects on islands where the local diesel power plant was supported by renewable energies and in some cases the island was even transferred to a 100% electricity supply system (SMA).

## 8 Three representative case studies

## 8.1 Simulation model

For this study a simulation tool was developed that was written in the widely used programming language Python. The tool includes all the technical aspects that are relevant for a PV diesel microgrid. It is important to note that the software is purely based on discrete energy balance calculations and does not use optimizer algorithms. This leads to a high advantage to comparable optimizer tools in terms of computation time. In the following sections the technical and economic basic parameters are described.

## 8.1.1 Technical parameters

For the simulation some key technical parameters need to be implemented in the simulation. One very important of these parameters is the minimum load factor (MLF). For this simulation the MLF is set to a value of 30 % even though many of the manufacturers propose a higher value.

Another important technical parameter for the operation of a diesel plant is the so called spinning reserve (SR). The value that is chosen for the SR strongly depends on the need for grid stability as described in section 6.2.5. For the simulation it is assumed that all generators run at 100 % power and only the last one in the cascade needs to hold the spinning reserve energy. In our simulation the SR value is set to 15 % of the nominal power of the corresponding generator.

The energy that the PV system provides may be too much especially for high penetration values. For the simulation it is assumed that the power electronic equipment is capable of reducing the power accordingly. Most of the todays inverters are able to reduce the output power of the PV plant by shifting the maximum power point (MPP) away from the optimal operation point.

The battery model that is used in the simulation is the simplest one imaginable. No losses and no aging processes are implemented. The optimal storage capacity of the battery is depending on

several parameters (especially on the load characteristics and the size of the PV system). Nevertheless for this report no optimization for the battery size was performed.

For the simulation a battery inverter is assumed that in case that all generators are switched off ("diesel-off-mode") is capable of forming the grid. It should be mentioned here that there are not yet many inverters that support grid parallel and grid forming capabilities.

It is important to keep in mind that the simulations were performed on an hourly basis. That means that some effects are not taken into account that might be of importance concerning the construction of a real micro-grid system. Especially transient effects such as start and stop characteristics of the diesel generators and the actual electrical charging and discharging power of the battery are not part of the simulation.

## 8.1.2 Economical parameters

To evaluate the economic potential of the integration of PV and batteries into an existing diesel micro-grid it is meaningful to calculate two different indicators. The first indicator is the amortization time that measures the time in years that are needed to get back the initially invested capital. The second indicator is a measure of how high the electricity costs are for the investigated system. The measure for this is called the Levelized Cost of Electricity (LCOE). The LCOE should not be compared between different studies, as it strongly relies on the parameters used, but it is well suitable to compare different systems with one another that are simulated within the same study.

Different assumptions on costs and prices are needed to calculate these two indicators. One central cost element is the cost of fuel. The costs are calculated as the product of the consumption in liters and the specific fuel price. The specific fuel price is estimated to be at 1.18 Euro per liter. This price includes the transportation costs of the diesel to the system under investigation. Here it needs to be emphasized that the fuel prices are strongly fluctuating. Neither inflation rates, potential price increases nor government subsidies and local support systems were included in these economic calculations. Additional simplifications that were assumed are:

- No credit costs were assumed, only the discount rate of 9% was used
- No taxes
- No additional transport costs for far remote places, e.g. only accessible by donkeys or small boats
- No operation and maintenance (O&M) costs implemented
- No variation of generator lifetime due to varying run-times

The specific costs for the initial investments and the specific fuel price are given in table 4

	Costs	Source
Photovoltaic system*	1550 Euro/ kWp	(Blechinger et al. 2016)
Battery system*	800 Euro/ kWh	
Generator System	580 Euro/ kW	(Blechinger et al. 2016)
Diesel fuel price	1.18 Euro/ liter	

The costs that are applied by 'Blechinger et al.' are based on average values of remote hybrid systems that were built up by the GIZ (Gesellschaft für Internationale Zusammenarbeit). They provide a good initial estimate to be made and make the results comparable, but they should be updated for individual cases to match better the framework conditions of the specific system design.

The comparably high specific price for the PV system is due to the fact that the remoteness of the system increases the overall costs and special inverters (including e.g. grid building capability) were included in the price determination.

