DEPLOYMENT OF HYBRID RENEWABLE ENERGY SYSTEMS IN MINIGRIDS

ASIAN DEVELOPMENT BANK

DEPLOYMENT OF HYBRID RENEWABLE ENERGY SYSTEMS IN MINIGRIDS

ASIAN DEVELOPMENT BANK

Creative Commons Attribution 3.0 IGO license (CC BY 3.0 IGO)

© 2017 Asian Development Bank

6 ADB Avenue, Mandaluyong City, 1550 Metro Manila, Philippines
Tel +63 2 632 4444; Fax +63 2 636 2444
www.adb.org

Some rights reserved. Published in 2017.

ISBN 978-92-9257-979-1 (Print), 978-92-9257-980-7 (Electronic)
Publication Stock No. TIM178889-2
DOI: http://dx.doi.org/10.22617/TIM178889-2

The views expressed in this publication are those of the authors and do not necessarily reflect the views and policies of the Asian Development Bank (ADB) or its Board of Governors or the governments they represent.

ADB does not guarantee the accuracy of the data included in this publication and accepts no responsibility for any consequence of their use. The mention of specific companies or products of manufacturers does not imply that they are endorsed or recommended by ADB in preference to others of a similar nature that are not mentioned.

By making any designation of or reference to a particular territory or geographic area, or by using the term "country" in this document, ADB does not intend to make any judgments as to the legal or other status of any territory or area.

This work is available under the Creative Commons Attribution 3.0 IGO license (CC BY 3.0 IGO) https://creativecommons.org/licenses/by/3.0/igo/. By using the content of this publication, you agree to be bound by the terms of this license. For attribution, translations, adaptations, and permissions, please read the provisions and terms of use at https://www.adb.org/terms-use#openaccess

This CC license does not apply to non-ADB copyright materials in this publication. If the material is attributed to another source, please contact the copyright owner or publisher of that source for permission to reproduce it. ADB cannot be held liable for any claims that arise as a result of your use of the material.

Please contact pubsmarketing@adb.org if you have questions or comments with respect to content, or if you wish to obtain copyright permission for your intended use that does not fall within these terms, or for permission to use the ADB logo.

Notes:
In this publication, "$" refers to US dollars.
Corrigenda to ADB publications may be found at http://www.adb.org/publications/corrigenda

CONTENTS

FIGURES AND TABLES

Figures

Tables

ACKNOWLEDGMENTS

This technical report was prepared under a regional technical assistance (TA) financed by the Asian Development Bank (ADB) (ADB. 2009. *Effective Deployment of Distributed Small Wind Power Systems in Asian Rural Areas*. Manila). The TA aimed to help its developing member countries to provide reliable, adequate, and affordable energy for inclusive growth. Originally focused at deploying small wind power systems, the TA has subsequently evolved to cover hybrid renewable energy systems including wind, solar, battery storage, and efficient diesel generation systems.

The report draws on activities related to the deployment and implementation of four pilot hybrid renewable energy systems in minigrids that were installed and commissioned in Maldives (two systems), Sri Lanka, and Bangladesh. The work on this report began in early 2015 and was completed in May 2017, building on findings from the real case studies in these countries. The ultimate goal of the report is to provide relevant technical guidance and recommendations for effective deployment of hybrid renewable energy systems in minigrids to achieve universal electricity access and energy efficiency in remote rural locations and small isolated islands.

The technical report was prepared by José A. Aguado of the University of Malaga (and of consulting firm Effergy Energia in Spain), who was engaged as an ADB consultant for the tasks related to implementing the hybrid renewable energy systems under the TA, and Mukhtor Khamudkhanov, principal energy specialist, Energy Division, South Asia Department, ADB, who supervised the work on the pilot hybrid systems. The report also benefited from initial contribution of Antonio Lopez Martinez (former energy specialist of ADB) and peer review by Susumu Yoneoka, energy specialist (Smart Grids), Energy Sector Group, Sustainable Development and Climate Change Department, ADB.

ABBREVIATIONS

AC	alternating current
ADB	Asian Development Bank
BESS	battery electric storage system
BMS	battery management system
CAPEX	capital expenditures
DC	direct current
DSM	demand-side management
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
LIB	lithium-ion battery
O&M	operation and maintenance
OPEX	operational expenditures
RE	renewable energy
SOC	state of charge
PV	photovoltaic
VAWT	vertical axis wind turbines

1 INTRODUCTION

1.1 Background and Context

1. Lack of access to electricity is one of the major barriers to human development, as we need it to power lighting, refrigeration, and other basic home appliances. Economic growth cannot be conceived without access to electricity. The percentage of population with access to electricity is undeniably one of the clearest indicators of the level of development of a country. According to the *World Energy Outlook 2016* [1] by the International Energy Agency, an estimated 1.2 billion people, which represents more than 16% of the world population, do not have access to electricity. Most of them are living in countries of Sub-Saharan Africa and developing Asia, mainly in rural or remote areas. Moreover, most rural communities with access to electricity have it at the expense of huge funds spent on subsidies for fossil fuels, which hampers the deployment of more sustainable energy sources. There are several institutions and initiatives worldwide working toward universal energy access with a special focus on developing renewable energy (RE) and energy efficiency. Among them, the United Nations' initiative Sustainable Energy for All [2], to which 102 countries have signed up as partners, seeks to achieve universal electricity access by 2030. The Asian Development Bank (ADB) is one of the leading regional development organizations that play a pivotal role in fighting poverty and fostering universal energy access.

2. There are several technical approaches to supply electricity to remote or isolated areas [3]. **The first approach** is to expand the national electricity grid, or connect to a continental grid in the case of island states. In many cases, the high cost of expanding the distribution power lines usually leads to economically unfeasible projects. The challenging geography in certain remote locations highly impacts distribution line expansion costs. Islands and areas with difficult logistics necessitate extra time and resources to deploy distribution power lines because, in the case of the islands, this usually involves submarine cables. Likewise, the magnitude of the demand determines the cost per kilowatt-hour (kWh) of grid expansion. A certain minimum level of consumed energy is necessary for project viability. Remote areas and small isolated islands have usually a small energy demand per connection, so the national authorities and/or utilities are less inclined to connect these communities to the electricity network. Moreover, security of supply and power quality issues are major concerns that utilities usually face in developing countries. Consumers may only have power during limited hours per day, and outages are quite common. Electricity network expansion usually comes with a demand load growth. However, if there is no resource capacity adequacy, connecting new consumers to the electricity network will just exacerbate the situation and decrease the quality of the electricity supply service.

3. The International Energy Agency estimates a threshold of about 100 kWh of electricity per person per year as a reasonable level of energy access. Solar lanterns, as well as stand-alone solar home systems, are crucial elements to provide energy for basic lighting, cellular phone charging and, in some cases, television. However, other more energy-intensive demands, such as workshop tools, refrigerators, rice mills, or irrigation pumps, are usually associated to higher economic and social developments. Minigrids are certainly an alternative that can provide such progress.

4. **The second approach** relates to installation of electricity home systems. Such energy systems are becoming more and more popular. They usually provide energy to an individual household or a small number of households, and are a technically robust solution, relatively inexpensive, simple to maintain, and easily accessible. The dispersed and distributed nature of remote settlements is a perfect setting for electricity home systems, particularly with RE sources, which is usually competitive in the remote areas. In most cases, remote and isolated locations can benefit from a single or a combination of solar photovoltaic (PV) systems, solar home systems, mini- or micro-hydropower plants, or even wind home systems. In these cases, the generation sources are often deployed close to the demand, avoiding distribution expansion costs.

5. **The third approach** is based on electricity minigrids or microgrids that can supply electricity at the local level through village-wide electricity distribution networks. Minigrids—with a 100% RE mix or hybridized with other technologies (i.e., diesel generators)—are fast to deploy, easy to scale up to meet future energy demand, and could be connected to a central grid when it becomes reachable.

6. Minigrids play an essential role in fostering rural electrification. They may use fossil fuel-based generation sources (in most cases diesel generators). Alternatively, they can also integrate indigenous RE sources. Since diesel generation sets usually require reduced up-front costs, they are still very popular. However, some RE technologies are already competitive in terms of levelized costs of energy (LCOE).[1]

7. A minigrid can be supplied by different types of energy resources and power plants. However, in this report, **we will concentrate on the minigrids that are supplied by hybrid RE systems with solar PV and/or wind sources backed with a battery electric storage system (BESS)**. Such hybrid minigrids allow generation sources to meet demand by synchronizing RE technologies with existing diesel generators. The bidirectional nature of the power flow on the BESS can charge an electrical battery storage system whenever excess energy is available from a renewable source or using a diesel generator. It can act as a direct current–alternating current (DC–AC) converter whenever energy is required from the battery. The inverter can also supply "peak shaving" services [4], as part of a control strategy, at the time the demand load exceeds the supply capacity of the diesel generator.

8. A hybrid minigrid usually provides an energy supply service with high quality standards, which can be even better than the service provided to customers connected to a central grid in some regions. Such minigrids supply enough power to meet domestic needs (lighting, refrigeration, communication, and water supply), public services (health facilities and schools) requirements, and to enable development of small businesses and services in local communities.

9. Due to their modularity, hybrid minigrids show an important advantage: generation adapts to demand growth since generation technologies can be easily scaled up.

10. Therefore, this kind of energy solution is a credible alternative to the existing diesel-powered minigrids. There is a multitude of diesel-based isolated grids with the total capacity measured in gigawatts that could be retrofitted with RE technologies. This is particularly the case of many remote rural villages and isolated islands in South Asia.

---

[1] The LCOE is a cost of generating a unit of electricity (usually kilowatt-hour) that can be calculated as a net present value of total costs incurred during a life cycle of a generating facility to its total electricity production during that period. It is an important value for justifying project investments.

11. In a minigrid, electricity is distributed at a local level without requiring access to the main network. The minigrid is normally managed by an operator that may have different legal forms to provide energy services to end users. Usually, the minigrid will operate under AC low voltage, although DC is also feasible, especially for very small minigrids. Minigrids have installed capacity ranging from 10 kilowatts (kW) to 1 megawatt, even though larger systems exist.

12. On the other hand, sharing limited energy resources among customers in a minigrid or microgrid requires a tariff structure that ensures the sustainability of the system, enforcing a rational use of the available resources.

1.2 Scope and General Objective

13. Many technical, financial, and socioeconomic factors come into play in the design of a hybrid RE minigrid. Efforts to adapt the design to the natural, present, and expected socioeconomic conditions of each location, in contrast to trying to standardize system designs, will pay off in terms of efficiency, user satisfaction, and sustainability of the system.

14. This publication aims to present state-of-the-art guidelines and recommendations for deployment of **solar PV–wind–diesel hybrid RE systems with a battery energy storage system** in minigrids, and to provide some insights on technical and implementation aspects of such systems.

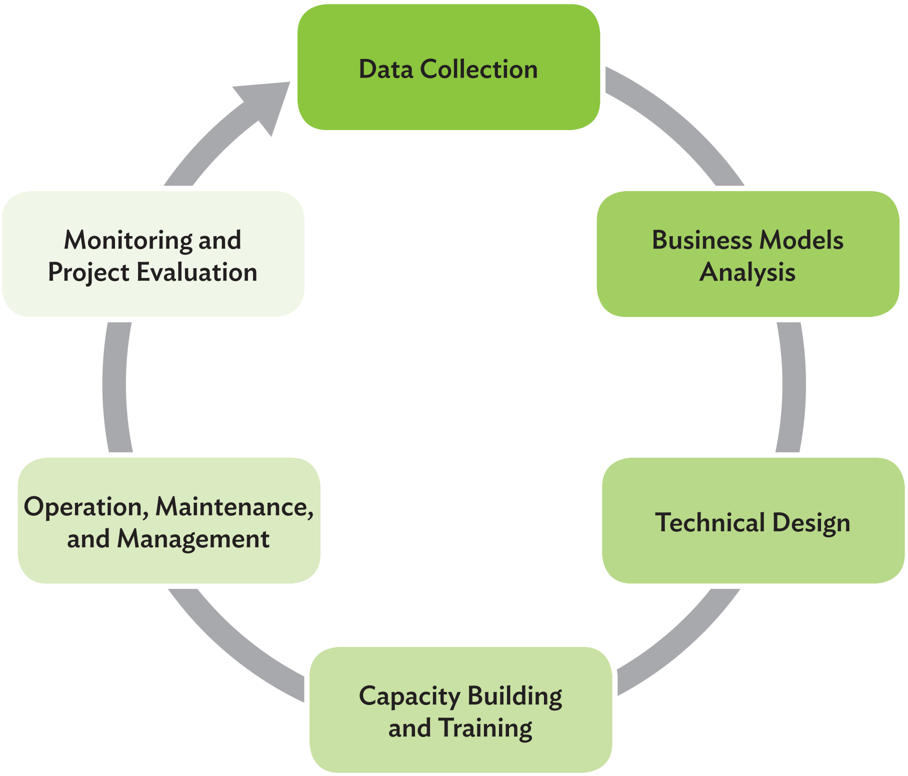
15. The topics covered by the guidelines range from data collection to operation and maintenance (O&M) issues with a special focus on technical design aspects. A couple of illustrative pilot projects are also described in this report.

2

SUSTAINABLE HYBRID RENEWABLE ENERGY PROJECT DEPLOYMENT

16. A series of implementation stages are required for the successful deployment of a hybrid RE minigrid project. They are summarized in .

