IEA INTERNATIONAL ENERGY AGENCY

Rural Electrification with PV Hybrid Systems

Overview and Recommendations for Further Deployment




PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

PVPS

Report IEA-PVPS T9-13:2013

INTERNATIONAL ENERGY AGENCY PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

CLUB OF AFRICAN NATIONAL AGENCIES AND STRUCTURES IN CHARGE OF RURAL ELECTRIFICATION (CLUB-ER)

Rural Electrification with PV Hybrid Systems

Overview and Recommendations for Further Deployment

IEA PVPS Task 9, Subtask 4, Report IEA-PVPS T9-13:2013

CLUB-ER, Thematic Paper

July 2013

ISBN : 978-3-906042-11-4

Author: Grégoire Léna (IED)

Contents

List of Figures and Tables

Foreword

This document is a joint publication of the IEA PVPS (International Energy Agency's Photovoltaic Power Systems Programme) Task 9 and the CLUB-ER (Club of African National Agencies and Structures in charge of Rural Electrification). It essentially builds upon past work undertaken by IEA PVPS Task 9 experts and training sessions and field surveys undertaken in the framework of the CLUB-ER activities. This publication has also benefitted from inputs from Task 11 of IEA PVPS (PV Hybrid Systems within Mini-grids), publications by the Alliance for Rural Electrification (ARE) and the International Renewable Energy Agency (IRENA). References to documents published by these institutions are listed in the Appendix.

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) that carries out a comprehensive programme of energy co-operation among its 23 member countries. The Copper Alliance, the European Commission, the European Photovoltaic Industry Association, the Solar Electric Power Association and the Solar Energy Industry Association also participate in the work of the Agency.

The **IEA Photovoltaic Power Systems Programme (IEA-PVPS)** is one of the collaborative R & D agreements established within the IEA and, since 1993, its participants have been conducting a variety of joint projects in the applications of photovoltaic conversion of solar energy into electricity.

The 23 participating countries are Australia (AUS), Austria (AUT), Belgium (BEL), Canada (CAN), China (CHN), Denmark (DNK), France (FRA), Germany (DEU), Israel (ISR), Italy (ITA), Japan (JPN), Korea (KOR), Malaysia (MYS), Mexico (MEX), the Netherlands (NLD), Norway (NOR), Portugal (PRT), Spain (ESP), Sweden (SWE), Switzerland (CHE), Turkey (TUR), the United Kingdom (GBR) and the United States of America (USA). The European Commission, the European Photovoltaic Industry Association, the US Solar Electric Power Association, the US Solar Energy Industries Association and the International Copper Alliance are also members. An Executive Committee composed of one representative from each participating country or organization heads the overall programme. The management of individual Tasks (research projects / activity areas) is the responsibility of Operating Agents. Information about the active and completed tasks can be found on the IEA-PVPS website www.iea-pvps.org .

The CLUB-ER

The **Club of National Agencies and Structures in charge of Rural Electrification (CLUB-ER)** is an operational working group dedicated to rural electrification in Africa. The CLUB-ER aims to accelerate the development of rural electrification in Africa by creating the conditions for a mutually beneficial sharing of expertise and experience between African agencies and national structures in charge of rural electrification. It is a network of over 30 public entities from 25 African countries: rural electrification agencies, regulatory agencies and commissions, rural electrification funds and national electricity companies having the mandate to implement the national policy on rural electrification.

Since its foundation in 2002, the CLUB-ER benefits from the funding provided by the French Agency for Environment and Energy Management (ADEME) and by the IEPF (Institut de l'Énergie et de l'Environnement de la Francophonie). Since 2008, CLUB-ER is also co-funded by the European Union through the ACP-UE Energy Facility, contract N° FED/2011/231-815, with one of the objectives being the publication of thematic documents and position papers that reflect the activities carried out by the CLUB-ER.

Acknowledgements

This report received valuable contributions from several international experts. Many thanks are due, in particular, to Erik Lysen, Anjali Shanker (IED), Caroline Nielsen (SERC), Michael Wollny (SMA), Georg Bopp (Fraunhofer ISE) and Brisa Ortiz (Fraunhofer ISE).

Abstract

The state of the art of PV / diesel hybrid systems for rural electrification is presented and the main issues to address – from the design, technical and implementation perspectives – are highlighted. Guidance is provided to enable sound decision making when considering solar PV hybrid systems to address rural electrification needs. Hybrid systems are explained and their markets and planning parameters are outlined. Issues relating to system sustainability and effective deployment are examined.

Executive Summary

Lessons from past projects show that, beyond problems related to the technology, many failures are due to inappropriate or unclear organizational schemes to operate and maintain the system and to the lack of appropriate energy management concepts.

With decreasing PV prices, PV / diesel hybrid minigrids attract significant attention from institutions in charge of rural electrification and donor agencies - to mitigate fuel price increases, deliver operating cost reductions, and offer higher service quality than traditional single-source generation systems. The combining of technologies provides interesting opportunities to overcome certain technical limitations.

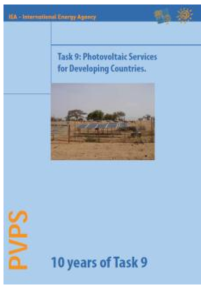
The future deployment of hybrid technology in developing countries will be driven by different factors according to the type of application addressed. The micro-hybrid system range for use as a reliable and cost-effective power source for telecom base stations continues to develop and expand. The development of small distributed hybrid generation systems for rural electrification to address the needs of remote communities will rely on the impetus given by institutions in charge of providing public services to rural customers. Capacity building and access to concessional financing will be the key enablers for the development of this segment. Medium-size distributed hybrid systems need political momentum to foster the involvement of the private sector. Larger isolated minigrids require substantial investments and then appropriate profitability. The question of the extension of the grid to these places is critical. The private sector should play a decisive role as investor and supplier of turnkey systems.

Lessons from past projects show that, beyond problems related to the technology, many failures are due to inappropriate or unclear organizational schemes to operate and maintain the systems and to the lack of appropriate energy management concepts**.** The main observed causes of weakness in the systems are: poor understanding of users and unplanned increases in the load, inadequate revenue, unavailable after-sales service, and unsuitable ownership models.

Applying solar PV technology to reduce generation costs in diesel plants requires significant capital / investment amounts compared to the more traditional types of projects that rural electrification funds and agencies have been familiar with so far. PV / diesel hybrid systems bring technical complexity in areas where skills are generally lacking. The development of a more secure environment is still necessary for private investors to be willing to participate. In addition, the lack of locally available after sales service and skilled personnel is hampering the development of this technology in the rural electrification sector. Public-private partnerships need to be promoted and facilitated. For the sustainability of the projects, local buy-in by the communities and end-users is essential. Adequate capacity building and training courses for local operation and maintenance will be necessary to ensure long-term viability. Agencies should encourage the involvement of local authorities from project planning to project implementation and monitoring, and additionally for local operation and maintenance.

Introduction

Photovoltaics, and other renewable energy technologies, can significantly contribute to economic and social development. To date, about 1.5 billion people in the world, many of whom live in isolated areas, still do not have access to electricity and to clean water, primary health care, education and other basic services; the impact of which to a large extent depends on access to electricity. In 1998 the IEA PVPS Executive Committee decided to form a new Task to more effectively address these issues. This was the very first IEA activity targeting non-OECD countries. In its first ten years, from 1999 to 2009, **Task 9** has dedicated its activities to the development of *'PV Services for Developing Countries'*. Recommended Practice Guides were produced covering issues such as programme design, institutional frameworks, sources of financing and business models, quality management and capacity building. The lessons learned were summarized in the publication "*10 years of Task 9*".



Responding to both the demand from various organizations, governments, banks and development agencies and to rapid technological developments, the scope of Task 9 was broadened in 2010 to '*Deployment of PV Services for Regional Development*'. Its activities cover:

• PV for rural community needs
• PV for minigrids and hybrid systems
• Integration of PV in the urban environment
• Large-scale PV systems

CLUB-ER activities (workshops, training, publications, participation in international conferences) revolve around five working themes:

• Theme 1: Strengthening of the impact of rural electrification on poverty reduction and sustainable development;
• Theme 2: Organizational charts of rural electrification, emergence of national private operators and cross-border electrification;
• Theme 3: Tools and technologies to serve rural electrification planning including Geographic Information Systems;
• Theme 4: Technical specifications adapted to rural electrification and cost reduction;
• Theme 5: Financial aspects of rural electrification (national and international funding mechanisms, pricing, taxation) and regulation.

In 2011, following an identification survey covering existing hybrid systems in West and East Africa, the CLUB-ER organized two training workshops on PV / diesel and wind / diesel hybrid solutions for rural electrification for its member organizations' engineers and technicians. Major manufacturers of specific product solutions for distributed generation operating in Africa were invited. This paper builds extensively on the inputs, analyses and exchanges from these workshops.

Scope of the document and target audience

This publication aims to present the state of the art situation of **PV / diesel hybrid systems for rural electrification** and to highlight the main remaining issues – from the design, technical and implementation perspectives. This document does not cover diesel hybrids using other renewable energy technologies. It also explicitly focuses on rural electrification, and primarily on rural minigrids. This document may lead to follow-on publications.

Decision makers from institutions in charge of rural electrification planning, electrification funds or donor agencies, as well as private stakeholders, will find within the document valuable information for sound decision making when considering solar PV hybrid systems to address rural electrification needs.

1 Hybrid systems: definition and expected benefits

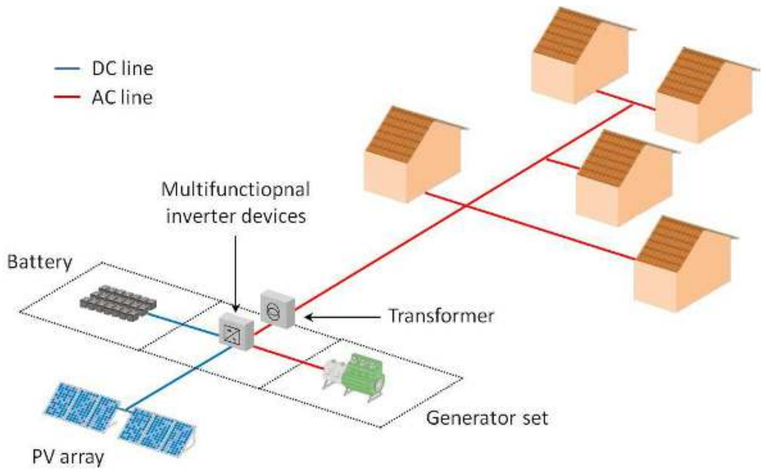
1.1 A context of new opportunities

The progressive electrification of areas not yet interconnected to the main electricity grid and too remote for grid extension has mainly been achieved through installation of decentralized generation units with diesel gensets and, to a lesser extent, via systems using a local renewable resource, such as solar PV stand-alone systems.

Each of these two technologies has its own limitations: the diesel genset option suffers from increasing fuel prices, added cost for both fuel transportation to remote areas and for operation and maintenance in remote areas, as well as genset inefficiency when run at low load factors; meanwhile solar energy is an intermittent energy resource, which requires storage when not used during generation time (daylight hours) and implies a high upfront investment cost but low operating costs. Combining both technologies makes it possible to offset some of these limitations. For this reason, PV / diesel genset hybrid-systems offer interesting opportunities and can be used productively within local minigrids.

A hybrid generation system is a system combing two (or more) energy sources, operated jointly, including (but not necessarily) a storage unit and connected to a local AC distribution network (minigrid). As PV power output is DC and minigrids operate in AC, at the heart of the hybrid system are the multifunctional inverter devices able to convert DC and AC currents, control the generation and storage systems and set up the voltage and frequency of the minigrid[1].

Figure 1: Schematic view of a PV / diesel hybrid system for rural electrification



The local minigrid might eventually be connected to the national grid. In that case, the existing hybrid generation facility would compete with centralized generation on the basis of generation cost, (generally higher than centralized generation cost) and on service availability and reliability (potentially an advantage versus supply from the national grid which is often being affected by blackouts and limited service availability in rural areas). In addition, the connection of such a minigrid to the national grid can provide stability to the public grid.

This document addresses PV / diesel hybrid systems consisting of a PV component, a diesel genset and a battery bank, connected to a minigrid of various sizes: From small village grids to larger sizes such as the independent grid of a small town. Micro hybrid PV / diesel systems without the minigrid are also

[1] The various functions listed here can either be performed by a central component (as shown in the schematic view) or by several distinct components connected between each other with a DC or an AC bus.

included. Solar PV plants connected to national or regional grids, without storage capacity, are not within the scope of this document.

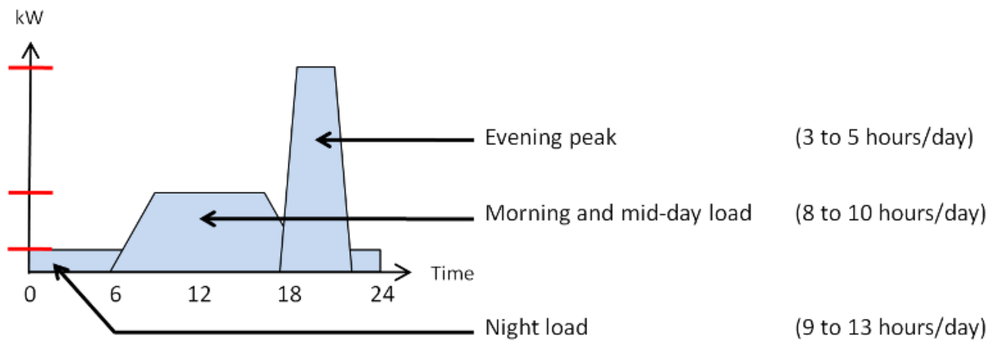
In the current context of the decrease in PV panel prices, PV / diesel hybrid minigrids attract significant attention from institutions in charge of rural electrification and donor agencies, mainly due to mitigation of the fuel price increase plus an expected operating cost reduction, and the possibility to offer higher service quality with a hybrid system than with traditional single-source generation systems.

1.2 Characteristics of a hybrid solution in a typical power plant for rural areas

Typical context of power needs in rural areas

The typical load curve for a rural village is generally composed of a prominent peak in the evening corresponding to lighting use, a morning/midday peak, and a base load. The base load is generally present in the morning, and in some cases extends to night hours. In many cases the peak load is two to five times higher than the highest power level of the base load. The energy demand in rural areas during night hours is quite limited (or non-existent in small villages) and hence the load level during the night is generally very low compared to the evening and morning peaks.

Figure 2: Typical load profile in rural areas



Generation systems consisting only of diesel gensets are generally not run to supply a very low load over several hours because, at a low load factor, gensets suffer from degradation, plus the highly inefficient fuel consumption makes this economically unviable. That is why the potential energy demand in the night is not served in small villages. The significant difference between morning and evening demand levels favours the use of two different gensets to better match these load levels.