The amortization time  $t_{am}$  is calculated in a very simple manner without including discount factors. The initial investment  $A_0$  is composed of the costs for the generators, the PV system and the battery. The annual income to pay back the investment  $Z_a$  consists of the savings due to the reduced diesel consumption.

$$t_{am} = \frac{A_0}{Z_a}$$

The amortization time is only one of the economic indicators. Even though it is telling us how many years we need to get our investment back and thus is an indicator for the investment risk another indicator is needed to evaluate the economics of the investment over the whole lifetime. The Levelized Cost of Electricity (LCOE) is one of these factors. It is important to note here that the LCOE is strongly depending on the assumptions the calculations are performed with. It is thus not recommended to compare these results to the LCOE values of any other studies. The LCOE needs to be used as a measure only to compare the results inside this study.

If the annual costs  $A_a$  as well as the annual energy yield  $E_a$  are assumed to be constant the following equation can be used for the estimation of the LCOE.

$$LCOE = \frac{A_0 + A_a \cdot \sum_{i=1}^n \frac{1}{(1+p)^i}}{E_a \cdot \sum_{i=1}^n \frac{1}{(1+p)^i}}$$

The *discount rate* p for the case studies was set to 9% as proposed in other studies (Blechinger et al. 2016). The project period of the LCOE calculation was chosen to be *20 years*.

#### 8.2 Results for the case studies

On the basis of the analysis given in section 7 three representative examples for diesel driven microgrids were chosen that are presented in the following. The three specific examples were selected primarily on the basis of their distinct load profiles, since these have a particularly large influence on the fuel saving potential and the LCOE. The three examples that were chosen are a hospital in Haiti with a load curve that fits well the PV production curve, a rural village in Nepal with load peak values in the morning and the evening and a mine in South-Africa with an almost constant demand curve. First an analysis of the corresponding dataset is given and then the results of a system simulation are presented.

## 8.2.1 Case study 1: Haiti - Hospital

#### Case Study 1: Haiti - Hospital

Location: Port Au Prince (18° 34' 15.05" N, 72° 15' 11.04" W), Haiti

**Description:** The presented hospital is actually consisting of three different hospitals and some educational institutions that are combined to a micro grid ("SolarSmartGridTabarre"). The grid is currently growing and further institutions and energy sources are added to the micro grid. The presented data are thus representing larger scale hospitals and cannot simply be transferred to small health centers. More information can be found on the homepage of the organization Nuestros Pequenos Hermanos (NPH 2017).

**Data Collection:** The data consist of hourly energy values. Thus the short term peak loads cannot be seen in data.

**Generators:** In the simulation four generators with 600 kW nominal power each was assumed as diesel power plant. In the reports on the system contradicting information were given on the power of the generators. But the ratio of the total generator power and the maximum load is 1.3 for the assumed generator power plant and thus seems to be realistic.

#### Peak value (kWh/h) and annual energy consumption: 1.8 MWh/h and 914 MWh



#### Load- and PV-data analysis:

Figure 9: Analysis of the load data and the normalized PV data for a hospital complex in Haiti

Regarding the daily load curves all stacked in the left top graph it can be seen that the variation is comparably small and a clear increase at midday can be observed. This fits well the PV energy as can be seen in the left bottom figure.

#### Analysis of the simulation results:

In Figure 10 it can be seen that the integration of PV based on peak power leads to a reduction of fuel consumption. This is either due to a reduction of the nominal power share at one of the generators or by switching off one or several of them.



Figure 10: Reduction of fuel consumption due to PV integration (black full line), amortisation time (red interrupted line), reduction factor for the added runtime of the generators (blue dot-dash line)

The fuel saving curve follows a linear path up to a PV penetration of about 1. For higher PV penetration levels the fuel saving potential is reduced. This is due to the fact that the mismatch between the demand side and the PV generation is increasing. That means that there is actually no generator left to be switched off.

This reduction in fuel savings leads to a negative influence on economic efficiency, so that the payback period of the solar system also increases. For the region where the fuel saving graph is linearly increasing the amortization is slowly increasing from 3 to 3.5 years of amortization time.

The minimum LCOE can be achieved at a PV penetration ratio of about 1.1 where the costs are at 27 cents and thus 6 cents lower that for the case without PV.

Even though the amortization time strongly increases at PV penetration values higher than 1.1 it can still be interesting for an investor to go to higher penetration values, as the time the generators are running is further reduced. Like this the noise of the machines is reduced and the life-time of the generators can probably be increased.

## 8.2.2 Case study 2: Rural village in Nepal

#### Case Study 2: Rural village in Nepal

Location: Upper Ghandruk (28° 27' 53" N, 83° 49' 33.92" E), Gandaki District, Nepal

**Description:** A small isolated town on a trekking route in the Annapurna massif. It has approx. 350 households along with small shops, hotels and restaurants for tourists. No national electricity has reached there and there is no possibility for grid extension. Even though the electricity production in Upper Ghandruk is supplied by a micro-hydropower plant the village is chosen here as example because of its representative characteristics. Many other villages in the Himalaya and other regions of the world have comparable load profiles.