Figure 1.2-1: Steps for the Deployment of Minigrid Projects



Source: Jose Antonio Aguado (Effergy Energia).

17. These implementation stages include the following:

(i) **Data collection.** To come up with a design that optimally adapts to particular conditions of each location, it is fundamental that present and future electricity demand, natural resources, existing infrastructure, and socioeconomic conditions are properly assessed.

(ii) **Business models analysis.** The financial sustainability of a minigrid project depends on the suitability of a business model chosen for the project. Different public or private agents can assume the different responsibilities in the deployment and O&M of a minigrid. The specific features of each location will determine the most sustainable model. Tariffs and subsidies need to be adequately adapted to the economic conditions to achieve a balance between affordability for customers and being able to cover O&M costs.

(iii) **Technical design.** The technical design process includes determining the optimal mix of generation and storage technologies, the best location for components, control architecture, and distribution infrastructure. This stage needs to be based on optimization studies using contrasted data for each specific project, as the best design is dependent on the particular conditions of each place (demand profile, natural resources, etc.).

(iv) **Capacity building and training.** Training electricity users and local staff in at least minor routine maintenance tasks is important for the proper functioning and maintenance of a minigrid, and should be carried out before and during the implementation of the minigrid project.

(v) **Operation, maintenance, and management.** Many minigrids fail prematurely after only a few years due to lack of proper maintenance. The different components of the minigrid should be inspected regularly, and maintenance planning should be agreed between different agents involved in the project.

(vi) **Monitoring and project evaluation**. For the sustainability of the project, it is crucial to monitor key performance indexes. Project evaluation will allow the project team to benchmark the system and provide actions to improve the project performance.

18. Lessons learned from previous projects point that, beyond technology barriers, many failures come from a lack of clear standards to operate and maintain the systems. Poor estimations of electric demand growth, incorrect understanding of customer behaviors, poor design of the tariff structure, and the lack of well-defined business models are the main reasons for minigrid failures.

3

DATA COLLECTION IN MINIGRIDS

19. Different minigrids will have different technical and socioeconomic needs, as well as different resources to supply them. Collecting enough reliable data is essential for a correct design. Failing to collect reliable data on the present and future needs, natural conditions and resources, and socioeconomic situation of the community, in which a minigrid is to be deployed, will most likely result in unsatisfactory and suboptimal designs.

3.1 Electric Demand Assessment

20. Demand assessment and load forecast in the planning stage is critical in optimizing the design of a hybrid minigrid. Oversizing the generation and/or storage capacity will result in poor cost-effectiveness of the proposed minigrid solution, while undersizing will result in inability to supply all demands and in customer dissatisfaction.

21. For a correct design of a hybrid RE minigrid, the following demand data should be collected:

(i) **Average daily energy demand (in kilowatt-hour)**. The average amount of energy that is consumed in a day gives an idea of the necessary generation and storage capacity, but it is not enough by itself for a proper design.

(ii) **Annual peak power (in kilowatt)**. The maximum expected level of power consumption needs to be quantified, as it sets the minimum generation capacity required to serve all demand.

(iii) **Daily load profiles**. This data corresponds to the hourly power consumption over 1 day in a minigrid. To figure out the energy sources installation and to analyze demand-side management (DSM) measures, it is of great importance to know at what hours of the day high and low demand periods take place.

(iv) **Seasonal variations**. Winter and summer electricity demand profiles can be quite different in some places due to the use of air conditioners and radiators, difference in daylight hours, etc. Assuming the load profile to be approximately constant throughout the year may not work in some locations. When measured data is not available for the whole year, seasonal variations should be estimated.

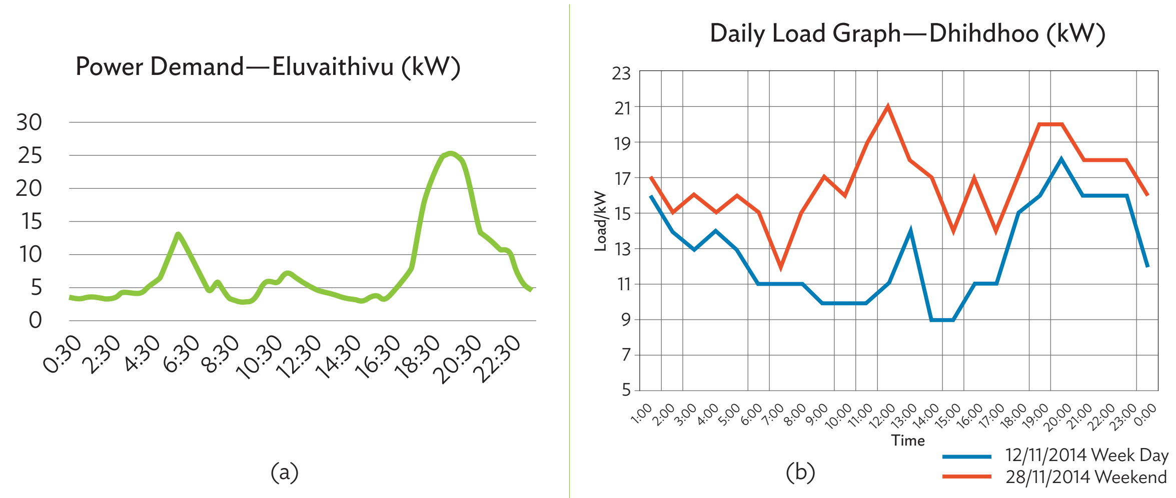
(v) **Customer segmentation**. An analysis and classification of the existing domestic, commercial, and public institution consumers should be carried out as one of the earliest stages in the planning of a hybrid minigrid project.

22. Current load demand in remote rural or island communities, which already have diesel-based electricity supply, can be estimated easily by installing data loggers in a power house. However, demand growth in these communities after implementation of a hybrid RE minigrid system is not easy to forecast. Access to uninterrupted and less expensive

electricity supply could (and should) encourage activities that may significantly transform the demand profile. DSM measures are important in this aspect to match consumption with RE generation as much as possible. In the rural communities that have no preexisting diesel minigrid, demand assessment is a more complicated task. In these cases, surveys on the desired electrical appliances and on ability and willingness to pay for electricity are conducted in households as the only way to estimate demand. Experience with other already functioning electrification projects in similar communities can also be a valuable input to estimate the demand, if available.

23. The typical load profiles in small islands and rural communities show their peak power demand in the evening after sunset, given that lighting constitutes a large percentage of the electricity consumption. This enhances the need for energy storage in order to shift some of the excess solar PV generation and save fuel consumption. The image below shows typical load profiles for two islands in Maldives and Sri Lanka.

Figure 3.1-1: Typical Load Profiles in Minigrids in (a) Eluvaithivu Island, Sri Lanka and (b) Dhihdhoo Island, Maldives



(a) (b)

kW = kilowatt.

Source: Jose Antonio Aguado (Effergy Energia).

24. A properly deployed minigrid project should accelerate the development of a community, causing energy consumption to increase in the first few years. That is why the project design should consider the demand (load) growth forecast for at least 5 years after the installation (period after which the uncertainty becomes too high in most cases). The load growth forecast is the most difficult part of the demand assessment process.

25. Planned public use of electricity and future projects that can arise with the new minigrid should be discussed in detail with local authorities. Some forecasting methods are based on macroanalysis, in which the system demand is estimated using a historical load data using regression and time series models. Other issues, such as population growth, emigration and/or immigration ratios, and gross domestic product indicators in the area, can be useful in estimating the demand growth. Regardless of the accuracy of demand estimations, the design of the minigrid should be flexible and expandable.

3.2 Solar Resource Evaluation

26. To optimally size and place PV installations, it is important to have an accurate estimation of the incident solar radiation throughout the year.

27. **Data collection.** The solar resource can be obtained from satellite-based solar models or measuring through ground-mounted sensors. Accurate and high frequency are usually available at ground-mounted sensors, while satellite-based models supply data with lower frequency of measurement but representing a longer history.

28. For accurate calculations of the energy yield of solar PV installations, two different components of the solar irradiation are required:

(i) Direct normal irradiance, also known as "beam radiation," is the amount of solar radiation from the direction of the sun. Solar PV panels with concentrator lens only capture this part of the solar radiation.

(ii) Diffuse horizontal irradiance, also known as "diffuse sky radiation," is the component of the radiation that comes from reflections from the atmosphere and clouds. Traditional flat-plate solar PV panels capture this component of the solar radiation as well. Thus, it needs to be considered in calculations.

29. Reliable solar models based on the use of the satellite and atmospheric data are available. There are several online sources that offer the solar data in the form of typical meteorological years, such as of National Renewable Energy Laboratory [5]. A typical meteorological year for a location is a time series that provides solar radiation and temperature data for a whole year, usually in hourly periods.

30. **Data quality assessment**. Solar radiation data coming from the observations on the surface (as data from weather stations and measurement equipment) should be subject to a quality analysis to verify their use for the solar resource estimation in each case. The solar industry usually prefers working with uncertainty, the nature of which is probabilistic. Figures such as P-90, P-70, P-50, and similar values describe an annual value of power production from RE resources that will be exceeded with a certain percentage probability. For example, if the estimated energy yield is given a P-90 value, it means that the given energy yield will be greater with a probability of 90%. Typical meteorological years usually have a "Tier" (1, 2, and 3; with 1 being the best) classification, which indicates the relative quality of the collection site.

31. **Data evaluation.** Average annual irradiation levels over 4.0–4.5 kWh per square meter per day (kWh/m^2/day) will result in attractive PV annual energy yields. The annual average is a good indicator of the quality of the resource, but seasonal variations are important, and influence the resulting optimal design when they are significant (specifically in locations far from the equator and with long rainy seasons).

32. When the data is not available in a short time interval for a whole year, but in monthly averages, generic time series can be generated for simulations that will yield very similar results to real measurements. Several models can predict hourly extraterrestrial radiation accurately, given the coordinates of the location as a function of the time of the year. The actual radiation that strikes the PV panel depends on the amount of extraterrestrial radiation filtered in the atmosphere, mainly by clouds. The quotient between actual average horizontal

incident radiation and extraterrestrial radiation is commonly referred to as clearness index. Synthetic hourly clearness index data can be generated from average monthly radiation data, which can be found with acceptable resolution for most locations. Best practices employed for the collection and use of solar resource data in designing solar energy installations can be found in the relevant literature [6].

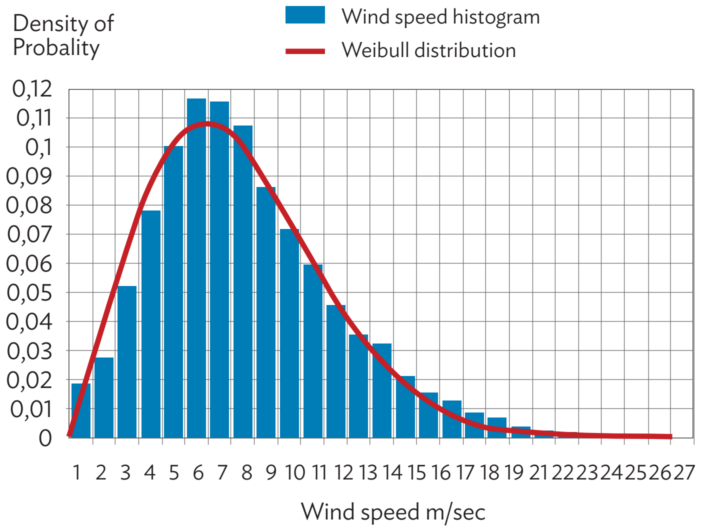
3.3 Wind Resource Evaluation

33. The wind resources in a place can be considered "bankable" when a project developer has collected enough solid data to demonstrate that it provides adequate power to generate sufficient revenue to pay back a loan.

34. Wind resources are not as easy to evaluate as solar resources. Databases for wind speeds are available for many locations, but differently from solar radiation, and average wind speed can vary greatly over a reduced space. Factors such as roughness of the surface, altitude, and obstacles (such as buildings and trees) have a considerable impact on the average wind speed.

35. Moreover, average wind on its own is not even a complete indicator of the wind resources, as the power generated by turbines is not a linear function; two yearly wind profiles with the same average speed can result in considerably different energy yields. The most common method of condensing wind resource information is through a probability distribution that expresses how likely it is for wind speed to be over each value. The Weibull distribution is the one that fits best to wind speed histograms. It is determined by the average wind speed and a shape factor *k*. The shape factor is in the 2–3 range, lower values of *k* indicate that values deviating from the average wind speed are more frequent (a flatter distribution). Figure 3.3-1 shows a wind histogram and its fitting Weibull distribution.

Figure 3.3-1: Wind Histogram and its Fitting Weibull Distribution



m/s = meter per second.

Source: Jose Antonio Aguado (Effergy Energia).

36. The assessment of wind resource can be divided into two phases:

(i) The first phase of wind resource assessment involves scanning the territory for suitable wind resource areas based on information from meteorological stations nearby that is provided by local authorities, or information observable in field visits. This should be enough to identify potential wind turbine installations. If no suitable terrains are found, then the installation of measuring equipment for further investigation is not justified.

(ii) Once a few suitable areas have been identified during preliminary stage, the final approach would require installing meteorological stations that record wind speed during a sufficient period of time and evaluating obtained data. This is the most reliable way to assess the wind resource and make informed decisions on whether it is profitable or not to install wind turbines, and which particular site offers the best wind resource. Ideally, measurements should be taken at least a year to register seasonal variations and intraday trends. An overview on wind resource estimation is available in the relevant literature [7].