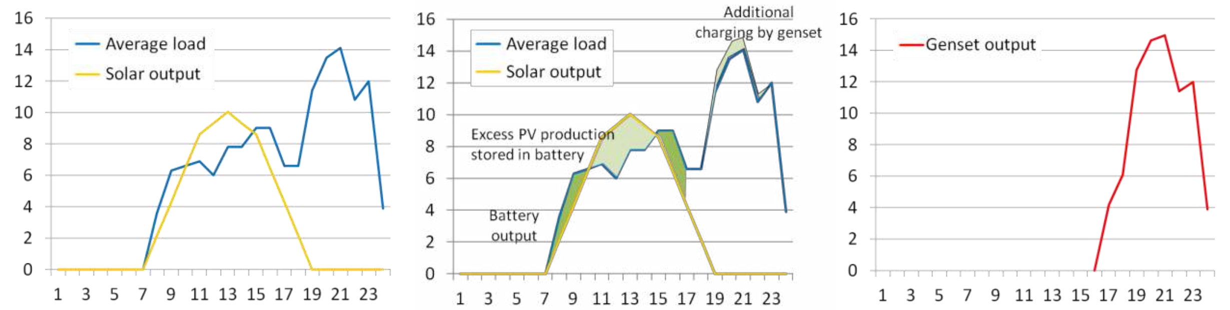
Advantages of hybrid systems in this context

In this context, hybridization with PV and a battery bank provides the opportunity to supply a low load for many hours overnight using a battery system and, according to the installed PV capacity level, to cover partly or fully the morning and mid-day load. The diesel generator is used to cover the evening peak and complete the battery charge if required[2].

[2] This is not the only way to run a PV / diesel hybrid system. For instance, the renewable energy, through its storage in the battery bank can be used to provide additional power to meet spikes in power demand and reduce the load on a genset that would run continuously. Between these two different operational strategies many others exist. This paper focuses on the strategy detailed above because it appears as the most relevant one for the typical conditions encountered in the electrification of rural villages in developing countries. More information is available in [12] and [13].

The following figures are based on the load curve of an actual diesel genset power plant supplying the village of Ain Ehel Taya in Mauritania[3]. The figures show the actual production of the existing 55 kVA diesel genset today (average daily load curve) and after adding a 16 kWp PV system with 150 kWh battery, for a daily energy demand of 140 kWh.

Figure 3: 16 kWp hybrid system in Mauritania: average daily load curve, solar output, battery and genset use (values in kW)

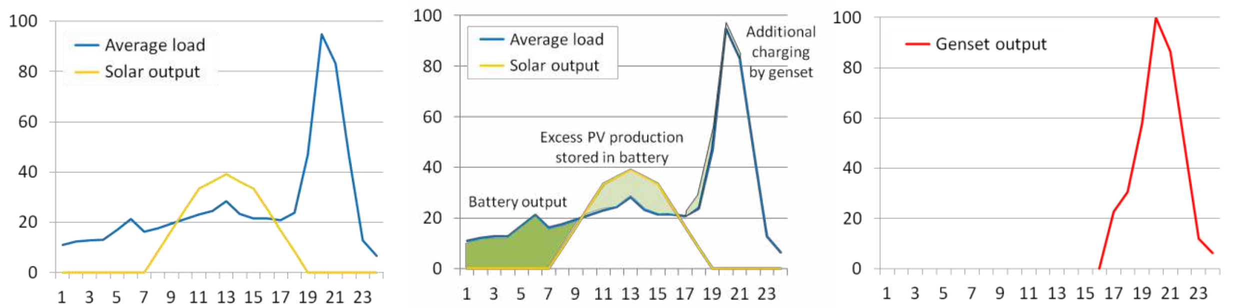


Source: IED

Here the yearly PV penetration rate[4] is 35%. Hybridization significantly reduces fuel consumption, improves genset performance (because genset running hours at low load are reduced), reduces genset usage and thus extends its lifespan.

The following figures show the production of a 70 kWp PV system with 600 kWh battery added to a diesel plant equipped with three diesel gensets (73, 125 and 175 kVA) in Cambodia, currently being studied.

Figure 4: 70 kWp hybrid system in Cambodia: average daily load curve, solar output, battery and genset use (values in kW)



Source: IED

In this case the PV penetration rate is 45%. Hybridization allows supply of the base load with battery instead of using a small genset for 16 hours a day, which would result in poor performance and a shortened lifespan.

[3] This diesel genset power plant was installed in Ain Ehel Taya in 2007 with co-funding from the Agence Française de Développement and the Mauritanian Government.

[4] The PV penetration rate is calculated by dividing the amount of energy produced by the PV system by the total amount of energy delivered by the hybrid power plant over a year. This is different from the instantaneous penetration rate that, at a given time, is the ratio of the power produced by the PV system and the active power consumption of the loads.

Remaining issues

Major issues appearing while shifting from a pure diesel model to a PV / diesel hybrid model are related to access to funding, increased technical risks and the need for more qualified personnel.

Funding

Because of their low population density and scattered settlements, providing electricity services in rural areas is difficult to achieve without any kind of subsidy system. This is true for genset-based solutions as well as for hybrid systems.

Existing subsidy schemes for distributed generation include subsidy on investments (equipment for generation and infrastructure, customers' connections, etc.) and subsidy on operating costs (typically subsidy on fuel expenses borne by local operators).

→ In countries where electricity is subsidized (end users do not pay the real cost of power) this implies that shifting from a conventional genset-based power plant to a PV / diesel hybrid system induces a displacement of the subsidy from the operating costs to the initial investment. This is a significant change for the public authorities in charge of subsidizing rural electrification. It also brings a change of perspective for the donor agencies.

→ Where the investors are private companies, it raises the issue of the willingness of investors to tie up investment funds over a period of a minimum of 10 years, plus the ability to raise funds for such capital-intensive investments.

Need for more qualified personnel

The technology shift induces a change in the required technical skills of operators and installers. This creates new opportunities for local distributors of equipment, but keeping skilled personnel in rural areas is sometimes difficult.

→ Capacity building, training, promotion of the technology and support allocated to local equipment and service providers should be part of a comprehensive approach to foster the development of this technology in developing countries.

Technical risks

Batteries and inverters introduced in the system bring additional technical risks compared to systems based on diesel gensets only.

→ Availability of spares, distribution channels reaching rural areas, and after-sales service for troubleshooting with electronic inverters is fundamental in ensuring continuity of service. Bundling projects to cost-effectively service the systems and dispatch spares can help to address this issue.

General highlights regarding advantages and issues of hybrid systems

- Today the main advantage of hybridizing a diesel genset power plant is the ability to provide a better service quality with extended service hours, together with a reduction in fuel use and genset usage.
- PV / diesel hybrid technology still needs to be subsidized for rural electrification.
- This technology is significantly more complex than simple diesel gensets.

2 Current status of PV / diesel hybrid installations

2.1 Overview of the development of hybrid technology in Africa

This section is based on information shared by representatives of rural electrification agencies and other institutional member of the CLUB-ER during two workshops on hybrid systems held in 2011 in Mali and Kenya. These workshops gathered together delegates from 40 African public institutions, companies and representatives of manufacturers and operators, during which lessons learnt, technologies and design, current status in each country and future plans were discussed.

Mali

Mali has the largest installed PV / diesel hybrid minigrid in Africa: A 216 kWp system implemented in 2011 thanks to cooperation between the national utility EDM and a private operator with funding from the Malian Bank for Commerce and Industry. Presently, the World Bank and the AfDB are funding a project (SREP), including a hybrids component, that plans to implement PV arrays in existing diesel power plants in 40 localities comprising a total of 5 MWp PV and a total investment budget of 58 million USD (11,600 USD per kWp PV). Another programme managed by the rural electrification agency (AMADER) is currently hybridizing 17 localities for a planned total of 1 MWp PV power. Several private operators plan to add PV capacity to diesel power plants (Kama SA: 300 kWp, SSD Yeelen Kura: 300 kWp planned in addition to existing 72 kWp hybrid plant, and Tilgaz: 22 kWp).

Senegal

Senegal has been one of the most active African countries in the implementation of hybrid technology. With Isofoton from Spain, a 13 billion FCFA (20 MEUR) programme has implemented nine hybrid power plants in remote areas and islands in the Saloum Delta to provide electricity service to 5 000 households and several productive activities. In association with GIZ and DGIS Netherlands, a 685 million FCFA (1 MEUR) programme has implemented 16 hybrid power plants (5kWp PV, 11 kVA diesel each) and an extension of this programme plans to add 50 more hybrid systems. Two larger hybrid power plants are planned on islands in Casamance (30 kWp PV and 50 kVA diesel each).

Tanzania

Tanzania's Rural Electrification Agency (REA) perceives hybrid technology as one of the solutions to provide reliable and affordable electricity supply in isolated areas. Private developers presently manage the development of hybrid systems while REA provides support to developers through capacity building, technical assistance, promotion of the technology and awareness raising. REA is planning to use various financing schemes to further develop hybrid technology.

There are currently several hybrid systems installed, mainly in the range of 1 to 10 kWp PV. There are plans to implement systems that include wind energy.

Rwanda

Since 2007, PV / diesel hybrid systems have been installed in 50 remote health centres (typically with gensets rated at 16 to 20 kVA and 3 to 6 kWp PV arrays). Diesel generators are used as back up to PV supply. Hybrid systems are owned by beneficiaries and are financed through grants from different international development partners working with the Ministry of Health. These systems have reduced fuel consumption and enabled the use of new medical equipment, but maintenance remains a challenge for the beneficiaries.

Mauritania

In 2013, with 2.3 MEUR of funding from the European Union, Mauritania's Agency for the Development of Rural Electrification will implement six hybrid PV / diesel power plants spread across the country. Three of them will consist of an addition of 15 to 20 kWp PV to existing diesel power plants, and three will be new power plants each equipped with 25 kWp PV and two diesel gensets.

Uganda
Presently, hybrid systems in the 5 kWp range have been implemented at rural district headquarters and at a few industries. The deployment of this technology is still at the infant stage.
The Rural Electrification Strategy and Plan established in 2011 aims to connect over 500,000 new electricity customers to the main grid, independent grids, and to solar PV systems, with the support of local institutions (Rural Electrification Fund, Rural Electrification Board and Rural Electrification Agency). These institutions are willing to promote PV / diesel hybrid technology. REA has budgeted for feasibility studies in 2011-2012 for hybrid solutions in Koome and Buvuma Islands (hybrid systems with wind, solar and diesel sources).

Kenya
In 2011, a PV / diesel hybrid power plant was implemented (10 kWp PV, 80 kVA diesel). It was the first of its kind in the country, with the implementation managed by KPLC.

Burkina Faso
Burkina Faso's Fund for the Development of Electrification has initiated a project in 2012 to add a solar PV component to existing diesel power plants in the Sahel region. A previously installed PV array at the diesel plant in a remote locality in Sahel will soon be connected to the main grid.

Madagascar
In 2010, two hybrid systems based on PV were implemented: One funded by the government (7 kWp PV, 12 kW diesel) and one by the African Development Bank (8 kWp PV, 100 kW diesel).

This brief overview, which does not claim to be exhaustive, shows that there is explicit interest for the technology, in particular in areas where no other resources are available, other than the sun. Most of the projects implemented in recent years were pilot projects, mainly small hybrid systems in the range of 5 to 30 kWp PV, strongly supported by donor financing. But larger projects are emerging, in particular in Mali.

African agencies in charge of rural electrification are progressively acquiring knowledge about actual costs and are receiving technical feedback. This technology is still emerging and large-scale governmental programmes have yet to be launched. The issue of the large upfront capital cost remains a major hurdle today.

2.2 Presently available product solutions

The recent and increasing interest in PV / diesel hybrid solutions stems from two sources: the need for improved electrification solutions for remote locations where the rising cost of diesel is a major problem, and the fact that PV / diesel minigrids are seen as potentially being an important adjunct to the PV market in OECD countries.

Among the components of a hybrid system, the genset, the batteries and now the solar PV panel are commodity products. The key components in which reside the technical added value are the inverters. They perform several functions:
- Controlling the operating point of the PV array and optimizing its output;
- Inverting DC current (from either the battery or the PV) into AC and rectifying the AC current into DC to charge the battery ;
- Controlling the charging process of the battery to extend its lifespan.

These functionalities may be split between several distinct units or some functions can be combined in a central unit component.

Multifunctional inverters for hybrid minigrids are different from grid-connected PV inverters that match their voltage, frequency and phase with the utility-supplied sine wave of the grid. For safety reasons, the latter are required to shut down automatically upon loss of utility supply. On the contrary, multifunctional inverters used in hybrid systems are designed to form the minigrid, i.e. they set the voltage and frequency of the minigrid. They are referred to as **grid-forming inverters** or **islanding inverters**.

For the remote or rural electrification applications, this key component was developed mainly by solar inverter manufacturers developing products for PV plants typically in the range of 1 kW to 20 kW, in the form of single PV inverters and battery charge controllers of similar power range. Combining multifunctional inverters with PV inverters or charge controllers, these modular products allow for system sizes of up to 300 kW of PV output power.

Table 1: major manufacturers of multifunctional inverters for hybrid application, with power range addressed

Manufacturer*	Multifunctional inverter: output power level**					
Outback Power	modular:	2 to 3 kVA	1ph	up to:	**27 kVA**	(3x3x 3kVA)
Schneider Electric	modular:	4 to 6 kVA	1ph	up to:	**54 kVA**	(3x3x 6kVA)
Studer	modular:	0.5 to 7 kVA	1ph	up to:	**63 kVA**	(3x3x 7 kVA)
SMA	modular:	5 kW, 6 kW, 8 kW	1ph	up to:	**180 kW**	(3x12x 5 kW)
Ingeteam	modular:	10 kW, 45 kW	3ph	up to:	**195 kW**	(15 kW+ 4x 45 kW)

* Ranked according to rated output power of multifunctional inverter
** Power units: kVA for DC bus systems, kW for AC bus systems. 1ph and 3ph: single or three-phase units

The higher power range (from <50 kW to MW) can be addressed with Uninterruptible Power Supply (UPS) systems. These are mainly used in industries or activities where potential power failures from grid supply cannot be afforded. According to power needs and response time, UPS generally constitutes battery banks and/or diesel gensets. Some of the major manufacturers of UPS systems have products or activities linked to the solar PV market. Among them are AEG Power Solutions (which has already implemented a UPS system within a PV / diesel hybrid in Mali), Schneider Electric, SIEL, Woodward [1].