**Data Collection:** The data were recorded at the micro-hydropower plant that supplies the whole village with electricity. The data was converted to hourly energy values.

Generators: 2 x 50 kW

#### Peak value (kWh/h) and annual energy consumption: 79 kWh/h and 414 MWh



#### Load- and PV-data analysis:

#### Figure 11: Analysis of the load data and the normalized PV data for a village in Nepal

The stacked daily load profiles show a peak in the morning and one in the afternoon. This does not totally fit the simplified profile presented in 7.1. This might be due to the fact that the village under investigation is dominated by tourism with differing load characteristics.

#### Analysis of the simulation results:



Figure 12: Reduction of fuel consumption due to PV integration (black full line), amortisation time (red interrupted line), reduction factor for the added runtime of the generators (blue dot-dash line)

The analysis of the simulation results for the rural village in Nepal shows strong deviations from the results of the Haiti case. The overall fuel saving potential is much lower for the village. This is due to the fact that there is a strong mismatch between the PV generation and the consumption. A high share of the consumption takes place in the morning and evening times when the solar production is not very high. At noon when the main production takes place the consumption is comparably low.

This also reflects in an amortization curve that is not flat as in the case of Haiti but it shows two linearly increasing regimes. Up to a PV penetration of 0.5 the amortization time is lower than 4 years, but the slope strongly increases for higher penetration values.

The mismatch between production and consumption can also be seen in the on-time reduction curve. The maximum value that is reached for a PV penetration factor of 2 is at about 0.65. In the Haiti case-study a value of 0.55was reached.

The lowest LCOE is reached close to a PV penetration of 0.7 with a value of 0.31. The cost reduction is thus only 2 cents what is low compared to the 6 cents that can be save in the Haiti case.

#### 8.2.3 Case study 3: South African mine

#### **Case Study 3: South African mine**

Location: Mining region near Johannesburg

Description: Iron ore mine

**Data Collection:** No detailed demand data was available for the system and therefore a synthetic data for iron ore extraction and processing was used (Donald I. Bleiwas 2011).

Generators: 4 x 2.25 MW

#### Peak value (kWh/h) and annual energy consumption: 6.9 MWh/h and 53 GWh

**Load and Results:** From the load profile, it is obvious that the load demand is almost constant throughout the year. This is because the mine operates day and night and creates a relatively constant load profile.

#### Load- and PV-data analysis:



#### Figure 13: Analysis of the load data and the normalized PV data for a mine in South-Africa

The load characteristics of the mine presented here is very constant over the whole day and year. As this is a generic load profile dominating events such as failure, repair or replace events are not taken into account. And it is important to keep in mind that hourly load data were used obscuring the fact that some processes in the mine are batch processes leading to high load peaks. As the rotating

masses of the generators can overtake short events of this kind and the generators are oversized accordingly the simulation presented here is still giving a realistic scenario.

#### Analysis of the simulation results:



Figure 14: Reduction of fuel consumption due to PV integration (black full line), amortization time (red interrupted line), and reduction factor for the added runtime of the generators (blue dot-dash line)

The results of the South-African mine simulation show values that are quite different compared to the Haiti and the Nepal case-study. The increase of the fuel saving curve is linear up to a PV penetration of 1.2. This also results in low amortization times of about 3 years for the penetration factor of 0.875.

The lowest LCOE is reached at a PV penetration value of 1.35 with a value of 27 cents. This is 5 cents less than the electricity price is without PV. Interestingly the LCOE is at 28 cents at the very high penetration value of 2 and thus comparably low. However the amortization time of 4.6 years is much longer than for the lowest LCOE value.

## 9 Integrating a battery into the PV diesel micro-grid

Many of the systems that are of interest in this study can potentially profit from the integration of a battery storage system. One main reason for such an integration can be the increasing share of PV self-consumption and hence a further reduction of the fuel consumption. The influence on the Levelized Cost of Electricity (LCOE) will be investigated for the three case-studies in the following.