37. It is important that measuring equipment is placed at a similar height to the wind turbines that could be installed in that site. The variations of wind speed with height are sometimes estimated as a function of the terrain roughness using the power law or the logarithmic profile, but results are generally not very accurate when compared with real measurements.

3.4 Other Relevant Data

38. Other important information that should be assessed and considered before the design of a hybrid RE minigrid project includes climate conditions, existing power generation and distribution infrastructure, availability of space and skilled labor, and socioeconomic constraints.

39. Climate conditions (apart from solar radiation and wind energy potential) are very important as they influence the technical aspects of the design. Extreme temperature conditions influence the choice of a battery type or the location in which they should be installed, the need for forced ventilation, etc. Similarly, humidity and salty air conditions in islands reinforce the need for extra protection against corrosion in solar PV frames or wind turbine blades. In places where very strong winds can happen, extra safety measures should be considered in the installation of rooftop solar PV panels, and especially wind turbines. For example, some manufacturers offer turbines that can be folded down to protect them from hurricane winds.

40. In places where there is an existing diesel-based minigrid, the age, efficiency, and adequacy of the nominal power of the generators should be assessed. In most cases, these generators are old and lack proper maintenance, resulting in very high specific fuel consumption. Sometimes, the generator sets are not in bad condition, but they come from donations from other places and have not been adapted to the demand level of the location: thus, they work at a low percentage of their rated power, resulting in very poor efficiency. In any case, the specific fuel consumption should be measured. If it is too high (over 0.4–0.45 liter per kilowatt-hour), investing in new efficient generators will definitely pay off in most cases, except maybe for systems designed for very high RE penetrations where diesel

generators are only used occasionally. If the existing diesel generators are kept, they will probably require new controllers to work in parallel with inverters.

41. A diagram of the distribution lines containing information on the geographical layout and types of cables and protection used must also be studied to determine what kind of expansions and updates will be required for the new minigrid.

42. Space is another important issue, especially in small islands. The feasibility and/or profitability of solar PV and wind installations are often constrained by the lack of sufficient, suitable, public-owned land. The possible layout of installations should be consulted with local authorities prior to the calculation of the optimal generation mix, as it is often a limitation in the design.

43. Logistics should not be overlooked either. For example, the installation of wind turbines of a certain size might be constrained by the difficulties and high costs in its shipping and installation in islands and remote rural areas.

44. Finally, having a clear picture of the socioeconomic reality of the community, where the minigrid will be installed, is crucial for a good design. These aspects influence both the technological design of the minigrid as well as the most suitable business model for it. Some of the most relevant aspects are the following:

(i) **Industrial and/or commercial activities**. The current economic activities in the community and especially potential ones that could arise with reliable access to electricity are very important, as the RE minigrids should target self-sustainability in the future, without relying on government subsidies. The minigrids should be designed to favor potential economic growth in these communities.

(ii) **Willingness to pay**. The consumers' ability and willingness to pay for electricity should be assessed to consider the most adequate tariff structure and business model.

(iii) **Availability of skilled (or willing to be trained) local labor**. To implement sustainable RE minigrids, it is desirable that those members of the local community who understand the functioning and limitations of the system can participate in its maintenance.

4 BUSINESS MODELS, AND SUBSIDY AND TARIFFS

4.1 Business Models

45. Communities, private sector companies, the state, or a combination of those three agents in which each one owns and manages a part of the system, may own minigrids. The deployment and management of the hybrid RE minigrids requires technical expertise in installing, operating, and maintaining the system, as well as skills in its financial management. The lack of local experts in these areas poses a risk to the sustainability of the hybrid RE minigrid projects. There are different business models to pay initial investment and O&M costs, which can be widely classified as follows:

(i) **Utility-based model.** A utility company manages all or most of the minigrid. This utility company may be a cooperative, owned by private investors, or a public institution. This is probably the most common approach in the developing countries. This model has several advantages. On the one hand, a local utility company will supposedly have experienced and skilled operators as well as a better link to local authorities. On the other hand, that connection to the local authorities could mean that utility companies are more driven by political agendas. Also, in many cases, these utility companies have an inefficient centralized management structure and/or a weak financial situation that can lead to maintenance not being properly taken care of.

(ii) **Private sector operator.** In this model, a private agent owns and manages the minigrid, usually after having won a concession by the local government. In most cases, given the low energy consumption and low income in small islands and rural areas of the developing countries, the private sector is unlikely to build sustainable projects without financial support from the local authorities. It is important that such support—in terms of technical assistance and subsidies—is clear and bound from the beginning. Private companies might be able to offer better services for O&M of the minigrid. However, in many cases, private companies would not have the necessary financial support to make minigrid projects profitable for them.

(iii) **Community-based model.** In some cases, it is the local community that owns and manages the minigrid, taking care of maintenance, tariff collection, etc. Public ownership of the minigrid by the community can translate into more involvement and thus better maintenance, as well as less bureaucratic impediments. Another advantage is that jobs are created within the local community. The obvious disadvantage is the lack of local experts, which will translate into higher costs when they are needed. This approach requires intensive technical, financial, and social capacity building. This model could also be vulnerable to corruption and abuse of some members of a community committee in charge of the minigrid. The community-based organizations should have defined legal rules and contractual arrangements in place to ensure payments.

(iv) **Hybrid models.** Hybrid models are a combination of the abovementioned models, in which different agents own and operate different parts of the system. Different situations can occur in terms of who owns what, and who is responsible for different O&M tasks. This kind of business model is site-specific. For example, minigrid generators and a distribution system could be owned by a utility company, while a community organization could be in charge of daily O&M, and private companies can provide the occasional consultancy on more advanced technical issues. In some other minigrids, a private project developer owns the generators and gets paid based on a power purchasing agreement, while a utility company is responsible for the distribution and tariff collections. When properly established, these models can be the most efficient, as they can combine the expertise of the different agents. However, they are subject to possible conflicts arising between the different agents involved.

4.2 Subsidy and Tariffs

46. In remote rural or island locations, a sustainable hybrid RE minigrid electrification tariff should at least cover O&M costs of the system, although the opportunity for profit is necessary to attract private investors. In places where minigrid tariffs are not regulated, a project developer and consumers can agree on tariffs freely. However, households in rural communities have generally both low energy consumption and income, and, in many cases, revenues from consumer tariffs are not even sufficient to cover O&M costs of the system.

47. The funding to support a hybrid RE minigrid project can come from three main sources:

(i) debt and equity with banks and private investors,

(ii) financial incentives and subsidies from the local government, and

(iii) electricity consumer tariffs.

48. The balance among these resources determines the financial sustainability of the hybrid RE minigrid.

49. When designing a hybrid RE minigrid in a rural community, it is important for the sustainability of the project to come up with productive uses of electricity to ideally get rid of subsidies over time. However, in low-income developing countries, in most cases financial assistance from governments is critical to maintain the minigrid with affordable tariffs for end users.

50. Capital subsidies are a common form of support from governments to reduce the initial investment of a developer, and are usually tied to an O&M compromise from the project developer. In some countries, a government regulates minigrid tariffs to be affordable while providing the developer with an ongoing subsidy that ensures a profit margin. Support in O&M can also be negotiated. Subsidies can be given directly to consumers, by paying for their connection fee, new efficient appliances, home wiring, etc. Other ways of support from the local authorities to the project developers include lower taxes and accelerated depreciation, lowering or suppressing import duties, etc.

5 TECHNICAL DESIGN CRITERIA

5.1 Achieving the Optimum Generation Mix

51. Once demand and indigenous RE resources have been assessed, we must determine which combination of controllable generation, renewable generation, and energy storage will translate into a lower energy cost. In this first stage of the design, the objective is to find a mix of generators that balances initially required investment and operating costs to ensure the most economical and reliable electricity supply. This search for the optimal lowest average cost of energy is often constrained by factors relating to space availability (for solar PV and wind installations), initial investment, capital availability, etc.

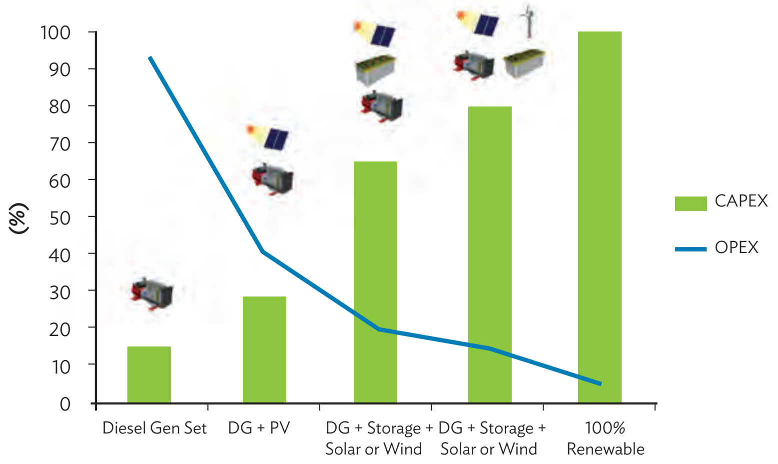
52. Calculation of optimal generation mix is a multidimensional task since many factors affect the optimum combination of different technologies. The typical load profile, fuel price, and solar and wind resource quantity at the selected location are the most important influencing factors on calculations.

53. Very often the optimal solution combines renewable generation and energy storage with controllable diesel generators, because 100% RE generation system requires oversized generators and storage to be able to supply all electrical demand throughout the year. RE generation has low operational costs since it uses free indigenous energy resources, but requires more initial investments, mainly because of the need for the energy storage. On the other hand, diesel generator sets have lower capital costs and are controllable (which means they do not require energy storage).

54. If a minigrid is designed to supply power 365 days of the year, the system that translates into a lower cost of energy in many instances combines diesel and RE generation (solar PV, wind, or both). Whether battery energy storage is required depends on the RE penetration level. The RE or power penetration index refers to the fraction of energy or power that the RE sources represents with respect to the total demand. In terms of power, we consider a minigrid with very low or low penetration of up to 10%–20% of the peak demand; a moderate penetration will result in up to 50% of the peak load; while levels of beyond 50% of the peak load are considered minigrids with high penetration. This classification is given only for illustrative purposes since case-specific analysis is required for an accurate clustering. RE penetrations over 50% may cause instability of the system due to the intermittency of solar radiation and wind speed. Stability studies, including simulations of potential worst-case scenarios and detailed models, are essential to justify the energy storage requirements.

55. The optimal percentage of RE generation substantially varies depending on the location of the RE minigrid as a result of the abovementioned factors [8].

Figure 5.1-1: Operational Expenditures versus Capital Expenditures for Several Generation Mix Configurations (%)



CAPEX = capital expenditure, DG = diesel generator, OPEX = operational expenditure, PV = photovoltaic.

Source: Jose Antonio Aguado (Effergy Energia).

56. The LCOE is a good indicator of the cost-effectiveness of a particular generation and storage mix, and can thus be used to compare different alternatives. Figure 5.1-1 shows the average monetary cost per kWh of supplied demand over the whole life of the project (operational expenditures [OPEX]) and the initial investment cost (capital expenditures [CAPEX]) for several generation mix configurations. To properly calculate the LCOE, cash flows should include all types of expenses: initial investments costs, replacement costs, fuel costs, other O&M costs, cost of unsupplied demand, etc.

57. Several free software packages for evaluating RE minigrid projects are available. A review of them can be found in the relevant literature [8].

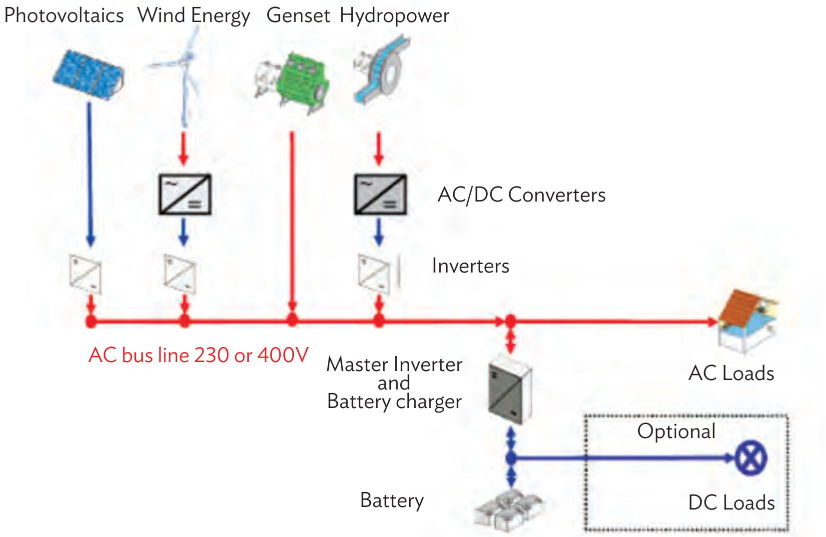
58. A more complete, licensed-based software for microgrid and distributed generation power system design and optimization is HOMER Energy [9]. This is a useful tool because it allows the calculation of annual cash flows for many different system configurations by simulating their operation hour-by-hour for a year. However, this tool cannot model many important aspects such as voltage and frequency stability, environmental considerations, etc. Determining the best generation mix is not as simple as introducing a few inputs in a single piece of software, as many factors are absent, but it can provide a good starting point in this process.