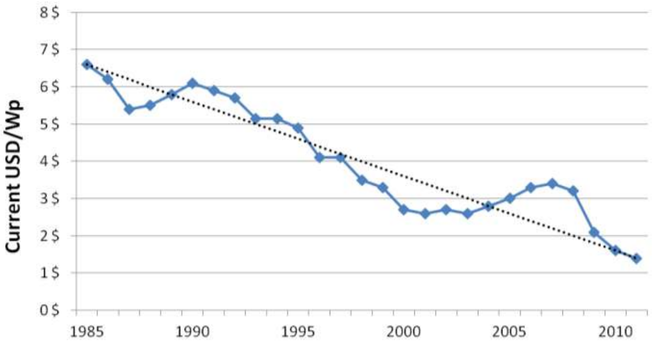
2.3 Cost and operational issues of hybrid systems

Current investment cost

Rural electrification agencies as well as many operators of small diesel minigrids are aware that hybridization can help to provide a better service and reduce production costs compared with single-source systems. **The cost of solar panels has been steadily decreasing** and this trend favours a broad deployment of PV hybrid systems. However one also has to consider that a hybrid system has many other components besides the PV array. **The cost of the storage component is significant**. In addition, the battery charge control feature of the **specific inverters for hybrid systems makes them more expensive** than grid-connected inverters, and these make a **significant cost difference compared to simple PV power plants connected to the grid.**

Figure 5: Pricing trend of solar PV panels 1985-2011

Source: 1985-2010 data from Paula Mints, Principal Analyst, Solar Services Programme, Navigant. 2011: based on current market data



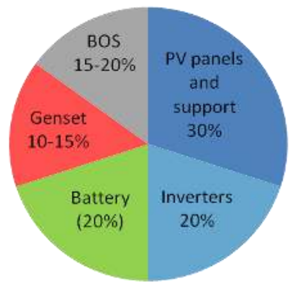
Data collected on recent systems installed in Africa and Asia show that the typical real installed cost of a complete PV / diesel hybrid system is in the range of 5 500 to 9 000 EUR / kWp with variations according to system size and location. Diesel gensets are widespread in developing countries and products and services for those are readily available. On the contrary, solar PV distributors and installers with a significant market base and experience are far fewer, implying increased costs for that part of the system and some variations according to the country considered. Examples of cost structure of two hybrid systems are shown in the table below. Despite variations due to system size and location, the cost structure of a PV / diesel hybrid system typically follows the breakdown shown in the pie chart.

Table 2: Cost structure of two hybrid systems in Senegal and Cambodia

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

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

Figure 6: Typical cost structure of a PV / diesel hybrid system

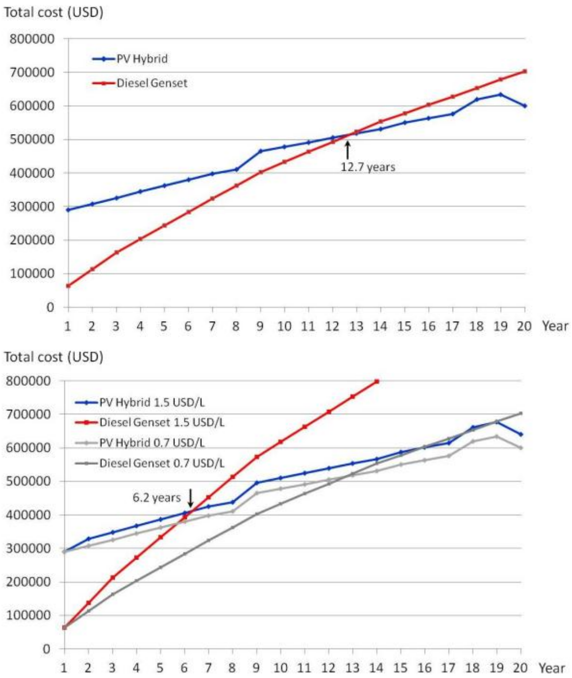


Operating costs and payback period

The prime goal of adding a solar PV component to an isolated diesel power plant is generally to reduce its fuel consumption. The payback time for the investment in the PV generator and storage system to be compensated by fuel savings makes economic sense if it is reasonable and acceptable to the investor.

The following are the results of a simulation for a 60 kWp hybrid system on an island in Ecuador [2]. Under the local conditions, and with a solar energy penetration rate of 93%, the calculation shows a payback period of 12.7 years, with the assumption of a constant fuel cost (0.7 USD/L). Compared to a simple genset solution, the levelized cost of energy is reduced by 15% (0.46 USD/kWh compared to 0.54 USD/kWh). With a higher fuel cost (1.5 USD/L) the payback period is reduced to 6.2 years.

Figure 7: Example of 60 kWp PV / diesel hybrid system in Ecuador: simulation of total accumulated costs over 20 years.



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

Source: [2]

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

Adapted from [2]

Operations and maintenance issues

PV panels

Beyond the local solar resource and the cost of fuel (and its potential escalation), many other parameters influence the actual payback period of a hybridization investment. Solar PV panels have a long lifespan (more than 20 years), but their yield gets slightly reduced over time. This parameter has to be computed in the economic analysis across the project timeframe. PV panel manufacturers generally guarantee 90% of initial performance after 10 years and 80% after 25 years. Further, the actual possibility of resorting to the guarantee, if needed after a few years, remains an open question in areas where distributors are not well-established companies.

Battery bank

The lifespan of the battery depends on many parameters related to the way they are operated and to external conditions, in particular the ambient temperature. For instance, typical lead-acid batteries designed for solar energy applications will lose between 15% to 20% of their lifespan (the number of charge/discharge cycles they can perform) for each 5°C above the standard temperature of 25°C. In addition, the deeper the battery is discharged at each cycle (depth of discharge), the shorter its lifespan. This implies that to reach an optimal battery lifespan, one has to install a large enough battery to achieve a suitable depth of discharge. Considering the battery cost (around 20% to 30% of total system cost) it is reasonable to design the battery bank and its operating conditions to last for six years minimum and ideally eight to ten years.

Inverters
An inverter's lifespan can extend to more than ten years, but this component is a high-technology product and the replacement of a failing component has to be undertaken by a technician from the supplying company. The specific complexity of the inverter often requires that a proper after-sales service plan be implemented to ensure long-term sustainability of the system. Risks associated with the failure of an inverter should be considered, especially in remote locations or countries with very limited presence of specialized suppliers.

Diesel generator
Regarding the diesel generator, major maintenance operations should be considered with respect to the cost and unavailability of the equipment. Gensets in the range of 30 kVA to 200 kVA would typically need a major maintenance operation after 15,000 to 25,000 running hours.

Evolution of the load
The evolution of the load can also affect the share of each energy source in the total power supply of the hybrid system. This can affect the payback period as well. Generally a load increase would mean a reduction of solar energy stored and an increase of solar energy injected directly, and thus a reduction in storage losses. However, a significant load increase in the segments of the daily load curve that are to be supplied by the battery bank and associated inverter will entail higher discharge currents and thus reduced cycle efficiency.

Key highlights regarding the barriers of high upfront cost and technical risks
Under the current prices for specific equipment for hybrid systems, and taking into account the risks mentioned above, the potential 15% reduction of the levelized kWh cost in the above example will appear insufficient to a private investor to cover the possible causes of long term cost overruns without substantial public support (subsidy).

→ The above analysis confirms the need for a strong public-private partnership to mitigate and share risks
- Engagement of the private sector by way of capacity building, ensuring high levels of maintenance and quality;
- Public sector engagement for a programme approach, and probably subsidy / financial support during the initial years to build skills and to develop the market.

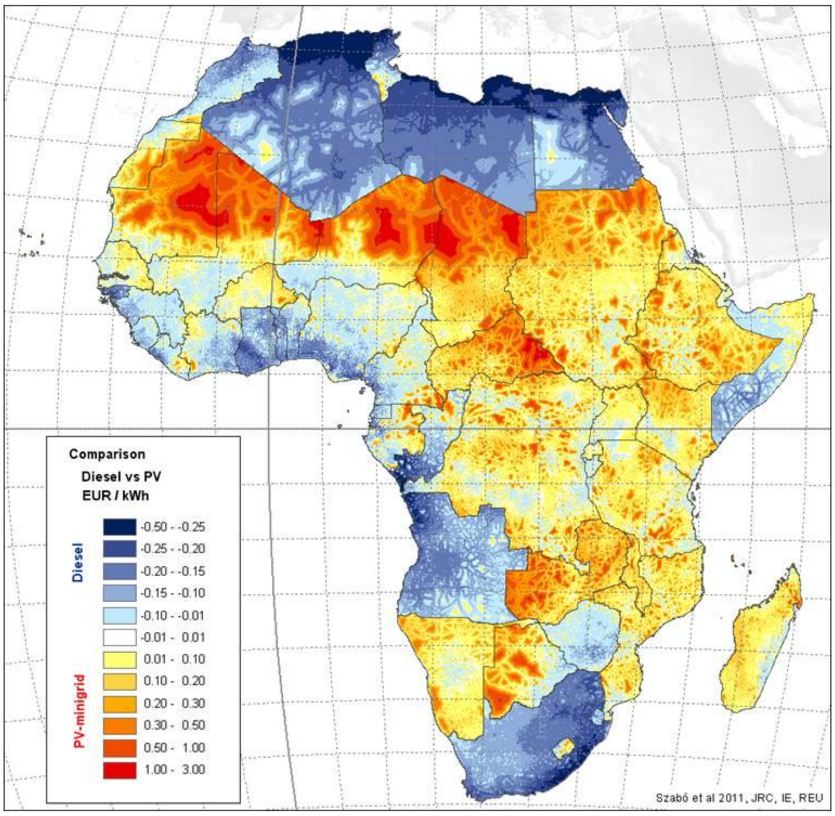
The kWh cost of the hybridized system directly depends on the local solar resource (which determines the cost of electricity generated by a PV system of a given cost) and on the cost of local diesel fuel (including transport cost to the site).

→ At the 2012 costs of PV systems and the real cost of diesel, the areas where hybridization makes sense are limited to places where the solar resource is very high or where fuel transport is very expensive.

The following map of Africa provides an example of areas where the diesel option and the solar PV option are the least cost options.

Because the price of fuel is likely to continue to rise in the future, at the same time as the price of the other components will most likely reduce, areas where hybridization makes sense will certainly expand.

Figure 8: Map of estimated cost of kWh delivered by a diesel generator and by a PV system with a minigrid in Africa



More information about this map can be found in [3] and [4].

3 Market analysis and key indicators for project planners

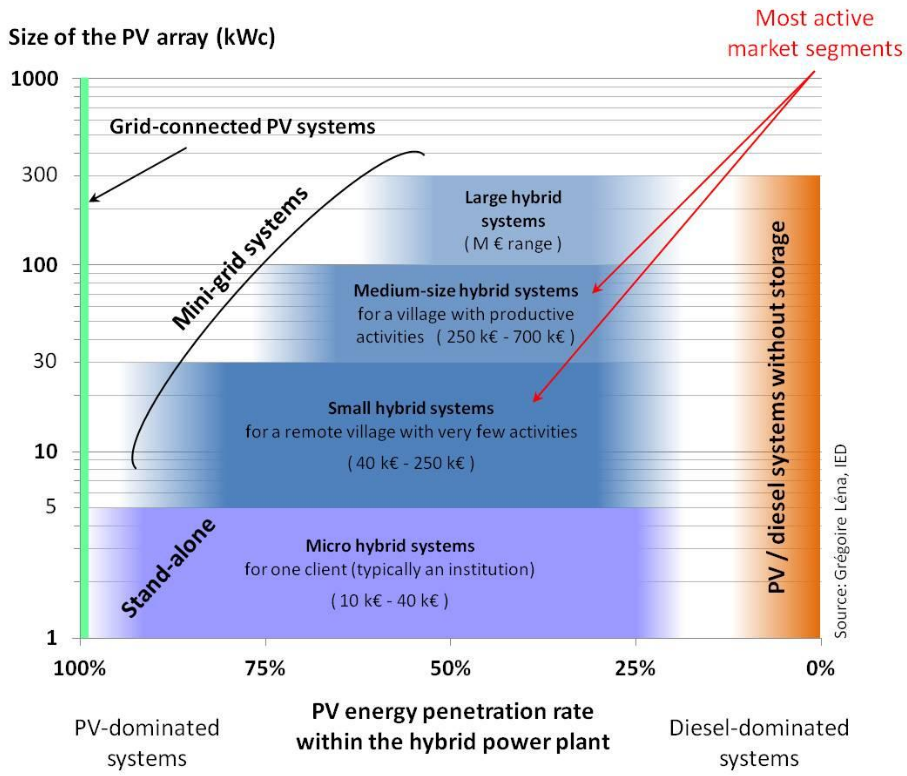
3.1 Suggested market segmentation

There are different levels or stages in the process of electrifying localities that are at a distance from the main electricity grid:

- Pre-electrification strategy generally starts with providing power to communities through individual solutions (solar home systems for households, stand-alone systems for basic services such as health centres, etc.). Micro-hybrid systems are a suitable solution for institutions such as health centres that require reliable power supply during the day.
- Basic electrification of a remote locality, via a small power plant, will first seek to cover essential needs such as the lighting requirements of households and essential services (local health centre, other community services, etc). Small hybrid systems with a PV component in the 5 kWp to 30 kWp range can typically serve this application.
- The localities in which there are small commercial or productive activities using power provided by small individual gensets (before any common power service is implemented) require a more advanced electrification facility which should be able to meet the needs of these economic activities and their potential growth. Medium-size hybrid systems (30 kWp to 100 kWp PV) are suitable for this segment.
- Finally, the localities benefiting from more developed economic activity (and hence generally powered by a genset-based power plant) but far from the national electricity grid can benefit from the development and cost reduction of hybrid systems technology.

Hybrid systems can be used to power each of these segments. Between these four market segments there are differences in terms of the budget required for the hybrid system able to meet the needs, in the type of equipment, and in the organizational and operational aspects as well.

Figure 9: Market segmentation for PV / diesel hybrid systems for rural electrification in developing countries (type of system with upfront investment cost)



More information about the key parameters pertaining to each of the market segments is given in the following chapter, with a reference to the typical size of the PV component and load ranges. These load ranges do not refer to village population numbers because the rural per capita consumption can vary widely between countries.

3.2 Key information for decision making in rural electrification with hybrid systems

3.2.1 Basic electrification of institutions (micro hybrid systems below 5 kWp)

→ **This type of system supplies one client:** An institution such as a school, an administrative office, a health centre or a community centre, having most of their activities occurring during working hours. The peak load and daily energy demand can vary significantly, depending on the user of the system.

An institution typically has its largest power demand during working hours, usually daytime. Appliances in use requiring electricity may be office equipment such as computers, copy machines and printers. Depending on the specific user, it may, for example, also comprise laboratory equipment for a school, refrigerators for cooling medicines at a health centre, charging of batteries and mobile phones for villagers at a community centre, or electric tools at a vocational training centre.

The power demand may have a peak at some point of the day, or may be relatively constant during working hours. Sometimes a smaller load is present outside working hours, for example security lighting or refrigerators. Further, some institutions may have activities in the evenings, such as boarding schools and health centres with admitted patients. However, the power demand in the evening hours is typically lower than the power demand during the daytime.

Since the highest power demand occurs during sunshine hours, a significant share of the PV generated electricity can be used directly when generated. A storage system should preferably be large enough to supply the evening and the night loads in order to limit the use of fuel based power generation and hence the running costs. If there is a peak in power demand during daytime, a fuel-based generator can be used to cover that peak demand together with the PV panels. Using a hybrid solution to cover the demand peaks, instead of using only PV, will limit the required size of the PV production unit needed, which can lower the investment cost of the system.

Another option, particularly useful if explicit peaks in power demand do not occur, is to design the system so that the normal load can be supplied by the PV generation together with the batteries when favourable to normal weather conditions occur. For days or periods of higher power demand, or lower electricity production from the PV panels due to low solar irradiation, the fuel-based generator can be used to charge the batteries and supply the loads. Hybridization would also, in this case, lower the investment costs since the system can be designed for quite favourable conditions, at the same time as increasing the reliability of the system.