Finding the right size of a battery system for a diesel driven micro-grid is an optimization task that needs to be performed for every individual case. In this study the focus does not lie on the optimal battery size but on the principal effect that storage may have on the economics of such a system. Thus a rule of thumb was derived that is sufficient for following analysis. For this the village in Nepal with an average hourly load of 47 kWh/h was used as case study for a variation of the battery size. The results for 7 different battery sizes can be seen in Figure 15. It can be seen that compared to the case without battery for high penetration factors (>1.3) all LCOEs are lower. However the lowest LCOEs are achieved with comparably low capacities (30 kWh and 60 kWh) at penetration factors between 0.6 and 1. The maximum load taken from the data is 79 kWh. From this the rule of thumb is taken that storage with 30% of the maximum load value can lead to optimal LCOE reductions.



Figure 15: Fuel saving potential and LCOE for the Nepal case study with 7 different battery sizes

Following this rule storage system of 24 kWh was chosen for the Nepal village case leading to the results presented in Figure 16. It is important to note that the LCOE at a PV penetration of 0 is 1 cent higher compared to the system without battery presented above. Of course such a system is not presenting a realistic case as no PV is available to charge the battery.

The lowest value that can be achieved is found at a penetration level of 0.7 and is at 30 cents. This is also 1 cent lower than the lowest value that could be achieved at the system without battery.



Figure 16: Fuel saving potential, on-time reduction and amortization time as a function of the PV penetration factor for the Nepal case-study with a battery storage of 24 kWh corresponding to 30% of the maximal load

In Figure 17 the results for the simulation of the Haiti – Hospital case study is presented including battery storage with a capacity of 540 kWh corresponding to 30% of the maximal load the average hourly load is 104 kWh/h. We see that the amortization curve shows a minimum at a PV penetration factor of about 0.875. Here the amortization time is at a value of around 3.7 years.



Figure 17: Fuel saving potential, on-time reduction and amortization time as a function of the PV penetration factor for the Haiti case-study with a battery storage of 540 kWh corresponding to 30% of the maximal load

The presence of such a minimum in the amortization curves is due to the fact that the battery is not often charged by the PV system, because most of the solar energy is directly consumed by the loads in the system. When the PV penetration factor increases more energy surplus can be stored in the battery and thus less energy is lost. The PV system size is reaching an optimum, as on even bigger PV Penetration rates, the battery is not capable to absorb the surplus energy and again solar energy is lost.



Figure 18: Fuel saving potential, on-time reduction and amortization time as a function of the PV penetration factor for the South-Africa case-study with a battery storage size of 2070 kWh corresponding to 30% of the maximal load

For the South-African mine with an average hourly load of 6.0 MWh/h the simulation results are presented in Figure 18. We see that amortization values of 3.5 years can be reached for a comparably high PV penetration level of 1.1. Even for the very high PV penetration level of 2 the amortization time is only 4.75 years.

The lowest LCOE again is the same as for the simulation without storage. However the price could be reduced for a very high penetration level of 2 by one cent.

## **10 Results**

The systems under investigation were typical diesel driven micro grid use cases, a Hospital complex in Haiti, a rural village in Nepal and a mine in South-Africa with quite different electric demand profiles. To get comparable results for all systems the same specific component costs were assumed. For individual cases the costs should be adjusted to better match the framework conditions of the system under investigation.

The following results are only possible if the listed technical conditions are given. If these technical conditions are not given the fuel savings and the LCOE reductions are 2 till 3 times lower.

- In order to not only enable high PV penetrations, but as well constant grid stability, a fast reacting and reliable diesel generator control unit including a fuel saver it required
- Adjusting the diesel plant structure by-resizing and cascading of the diesel units to account for the PV contribution (e. g. adding a low-load generator unit to the plant)
- Apply diesel generators which can reliably operate at 30% load factor

The results are valid only for regions that do not show a particularly high reduction of solar radiation during winter. In regions where the solar radiation during winter is very pronounced the fuel savings are lower and the LCOE and amortization time is longer.

The simulations showed a reduction of fuel consumption and the levelized costs of electricity (LCOE) for all systems and all PV penetration levels based on peak power except for very high PV penetrations (> 150%) for the case of the rural village in Nepal. The benefits were particularly high for the Hospital case in Haiti where the demand fitted very well the PV production curve and the mine case in South-Africa where the load was extremely constant on a high level.

Concerning the minimum value of the LCOE the PV penetration levels for the three case studies were very different. For the hospital in Haiti a PV penetration level of 110% was found as optimum leading to a fuel saving of about 30% and a cost reduction of about 6 cents. For the rural village in Nepal the minimum was found at a penetration level of about 65% resulting in only about 12% of fuel saving and two cent price reduction, caused by a high demand in the morning and the evening which do not fit with the PV production curve. Reducing in the Nepal case the minimum load factor of the diesel generators from 40 % to 0% the LCOE can be reduced by 1 cent and the fuel savings increased by 4%. For the mine in South-Africa a minimum LCOE value was simulated for a PV penetration of 135%. Here a fuel saving reduction of about 27% and a LCOE reduction of about five cents could be achieved.