5.2 Minigrid Power System Architecture

59. Once the best possible generation mix is established, the type of voltage (either AC or DC) and a distribution line configuration that will link different components together have to be decided. There are several options:

(i) **Electricity generation coupled at AC bus line.** Generation sources are synchronized to an AC bus line either directly or using a DC/AC converter. Both alternatives assume a bidirectional inverter in charge of controlling the power flows in the minigrid including battery charging. The battery can also supply DC loads directly.

Figure 5.2-1: Alternating Current-Coupled Configuration

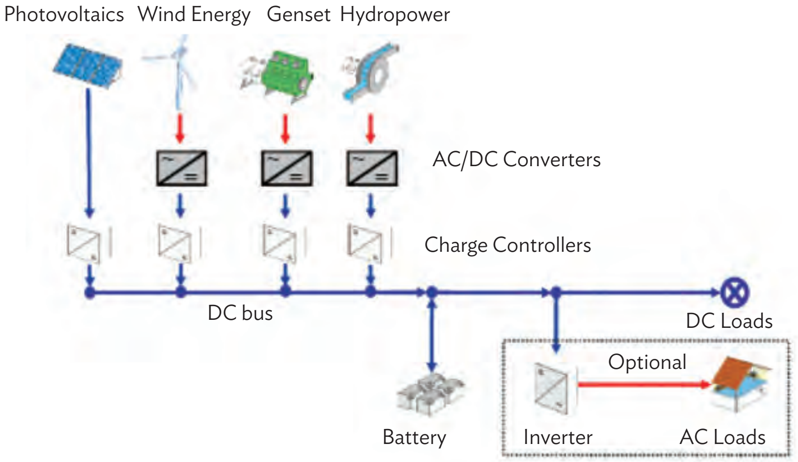


AC = alternating current, DC = direct current.

Source: Alliance for Rural Electrification. 2011. *Rural Electrification with Renewable Energy. Technologies, Quality Standards and Business Models.* Brussels.

(ii) **Electricity generation coupled at DC bus line.** Generation sources are connected to a DC distribution bus through power converters and charging the battery directly, ensuring efficiency of the system. AC loads can also be fed through DC/AC inverters. Furthermore, the DC loads may be directly connected to the DC bus.

Figure 5.2-2: Direct Current-Coupled Configuration

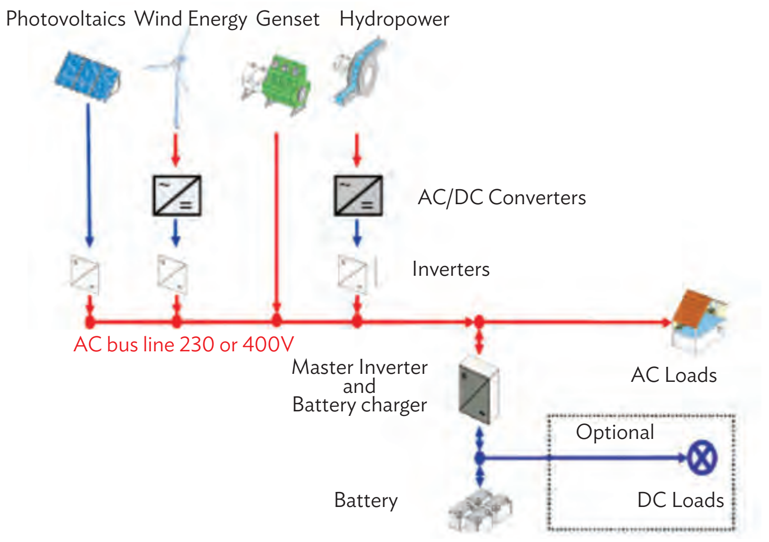


AC = alternating current, DC = direct current.

Source: Alliance for Rural Electrification. 2011. *Rural Electrification with Renewable Energy. Technologies, Quality Standards and Business Models.* Brussels.

(iii) **Electricity generation coupled at DC/AC bus lines.** A master inverter is responsible for supplying energy to the AC consumers. The DC loads may be fed by the battery. The AC generation sources may be directly connected to the AC bus line. Alternatively, they may need a DC/AC converter to ensure stable coupling of the components.

Figure 5.2-3: Alternating Current and Direct Current-Coupled Configuration



AC = alternating current, DC = direct current.

Source: Alliance for Rural Electrification. 2011. *Rural Electrification with Renewable Energy. Technologies, Quality Standards and Business Models.* Brussels.

60. There is no general rule for the selection of the best configuration. Main elements to consider include the daily load profile, preexisting distribution network, nature of loads, size in terms of installed power of the system, size of the system in term of distances, etc.

5.3 Stability and Control Strategies in Minigrids

5.3.1 Stability in Minigrids

61. Solar and wind technologies are classical elements of a hybrid RE minigrid. As solar energy is abundant, solar PV systems can be used almost everywhere. However, solar PV energy is nondispatchable due to intermittency of its source. The power output of small wind turbines highly depends on particular site conditions and it is also intermittent. To minimize risks of blackouts, maximize the lifetime of energy sources (especially electrical battery storage), and reduce investment costs, diesel generators are usually integrated as complementary energy sources or simply backup.

62. An energy management system is the key tool to coordinate all agents involved in a minigrid. It is responsible for the optimum operation of the minigrid dispatching generation sources, loads, and controlling battery power flows.

63. Operating a hybrid RE minigrid with medium and high RE penetration normally requires a multilevel control strategy. Such a strategy enables maintaining stability and power quality. It also allows achieving reliability, and economic and environmental objectives. The minigrid's control strategy is usually a hierarchical operation. At the operational security level, the main objective is to maintain the grid stability,[2] while at an economic operational level, the objective is to optimally dispatch generation sources, batteries, and flexible loads.

64. The analysis of the stability in small island power systems is quite different than in large interconnected power systems. In large systems, the size of all the individual components is small in comparison with the size of the entire system. A sudden change in the load, the loss of one generator, or any imbalance, does not generally lead to an unstable situation or a significant change in the system frequency due to high system inertia (kinetic energy stored in rotating masses of many generators).

65. The situation is completely different in the island or rural minigrids. These systems have low inertia and, thus are more susceptible to changes in the individual components. For such power systems, imbalances produced by a sudden rise or decrease of the power demand, or the loss of one generator is about the order of magnitude of the system. This can lead to a big frequency surge in the event of loss of generation or a big load change. This issue is what makes high RE penetration in minigrids a challenge, as clouds and fast changes in the wind speed can cause the power production to sharply drop or increase in a few seconds. This implies that the hybrid RE systems must be able to quickly compensate these sudden power changes, and generators spinning reserve and the energy storage are the key parameters to adjust depending on RE penetration and system architecture.

5.3.2 Control Strategies

66. Minigrid control tasks can be roughly divided into two levels:

(i) **Primary control (lower level)**. Implemented on generators and inverters to keep the minigrid in a stable state by balancing generation and consumption in the short term.

(ii) **Secondary control (higher level)**. Usually referred to as an energy management system or power plant controllers to optimize system operation. It acts in a slower time frame.

67. To understand the different control architectures in minigrids, it is important to know the different roles that a generator and an inverter can have in the minigrid operation. Power units can be classified as follows:

(i) **Grid-forming unit.** This unit controls frequency and voltage by balancing total generation and demand. A diesel generator or a battery inverter can play this role in the minigrid. It can be modeled as a voltage source.

(ii) **Grid supporting unit.** Grid supporting units can adapt their output based on commands sent by a supervisory controller, which is often incorporated in the

---

[2] "Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

grid-forming inverter of the grid. This is the case of slave inverters in a master–slave configuration. They can be modeled as controllable current sources.

(iii) **Grid parallel unit.** Uncontrolled load and generators, such as uncontrolled wind and solar PV systems, fall under this category. These devices are designed to feed as much power into the minigrid as possible. They can be modeled as an uncontrolled current source.

68. According to the geographical layout of controllable generation and demand, minigrid architectures can be classified as centralized or decentralized:

(i) In **centralized architectures,** controllable units are physically placed close to each other, often in the power house. The short distances allow the installation of fast communication cables between them. In this manner, a centralized supervisory control can send reference signals for a primary control to the other units using industrial communication protocols. This kind of communications between inverters and generators offers some extra flexibility on system operation.

(ii) In **decentralized architectures,** controllable units are distant from each other. This can be favorable in terms of the power flow and distribution losses since the power can be generated closer to the loads. On the other hand, it makes fast communication links between units much more expensive. In these cases, it is often preferable to implement a primary control strategy based on local measures at the terminals of controllable units, such as active power/frequency and reactive power/voltage droop control. A centralized supervisory control that does not require such fast communications can be used for secondary regulation.

69. According to the type(s) of power unit(s) for primary control of the minigrid, three main control architectures can be distinguished:

(i) **Diesel-dominated minigrid**. This configuration is suitable for minigrids with a low RE penetration and no energy storage. The diesel generator set is the grid-forming element acting as a voltage source that other sources (solar PV and battery inverters, wind turbines' synchronous generators or inverters) have to synchronize to, such that at least one of them needs to be online. In this type of minigrid, the electricity quality and system stability depend on the generator's capacity to react to changes in electricity balance and other disturbances. The characteristics of the generator governor and excitation systems are key for the stability of the systems with this configuration. The higher the penetration of renewable power, the more difficult it becomes for a diesel generator to maintain stability without help from storage systems, as sharp changes in renewable generation (passing clouds, wind gusts, etc.) represent a higher change in the output of generator sets.

When a single generator set provides primary regulation for the whole minigrid (a slack unit), this generator set can function in isochronous (fixed speed) mode. This means that changes in the net load (demand–uncontrolled generation) initially translate on a speed (frequency) deviation until the governor control, usually relying on a proportional–integral controller, restores the torque for the new power level at reference frequency.

However, when operating several units in parallel droop control, that establishes a way for them to share power variations proportionally to their rated output.

With this control strategy, diesel generators balance their active and reactive power generation with the load based on the frequency and amplitude of the voltage in its terminals. Transient imbalances result in a steady-state error of the voltage frequency and magnitude with respect to their reference values. A second slower control loop changes the parameters of the droop control to restore reference values in the steady state.

Generator sets normally function under operating constraints that keep O&M costs low by providing, at the same time, electricity with acceptable quality and reliability levels. These constraints reduce the ability of the generator sets to react to large, quick changes in electricity supplied to the minigrid by RE sources. Size and ability to function at low load percentages is important in this configuration, as it forces generator sets to stay running even in periods of high renewable penetration. This means some renewable generation must be curtailed or transferred to controllable loads to keep generator sets running over a minimum power level, thus not making the most out of the fuel consumption reduction that RE sources are meant to provide.

(ii) **Single-switched master minigrid architecture**. These architectures are typical for small village minigrids with a higher renewable penetration. In this architecture, the grid-forming task is switched between the generator set and the battery inverter, allowing the minigrid to operate at times without a running diesel generator to save fuel and achieve high RE penetrations. In this configuration, DC sources such as a solar PV module can be directly connected in DC arrangement to the battery via a charge controller. AC connection of a solar PV module is also possible or a combination of DC-connected PV modules that directly charge the batteries and AC-coupled arrays. The choice of one coupling over the other depends on the system demand and specific components, and none of the couplings are most efficient in every situation.

Controlling PV generation with DC coupling is perhaps simpler. With this configuration, the battery acts a reservoir, absorbing or providing the difference power between solar PV generation and demand. When the battery becomes fully charged, the charge controller that interfaces it with the solar PV generator is designed to reduce the power drawn from it, maintaining the DC bus voltage at nominal value.

Control in an AC-coupled system is more complex—although the technology for it is also commercially available in battery inverters, and it has been proven worthy in many applications—as the bidirectional grid-forming inverter of the battery needs to function in all four quadrants (absorb/generate active/reactive power) and seamlessly transition between them. When the battery is fully charged, the master inverter needs to signal PV inverters to curtail their output, not overcharge it. This can be done through a communication channel, although some inverter manufacturers use a droop-based approach, in which the master inverter increases the minigrid frequency and the PV inverters detect it and curtail their output, if necessary, to maintain the power balance. This method presents a clear advantage when the inverters are far apart from each other. However, when inverters are colocated, using a dedicated communication offers more flexibility in terms of operation modes.

Although the architecture is referred to as a single-switched machine, it does not mean that the battery inverter is always one unit. More units can be paralleled in a master–slave configuration using communication buses depending on the maximum power required.

The secondary control is often programmed in the master inverter of the battery and has the task of synchronizing and bringing online diesel generators following an algorithm that depends on the state of charge of the batteries and the current load. Some more advanced systems will have external algorithms for the secondary control that factor load and renewable generation forecast to save fuel, optimizing the use of batteries and DSM measures.

(iii) **Multimaster inverter-dominated minigrid.** Unlike the single-switched master architecture, in this control scheme, several generators and inverters can share the task of forming the grid. In this way, there is not a single master unit and reliability is increased. This architecture is most suitable for decentralized architectures in which the system can be expanded by connecting more generators in any point of the minigrid.