Power systems at institutions such as health centres, schools and administrative centres have the advantage of having one manager. Careful operation and flexible use of electricity, based on the daily status of the power system, can in many cases be more easily applied than within a system with responsibility divided between many users. Consequently, the risk of sudden power shortages is lowered and the frustration often arising when a technical system does not deliver the expected service is limited, resulting in higher user satisfaction. Further, essential loads can to a larger extent benefit from a secured access to electricity, and the lifetime of components in the system can increase.

Example of an existing installation with a micro hybrid system

In 2008 a PV-diesel hybrid system was installed at Ihushi Development Centre (IDC), near Mwanza, Tanzania[5]. Earlier, several small PV-systems were used and a diesel generator was needed in a carpentry workshop. As many as possible of the components formerly used in the small PV-systems were used to form the central micro-grid, and additionally required equipment was purchased.

IDC is a community-based organization running several projects in the village and a vocational training centre for sewing, carpentry and masonry. At the centre, there are classrooms, a carpentry workshop, a preschool, a business centre where computers can be used and courses are held, a meeting hall that can be rented for large meetings and special occasions, a guest house, two offices and a kitchen. The hybrid system supplies power for lighting, computers, a copy machine, a TV, a refrigerator, the charging of mobile phones for the villagers, and occasionally hand tools for carpentry, an electric iron or electric sewing machines.

The supply side of the hybrid system includes a 655 Wp PV array, using two different types of modules, and a 12 kW diesel generator. The three-phase diesel generator is mainly powering machines in a carpentry workshop, and one phase is connected to the PV system making it a hybrid system. A battery bank of five 12 V 200 Ah valve-regulated lead acid batteries form the energy storage. The system has a charge controller with MPP tracking, a bi-directional inverter with maximum output of 1 500 W, and a voltage stabilizer stabilizing the power entering the system from the generator. The distribution system is divided into AC and DC sections supplying different loads. DC is used at night for security lighting purposes, while AC power is used mainly during the daytime. The DC load is stable at about 50 W throughout the night, with a slightly higher power demand in the evening. The energy used in the DC system amounts to less than 1 kWh/day. The AC load is of a more unstable nature, varying over the day as well as from day to day and from week to week. There is no AC power demand at night. During working hours, the average AC power demand is around 150 W with peaks of around 500 W. The total energy consumption is around 1.5 kWh to 2 kWh per day not including weekends.

Source: Caroline Nielsen, SERC Dalarna University

[5] More information about this system can be found in [16].

3.2.2 Basic electrification of a small rural village (small hybrid system: 5 to 30 kWp)

Small hybrid systems are suitable for supplying the power needs of a small rural village where the energy consumption is quite limited; for instance a village with no, or very few, productive or commercial activities.

→ Village with a **peak load in the range 30 kW to 60 kW**, and a daily power consumption of **150 kWh to 300 kWh/day**.

The typical daily load curve of a remote village with limited energy needs shows a low base load that can be supplied by solar energy and a battery bank. The battery bank would store the equivalent of one day of solar energy generation. The peak load is generally in the evening due to lighting uses. To meet this peak, either the battery or the diesel genset is used. In addition, if the battery is low, the genset is automatically started and charges the battery simultaneously to supplying the clients.

Hybridization allows longer service hours to be provided than with a pure genset-based power plant, because the battery can serve very low loads that are difficult and costly to supply with gensets. Compared to a pure PV option, hybridization allows a smaller PV array and a smaller battery.

These systems can achieve a significant yearly PV penetration rate: 40% to 90% for instance. In systems with high penetration rates, the diesel genset plays the role of a backup device used to compensate for insufficient solar supply occurring a few days per year or to cover some uncommonly high peak loads.

→ **Stakeholders considering electrifying a remote locality of this type** with either grid extension, a genset-based power plant or a hybrid system should consider the parameters presented in the table below.

Table 3: Matrix for decision-making pertaining to small hybrid systems

Small hybrid systems (3kWp to 30 kWp PV)	Remote village with very few activities	**Peak load 30-60 kW**	**150-300 kWh/day**	**low growth rate**			
	Option	**Key figures for economic / financial analysis**				**Level of service**	**Required operating skills**
	Grid extension	distance to grid	MV line cost 8-13 k€ / km	yearly sales 55 to 110 MWh / year	timeline for grid extension	full service	no
	Diesel-based power plant	initial investment (incl. 1 genset) 40-70 k€	actual cost of diesel fuel kWh tariff	-if mandatory subsidy on diesel: for a total of 55 to 110 MWh / year (Ex: 8 to 16 k€/year)* -yearly O&M costs	genset lifespan	limited service schedule (no base load)	basic local skills (genset maintenance)
	Hybrid-based power plant (Ex: 30 kWp PV)	initial investment 180-250 k€ + battery renewal (8 years) 35-50 k€	accessible penetration rate > 40% kWh tariff	-reduced mandatory subsidy on diesel: @40% PV penetration: 30-65 MWh / year (Ex: 3 to 7 k€/year)** -reduced O&M costs	-payback period -long lasting PV investment (25yrs) -battery lifespan -increased genset lifespan	24-hour service possible	training required for operator + distant support

Investment data shown for comparing options does not include cost of the local MV / LV grid or minigrid.
Initial investment and battery renewal cost for the PV / diesel hybrid option are based on a 30 kWp system as an example.
*Based on a 30% subsidy on 1.00 €/L fuel price and genset consumption 0.5 L/kWh
**Based on improved genset consumption: 0.35 L/kWh

This type of village would typically be within the mandate and scope of public electrification bodies. The public bodies would generally have a subsidy scheme for this category of customers (in some Sahelian countries, a subsidy on fuel). The choice of the hybrid option would make economic sense if the timeline for the electricity grid to reach the area is long (10-15 years), if the total cost of fuel including transport to the location is high and mandatory fuel subsidies (if they exist) are high, if the feasible penetration rate is significant (>40%) and if a concessional loan or subsidy is available. In addition, local operators should have the ability to operate a slightly more complex system than a genset.

The remoteness and the limited yearly sales of electricity in such a village are not very attractive for an independent power producer. If a private operator were to invest in such a location, it would favour the least risky option: a diesel-based minigrid. Public-Private partnership is relevant here, with the public sector for the investment and a private operator, functioning with a performance based contract. From the technical point of view, this category of hybrid system typically uses assemblies of small modular inverters of 3 kW to 10 kW. These small units can be assembled to form 3-phase grids of higher power levels. The main manufacturers of multifunctional inverters for this range of hybrid systems are Studer, SMA, Ingeteam, and Schneider Electric.

Regarding operation and maintenance, and considering that in remote areas it is difficult to maintain skilled personnel, the system should be designed to be simple and robust. Regular visits by skilled technicians, organized as a tour to cover different hybrid installations in a specific area, could be a good way to ensure proper system operation through sharing the costs of maintenance visits. This segment is presently perceived as particularly attractive by rural electrification agencies in Africa.

Example of a 16 kWp hybrid system in Mauritania *Source: IED*

The village of Ain Ehel Taya, in the Adrar region, 40 km from the regional capital Atar comprises 340 households. A small power plant, equipped with a 55 kVA (44 kW) diesel genset supplies power to 220 clients. The load curve shows the typical shape with a peak load of 28 kW in the evening in the summer season, but during morning hours the base load is significantly lower (around 9 kW). For this reason, the average genset load factor is low (21%), with high fuel consumption as a consequence. Local power demand is expected to grow at a rate of 3%.

A hybrid system has been designed and optimized to be able to absorb this demand growth, reduce the fuel consumption, and optimize the use of the existing genset. A 15 kWp PV system is planned, with a 145 kWh battery bank and a 16 kW inverter. Simulation shows that the PV system will provide around 40% of power needs and that the genset will be used more efficiently (57% load factor after five years). The cost of hybridization is financed through a subsidy, for which the payback period will be 8.3 years (including the replacement of the battery after nine years).

Example of a 5.2 kWp hybrid system in Senegal

This system has been visited and analysed within CLUB-ER activities in 2010

Resulting from a local initiative developed within the PERACOD programme, a hybrid system has been installed in the remote village of Sine Moussa Abdou in the Thiès region, to supply electricity to the 900 inhabitants of the village. It is composed of a 5.2 kWp PV array (complemented by a 5 kW wind turbine) with a 120 kWh battery bank and a 8,5 kVA diesel genset, used only as a back-up for the days when solar and wind energy would not have charged the battery enough for the evening load. Users are equipped with smart meters that closely monitor local consumption and the installation is also used as a pilot project to test smart meters and the wind-solar-diesel hybrid system.

The overall installation was financed by the GTZ (PERACOD programme: 50 k€ for the building and inverters), SEMIS (50 k€ for engineering), and INENSUS Germany (70 k€: windturbine, genset, battery bank).

Example of the ERSEN programme in Senegal, co-funded by GTZ and the Government of Senegal
Since 2009, this programme is funding and installing, among other electrification solutions, PV / diesel hybrid systems in rural areas of Senegal.

Technical choices
The hybrid power plants of this programme are small PV / diesel hybrid systems (5kWp PV, 10 kVA Diesel gensets) with <50 kWh lead-acid battery banks. They serve villages of 500-800 inhabitants (50-80 households) with an evening peak estimated at 4 kW. Solar is the main energy source and the diesel genset is used as a back-up. Because of local conditions (insects, humidity and salinity for island sites), equipment is planned with the following lifespan: battery renewal after eight years, inverters - ten years, diesel generators - ten years.

Administrative and commercial organization
During the first six months, GTZ provides technical support for management of operations of the hybrid power plants, and these activities are later transferred to local private operators who have invested in the equipment. Operators run the systems, manage the maintenance and collect payments. Tariffs are set by the national regulator.
To improve the collection rate, which remains a problem (especially during hunger gap[6] for very isolated communities), village management committees have been set up to ensure the pre-collection of payments.

Results and issues
The electrification rate within a village with a hybrid system reaches about 65% six months after commissioning. However the main problem is that power demand often overloads the system, indicating that the sizing is not appropriate and/or attention has not been paid to customer education, load management and usage feedback.
Source: ASER Senegal

[6] The hunger gap is the period between harvests during which poor farmers have already exhausted not only available food stores but are also not having access to affordable and adequate food.

3.2.3 Electrification of a village with productive activities (medium size hybrid system: 30 to 100 kWp)

Medium-size hybrid systems are suitable to supply the power needs of a village where productive and commercial activities use energy during the daytime.

→ Village with a **peak load in the range 60 kW to 150 kW**, and a daily power consumption of **300 kWh to 1000 kWh/day**.

The typical daily load curve of such a village shows a significant power demand at midday and in the early afternoon. There is generally a higher load in the evening due to lighting uses. There is a base load during the night. The genset (or two synchronized gensets) of the hybrid system is used to cover the evening peak. The night load is supplied by the battery. As a result of the midday load, a significant share of solar energy is used directly when it is generated. The required battery capacity is defined according to the excess PV production and to the amount of energy required to cover the night load after being fully charged in the evening by the genset. Battery capacity may be proportionally smaller than for small hybrid systems if the night load is low; in that case a battery capacity of 0.5-0.8 times the daily solar energy generation could be sufficient.

Reaching high PV penetration rates in this category of systems requires very large initial investments. That is why the accessible range of PV penetration rate would not be higher than approximately 60%.

→ **Stakeholders considering electrifying a remote locality of this type** with either grid extension, a genset-based power plant or a hybrid system should consider the parameters presented below.

Table 4: Matrix for decision-making pertaining to medium-size hybrid systems

Medium size hybrid system (30 to 100 kWp PV)

Village with productive activities	Peak load 60-150 kW	300-1000 kWh/day	expected growth			
Option	**Key figures for economic / financial analysis**				**Level of service**	**Required operating skills**
Grid extension	distance to grid	MV line cost 8-13 k€ / km	yearly sales 110 to 370 MWh / year	timeline for grid extension	full service	No
Diesel-based power plant	initial investment (incl.2 to 3 gensets for load following) 80-150 k€	actual cost of diesel fuel kWh tariff	-if mandatory subsidy on diesel: for a total of 110 to 370 MWh / year (Ex: 12 to 40 k€/year)* -yearly O&M costs	gensets lifespan	full service	synchronized gensets operation & maintenance
Hybrid-based power plant (Ex: 70 kWp PV)	initial investment 420-560 k€ + battery renewal (8 years) 80-110 k€	accessible penetration rate > 40% kWh tariff	-reduced mandatory subsidy on diesel: @40% PV penetration: 65-220 MWh/year (Ex: 7 to 24 k€/year)* -reduced O&M costs	-payback period -long lasting PV investment (25yrs) -battery lifespan -Reduced genset investment (no unit for baseload), increased lifespan	full service	synchronized gensets O&M + training & distant support required

Investment data shown for comparing options does not include cost of the local MV / LV grid or minigrid.
Initial investment and battery renewal cost for the PV / diesel hybrid option are based on a 70 kWp system as an example.
*Based on a 30% subsidy on 1.00 €/L fuel price and genset consumption 0.35 L/kWh

The amount of capital required in this range of hybrid power plants is significant (200 to 900 kEUR, compared to 80 to 150k EUR for a diesel plant), and would generally imply the involvement of commercial banks and the private sector.

From the point of view of a private investor, providing capital for the investment for the PV option must be attractive. The savings in generation cost (versus the diesel option) should pay back the initial investment in a reasonable timeframe and provide a suitable rate of return. To be viable from an economic and financial point of view, and to attract investment, a medium-size hybrid system has to be extremely efficient. Environments with low fuel costs or with limited solar resource would make it difficult for such a system to compete with diesel-based power plants.

The risks associated with this type of system have to be considered as well. There are technical risks (potential equipment failure, improper battery management), forecast risks (lower demand than expected, potential connection of the locality to the main electricity grid) and commercial risks; tariff stability is required. The investor would require a long-term power purchase agreement, and may impose a take-or-pay condition.

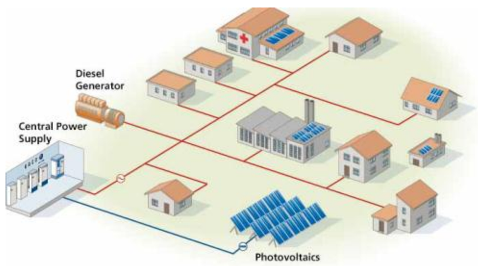
Public co-financing and risk sharing instruments are required to attract private investors.

From the technical point of view, this category of hybrid systems typically uses assemblies of modular inverters of 5 kW to 45 kW. The main manufacturers of multifunctional inverters for this range of hybrid systems are SMA and Ingeteam.

Properly operating the synchronized gensets and controlling the smooth operation of the electronic equipment (inverters) of the PV system require well-trained personnel on site. In addition, a distant support scheme would be required for trouble-shooting and for assistance if some equipment failure requires the replacement of a component.

This segment is presently perceived as particularly attractive by rural electrification agencies in Africa and beyond.

Example of a hybrid system for research and development



The Fraunhofer ISE research institute and the inverter manufacturer KACO new energy are presently operating and studying a PV / diesel hybrid system in Germany. The system consists of a PV array providing 51 kW (max. output), grid-forming inverter (120 kW), high efficiency charge controllers, a dual battery system which combines the economic efficiency of lead-acid batteries (288 kWh) with the high efficiency and cycle durability of lithium-ion batteries (96 kWh) and intelligent meters which allow new approaches to consumption management. The mini-grid concept is also designed to enable it to be connected to the national electricity grid in the longer term.