By adding a battery to a PV diesel system, the LCOE remains the same or even decreases slightly in the case of the rural village were the demand do not fit well with PV production curve, but allows for higher PV penetration and a higher fuel saving of about 5%. As a rule of thumb, a small battery capacity of 30% of the maximum load value which acts as spinning reserve could be assumed to be reasonable, depending on the battery system cost that was estimated with 800 Euro/ kWh.

# **11 Recommendations and Lessons learned**

The integration of PV into diesel driven micro grids reduces the fuel consumption and the levelized costs of electricity (LCOE). In order to achieve this, the following technical findings were identified and listed below:

- Small PV penetration shares of 5-50% based on peak values can be integrated relatively easy
  without additional control. The maximum acceptable PV power without a fuel save controller
  can be calculated by subtracting the minimum load of diesel generator (if several generators
  are used the smallest one is chosen) from the minimum demand at noon.
- Higher shares of PV penetration require a suitable energy management such as a supervisory engine and generator control with an integrated fuel save controller.
- In order to not only enable high PV penetrations, but as well constant grid stability, a fast reacting and reliable diesel generator control unit it required.
- Battery systems can compensate for the required spinning reserve to enable diesel-off mode and further increase the renewable share.
- When purchasing new or repowering old generators, the sizing of the diesel generator setup should be reconsidered by adapting the diesel aggregates to the load conditions and the PV contribution (e.g. adding different generator sizes and/or low load generator units to the system).
- Adding a demand side management that sheds or adds dispatchable loads (e.g. water pumping, cooling/heating, etc.), can be a very effective way to raise the renewable share.

General and economic findings concerning the sizing and integration of photovoltaic and batteries are given here:

- 1) The Integration of PV always makes economic sense.
- 2) A reduction of the levelized costs of electricity (LCOE) and fuel consumption for all systems was found for PV penetrations < 150%.
- 3) To estimate the appropriate PV penetration, the fuel savings and the LCOE a system simulation and sizing is necessary.
- 4) Depending on the use case and the system control, different PV penetration levels are reasonable.
- 5) Without a fuel save controller PV penetrations of 5-50% will result in relative low fuel savings of 1% till max 10%.
- 6) For higher PV penetrations a fuel save controller must be implemented. In such cases the optimized PV penetration is often between 65% and 135% which result in fuel savings of 10% till max 30% (if finding 7 is realized).
- 7) The fuel reduction potential can be increased if cascaded generators are used in the system and even more if they accept a low minimum load factor (MLF).
- 8) If the electrical demand fits well with the PV production curve, higher values of the fuel savings mentioned above are achievable.
- 9) If the demand do not fit well to the PV production curve e.g. for rural villages (demand peaks in the morning and evening), only the lower values of the fuel savings mentioned above are achievable.

- 10) For consumption cases where the load is quite constant at day and night like in the case of a mine, high PV-penetrations higher than 130% can be chosen.
- 11) The integration of batteries can act as a spinning reserve and enable diesel-Off Mode when the battery inverter is able to build the grid. This avoids inefficient low load operation of the diesel generator. In addition it can increase the fuel saving and decrease the LCOE.
- 12) The payback (amortization) curve for systems with integrated small battery storage, e.g. with a capacity of 30% of the peak load value (0.5-1h storage time), shows a local optimum. With this optimum the payback time is in the range of 4 years, please note that these values were calculated for specific (conservative) battery costs (including battery inverter) of 800 Euro/kWh.
- 13) Even though larger storage capacities can lead to an increase in LCOE, this can make sense from the point of view of CO2 reduction. Furthermore with help of a larger battery the runtime of the engines can be reduced and thus a decrease in noise pollution can be achieved.
- 14) The integration of batteries with storage times between half a day and one day allows (especially in cases were the demand do not fit well the PV production curve) higher fuel savings up to 30% but also makes the LCOE increase. Particularly if the battery prices are further reducing and the diesel prices are remaining on a high level the increase of the LCOE will be moderate or negligible.
- 15) For regions where the solar radiation is reduced significantly during winter, the fuel savings are lower and the LCOE and amortization time are higher.

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ISBN 978-3-906042-85-5