In these minigrids, the control system cannot make use of high-bandwidth communication channels because of their high cost. For this reason, the droop methods, which make use only of local measurements for primary control, are more convenient. With this method, the reference frequency and voltage of the grid-forming inverters are a function of their active and reactive power output, as it is done for paralleling diesel generators. Under this operation mode, grid-forming inverters can share the task of the primary control with other inverters and diesel generators. Likewise, frequency variations are applied for energy management without using a communication channel. For example, when there is an excess of solar PV energy and the batteries are already fully charged, the master inverters can raise the frequency as a signal for solar PV and wind inverters to curtail their output. Similarly, when there is not enough capacity to meet the load, the master inverters can lower the frequency as a signal to disconnect some controlled loads.

70. The most suitable control strategy will depend on the level of RE penetration and the distances between elements of the minigrid.

71. In **minigrids with a low RE penetration**, in which a diesel generator is always running, the control strategy is to use the generator sets as the grid-forming elements. When the minigrid is designed to be able to function without a running diesel generator to have a high share of RE, then the control strategy needs to allow battery inverters to form the grid.

72. For small systems, where generating units are not very disperse, a single-switched master can be used, in which inverters and generators are linked with fast industrial communication channels. This configuration offers more flexibility in the operation and higher power quality. When RE penetration is high and generators are located far apart from each other, high-bandwidth communication channels between generators become too expensive, and a multimaster inverter-dominated strategy that employs only local measures of frequency and voltage is better.

5.4 Demand-Side Management and Energy Efficiency

73. **Demand-side management (DSM)** refers to the ways an electricity consumption profile can be shaped to reduce costs by cutting overall consumption or shifting demand to accommodate it to uncontrollable generation, and avoid large power peaks.

74. Minigrids are different in terms of generation mix, size, and financial support, and thus different DSM strategies will be suitable in different cases. A first important distinction that can be made to correctly plan DSM strategies is to choose between power-limited and energy-limited minigrids. In the power-limited minigrids, DSM should focus on spreading demand more evenly throughout the day to avoid power peaks that the system cannot withstand. In the energy-limited minigrids, as would be the case of minigrids mainly based on the RE generation and battery storage, a total energy consumption needs to be regulated as well.

75. DSM actions can rely on devices that automatically control electricity consumption (such as current limiters, prepaid meters, etc.), on policies adopted by a minigrid operator that aim to shape the demand profile to better adjust it to generation (load scheduling, tariff incentives, etc.), or a combination of both. Some of the most common DSM strategies and technologies are described here:

(i) **Use of efficient lighting and/or appliances.** Probably the most effective and simplest strategy to reduce energy consumption is by investing in more efficient loads. Even if consumers cannot afford or are not willing to pay for more up-front expensive, energy-efficient light bulbs and other devices, dedicating part of the available capital for a minigrid project to finance efficient light bulbs can be profitable by reducing initial generation capacity investment and fuel expenses. Incandescent light bulbs are cheaper up front, but compact fluorescent lights and especially light-emitting diodes (LEDs) totally outperform them in terms of efficiency and durability. In rural environments, lighting forms a large share of the total demand, and thus investing in efficient light bulbs is key to reducing initial investment cost in generation elements, and operating costs in fuel and interruptions in supply due to overload. Efficient low-power water heaters and cooking appliances can also considerably reduce peak demand.

(ii) **Load scheduling**. To match demand to generation in time, a common practice is to shift nonessential load to times of low demand or high renewable generation. This strategy makes the most sense in large- and medium-sized minigrids that supply some small industrial processes, rather than in small rural populations, in which households account for most of the demand. These schedules can be enforced in different manners such as contracts, and more advanced and expensive smart-meter devices, or incentivized by cheaper tariffs during the hours to which demand should be transferred. Besides moving already existing demand, encouraging the creation of other activities that represent a deferrable load—such as water desalination plants or ice machines—that would run in times of excess energy in renewable generation-based minigrids can improve the overall economic performance of a minigrid.

(iii) **Restricting residential appliance use.** In some cases, there is a lack of capital to install generating capacity or to afford the cost of fuel that would allow all desired electric consumption in households. Thus, it is necessary to limit the amount and type of appliances that can be connected to the minigrid. In newly-built rural distribution systems, this can be done by installing current limiters in each house. For existing systems, one way to proceed might be more oriented to community education and agreements, although these measures alone will be ineffective in many cases and the use of current limiters might prove itself necessary. A more advanced (and more costly) way to impose these restrictions is through the use of "smart meters" that limit consumption based on a maximum power at each time and maximum energy over a period of time.

(iv) **Tariff structure.** Properly designed tariffs are crucial in enforcing a demand profile that works well for a minigrid. Tariffs can be based on the maximum power that the user is allowed to consume, the maximum amount of energy over a given period, or a combination of both. Logically, in the power-limited minigrids, the focus for tariffs should be on limiting the amount of power for each consumer to avoid possible overloads, while in systems based mostly on RE and storage, total daily or weekly energy limitations can be more important. More advanced options, such as real-time varying prices, and current limitations have been tested in more advanced countries with good results, but are still not a very viable option for rural environments.

(v) **Prepaid meters.** With this type of meter, users purchase a code that adds a certain amount of power to their meter. These meters allow consumers to better control their consumption by making smaller, more frequent payments. Although prepaid meters have a higher initial investment cost than regular meters, and require a vending system, they can result in savings for the minigrid operator by reducing part of the burden of reading meters and preparing bills, considerably simplifying the money collection process. Another important advantage is that it allows grid operators to forecast power demand more accurately based on the amount of energy purchased. Some prepaid meters will only control the amount of energy consumed, while more sophisticated versions can also allow the purchase of energy with different peak power limits.

6

CAPACITY BUILDING AND TRAINING

76. Specific training on O&M for local power operators of the hybrid RE minigrid has to be provided. The training program can start during the installation of the microgrid or right after the start-up. Some further training would be beneficial on concepts such as DSM.

77. Community awareness is also crucial. It is important for the sustainability of the RE minigrid that the users have a basic understanding of the components of the minigrids, and its limitations in the amount and type of power it can supply. Local authorities should be involved in raising awareness by organizing community meetings and technical activities.

7 OPERATION AND MAINTENANCE

78. Regular maintenance is required for keeping a minigrid in good condition, as well as identifying any possible glitches and mechanical problems. The system operator should be the entity carrying out regular maintenance. Many problems, though, are difficult to identify, so a periodic overall check by a professional is recommended. In the case of large hybrid RE systems that supply energy to a community, at least one qualified electrician should be part of the hybrid RE system operator's staff.

79. A maintenance fund is a common characteristic of successful hybrid RE minigrids. Besides the importance of having access to the capital cost of projects, establishing a sustainable finance stream for regular maintenance can be challenging. It is not uncommon that initially successful installations failed shortly after because there was no access to maintenance funds. This is particularly important for replacement of some elements such as batteries. A business model based on selling energy services is crucial to avoid problems caused by lack of funds needed to cover O&M costs.

80. Any electrical system requires regular maintenance over the long term. Solar PV systems require a reduced number of hours in terms of maintenance compared with other electrical devices (for instance, diesel generators). Some other electrical devices such as lead-acid batteries used in some RE facilities require regular checks.

7.1 Photovoltaic Power Plant Maintenance

81. The solar PV plant requires maintenance of the PV panels to achieve optimal performance. The frontal surface (glass) area of the solar PV module must remain clean from excess dust and dirt [10].

82. The typical solar PV plant maintenance includes the following [11]- [10]:

(i) To remove dust and dirt from the solar PV modules, wash the panel with water. If the module has other droppings, which are harder to remove, rub the panel surface with a sponge dipped in cold water. Special detergents specifically manufactured to clean solar panels should be used.

(ii) A visual inspection can detect defects in the modules, such as cracks, delamination, fogged glazing, or water leaks. Location of identified defects should be noted in a system logbook to monitor if their further deterioration would affect output. Modules with fractured or damaged laminates will ultimately become vulnerable to moisture and develop high leakage currents. If this is the case, they have to be removed from the array and replaced. Most solar PV modules use tempered glass that breaks into small pieces when it is stressed or impacted [10]. While the physical damage could be noticeable in the case of impacts, fractured glass may not be visibly evident from a distance in a solar PV module.

(iii) Degradation of the module is usually signaled by delamination, moisture, or corrosion, especially close to cell busbar connections and edges of laminates.

(iv) The condition of the array-mounting frame has to be monitored. The array-mounting bolts need to be checked for bolt rusting. The frame and modules should be firmly secured. The junction boxes are required to be checked to confirm that the wires are not chewed by rodents or insects.

(v) The DC connectors, used to connect the modules between them, should be periodically checked. Dust, salt, or moisture can pass through the insulating joint, leading to accelerated corrosion of the metallic contacts. Over time, the copper section is decreased due to the corrosion, forming a hot spot and causing damage to the connector. The damaged connectors should be replaced.

(vi) All debris around solar PV arrays should be removed during maintenance operations since they present a potential fire hazard. Furthermore, a shadow control over the PV panels is required since this can highly impact the array power output. If during the visual observation the extent of shading problems is difficult to establish, a solar shading evaluation tool may be applied.

7.2 Small Wind Turbines Maintenance

83. Small wind turbines normally require a higher level of maintenance compared with PV power plants, as the particular maintenance specifications depend on the design and the operating conditions (e.g., strong or moderate wind site). Generally, wind turbine maintenance involves some simple tasks such as greasing, visual and audio inspection, and checking of guy-wires and bolts and/or screws once or twice a year. Other intense maintenance (e.g., refurbishment of rotor blades and changing of guy-wires) could be needed in the medium term (2 or 3 years) [12].

84. To achieve good performance indicators, regular and planned maintenance actions have to be in place. Repairs and availability of spare parts are the main challenges to long-term operation of small wind turbines. Increasing number of installations in RE minigrid areas include remote control systems to monitor performance and potential failures at early stages.

85. It is advisable that the manufacturer or a specialist develop specific guidelines with respect to planning, installation, and maintenance of the RE hybrid minigrid. These guidelines, involving project developers, have to be enforced over a certain period of time to guarantee proper O&M. Alternatively, a local training component should be included in every project.

86. The typical small wind turbine maintenance includes the following [12]- [13]:

(i) **Periodic tower check.** Guy-cable tension, clips, and attachments must be checked periodically. Nuts and bolts at the bottom of truss towers should also undergo periodic checks.

(ii) **Oiling and greasing the moving parts.** Wind turbine manufacturers provide specific manuals and guides to explain how the oiling process should be carried out, and specify the type of oil that should be used. A small wind turbine must be greased once or twice a year. Wind turbines located in strong wind sites need no less than two greasings per year.

(iii) **The blades should be inspected annually.** If the cover blade paint cracks or the leading edge tape tears away, the exposed fiberglass or wood will wear away fast. In addition, moisture that penetrates into the blades causes the rotor to become unbalanced, stressing a wind generator. Most likely, blades may need to be replaced after 10–15 years. With appropriate installation and maintenance, a turbine can last about 20 years. With proper maintenance the amount of mechanical noise produced by a wind turbine may be minimized.

87. A wind power turbine involves moving parts and tall towers. A tilt-down tower is recommended, where possible, since it can be lowered to the ground to enable maintenance service. However, the tilt-down tower also requires training and special equipment to lower it down as even a 1 kW turbine requires approximately 700 kilograms of force. Small wind turbines that require climbing must have a work platform, a fall-arrest system, and fall-arrest anchorages to ensure safety of the personnel at work. Lowering or climbing a wind turbine tower requires training in tower safety.

7.3 Diesel Generator Set

88. The generator sets installed in isolated minigrids normally range from 5 kW to several hundred kW of capacity, depending on the load demand and capacity of the hybrid system [14]. Smaller generators of under 5 kW typically use gasoline as fuel, while larger capacity generators rely on diesel. In hybrid power systems, the advantage of the diesel generator set is its dispatchability. The generator sets improve the service quality and supply security, because they are able to balance the intermittent power output of renewable energies.

89. The lifetime of a diesel generator is normally 3–5 years of continuous operation. In hybrid RE minigrids, the operation strategy is to minimize the fuel consumption and maximize the lifetime of the generator, preferably to 20 years or even more.

90. A diesel generator set requires regular inspections for oil level at intervals prescribed in the engine manual. It is advisable to install a running-hours meter to determine when maintenance is due.

91. To conduct the preventive maintenance of a common diesel generator set, it is necessary to at least fulfill the following tasks, and to follow other periodic maintenance and testing procedures proposed by the manufacturer :

(i) Fill the fuel tanks often.

(ii) Change diesel engine oil after every 1,000 running hours and approximately every 4 months, whichever comes first.

(iii) Replace a fuel filter element and inspect gaskets for damage. This task should be carried out at least every 1,000 hours of operation.

(iv) The starting battery should be checked once a month, and if the diesel generator set is not in use for a long time, the battery should be recharged. In no case the battery voltage should be lower than 12 volts.

(v) Clean a primary air filter and prefilter elements every 60–70 hours or as required in the operation manual. The generator should not be used if the air cleaner element is clogged or damaged.

(vi) Check for loose, damaged, or missing parts in the diesel engine once a month.

(vii) Check for worn alternator brushes every 1,000 hours or as required. The length must be a minimum of 1.2 centimeters. Replace the brushes if it is required.

(viii) Replace fuel injectors each 1,000 hours of operation.

(ix) Replace a fuel injector pump each 2,000 operating hours.

(x) Check the fuel filter bowl for water or other contaminants. Check for evidence of fuel leaks.

7.4 Battery Electric Storage Systems

7.4.1 Lithium-ion Batteries

92. Lithium-ion batteries (LIBs), like any other battery, are rechargeable storage devices. Their operation is based on the ion movement within the cells, from the negative electrode to the positive electrode during the discharge and back, when charging.