An energy management system is connected to the different energy sources and loads in order to ensure that the system works as efficiently and cost-effectively as possible and that the resources used are optimally deployed in energy and economic terms. This device helps to calculate the consumption and controls it via a variable electricity price. For example the energy management system will switch the water pumps on only if there is plenty of cheap energy available.

Source: Fraunhofer ISE

Example of a 72 kWp hybrid system in Mali

This system has been visited and analysed within CLUB-ER activities in 2010

The hybrid power plant of Kimprana in Mali was jointly developed with the Dutch Cooperation. It is currently operated by the energy service company SSD Yeelen Kura. It serves 217 households (approximately 3,000 people). The investment cost of the solar component (excluding gensets and local grid) was 328 MFCFA (500 k€), bought by SSD Yeelen Kura / FRES / Dutch Cooperation.

The PV field totals 72 kWp. The specific feature of this plant is that it is subdivided into two sub-arrays with distinct roles and different regulators: a first sub-array (34.5 kWp) is connected to six inverters, SMA Sunny Mini Central (400 V DC) assembled in three phases; a second sub-array of 37.5 kWp is connected to a battery bank (48 V DC) via a DC/DC charge controller unit, and a set of nine bidirectional inverters SMA SI 5048 assembled to create a three-phase 380 V AC supply.

The battery bank (1185 kWh) has been designed to supply the equivalent of three consumption days. The 175 kVA genset is turned on manually in the event of insufficient PV production and low battery level. The system was designed in order for the genset to be used less than 500 hours per year.

Operation began with a 24-hour service, but customers tended to consume more than what they were able to pay for. This is why the SSD then limited service to 14 hours per day, and later on to 10 hours per day. The PV and battery bank now sufficiently cover present consumption, and the genset is rarely used.





3.2.4 Large hybrid system for a small town with economic activity (>100 kWp system)

Large hybrid systems can supply the power needs of towns having a local “island” grid, not connected to the utility grid.

→ This type of town would have **peak loads above 150 kW**, and **daily power consumption higher than 1000 kWh/day**.

Power plants for this type of town generally comprise several synchronized gensets in order to efficiently follow the load. The solar and battery components should make it possible to completely shut down the diesel generators for several hours per day, reducing fuel consumption and reducing genset usage.

Systems of this range are built around large UPS systems. The manufacturers of UPS products for industries that cannot afford a power shortage have developed extensive know-how on energy management between various AC and DC sources. The inverter/charger UPS units manage the whole system in order to preserve the battery life and to maximize the use of solar energy. These systems can be linked to the paralleling controllers to govern the gensets' operations.

The battery capacity would be chosen in order to be able to shut down the diesel component for a certain period. The suitable rated capacity of the battery capacity is based on the load level during the time the genset will be shut down and the desired duration of the shutdown. A precise economic analysis provides the optimum values for these parameters.

The accessible penetration rates depend on the actual shape of the load curve.

Large systems benefit from economies of scale in the cost of the PV array and the battery bank. In areas with good solar resource, the cost for generating one kilowatt-hour from solar PV can reach profitable values compared to the cost of one kilowatt-hour generated from diesel.

This type of town may have a significant potential for economic development and the question of their future connection to the main grid should be considered when assessing the economic value of the project, comparing the timeframe for grid connection versus investment payback period.

→ **Stakeholders considering a hybrid system for this kind of town** should consider the parameters presented below.

Table 5: Matrix for decision-making pertaining to large hybrid systems

Large hybrid system (above 100 kWp PV)

Small town with significant economic activity	Peak load > 150 kW	> 1000 kWh/day				
Option	**Key figures for economic / financial analysis**				**Level of service**	**Required operating skills**
Grid extension	distance to grid	HV and MV line costs	development potential of the locality	timeline for grid connection	full service	No
Diesel-based power plant	genset cost 200-300 € / kW +BOS cost	actual cost of diesel fuel kWh tariff	-cost of kWh generated from a pure diesel plant -yearly O&M costs	gensets lifespan	full service	synchronized gensets operation & maintenance
Hybrid-based power plant	PV array 1500 k€ / kWp battery renewal (10-12 years) 150 k€ / MWh +BOS cost	accessible penetration rate kWh tariff	- cost of kWh generated from the PV array -reduced O&M costs	-payback period -long lasting PV investment (25yrs) -increased genset lifespan	full service	synchronized gensets O&M + training on UPS systems
Investment data shown for comparing options does not include cost of the local MV / LV grid or minigrid						

Here again the high capital costs, the type of technology used (UPS) and its novelty in the context of electrification in developing countries, requires strong cooperation between the stakeholders and with local authorities.

The financing constraints and the type of risks associated with this market segment are similar to those of the medium-size hybrid power plants, with an increased need for public-private partnerships and long term agreements for these larger investments.

Because towns with significant economic activity may not remain off the national interconnected grid for very long, the question of the timeframe for this interconnection is essential.

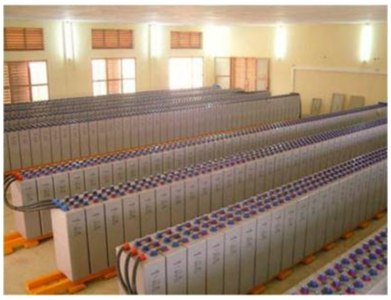
On the technical side, the involvement of the system's suppliers is essential because of the innovative nature of the combination of UPS and solar energy technology in developing countries.

Example of a large hybrid installation

This system has been visited and analysed within CLUB-ER activities in 2011

In 2011, Energie du Mali (EDM-SA), in partnership with the Bank for Commerce and Industry (BCI Mali SA) and private company ZED-SA, has implemented a major hybrid power plant to supply the town of Ouelessebougou. The project consisted of the hybridization of the existing diesel power plant (2x 275 kVA, 400 kW peak power) with a 216 kWp photovoltaic park and a 1600 kWh OPzV battery bank. The UPS system is composed of three inverters; Protect 4.33 form AEG Power Solutions rated 220 kVA each. The system supplies some 500 homes. The hybridization allows the gensets to be shut down during the day and to reduce their usage time by 75%.
The budget of this project was 1.18 billion FCFA (1.8 million EUR).





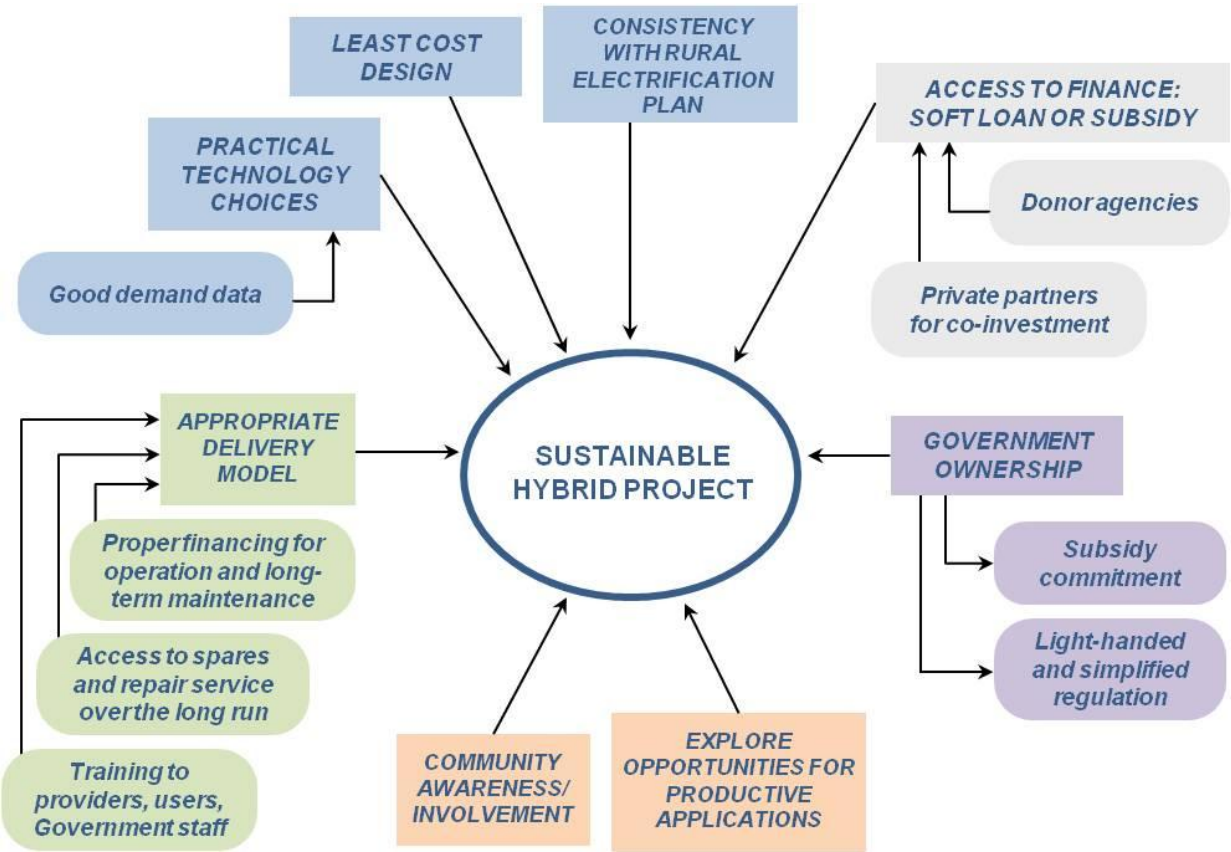
4 Challenges and recommendations for systems sustainability

Presently, rural electrification agencies in developing countries and donor institutions pay increasing attention to hybrid systems powered minigrids to address electrification needs of rural localities. Most of the places that programmes presently target are villages that can be powered by small and medium size hybrid systems. The following recommendations are thus mainly focused on this range of systems.

4.1 General principles

To maximize the chances of sustained operation of a hybrid minigrid over the long term, fundamental project management principles must be observed. These principles can be characterized according to the various stakeholders of the project. The following figure shows the roles of these stakeholders: the role of the project designer in terms of technical choices and delivery/business model, the role of the government, the involvement of the local community, and the necessity for a suitable finance scheme[7].

Figure 10: Project management principles for sustainable off-grid hybrid power facility



[7] Adapted from World Bank report "Operational Guidance for World Bank Group Staff. Rural Electrification Projects: Principles and Practices" [14]

4.2 Recommendations for designing sustainable systems

This section aims to highlight the key information that project planners and system designers should be aware of when planning and designing a hybrid system. Additional information can be found in IEA PVPS Task 11 publications listed in the Appendix.

4.2.1 Basic pre-feasibility assessments

In a project to electrify a locality with a PV / diesel hybrid system, the assessment of the relevance of the hybrid solution versus a pure genset-based option must be based on the available investment budget. A project holder may consider, as a rule of thumb, that one third of the budget for the capital cost will be dedicated to the PV array itself. According to current prices of PV panels, one can then easily estimate the rated power of the PV array that is financially accessible. With reference to local solar resources, one can then get a rough estimate of the available daily production from the PV array[8].

→ If the estimated available daily PV output is less than 30% of the average daily needs, one could question the relevance of the choice of a PV hybrid system.

Information on the output of the PV array provides a rough estimate of the potential reduction in the diesel-based power generation and associated fuel use and expenses, compared to a pure genset-based option.

A comparison of capital costs added to cumulated yearly expenses for both hybrid option and pure genset-based option, for a standard growth scenario, provides a rough estimate of the break-even point and the payback period if the hybrid solution is chosen. The replacement of the battery bank after seven to nine years, with a cost roughly equivalent to one fifth of the available budget, should be included in the cumulated expenses.

→ One should compare the estimated payback period with the agenda for interconnection of the area to the main grid and other risks that could occur during the estimated payback period.

If grid connection is foreseeable in the medium term, and the hybrid solution is seen as an interim solution, one can consider that the PV array could later then be connected to the grid for direct injection onto the grid. PV inverter components installed initially can serve this purpose if they are designed for grid coupling, with respect to local norms and procedures [5].

If considering the hybridization of an existing diesel power plant, one should assess the quality of the existing equipment and consider the costs of retrofit operations if some are required.

4.2.2 Load forecast

Reliable information on the local load curve is essential, because this curve determines the design of the system. In order to assess the future load curve, one can build on present energy uses (if the location already has some basic electrification system such as individual gensets for instance), together with a detailed local survey plus comparison to feedback from localities that have been electrified in the surrounding area.

→ The forecast of the power demand should be done as accurately as possible. A poor forecast readily leads to designing inadequate systems that will face early obsolescence.

---

[8] Maps published by PV GIS (http://re.jrc.ec.europa.eu/pvgis) covering Europe and Africa provide information on the average yearly PV output per kWp of a typical PV system suitably installed in the considered location. A part of this production will be lost in the battery cycling, but the calculation of these losses requires a detailed analysis.

When designing a hybrid system, more data are required on the load profile than for a simple genset-based power plant. The following are required:

- average daily total energy required (kWh)
- time and value of the average daily peak power, and value of the maximum peak power in high season (kW)
- average and maximum demand levels (kW) during the hours when the solar PV component is generating energy
- quantity of energy used during low base load periods, typically during the night (kWh, time period)

→ A precise daily load profile with hourly data and also expected seasonal variations are required for the design stage.

The future evolution of this load curve has to be assessed, taking into account that the connection of customers will be gradual, that customers will also increase their individual consumption, and that new specific needs can emerge, particularly as a consequence of the development of productive activities.

→ The forecast should be extended to at least five years after the system's installation date. A forecast of the potential evolution scenario after ten years will be required to assess the sustainability of the chosen design.

It is suggested that the system be designed in order to meet the forecast load for year 5 for instance, as this is generally the timeframe beyond which many uncertainties can arise for a rural locality. This can of course be adjusted according to specific site conditions. The sustainability of the chosen design and the potential required incremental changes could then be assessed using the year 10 scenario.

The impacts of a load evolution that may deviate from the forecast path should be assessed: impacts on the genset, on inverter components and on the battery. The appropriate preventive options or design adjustments to make the system more robust should be identified. Robustness is often better than high efficiency.

4.2.3 System design

The operational strategy of the system will define the system design. The optimization of the operation mode should focus on efficiency of the diesel genset and battery operation, and target the prolongation of their operational life. For this purpose, optimizing the load factor of the genset and the cycling of the battery is important and has a strong impact on the sizing and on the life cycle cost of the system.

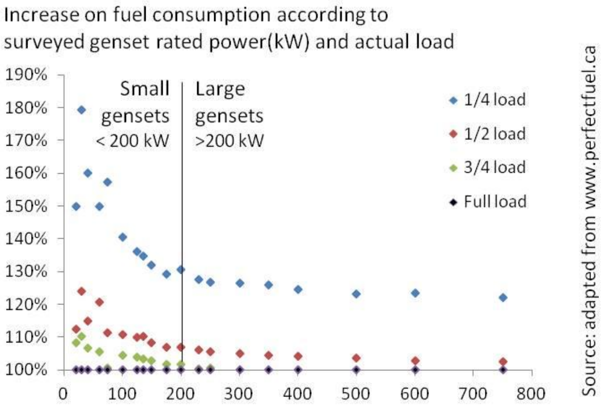
Diesel genset(s)

According to the reliability level desired by the users, one can decide to install one or more generators in order to be able to provide full service, even during maintenance periods. In addition, for systems around 50 kW or larger, one can consider operating multiple gensets of different sizes to optimize their load factors.

Gensets, especially the ones below 250 kVA (200 kW), experience significant efficiency loss (increased fuel use per kWh generated) when used at low load factors (<40%) as shown in the associated figure, and all gensets suffer degradation if repeatedly used for long time periods at low load factors.

→ Designers should ensure that the diesel gensets run as much as possible at a load factor higher than 40%.

Figure 11: Increase in fuel consumption for gensets run at low load factor



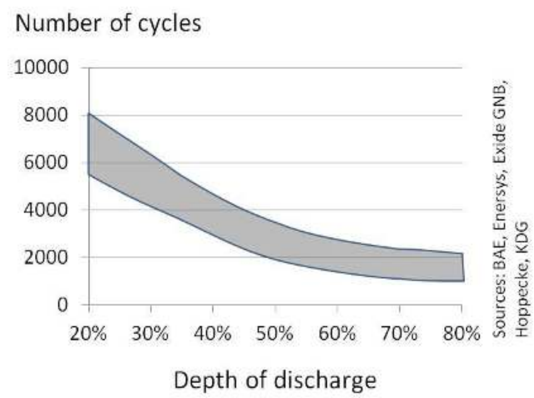
Battery bank

Today the most suitable storage technology for hybrid systems in rural electrification[9] is lead acid batteries with tubular plates, either vented lead acid (VLA: flooded batteries with liquid electrolyte to be regularly refilled) or valve-regulated lead acid (VRLA: maintenance-free batteries)[10]. The chosen battery should be specifically designed for solar applications.

The battery capacity should be designed so that the battery is able to store the entire energy required to cover the load during the hours when the genset is not supposed to run and solar output is not available (generally night hours and morning hours if morning load is low).

The battery cycling should be designed in order that the battery is able to store excess PV production and that it cycles within a discharge depth that allows enough cycles for the battery to last for at least six years (typically 2200 cycles at 50%-60% depth of discharge, considering one cycle per day) and ideally for eight to ten years. Because of the strong impact of temperature on battery service life (a temperature increase of 5°C decreases the service life by 15%-20%), design of the battery room should ensure that batteries are kept at the lowest temperature possible.

Figure 12: Lifespan according to depth of discharge (for 2V cells OPzS and OPzV)



The battery lifespan (measured in number of cycles) depends on the depth of discharge reached at every cycle: the deeper the battery is discharged at each cycle, the shorter its lifespan, as shown in the associated figure for VRLA and VLA batteries.

The smaller the battery capacity, the cheaper the initial battery costs; however a smaller battery would be more deeply discharged and its lifetime would thus be reduced and its replacement cost increased.

Because the battery recharge process ends with a very low power load (constant voltage, diminishing current) it is preferable to have this end-of-cycle charged by the genset rather than by the PV array, and

[9] Details on other options for energy storage in hybrid systems can be found in [11] and [15]

[10] The DIN reference for VLA (flooded) tubular plate batteries is OPzS, and it is OPzV for VRLA (sealed) tubular plate batteries.

at a time when the genset operates at a good load factor. This operating mode allows for maximising the usage of solar energy.

A battery's total capacity (i.e. the total amount of current it can deliver multiplied by the duration of that supply) is reduced when discharged with a high current. This means that if the power load that the battery has to supply increases every year, after a few years the battery will not only be depleted more quickly (because a higher power level means a shorter delivery time for a fixed amount of stored energy) but also because in addition its total capacity gets reduced by higher discharge current. This has to be taken into account when considering locations with significant demand growth.

→ Operational conditions, and their evolution, have a strong impact on battery lifespan. The system designer should ensure that a safety margin is included in the sizing of the battery and that its operation mode optimizes its lifespan.

Multifunctional inverter

The multifunctional inverter system comprises a device that controls the operating point of the PV array and optimizes its output, devices that invert DC current (from either the battery or the PV) into AC and rectifies the AC current into DC to charge the battery, and a device that is controlling the charge of the battery to extend its lifespan. These functionalities may be split between several distinct units or combined in a central piece of equipment.

The rectifier and charge controller component should be chosen so that both the PV and the genset can charge the battery. The rated charging current should match the battery maximum charge current. The charge controller should be able to manage the various charge steps, including regular equalization and float charge to maximize battery lifespan.

The inverter component should be designed in order to be able to supply the load when solar output is not available and the genset would not run at an efficient load factor. Seasonal variations of the load and its yearly growth should be taken into account when specifying its rated capacity.

The multifunctional inverter devices are controlling the operations of the different energy sources of the system. A failure in one of its components would significantly hamper the functioning of the entire system. Improper settings for the various thresholds that control the shift between sources may affect the lifespan of the battery or the efficiency of solar energy use.

→ The system designer should specify the multifunctional inverter and its operating mode with a focus on quality, robustness, simple operation and durability.

Optimization of the system design

There are many parameters that have to be taken into account when designing a PV / diesel hybrid system. Identifying the best option involves choosing a technically efficient option that is also optimized according to an economic and financing perspective.

Design tools have been developed for such complex optimization. One can find suitable guidance regarding available tools and the type of task they can help to perform in the report published by IEA PVPS Task 11 "Worldwide overview of design and simulation tools for hybrid PV systems" [6]. For modelling the behaviour of various system options and identifying the least-cost design, the free software HOMER[11] is of value.

[11] Available at www.homerenergy.com

Table 6: Key recommendations for designing a sustainable hybrid system

	Component	Recommendation
Design	PV array sizing	Able to supply more than 20% of the daily load at year 1
	Diesel genset sizing	According to peak load in high season at year 5
	Battery sizing	According to excess PV energy at year 1 and energy required during low load periods at year 5
	Multifunctional inverter Rectifier component specification	Charge control able to maximize battery lifespan
	Inverter component sizing	According to load level during periods when there is not sufficient solar supply and load is too low for efficient genset use, for high season at year 5
Operation	Diesel genset operation	No (or limited) periods with load factor below 40%
	Battery operation	Optimizing battery lifespan

Adapted from [7]

4.3 Recommendations for sustainable operational management

Lessons from past projects show that, beyond problems related to the technology, many failures are due to inappropriate or unclear organizational schemes to operate and maintain the system and to the lack of an energy management concept that encourages the responsible use of energy when supply is limited [8].

The main observed causes of weakness in the systems are unplanned increase of the load, inadequate revenue, unavailable after-sales service, and unsuitable ownership models.

Unplanned increase of the load (either caused by inefficient use of energy or by unexpected new loads). Promotion of energy efficient appliances and customer information regarding rational use of energy should be a part of any rural electrification project.

Inadequate revenue or lack of provision for maintenance
As a basic minimum, the project should generate a cash flow sufficient to cover O&M costs, and be built around existing local businesses or public institutions in order to increase critical mass, revenue, and local involvement. Because it is sometimes difficult and costly to retain skilled personnel in a remote village, an operator could valuably operate on a bundle of hybrid systems in a given area to reduce operations and maintenance costs.

Unavailable after-sales service
Access to service and spare parts is very critical in the case of electronic components. In the case of failure of one component, the necessary diagnosis and replacement is often an issue. In addition to initial training sessions, it is required that manufacturers and/or local distributors provide an adequate after-sales service for the inverters. The long-term continuity of the after-sales service is important.

Suitable ownership and responsibilities model
It is important that clear contractual agreements are made determining who invests, who develops the project, who owns the installation, and who operates and maintains the system. To ensure sustainability, ownership rights and the role of each partner have to be made very clear, and detailed in

contractual agreements. Various models of distribution of responsibilities are possible: community-based model, private sector-based model or even utility-based model. Local social and economic conditions should guide the project manager to choose the appropriate model. Valuable inputs regarding the advantages and suitability of each model according to the local conditions can be found in the ARE-USAID report “Hybrid mini-grids for rural electrification: lessons learned” [2].

Whatever the chosen ownership model, both the involvement and support of the local community are essential for the long-term sustainability of the project. Participation by the users from an early stage in the project definition, in project execution and in operation helps to realize a design that matches the actual demands and makes the final users take more responsibility for wise use and maintenance of the installations [8].

5 Perspectives for wider deployment

5.1 Increasing involvement of public stakeholders and the private sector

A few years ago in developing countries, hybrid systems were limited to small-scale applications, typically for the power supply of clients with specific needs such as rural institutions. One of the driving forces of present developments is the need to reduce the operating costs of isolated power plants.

Applying solar PV technology to reduce generation costs in diesel plants requires significant capital / investment amounts compared to more traditional types of electrification projects that rural electrification funds and agencies have been familiar with so far (stand-alone PV solutions are generally of a smaller power range and small diesel-based power plants have inexpensive upfront costs).

Governments and public agencies are increasingly aware of the benefits of hybrid technologies. It is expected that, along with this growing interest, there will be more funding available from electrification funds for this technology. Nevertheless, with the increasing sizes of the hybrid power plants that are planned, the involvement of the private sector to complement public funding will be increasingly required.

If the local political will can play the role of the trigger by setting up programmes and implementation plans for the development of hybrid systems, the participation of the private sector should be the enabler for the actual realization of these projects.

In addition to the risks associated with classical decentralized electrification technologies, PV / diesel hybrid systems bring technical complexity in areas where skills are generally lacking. The development of a more secure environment is still necessary for private investors to be willing to participate.

Public-private partnerships should thus be promoted and facilitated.

Within these partnerships, distributors of essential products, in particular inverters, have a role to play. The availability and quality of after sales service for these products in the areas where hybrid systems are installed is a factor that would help in reducing technical risks.

For the sustainability of the projects, local buy-in by the communities and end-users is essential. Adequate capacity building and training courses for local operation and maintenance will be necessary to ensure long-term viability. Agencies should encourage the involvement of local authorities from project planning to project implementation and monitoring, and also for local operation and maintenance.

5.2 Need for broader product portfolios and increased competition

The development of PV / diesel hybrid systems for rural electrification has been largely underpinned by the reductions in PV panel costs, and also mainly because of developments of suitable inverter products in a range that fit with the needs of remote rural communities.

Today there is an expanding demand for similar solutions for higher power ranges. There are presently a few manufacturers of grid-forming inverters who address this market with suitable products, but the power range is not extensively covered, particularly the range of inverters for hybrid systems comprising 50 kWp to 150 kWp PV arrays. Furthermore, the fact that there are a limited number of players limits the competition and provides few supply options to the project holders.

In addition, the presence of distributors and sales representatives from the major inverter manufacturers is limited in developing countries. The lack of locally available after sales service and skilled personnel is hampering the development of this technology in the rural electrification sector.

Regarding the technical design and optimization of hybrid systems (which is significantly more complex than for traditional one-source power plants) some tools have been developed, mainly by research institutions. However these tools are limited either in their user-friendliness, the options they offer, or by the lack of libraries of commercial equipment (inverters, batteries, etc.) included in the software. Tools attached to a manufacturer's product portfolio exist as well, for instance the SMA off-grid configurator. A broader offer of such tools would benefit the industry manufacturing technical solutions for hybrid systems.

5.3 Future deployment scenario

The future deployment of hybrid technology in developing countries will be driven by different factors according to the type of application addressed.

The **micro-hybrid system range** for use as a reliable and cost-effective power source for telecom base stations is presently developing and should continue to expand widely, thanks to the reduced operating cost that these solutions bring in comparison to the diesel-based option. This market segment benefits from a well structured and demanding client base, the telecom companies. The development of this application may attract systems manufacturers and their distributors, installers and service providers in developing countries and bring reliability and standardization to this segment.

The development of **small distributed hybrid generation systems** for rural electrification to address the needs of remote communities will rely on the impetus given by institutions in charge of providing public services to rural customers. Capacity building and access to concessional financing will be the key enablers for the development of this segment. This segment could benefit from standardized technical solutions developed by the manufacturers.

The **medium-size distributed hybrid systems** still need a political impetus to foster the involvement of the private sector. With the implementation of mechanisms to mitigate risks and agreements that help fair sharing of the risks between private investors and other stakeholders, this segment can significantly develop if PV panel and inverter costs continue to decrease. Standardization will be less feasible in this segment because of the impact of local specificities on the design of the system that limit replication (in particular the local load profile). However, component modularity might offer in the future standardisation opportunities, with the associated cost and reliability benefits.

Larger isolated minigrids require both substantial investments and associated substantial profitability to attract investors. The private sector can play decisive roles as the turnkey systems supplier and the investor. The question of the extension of the grid to these places is essential and directly related to the cost difference between centralized and distributed generation. The rise of fossil fuel costs and/or the removal of subsidies on fuel may be the main driver that could favour the development of large renewable-based minigrids and large hybrid systems in countries relying exclusively on fossil fuels for power generation.

6 Appendix

6.1 Documents related to hybrid systems produced within the CLUB-ER

Within the framework of the activities of the CLUB-ER, a survey of existing hybrid systems in Mali, Senegal and Tanzania was conducted in 2010.

In 2011, two workshops including a training session on hybrid system design for rural electrification agencies were conducted in Bamako (French session, July 2011) and in Nairobi (English session, November 2011). These resulted in experience sharing between the members of the CLUB-ER and significant capacity building regarding planning and designing of hybrid systems for rural electrification agencies.

The presence of manufacturers of inverters (SMA, Studer) and private companies in the sector of wind energy, including installers / project holders (Dutch Small Wind, WinAfrique, Windpower Serengeti) provided valuable inputs regarding the technologies' possibilities and feedback from past projects.
The information developed and shared during these workshops helped producing the present document.

All presentations of these two CLUB-ER workshops (French session and English session) are available at: www.club-er.org

6.2 Summary of ARE - USAID publication on hybrid minigrids

Hybrid mini-grids for rural electrification: lessons learned

Currently around 1.5 billion people worldwide live without access to electricity, and without a concerted effort, this number is not likely to drop. Grid extension is often highly costly and not feasible in isolated rural areas, or is unlikely to be accomplished within the medium term in many areas. In such situations, electricity mini-grids can power household use and local businesses. They provide centralized electricity generation at the local level using a village distribution network and, when fed with renewable or hybrid systems, increase access to electricity without undermining the fight against climate change.

Members of the Alliance for Rural Electrification (ARE) have been involved in the implementation of hundreds of mini-grid projects around the world. The lessons learned from these projects, which are summarized in this report, provide insights on the key issues that must be considered to devise sustainable, replicable models for the scale-up of hybrid mini-grids. Implementing sustainable hybrid mini-grids involves complex technical, financial and organizational issues that must address the end-users and their needs, capacity building and training, tariff and subsidy setting, and institutional strength.

I. Technical Issues

The combination of generation sources and components selected for a hybrid system will have a real influence on the lifetime of the system and its affordability to end-users. Despite the fact that the economic situation of rural areas pushes for technology choices made on a short term least-cost basis, quality has a dramatic influence on the system's lifetime and no compromises should be made on the quality of system components to reach the real long term lowest generation costs.