93. The LIB cells have essentially three components: the positive electrode (cathode), the negative electrode (anode), and the electrolyte in between both. The positive electrode is usually made from a chemical compound called lithium-cobalt oxide (LiCoO2), which is the most common. There are several other types of LIBs such as lithium iron phosphate (LiFePO4) or the lithium–titanate battery; the latter type has a faster charge ratio than the other batteries of the lithium technology.

94. Although LIBs are not maintenance-free, they require less maintenance compared with other storage technologies. LIBs require routine maintenance and care in their use and handling, which are mainly related to the environment control and to ensure proper battery operation:

(i) Through a routine systematic check and detailed record on the power system usage, as well as the work of a battery management system (BMS) and a charger, detect hidden dangers and solve problems in time.

(ii) Regularly check connecting bolt-down fuses, contactors, and fuses, as well as the degree of tightening for all bolts connecting the battery poles.

(iii) Regularly inspect connection reliability of all power connectors and electrical connectors, and check the insulation of the electric circuit and connection of cables and bus bars.

(iv) Check the battery voltage and current differences between BMS detected and actual measured data, BMS signal acquisition accuracy, as well as whether the state of charge (SOC) calculation precision calibration is required.

(v) Check the consistency of the whole set of batteries. If the static or dynamic voltage difference of the battery is too large, operate as troubleshooting steps.

95. LIBs work by the electrochemistry reaction; however, cycling (charging and discharging processes), elevated temperature, and aging diminish the performance over time [15]. Manufacturers (for laptops and mobile phones) apply a conservative approach and state the life of LIBs in the majority of consumer products between 300 and 500 discharge and charge cycles. Nevertheless, other LIB applications, as well as an electric vehicle or an energy storage in electric grids, need to increase the lifetime above 10 years. It is possible to increase the battery life if the degradation mechanisms are known.

96. Evaluating the battery life on counting cycles is currently an intense research topic. In view of a cycle count, certain device manufacturers suggest battery replacement on a date-stamp. This method is also not reliable because it ignores specific charging and discharging power profiles as well as environmental conditions. A battery may be replaced before its specified time due to intense use or unfavorable temperature conditions.

97. One of the key performance indicators of an LIB is its storage capacity. The storage capacity, measured in kWh, is usually a clear index of the battery health. Other parameters such as internal resistance and self-discharge are also important indicators, although they have lower relevance in predicting the end of battery life.

98. Full storage capacity is expected during the first year of service; however, the effect of shelving may have impact on the performance.

99. Referring to the work temperature, LIB deteriorates from stress when exposed to heat and from keeping a cell at a high charge voltage [15]. A battery dwelling above 30°C is considered high temperature and, for most LIBs, a voltage above 4.10 volt per cell is considered as high voltage. Exposing the battery to high temperature and dwelling in a full state-of-charge for a long time is more stressful than cycling.

7.4.2 Lead-Acid Batteries

100. Lead-acid batteries must also be kept indoors protected from extreme temperatures and dirt, but they do require some more periodic maintenance.

101. Lead-acid batteries, along with small wind turbines, are usually the equipment that most maintenance operations require in a hybrid RE system. Battery life is highly influenced by regular care.

102. There are two main types of lead-acid batteries used in hybrid minigrids [15]: (i) wet cell flooded batteries where the electrolyte level has to be regularly checked; and (ii) completely sealed or gel cell batteries that have no access to the electrolyte, but include a regulated valve.

103. Maintenance operations for these types of batteries should consider checking the electrolytes, retightening terminals, measuring cell voltages, checking specific gravity, and following other maintenance and/or testing suggested by a manufacturer.

7.5 Power Electronic Equipment

104. Inverters are usually placed in a clean, dry, and ventilated area that should be separated from a battery bank. Avoiding dust accumulation is essential for a proper maintenance. A visual check should verify that main alarms in a control panel are working fine, and that wire connections are not loose.

105. In the relevant literature [16], the authors describe typical requirements for inverter inspections as follows:

(i) Remove any excess dust from the unit, especially from the heat sinks. This should only be done with a dry cloth or brush. Check that “vermin” has not infested the inverter (typical signs of this include spider webs on ventilation grills or wasp nests in heat sinks). Contact a system supplier if you suspect “vermin” is inside the inverter.

(ii) Check that the inverter is functioning correctly by observing LED indicators, metering, and/or other displays on the inverter.

(iii) Check that control functions for remote starting of diesel generator set (if installed) are operating. Ensure that the diesel generator set is starting and stopping at correct battery voltage levels as specified by a manufacturer (refer to a system supplier or inverter operating manual).

(iv) Clean filters.

(v) Test fans for proper operation.

(vi) Check fuses.

(vii) Check torque on terminations.

(viii) Check continuity of system ground and equipment grounding.

(ix) Check mechanical connection of the inverter to the wall or ground.

7.6 Electrical Distribution Network

106. Most of electrical distribution networks should undergo periodic maintenance. The periodic maintenance is relatively simple, and is based on inspection, evaluation, and reparation. In rural electrification projects, the power networks are overhead lines, and the most common problems are related to the electrical network wire damage and corrosion of clips, bolts, nuts, and other attachments.

8

MONITORING AND PROJECT EVALUATION

107. Monitoring key performance indicators in a minigrid allows to better understand if a system is operated in a technically and economically sustainable way. Moreover, understanding the relations among the different parameters in a hybrid RE system will help determine whether the power system is working below its limits or if more loads can be connected to the system.

108. The basic measurements required to analyze the performance of hybrid RE systems are

(i) battery voltage and SOC;

(ii) energy produced by the RE sources: mainly solar PV, energy produced by wind turbines or mini-hydro power generators;

(iii) energy produced by diesel generators;

(iv) energy consumed by the load, DC and/or AC; and

(v) fuel consumption.

109. However, to have a complete knowledge of the RE system performance, it is recommended to monitor and store the following measurements:

(i) solar radiation over the PV modules;

(ii) ambient temperature;

(iii) battery temperature;

(iv) PV module temperature;

(v) wind speed (in case the RE system has wind turbines);

(vi) DC voltage and DC current of the PV generators;

(vii) AC current and AC power of the PV generators;

(viii) charge and discharge current (DC and AC) of the battery;

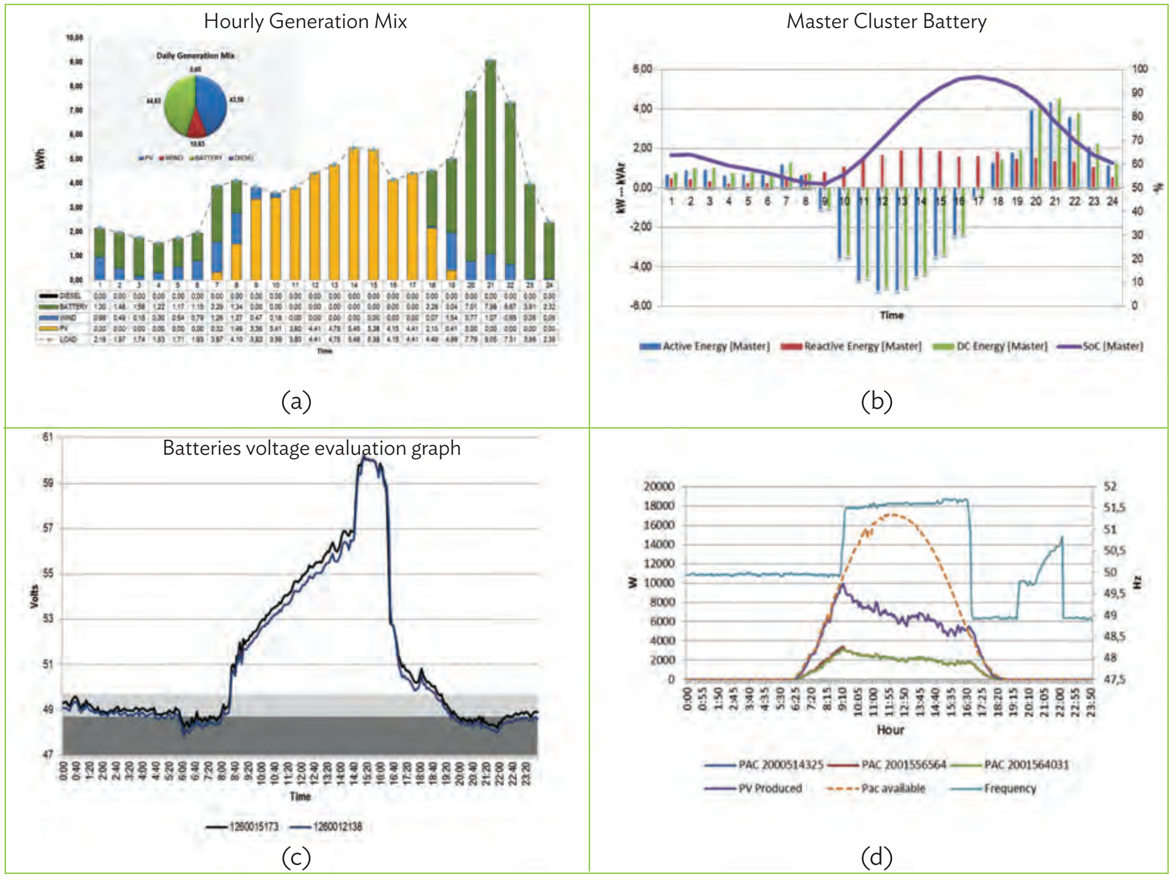
(ix) battery SOC and state of health. Some manufacturers calculate the estimated error of SOC; and

(x) time of function of the diesel generator.

110. Ideally, these variables should be captured automatically by data loggers at least within 1 hour. The modern components of the hybrid RE system provide this automatic data acquisition capacity. Storing all the information on power production, battery voltage, and SOC, as well as other related technical information, results in a complete and detailed operation monitoring process. Many manufacturers have all this performance aggregated in the electronics inside the inverters, using robust communications protocols to send the information to a data logger. The hybrid RE system operator will have all the information easily accessible for future analysis. Even if an automatic data acquisition system exists, manually recording main performance values is advisable, because it establishes a general alertness among operation staff.

111. The meteorological variables are used to estimate the actual amount of available energy that solar PV and/or wind generation can produce in good conditions. These estimations help to detect problems and calculate the energy excess. The system operator needs it to improve the efficiency of the system performance. Figure 7.6-1 shows the different parameters monitored from the operation of a hybrid RE system.

Figure 7.6-1: Examples of Monitored Variables in a Minigrid. (a) Hourly Generation Mix, (b) Master Cluster Battery Outputs, (c) Battery Voltage Regulation, and (d) Active Power Output and Frequency



(a) (b)

(c) (d)

DC = direct current, kVAr = kilovolt-ampere reactive, kW = kilowatt, kWh = kilowatt-hour, PAC = power at alternating current side, PV = photovoltaic, SOC = state of charge, W = watt.

Source: Jose Antonio Aguado (Effergy Energia).

112. In recent years, there is a growing interest in “big data” analytics and the Internet of Things [17]. Nowadays, huge amounts of measurements can be stored locally or remotely at a much lower cost than before. Techniques for managing, filtering, classifying, and analyzing big volumes of data are an intense research topic. The interest in big data analytics in the power sector is mainly focused on large utility grids with hundreds of thousands of consumers, where the amount of information that is measured is rather difficult to manage. However, minigrid project developers can also benefit from big data analytics to improve aspects of their projects, such as DSM strategies, tariff designs, and other project aspects by extracting conclusions from large sets of measurements. Energy management strategies (i.e., battery management) can also be improved by learning from large sets of measurements. Big data analytics also constitutes a learning tool for future designs, as having large periods of recorded measurements is very useful for extracting conclusions about the aspects of past designs that have not worked as expected and could have been improved. Predictive maintenance is also made easier when frequent measurements of all system parameters are taken and stored, as abnormalities and decreases in efficiency can be automatically detected with proper big data analytic algorithms.

9 ILLUSTRATIVE PROJECT DESIGNS

9.1 Eluvaithivu Island, Sri Lanka

113. Eluvaithivu is a small island located in the sea of the Jaffna peninsula, in northwest Sri Lanka, 2.9 kilometers (km) away from the nearest mainland point. The island has a rectangular shape, being around 3 km long, with an estimated surface of 1.4 km^2. It has a small, yet stable, population of around 800 inhabitants.

114. Fishing is the main activity in Eluvaithivu, while making products out of palm trees is another common activity. The island has one hospital and two schools. The Kannakaiamman Thurai Jetty in Kayts, located on the island of Velanai, is the only access to Eluvaithivu. The climate of Jaffna region, in which the island of Eluvaithivu is located, is considered tropical monsoonal with a seasonal rhythm of rainfall. The temperature range during the year is very narrow, as it changes from 23°C to 33°C. The following tables and figures summarize the conditions that existed prior to project implementation and the proposed hybrid RE system at the time of project design.