To increase efficiency gains and cost savings, priority should be given to sizing the system appropriately and to energy efficiency. In fact, regardless of the choices, energy efficiency is very important since it can influence dramatically the energy load, and therefore the amount of power generation required. This will impact investment costs and the financial viability of the project. In fact, for most countries supply and demand side management should constitute the first energy policy. In many rural communities, there is a tendency to focus on the reduction of short-term investment costs, which will necessitate on-going awareness raising and efforts to bolster local availability of energy efficient appliances.

The decision on the energy sources to use is of course central. Diesel is an expensive resource often difficult to distribute in rural areas. Consequently, 100% diesel-fuelled mini-grids likely will be more expensive on a lifetime basis than hybrid ones, and they are also less autonomous as fuel availability cannot be assured. Hybrid mini-grids, in contrast, utilize local renewable resources, making it less likely that power will not be available.

Several types of renewable energy technologies can be utilized in mini-grids:

- Small or micro-hydro is the cheapest technology, but also the most site dependent, as it requires a river with specific flow rate and volume conditions. Small hydro is a mature technology that has been installed all over the world over the past 30 years.
- Solar photovoltaic (PV) is suitable for almost any location around the world and is also comparatively easy to install, maintain and scale up. However, initial investment costs are higher than those of other technologies.
- Small wind power technology is very site specific, since wind conditions vary dramatically from place to place therefore, wind resources must be carefully studied before a system is installed.

Batteries and diesel gensets are other important components of hybrid systems. The battery is a central element for the cost of electricity over the lifetime of the system. Appropriate energy management should maximize the lifetime of the batteries as replacement costs represent an important part of the overall project costs. The genset will play an important role in ensuring the battery is charged. The use of diesel generators should be minimized, as fuel is costly; however, the genset is important to ensure quality of service when the other technologies are low or when the demand is especially high. There should be always some kind of automatic management measures built into the system to protect critical components from severe damage, such as total depletion of the battery charge. Training of local operators and users is essential to ensure that the components are used correctly and will last throughout the whole projected lifetime.

Bus bars and local distribution network are the last key elements within a hybrid mini-grid. The choice of AC or DC current in particular has an impact on the system, its capacities and its price, as well as on the devices that can be powered. However, the choice of AC or DC mostly depends on the technologies to be coupled in the system as well as whether batteries will be used in the system. Single-phase distribution grids are cheaper than three-phase ones, but the later allow greater opportunity for commercial enterprises to obtain power and the possibility of future inter-connection to the national grid.

Field studies and exhaustive demand analysis are a basic pre-requisite for any mini-grid project, regardless of the technology selected. Over-sizing some components, such as wiring and the converters, can be a good idea to anticipate a future demand growth and facilitate the mini-grid's expansion.

II. Financial/Sustainability Issues

Financial and operation issues are critical to the long-term sustainability of mini-grids. Questions such as operations and maintenance, role of the private sector, tariffs and subsidies, and capacity building and training are essential to consider when developing rural electrification programmes. This is particularly true with the use of hybrid mini-grids. Key issues to consider follow.

1) Sustainable financial and technical solutions for operations, maintenance and management (O&M&M) are key to overall system success. A well-maintained and managed system can run over 25 years and this should be the target of every new system implemented worldwide. Therefore O&M&M have to be carefully integrated in the project business planning right from the inception in order to foresee a cash flow sufficient to cover these costs. The ownership rights and the role of each partner also must be clarified, to determine who is going to be responsible for what and for which investment.

If long-term O&M&M is the key indicator of a successful project/programme, many external factors will also play a role. Availability (of products, trainings, reliable actors willing to assume responsibility for O&M, spare parts) for instance is of the biggest importance as is access to finance at all project levels. Therefore, successful rural electrification programmes have to rely on functioning networks of local companies and financial intermediaries, which should be looked at and supported in parallel with or as part of the programme. This can be addressed in different ways: for example, through technology transfer and company agreements, well-designed call for tenders, technical and business trainings and support to business organizations. The financial sector especially is central and its absence is often critical in rural areas. Therefore, targeted capacity building actions as well as financial instruments such as guarantees and financial risk mitigation instruments are very important.

2) In general, access to information and to training is fundamental to ensure long-term programme success. Many stakeholders involved in the rural electrification project chain do not know how to deal with renewable energies, or may not be used to obtaining and paying for electricity. Hence, education,

trainings and information about the benefits of access to energy and of renewables are necessary prior to any project. Strong and targeted publicity campaigns explaining rural electrification programmes will also increase positive impacts.

3) In the future, the private sector must play a bigger role in investing, implementing and operating hybrid systems all over the world if investment is to be scaled up and the challenges to system sustainability are to be overcome. Several factors can be influenced to attract companies and investors over the long term:

- The first option to increase the economic attractiveness of rural electrification is to act on the size of the market. To become more interesting economically, projects should be built ideally around existing business applications or public institutions in order to increase their critical mass, potential profits, and local involvement (i.e., interest in maintaining a system)

- Another option is to support directly income-generating activities as part of the rural electrification project itself to increase the positive impacts on the community and generate the needed revenues to cover O&M&M and profits.

- Concentrating energy loads or bundling projects in attractive packages is another means of increasing market size and the attractiveness of rural electrification projects. Territorial concessions are a known and good strategy but they need to be simplified to diminish the costs and the time involved in the process.

4) Setting appropriate tariffs and subsidies (i.e., obtaining the right energy price) is probably the most important factor to ensure project sustainability. A sustainable rural electrification tariff must at least cover the system's running and replacement costs (break-even tariff), even though the opportunity for profit is key to attract private operators (financially viable tariffs). Tariffs must also maintain the balance between commercial viability and consumers' ability and willingness to pay.

Along with good tariff structures, smart combinations of subsidies are key to attract operators and ensure project sustainability. They can support the investment, the connection, the operation, and/or the output. Investment subsidies are a good solution if they go along with a good tariff structure, whereas Output Based Aid (OBA) schemes, if adequately planned, are powerful instruments to leverage private investments and ensure O&M. Other forms of support should be offered in parallel to project developers: tax credits; low import duties; site surveys; market studies; and capacity building.

Regulations, policies and the legal framework are another incentive or barrier to the development of economic activities. This is particularly true for rural electrification with mini-grids, which offer a long-term service requiring stability and suitable instruments. Regulation has to be an instrument favouring new projects, not a burden. It needs to be light and flexible for small power producers in terms of standards and tariffs, and at the same time, it has to protect rural consumers. Power purchase agreements (PPAs) are an especially important feature, since these contracts are regulating the relations between the different parties involved in a long- term rural electrification project with a mini-grid. PPAs frame these relations and must give enough confidence to the private and banking sectors to invest in a project. PPAs must be fair, binding, ban unilateral changes and protect every actor equally. PPAs should also be as standardized as possible to decrease administrative costs, increase efficiency, simplify procedures, and most of all to enhance market transparency and attract operators and lenders.

III. Organizational Issues

The development of sustainable mini-grid projects can follow several business models according to local social and economic conditions.

- The community-based model has been tried out extensively around the world with varying success, depending mostly on the involvement of the people and the pricing policy. The community has to be involved as soon and as much as possible through financial or in-kind participation and through the constitution of a social structure supervising the implementation and the O&M&M of the project. Even community-based organizations need structured legal rules and binding contracts should be signed to secure payments with clear penalties in case of contract breaches.

- Tariffs have to be determined in advance, but flat-fees with categories adapted to different users are usually a good option since consumption is generally low. Tariffs always have to be high enough to cover O&M as well as replacement costs. Some community-run mini-grids have proved to be successful and this type of organization can have many positive impacts on the community itself in terms of self-governance and local buy-in into the electrification system. However, this approach also needs a long preparation period and much technical and social capacity building to compensate for the lack of skills and the potential for social conflicts. Therefore, the introduction of another partner – either private or public – to take over some aspects of system management is preferable.

- Another business approach for mini-grid rural electrification is based on a private operator, whose participation is only realistic if a project is profitable and therefore attractive. Output–based aid and long-term concession, when well designed, can be attractive schemes to increase private sector participation; and a certain level of standardization is advised to reach a certain degree of replication and economies of scale. Strong and targeted marketing around the call for tenders and the programme is key to attract private sector participation. However, operators should be the main designer of their system based on costs and quality, but including consumer health and the environment as criteria. Private providers present the advantages of having some investment capacity and should have technical capacity, so that they can handle all operational issues. However, in order to be developed extensively in rural areas, this model requires significant training, both on technical and business issues. Also, this approach requires community involvement and a proactive private sector development component to build demand for electricity services.

- The utility-based model is another option that has been widely used around the world. Utilities generally have more experience, financial resources, and technical capabilities to carry out rural electrification projects. They can realize economies of scale and use their central position to take advantage of financing options, but many of them are also inefficient and lack commitment at the local level. If this model is to be successful, it has to follow a business-oriented approach. Because of their capacities and experience, utilities should have a role to play in the future; however, partnering with private sector and community-based organizations will allow them to avoid the barriers linked with their centralized management structure and size. This type of hybrid, public-private model is probably the most interesting structure, but is also the hardest to define because it can encompass many different approaches. Hybrid business models tend to be very site specific and thus can be quite diverse with changing ownership structures, O&M contracts, and other variables.

Continuing and adapted capacity building and training on technical, business, financing, and institutional aspects of project and programme development is necessary at every point of the project chain and must include every stakeholder. Lack of financial, institutional, and technical capacity is still one of the main reasons for unattractive programmes and misunderstandings between the public and the private sector, including the financial sector. General training on rural electrification should therefore be provided to all stakeholders. At the local level, detailed technical training for end-users (i.e., customers) must cover both electricity uses (energy efficiency, load management) and technical limitations of the mini-grid. The personnel responsible for O&M should also be trained right from project implementation, with follow-up training over the long term.

For the sake of project sustainability the involvement of all the local stakeholders of the project is fundamental: Local authorities should be involved from the inception, regardless of the business model chosen for the project. They can help assess electricity needs, conduct good project monitoring, help organize the community, enforce the rules, help develop local productive enterprises or added-value activities, etc. The participation of the local community can take different forms: Participation in the initial investment, connection fee, monthly payment etc. It is also fundamental that the disconnection policy be clear and enforced. Finally, tying salaries with system performance can increase the involvement of the local personnel responsible for the O&M.

Prepared by: Alliance for Rural Electrification (ARE)

ARE
Renewable Energy House
Rue d'Arlon 63-65
1040 Brussels
Belgium
Tel: +32 2 400 10 51
Fax: +32 2 400 10 10
http://www.ruralelec.org

6.3 Summary of PVPS Task 11 publications

Report IEA–PVPS T11-01:2011

World-wide Overview of Design and Simulation Tools for Hybrid PV Systems

Executive Summary

Off-grid PV systems and, in particular, hybrid PV systems are characterised by a high degree of complexity at the dimensioning stage. For this reason, as in many other fields, software simulation is an important aid. To get a world-wide overview of the available software tools and their features, a survey was initiated among Task 11 participants to learn about the tools they use. The survey questionnaire and subsequent analysis dealt with: licensing policy, cost, availability, features, application area, characteristics and quality of user interface and documentation.

Results were obtained for 23 software tools. In addition to tools focused on PV hybrid systems, the survey also gathered information on tools for the design of distribution networks for mini-grids.
The software tools can be divided into four groups:

1. **dimensioning tools**, which calculate the system dimensions on the basis of input data (load and climate data and system components),
2. **simulation tools**, which use the input data (load and climate data, system components and configuration) to simulate the behaviour of the system over a given period,
3. **research tools** with a high degree of flexibility and configurability to allow very complete simulation of different systems for research purposes, and
4. **mini-grid design tools**, which assist with the design of the mini-grid electrical distribution network.

Current software tools can greatly simplify and shorten the design process for PV hybrid systems. Several high quality tools are available at no cost. However they do have limitations. In order to maintain ease of use and limit complexity, dimensioning tools like RETScreen and PV*SOL usually limit the available options for energy sources, system architectures, and dispatch strategies. Simulation tools such as HOMER and Hybrid2 allow very detailed analyses. Both allow the inclusion of wind turbines in the system analysis. Only HOMER allows comparison between DC and AC coupled systems.
The research tools, such as TRNSYS and INSEL, and the standard commercial system simulators, such as MATLAB and Dymola, allow much more flexibility in defining energy sources, system architectures, and dispatch strategies, but at the expense of considerably more effort to learn the software and develop the models. For the standard commercial system simulators, with the exception of Simplorer, the models for PV and renewable energy components must be developed by the user, or obtained through cooperation with research institutions that have developed proprietary models.
A limitation is that no direct data exchange is possible among the programmes. This must be done by using (or developing) an auxiliary programme or with paper, pencil and manual input.

One of the key decisions to be made by the user when selecting a software tool concerns the desired focus of the calculations: preliminary feasibility study and general dimensioning (RETScreen), economic considerations (HOMER), a detailed technical configuration (PV-SPS, PV*SOL, PVsyst), system analysis (Hybrid2, PV-DesignPro) or detailed research (TRNSYS, MATLAB/Simulink).
In conclusion, it must be pointed out that the results of the system design and system simulation are dependent not only on the calculation algorithms of the programme concerned, but also to a high extent on the quality of the input data, i.e. the technical knowledge and experience of the programme user. The software will prove a very useful aid during the process of system identification. The output results, however, should always be appraised with the due critical objectivity!
The final outcome of the survey is a report that provides an overview of available software tools, their features and guidelines for the selection and use of the tools for particular applications.

Report IEA-PVPS T11-02:2011

The Role of Energy Storage for Mini-grid Stabilization

Executive Summary

Mini-grids may be designed to operate autonomously with or without connection to a central grid. While operating autonomously, they cannot rely on the central grid to provide stabilization to control the line voltage and frequency, balance supply and demand of power and manage real or reactive power.

Energy storage can provide stabilization in a mini-grid as follows: when the system works autonomously, storage provides or absorbs power to balance supply and demand, to counteract the moment to moment fluctuations in customer loads and unpredictable fluctuations in generation. When grid connected, energy storage systems also can provide ancillary services to improve power quality such as voltage and frequency regulation, harmonic filtering, and fault clearing (i.e. supply of short circuit current). This is named the power use of energy storage, contrary to the usual energy use of energy storage.

In this report the stabilization of mini-grid systems in the power range up to 100 kW with a storage time operation up to two minutes was studied. Ideally, energy storage for mini-grid stabilization must have these features:

- High power density (more important than high energy density).
- High efficiency and little change of efficiency with the change of the rate of discharge.
- Discharge duration at its rated power (or higher if possible) for a minimum of two minutes
- High reliability.
- Very fast response time.
- Flexible ramp rate.
- Low cost.

The self-discharge characteristic of the storage system is not so critical when it is used for stabilization due to the frequent opportunities to recharge.

Nine storage technologies have been studied. Most of them are electrochemical batteries: Lead-acid, nickel-cadmium, lithium-ion, sodium-sulphur, sodium-nickel-chloride, vanadium redox and zinc-bromine. The remaining two technologies studied are electrostatic energy storage by super-capacitors and mechanical energy storage by flywheels.