Table 9.1-1: Eluvaithivu Island: Situation prior to the Project

Eluvaithivu, Jaffna Peninsula (Sri Lanka)		
Installed generation **Old 100 kW and 25 kW diesel gensest**		 800 m
Population	800.00	
Measured peak (kW)	26.00	
Energy consumption (kWh/day)	180.00	
Specific fuel consumption (L/kWh)	0.58	
Estimated CO2 emissions (kg/year)[3]	101,563.00	

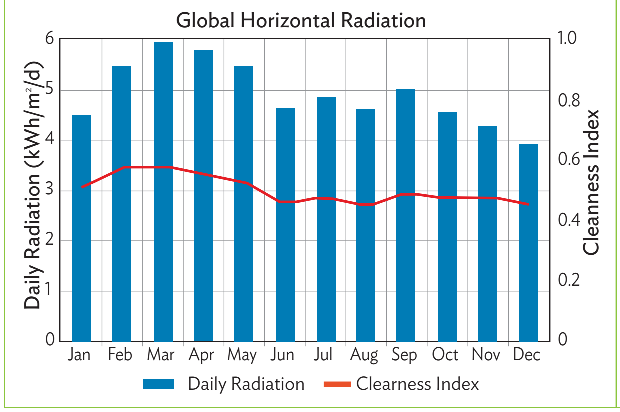
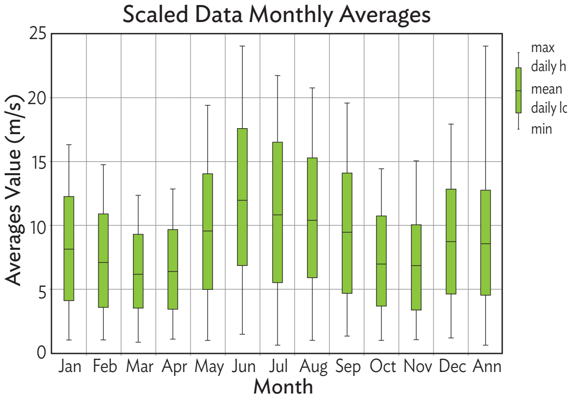
CO$_2$ = carbon dioxide, kg = kilogram, kW = kilowatt, kWh = kilowatt-hour, L = liter.

Source: Jose Antonio Aguado (Effergy Energia).

---

[3] The CO$_2$ emissions have been estimated considering the expected demand growth.

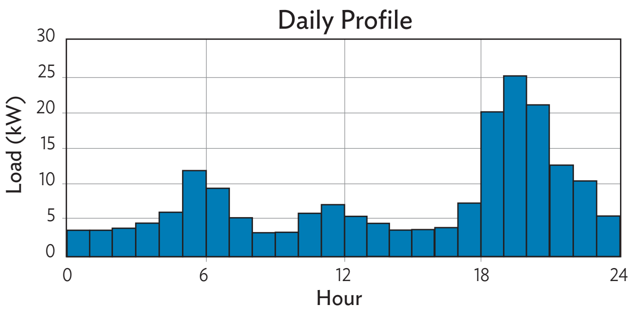
Table 9.1-2: Eluvaithivu Island: Renewable Resources

Renewable Potential	
Solar resource: Annual average 4.93 kWh/m2/day	Wind resource: Annual average 6.5 @ 12 meters height
	

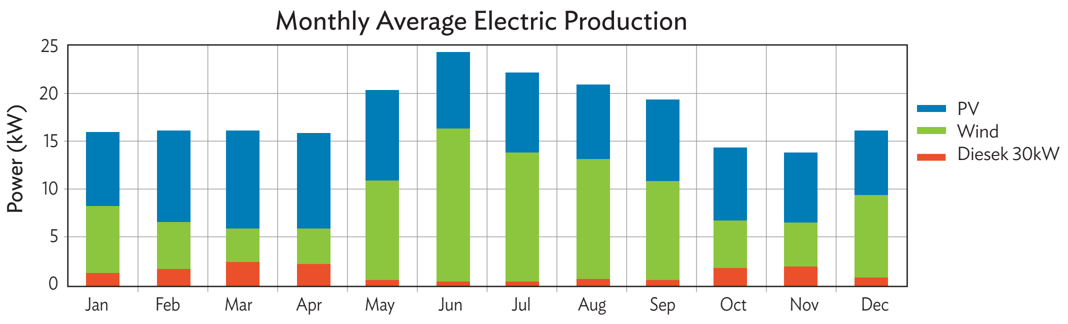
kWh = kilowatt-hour, m² = square meter, m/s = meter per second.

Source: Jose Antonio Aguado (Effergy Energia).

Table 9.1-3: Eluvaithivu Island: Proposed System

Proposed Hybrid System		
Photovoltaic	45 kWp	
Wind turbines	6x3 kW	
Total diesel Generator set 1	30 kW New 30kW generator set	
Batteries	26.9 kWh	
Battery inverters	30 kW	
RES penetration Estimated CO_2 emissions	93% 12,187 kg/year	

CO_2 = carbon dioxide, kg = kilogram, kW = kilowatt, kWh = kilowatt-hour, RES = renewable energy source.

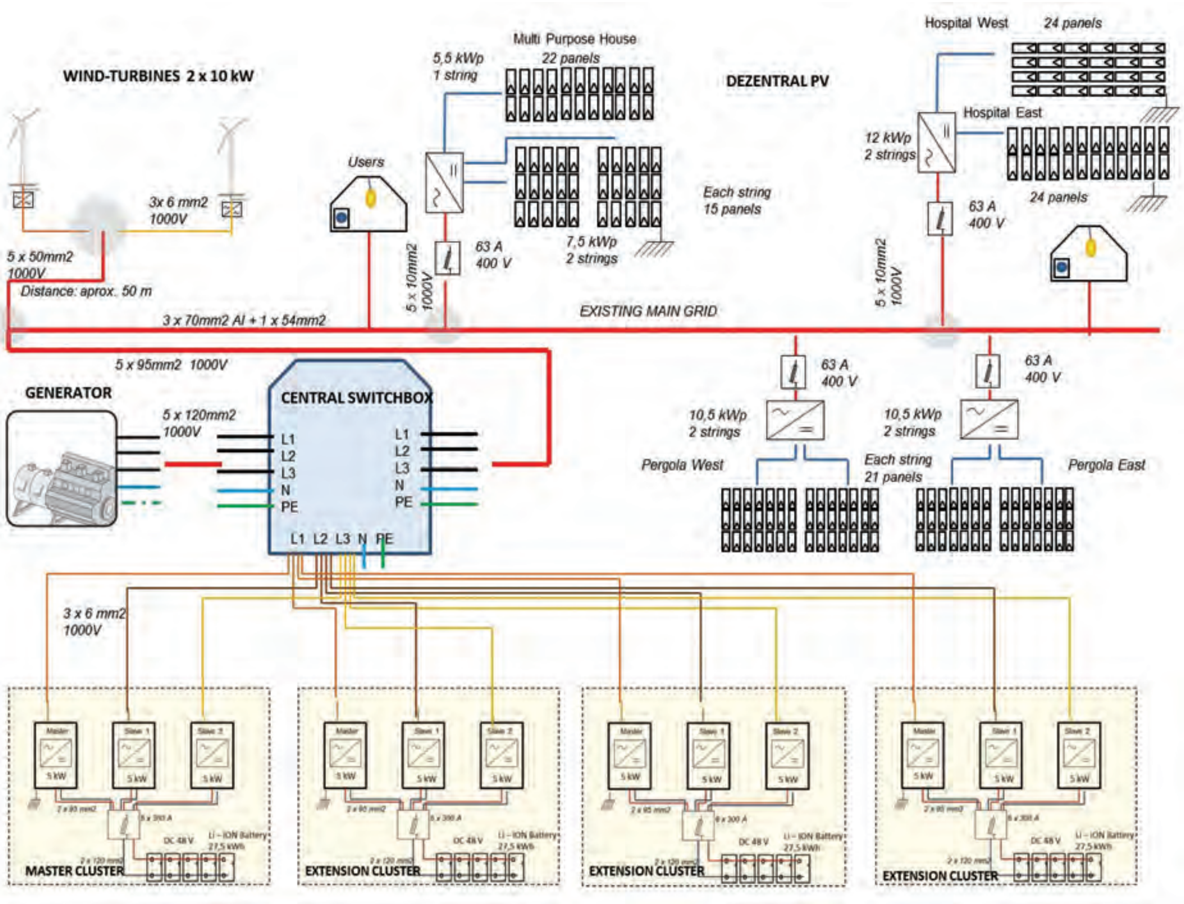


kW = kilowatt, PV = photovoltaic.

Source: Jose Antonio Aguado (Effergy Energia).

115. The estimated CAPEX of the hybrid RE system, including physical contingencies and works, is $450,000. With the proposed hybrid RE system design, the LCOE can be reduced from $1/kWh (with the existing inefficient generator sets) to $0.37/kWh. The system is coupled in AC and the control architecture is the single-switched master, in which the battery inverter balances the power in the hybrid RE system when possible. The diesel generator set is located close to the battery inverter that is linked to it through a communication channel to turn the generator set on only when the SOC of the battery is low. The following figure shows a basic electrical diagram of the hybrid RE system on Eluvaithivu Island.

Figure 9.1-1: Eluvaithivu Island's Electric System Diagram



A =ampere, Al = aluminum, DC = direct current, kW =kilowatt, kWh = kilowatt-hour, kWp = kilowatt peak, mm = millimeter, PV =photovoltaic, V = volt.

Source: Jose Antonio Aguado (Effergy Energia).

9.2 Rakeedhoo Island, Maldives

116. Rakeedhoo is a small island of approximately 200 square meters by 300 square meters located in the Vaavu atoll, 96 km to the north of the capital, Malé. Officially, there are around 370 inhabitants. Most of the houses are prepared for collecting rainwater in water tanks and are equipped with water pumps and pressure-tubes for distribution. The main income of the habitants comes from grants from relatives who live and work in Malé. The climate of Vaavu atoll, in which the island of Rakeedhoo is located, is considered tropical monsoonal with a seasonal rhythm of rainfall. The temperature range during the year is very narrow, from 23°C to 34°C.

117. The following tables show the situation that existed prior to the project and the proposed project design solution.

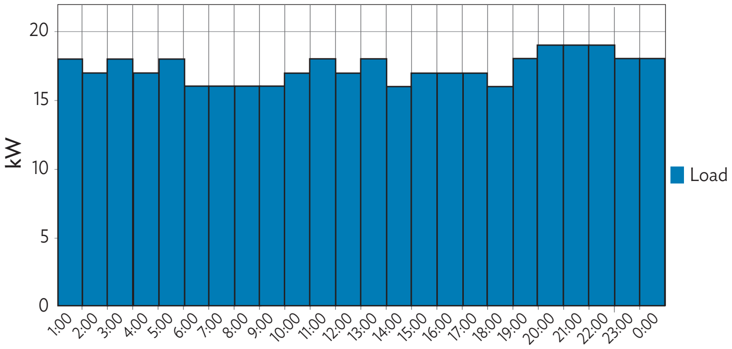
Table 9.2-1: Rakeedhoo Island: Situation prior to the Project

Rakeedhoo, Vaavu Atoll (Maldives)		
Installed generation: **40 kW (old) and 60 kW (new) diesel generator sets**		
Population	370.00	
Measured peak (kW)	22.00	
Maximum Energy consumption (kWh/day)	450.00	
Specific fuel consumption (L/kWh)	0.52	
Estimated CO2 emissions (kg/year)[1]	161,878.00	

CO_2 = carbon dioxide, kg = kilogram, kW = kilowatt, kWh = kilowatt-hour, L = liter.

Source: Jose Antonio Aguado (Effergy Energia).

Table 9.2-2: Rakeedhoo Island: Proposed system

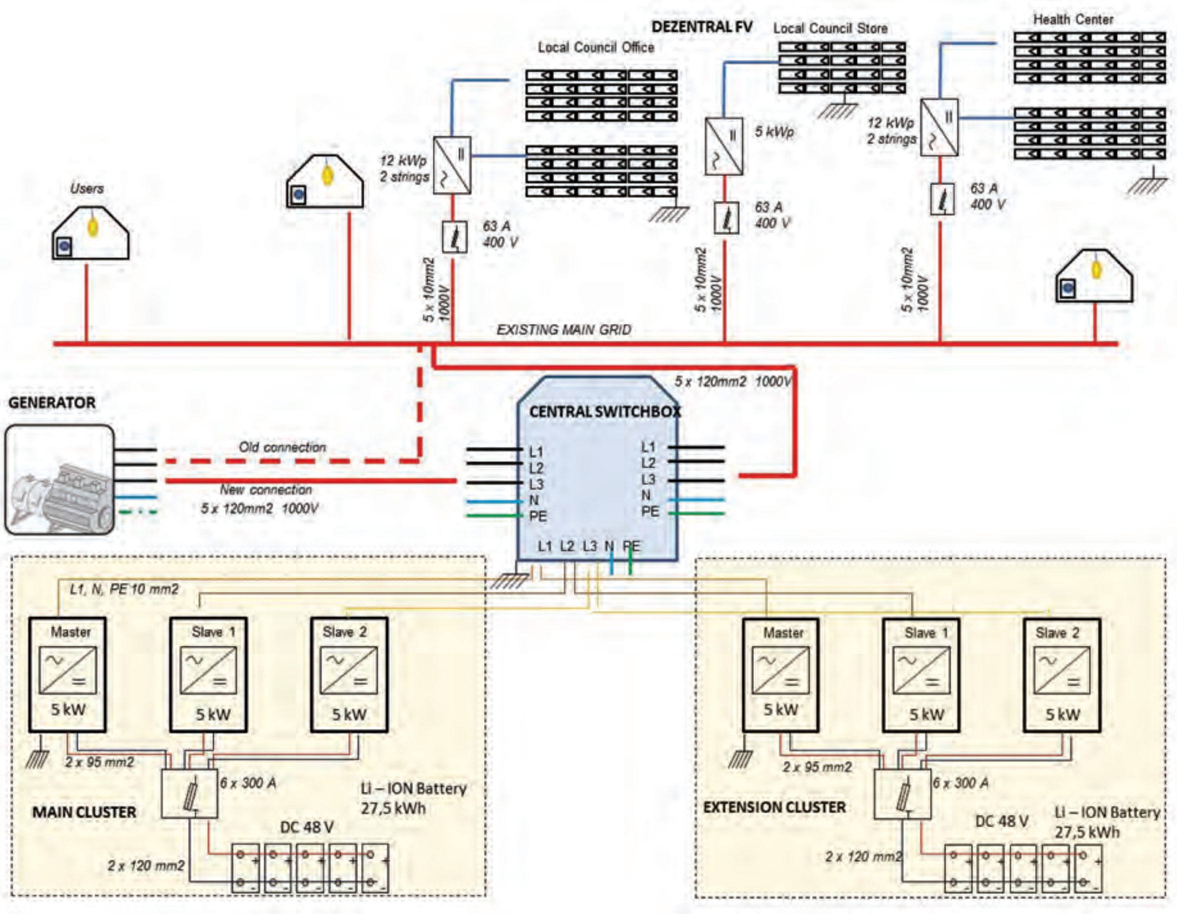
Proposed Hybrid System		
Photovoltaic	29 kWp	
Wind turbines	0	
Total diesel Generator set 1	30 kW Existing 60kW generator set	
Batteries	60 kWh	
Battery inverters	36 kW	
RES penetration Estimated CO_2 emissions	85% 12,187 kg/year	

CO_2 = carbon dioxide, kg = kilogram, kW = kilowatt, kWh = kilowatt-hour, RES = renewable energy source.