In this study, we conclude that four storage technologies are good choices for mini-grid stabilization because of their response time and their power density: **lead-acid, lithium-ion, super-capacitors and flywheels**. Among them, only lead-acid is a very mature technology ready to implementation in mini-grids. However, for a pure mini-grid stabilization application, the battery bank may have to be oversized to meet the power demand - i.e. the energy storage capacity is larger than required. Commercial use of lithium ion batteries is currently limited primarily to low power applications, with the exception of some electric vehicle applications. High power lithium batteries for stationary use have an emerging commercial status, but the cost remains high. Flywheels and super-capacitors are suited to mini-grid stabilization because of long deep-cycle life and good response time but their cost is at present an important disadvantage compared to conventional batteries.

It must be kept in mind that these four technologies are considered the most suitable to deliver a specific short-term power for this mini-grid stabilization. The technology assessment may be different for applications in which both long-term energy storage and short-term power supply are required.

Report IEA–PVPS T11-03:2011

Sustainability Conditions for PV Hybrid Systems

Executive Summary

Photovoltaic (PV) hybrid mini-grid systems are used to provide grid quality electricity to small islands and remote isolated areas/facilities 24 hours a day. PV hybrid mini-grid systems have unique environmental characteristics not found in other PV power systems, such as solar home systems (SHS) and grid-connected systems, because of the combination of PV, other power generation technologies, and energy storage.

Integrating PV into a small diesel mini-grid power system can significantly reduce the system's greenhouse gas (GHG) emissions. GHG emissions reduction of a diesel power system when combined with PV are attributed to eliminating inefficient use of diesel generators, avoiding dump load, and supplementing diesel power generation with PV-generated power when conditions allow. According to the case study in this report, supplementing diesel power generation with PV accounts for 84.9% of the reduction, eliminating inefficient use of diesel generator accounts for 7.7%, and avoiding dump load accounts for 7.3%. The case study shows diesel fuel consumption of a PV diesel hybrid system is 33% lower than a diesel power system.
GHG emissions reduction potentials vary among different PV power systems. GHG emissions reduction potential, per unit PV output in kWh, is highest with a SHS, lowest with a grid-connected PV system, and intermediate for PV diesel hybrid systems.

A life cycle analysis of GHG emissions reduction by a PV diesel hybrid system was conducted to confirm the result of the above case study. The analysis showed that the weighted average life cycle GHG emissions factor of a PV diesel hybrid system is 25.9% lower than for a diesel power system, even using very conservative assumptions.

The study recommends replacing diesel power mini-grids with PV diesel hybrid mini-grids as an effective measure for reducing diesel fuel consumption and GHG emissions, and supplying 24-h electricity services to small islands and other isolated remote areas/facilities.

IEA-PVPS T11-04:2011

Communication between Components in Mini-grids

Executive Summary

Off-grid PV systems and, in particular, hybrid PV systems are characterised by a high degree of complexity. Therefore data communication among the system components is important to manage, so as to coordinate the overall energy flow in the system. Communicating components in a PV hybrid system typically include the power handling components, such as energy generators, energy storage systems, loads, and switchgear, and also control and monitoring systems. The data communication system implements one or more of the following functions:

- *Control* – coordination of component operation for energy management, synchronization, parallel operation, protection, and other system requirements
- *Configuration* – initial component and system set-up, selection of operating modes, adjustment of set-points and parameters, and downloading of software upgrades from a single point
- *Monitoring* – providing consolidated data on status and performance of individual components and the entire system

Many control functions require “fast” communication with precisely synchronized information exchange occurring within microseconds or milliseconds. Supervisory control (energy management), configuration and monitoring functions can usually be carried out with a “slow” communication channel that does not required precise synchronization and allows information exchange with greater delays – fractions of a second to seconds. Fast communication channels are generally more difficult and expensive to implement over long distances. Therefore PV hybrid systems should be designed so that the components using fast communication are physically close to each other.

Design of a data communication system for a PV hybrid mini-grid requires selection of pre-defined procedures for regulating the transmission of data, called **protocols**, and a physical communications medium, often called the **data bus**. Copper wire remains the most common physical medium for PV hybrid communication networks, but wireless (radio) systems are increasingly used for slow communications, and optical fibre may find use in high performance applications. A large number of protocols have been defined and standardized for data communications. A complete PV hybrid communication system will use a multi-layer set of protocols to transfer information between the physical medium and the control software in the components. Many of the standard lower level protocol layers, such as RS485 plus Modbus, or CAN plus CANopen, are suitable for use in PV hybrid systems. However, there are, as yet, no widely used high level protocols, often called *standard information models,* for PV hybrid components. Individual manufacturers develop proprietary information models that allow their components to interoperate but these do not extend to components from other manufacturers.

Task 11 surveyed its participants to determine how they used data communication among components and what protocols they employed. Slow communication for monitoring, data acquisition, and supervisory control is commonly implemented. Fast communication for control is less common. According to the survey, the most typical hardware bus used by the industry to control the components for PV-hybrid systems is an RS485 bus with proprietary protocols to exchange information. The CAN bus is also used, again often with proprietary protocols. Standard, open source (non-proprietary) high level protocols are being developed for renewable energy applications. These include extensions of the IEC 61850 standard, originally developed for substation automation, and the Universal Energy Supply Protocol (UESP) specifically designed for hybrid energy systems.

Report IEA-PVPS T11-05:2011

Social, Economic and Organizational Framework for Sustainable Operation of PV Hybrid Systems within Mini-Grids

Executive Summary

In remote parts of the world where hybrid photovoltaic (PV) systems have been installed, it has been shown that, in addition to a suitable design and proper installation, non-technical aspects have to be considered. The social and economic aspects described in this report deal with long-term conditions for operation and management of hybrid PV systems and their overall sustainability. Considering organizational, social, and economic conditions in which PV hybrid power systems (PVHPS) are installed, operated and maintained, key lessons learned from designing and operating PVHPS systems are highlighted, typically:

- The design of the system should be adequate to the conditions and needs of the community (including importantly an equal role of women).
- Unfamiliarity of the developer with local conditions and a top-down "development" approach (design based on what developer assumes development should be) are negative factors.
- A condescending approach (ignoring know-how, contribution, capacity, voice, self-respect or dignity of local communities) has harmful effects.
- Inhabitants of communities (like everywhere) will always find new ways to consume electricity: systems must be planned to promote efficient and responsible consumption oriented to minimizing the load increase or to allowing easy and sustainable expansion.
- An understanding of the difference between literacy and education, and the capacity of the community to develop for themselves is essential, rather than a focus on the goal of the project. Knowledge in villages should be used and external dependency limited.
- An agreement must be reached in advance so that the users are aware of the energy limitations and of the need for efficient appliances.
- The system should be highly efficient and robust.
- Nothing is maintenance free: the operation and maintenance (O&M) of PV systems have to be paid for.
- The tariff paid by the users within their willingness to pay must be able to sustain at least operation of the system and replacement of its components.
- Follow-up actions after implementation, if supported and managed with users, prevent potential difficulties.
- Repairs in remote locations are difficult and expensive: logistics for spare parts and high-efficiency appliances could be critical.
- Vandalism, theft, and the adoption of preventive measures could be issues to consider.

Most failures are not due to technical problems but to the lack of a clear organizational scheme to operate the system (managing the O&M tasks and the user payments), and also to the lack of an energy management concept which encourages the responsible use of energy where supply is limited. Achieving sustainable, economic and widespread use of hybrid power systems is possible if local management schemes, effective policies, meaningful finance, and cooperation with/amongst system integrators, technology providers, and final users are put in place.

IEA-PVPS T11-06:2011

Design and Operational Recommendations on Grid Connection of PV Hybrid Mini-grids

Executive Summary

In the case where a PV hybrid mini-grid connects to a main grid, designers, grid operators, and the other relevant stakeholders should consider the following issues in the initial stages of design to ensure power quality and power supply reliability:

1) **Compliance with existing rules on power quality and grid connection**.
The design should comply with the rules prescribed in existing regulations on power quality and grid connection.

2) **Implementation of additional countermeasures specific to the site**.
If specific factors related to the site include security risks, power quality issues, and other reliability concerns, then necessary technical countermeasures should be added to the initial design, based on consensus of the stakeholders.

3) **Awareness of current standards developments.**
There are many activities in various regions of the world that aim to establish, revise, and unify standards focused on power supply quality at high penetration levels of renewable energy. Research and development is being conducted in the field to assist standards development. Stakeholders should stay current with these activities.

IEA-PVPS T11-07:2012

PV Hybrid Mini-Grids: Applicable Control Methods for Various Situations

Executive Summary

Traditionally, remote communities worldwide have been supplied electricity by diesel engine-generator sets (gensets). The use of renewable energy sources (RES) can reduce the environmental impact of power generation, displacing diesel fuel and reducing the overall electricity price. When there is high penetration of RES, the inherent fluctuating and intermittent power characteristics of RES and the highly variable load profile of remote communities create significant challenges for the grid forming (master) unit(s) that regulate voltage and frequency. These challenges can be addressed with suitable control strategies which should at one level, (primary control) maintain grid stability by balancing generation and consumption of power and, at the other level, (secondary, or supervisory, control) optimize the generation of all sources and operation of the energy storage units.

Hybrid mini-grids can be classified in several ways. In this report, a classification scheme based on the nature of the grid forming (master) unit(s), which balance power generation and consumption within the mini-grid, has been selected to discuss available control techniques and future developments.

Three classes are discussed. These are:

1. The **multi-master rotating machine dominated mini-grid**, which is a typical configuration for a diesel mini-grid, has multiple ac sources (fossil fuel gensets, PV inverters, and other RES) connected to the mini-grid and simultaneously supplying power. The gensets do the grid forming and the other sources follow the mini-grid voltage and frequency.

2. **The single switched master mini-grid** architecture has multiple ac sources connected to the mini-grid (typically battery and PV inverters and a fossil fuel genset), but the grid forming control is switched between the genset and the battery inverter(s). This allows the genset to be turned off. These architectures are typical in village microgrids.

3. **The multi-master inverter dominated mini-grid** also has multiple ac sources (fossil fuel gensets, PV inverters, battery inverters, other RES) connected to the mini-grid and simultaneously supplying power, but in this case certain inverters participate in the grid forming along with the gensets. This approach is well suited for mini-grids with many generators distributed throughout the network.

The primary control strategies reviewed above are capable of regulating mini-grid voltage and frequency to meet current user needs. The choice of strategy employed will depend on the architecture of the mini-grid (centralized or decentralized), the generation mix (diesel dominated or high penetration of renewable sources), and the economics of incorporating auxiliary stabilization mechanisms, such as energy storage systems or dispatchable loads.

These control strategies are typically easiest to implement in lower power, compact mini-grids with centralized generation. As power levels rise, and the grid becomes geographically larger and more dispersed, the challenges increase for the following reasons:

- reduced availability of standard, off the shelf components and systems
- greater challenges with communication among system elements
- greater challenges maintaining voltage regulation throughout the mini-grid

There is a need for more research and commercial development of control systems and components for large, distributed mini-grids.

IEA-PVPS T11-08:2012

Overview of Supervisory Control Strategies including a MATLAB® Simulink® Simulation Tool

Executive Summary

Designing the supervisory control is one of the most critical tasks in the planning process for hybrid systems and mini-grids. Even if the system is correctly sized and able to accommodate unforeseen events, a badly-planned supervisory control may lead to sub-optimal performances, longer downtimes and premature failure of the system.

In this report the state of the art in the field of dispatch strategies for generation sources and loads has been investigated. The following different possible goals of the supervisory control have been identified:

- Best economical operation
- Highest reliability
- Lowest carbon footprint
- Service delivery optimization
- Component lifecycle optimization
- Load optimization through demand side management
- Best quality of supply

Based on available dispatch control parameters, several supervisory control strategies are presented for typical hybrid system design categories. The designs are categorized according to the solar fraction, the level of load dispatchability, and the availability of storage. For each design category, one or several adapted dispatch strategies are identified. In total, ten dispatch strategies are described.

In reality, many hybrid systems cannot be classified easily and different control strategies should be compared. In view of the many different system design configurations, weather conditions and load profiles, it is important to simulate in detail the impact of the supervisory control strategy on the overall performance. As a result of the work on this activity, simulation software using the MATLAB® system was developed at the Fraunhofer Institute for Wind Energy and Energy Systems Technology, Kassel, Germany. This tool may be used as an aid for anticipating possible critical system states and to evaluate the performance of a given supervisory control strategy. Standard power units with their control parameters are provided. The simulation software model (tested with Simulink® 7.0) may be downloaded from the Task 11 web-site (www.iea-pvps-task11.org).

In the last Section of the report, the simulation tool is applied on a virtual mini-grid. Two different supervisory strategies are compared in terms of their technical and economic impacts. The simulation results confirm that a significant amount of fuel savings can be achieved by choosing an appropriate dispatch strategy.

6.4 Bibliography

[1] Solarpraxis AG, *Inverter and PV system technology - Industry Guide 2012,* RENI, 2012.

[2] Simon Rolland, Guido Glania, *Hybrid mini-grids for rural electrification: lessons learned,* ARE, USAID, 2011.

[3] S. Szabo, K. Bodis, T. Huld, M. Moner-Girona, *Energy solutions in rural Africa: mapping electrification costs of distributed solar and diesel generation versus grid extension,* Environ. Res. Lett. 6 (2011), 2011.

[4] S. Szabo, K. Bodis, T. Huld, M. Moner-Girona, *Spatial evaluation of viable RE technologies in rural areas using GIS science,* ARE Symposium "Merging Off-Grid Research and Business", 2011.

[5] PVPS Task 11, *Design and operational recommendations on grid connection of PV hybrid mini-grids,* IEA PVPS, 2011.

[6] PVPS Task 11, *Worldwide overview of design and simulation tools for hybrid PV systems,* PVPS, 2011.

[7] G. Seeling-Hochmuth, *Optimisation of hybrid energy systems sizing and operation control,* University of Kassel, 1998.

[8] PVPS Task 11, *Social, Economic and Organizational Framework for Sustainable Operation of PV Hybrid Systems within Mini-Grids,* IEA PVPS, 2011.

[9] PVPS Task 11, *Communication between components in mini-grids,* IEA PVPS, 2011.

[10] PVPS Task 11, *Sustainability Conditions for PV Hybrid Systems,* IEA PVPS, 2011.

[11] PVPS Task 11, *The role of energy storage for mini-grid stabilization,* IEA PVPS, 2011.

[12] PVPS Task 11, *PV Hybrid Mini-Grids: Applicable Control Methods for Various Situations,* IEA PVPS, 2012.

[13] PVPS Task 11, *Overview of Supervisory Control Strategies including a MATLAB® Simulink® Simulation Tool,* IEA PVPS, 2012.

[14] Ernesto Terrado, Anil Cabraal, Ishani Mukherjee, *Operational Guidance for World Bank Group Staff – Designing Sustainable Off-Grid Rural Electrification Projects: Principles and Practices,* 2008.

[15] IRENA, *Electricity storage and renewables for island power: A guide for decision makers,* IRENA, 2012.

[16] Caroline Nielsen, Frank Fiedler, *Evaluation of a Micro PV-Diesel Hybrid System in Tanzania,* Borlänge, Sweden: Solar Energy Resaerch Center, 2012.

ISBN 978-3-906042-11-4
9 783906 042114 >