Source: Jose Antonio Aguado (Effergy Energia).

118. The hybrid RE solution can reduce the LCOE in Rakedhoo from $0.67/kWh (with the existing generators) to $0.37/kWh, incurring CAPEX of $91,550 (without considering working capital and physical contingencies). The control architecture is of the single-switched master type, the battery inverter acts as the master until the SOC of the batteries is too low and it sends a signal for the diesel generator to start. The following figure shows a basic electrical diagram of the Rakeedhoo system.

Figure 9.2-1: Rakeedhoo Island's Electric System Diagram



A =ampere, DC = direct current, kW =kilowatt, kWh = kilowatt-hour, kWp = kilowatt peak, mm = millimeter, PV =photovoltaic, V = volt.

Source: Jose Antonio Aguado (Effergy Energia).

ANNEX A: POWER GENERATION TECHNOLOGIES IN MINIGRIDS

A.1 Photovoltaic Energy Systems

119. Photovoltaic (PV) systems convert sunlight into direct current (DC) electricity. Although performance is site-dependent, normally 1 kilowatt peak (kWp) installed will produce more than 0.75 kilowatt-hour (kWh) per day on average. The following characteristics of solar PV systems make them a preferred source of power:

(i) They generate with negligible impact on the environment, since they cause no noise or pollution.

(ii) They have no moving parts that wear out with use, and they require very little maintenance in most environments. In most places, the rain is enough to keep them clean.

(iii) They are modular, so they can be scaled up to match any power need, big or small, and they can be easily expanded, if needed. This also makes them easy to install and movable.

(iv) They are reliable and may last for a long time: the life expectancy of the PV modules is estimated at 30–40 years. The producers assume liability for 10–25 years.

(v) They use a solid-state technology and can be easily manufactured and installed.

120. On the other hand, the power that PV systems produce depends on the solar radiation striking the panel at each instant, which makes their power output nondispatchable and very irregular at times. A high share of PV power will require storage elements that can absorb sharp power variations caused by the passing of clouds and that allow saving some of the energy produced for hours of no sunlight.

121. The electrical power injected in the minigrid goes through several devices and steps: the solar PV module itself, DC–DC converter, DC–alternating current (AC) inverter, and maximum power point tracker. The overall efficiency of this process depends on the correct sizing and design of all devices. To evaluate this efficiency, there are two measurable types of efficiency in solar PV systems: the panel efficiency across its terminals and the PV generating system efficiency. The panel efficiency is acquired from the photo conversion efficiency of a PV cell defined as

$$\eta_{\mathrm{PV}} = \frac{P_{DC}}{P_{irr}}$$

where
- P_{DC} is the module DC output power; and
- P_{irr} is the irradiance level on the panel surface.

122. During a given day, the efficiency of the panel arrays depends on, among others, the temperature and the irradiance. The PV system efficiency can be estimated as

$$\eta_{\mathrm{PV}} = \frac{P_{out}}{P_{irr}}$$

where
-P_{out} is the power injected in the grid; and
- $Pirr$ is the irradiance level on the panel surface.

A.1.1 Types of Photovoltaic Generation

123. Solar cells can be classified into two main groups:

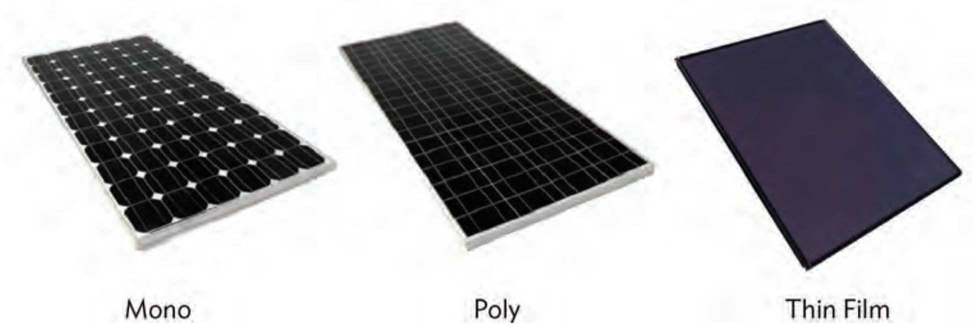
(i) **Crystalline silicon**. This is the traditional technology for solar panels, which comprises two main types of solar cells:

(a) **Monocrystalline silicon.** Melted silicon is solidified into a uniform crystalline structure. Good efficiencies in the range of 13%–18%. Good maximum power point per area ratio of about 150 watts per square meter (W/m^2). This type entails high manufacturing costs and therefore is expensive.

(b) **Polycrystalline silicon**. Melted silicon is poured into a mold, crystallizing in an imperfect manner and forming random crystal boundaries. Efficiency, at 12%–14%, is lower than that of monocrystalline cells. Maximum power point per area ratio of about 100 W/m^2. This type is slightly cheaper than monocrystalline.

(ii) **Thin film panels**. They are manufactured by depositing one or more thin layers of PV material (amorphous silicon, cadmium telluride [CdTe], copper indium gallium selenide [CIGS]) on a substrate, making paper-like cells. Efficiencies of commercial thin film rolls are still low (7%–10%), and are known to decrease with time of use. They work well with low diffuse radiation and are usually cheaper to make than crystalline silicon cells. The area needed to produce the same amount of power is greater than with crystalline silicon, but being so thin gives them the advantage of better adapting to surfaces such as walls or rooftops with less aesthetic impact.

Figure A.1-1: PV Panels Containing Monocrystalline, Polycrystalline, and Thin Film Cells



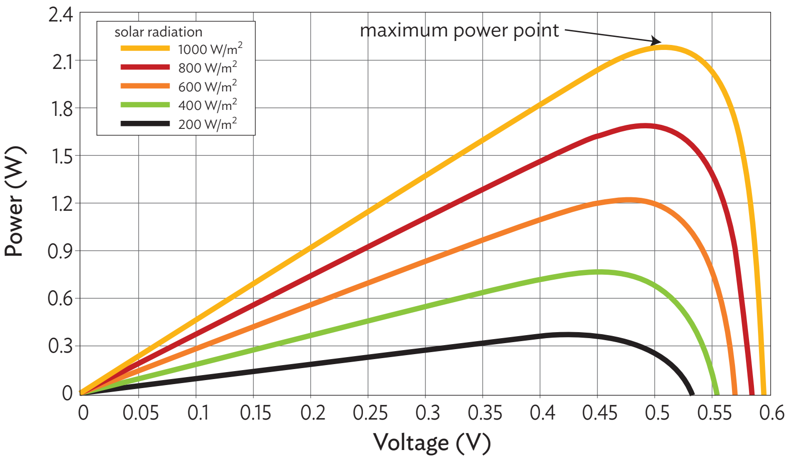
Source: Jose Antonio Aguado (Effergy Energia).

A.1.2 Array Configuration and Siting of Photovoltaic Installations

124. Several considerations must be taken into account for array configuration and PV installation.

125. **Array Configuration:** The number of modules in series, along with the minimum temperature of the location, will determine the required DC voltage input range of the inverter. The power output of PV cells varies with voltage for each given level of radiation.

Figure A.1-2: Maximum Power Point for Different Levels of Radiation



V = volt, W = watt

Source: Jose Antonio Aguado (Effergy Energia).

126. To extract the most possible power in each situation, electronic devices called maximum power point trackers (MPPT) are incorporated in PV inverters. When PV panels are far apart or have different orientations, they will be stricken by different levels of radiation and thus have different optimal voltages. In this case, there is a trade-off between the cost of installing more MPPT channels to extract the most of each module and grouping more panels in each MPPT.

127. When deciding where and how to place solar PV panels, the following (usually conflicting) factors should be taken into account: installation costs, array performance, easy accessibility for maintenance, and aesthetic and/or social impact.

128. Some basic considerations for solar PV installation siting are as follows:

(i) Partial shadows must be avoided completely, especially in hours of maximum radiation. Cells are connected in series and parallel to form modules; different levels of radiation striking each cell would result in different cell voltage that would originate circulating currents inside the panel (hot spot effect). This would result in temperature rise and damage the cells. To avoid this, cells are connected through diodes. Because of this, shading a small fraction of the surface of the panel results in a much larger power reduction than the shaded fraction. Special attention must be paid to avoid shadows cast by trees and buildings, and enough row separation should be considered when planning solar PV installations, so that panels do not shade each other during some hours of the day.

(ii) For the same reason, all modules in a series string have to be in the same orientation, and they must be kept clean.

129. While receiving maximum radiation in hot areas, it is recommended to keep the panels' temperature close to 25°C–30°C. Windier zones can help keep cool the panels incrementing their efficiency.

130. There are several options for array mounting:

(i) **Ground-mounted (rack, shade structure, pole, or tracking).** Ground-mounted installations will usually be easier to access for installation and maintenance. However, this can be more of a drawback as the panels would be more exposed to shading and vandalism. Pole mounting can sometimes be a better option than the classical racks, as they allow orientation changes. Pole-mounted automatic sun trackers are an expensive option and normally not cost-effective with the current prices of solar PV modules.

Rooftop mounted—Dhidhdhoo, Maldives

Shade structure ground-mounted—Dhiffushi, Maldives

Source: Jose Aguado (Effergy Energía).

(ii) **Roof-mounted (rack, integral, and stand-off).** Roof-mounted installations will normally be a better choice to avoid shading. Installation costs might be somewhat higher. Although less aesthetically pleasant, stand-off and rack mounting provide better cooling and access for maintenance than integral installations.

A.2 Wind Energy Systems

131. Wind energy systems are formed by wind turbines that transform the kinetic energy of the wind into DC or AC current and the necessary power electronics converters to transform this energy into DC or AC current of the voltage and frequency of the RE system.

132. Cost-effectiveness of wind power is site specific, as average wind speed can vary a lot within small areas. Wind power can be a good complement to solar PV generation, as it does not stop at night and, in most places, the months of low solar radiation are also the windiest months.

133. A combination of solar PV and wind energy could be the best way to achieve high RE fractions in places where the wind resource is good. It is commonly accepted, as a rule of thumb, that average wind speeds of over 5 meters per second indicate cost-effectiveness of wind power.

A.2.1 Types of Wind Turbines

134. Wind turbines can be classified as follows:

(i) **Small, medium, and large wind turbines.** Turbines suitable for minigrids are small or medium-sized turbines, while large turbines are used exclusively in grid-connected wind farms. Although there is no official classification, turbines with a peak power output below 50 kW can be classified as small, and up to 250 kW as medium-sized.

(ii) **Horizontal axis versus vertical axis turbines.**

(a) **Horizontal axis wind turbines** are the most common type of turbine for mid- and large-scale grid applications due to their higher aerodynamic efficiency and reliability. They consist of a two- or three-blade rotor mounted on a high tower, where speed of the wind is higher and less turbulent. They need to be oriented to align with wind direction to make use of its energy, and therefore require control mechanisms to change orientation of the blades. Three-blade turbines are the most common type because they are, in general, more aerodynamically efficient and reliable than two-blade turbines. However, some argue that the difference in cost can make two-blade turbines a better choice in some cases. Maximum power output varies proportionally with the area swept by the rotor.

(b) **Vertical axis wind turbines (VAWT)** are those whose main components are located at the base of the turbine and the main rotor shaft is set vertically. While horizontal axis wind turbines make the most sense for medium-sized and large applications, VAWT have some advantages that make them interesting for small wind turbines that can be installed in minigrids. They require less space so they can be packed together, closer to each other in wind farms, which is important, for example, in case of islands with limited available space. They are also less noisy, which might be a requirement in cases of limited space, where they must be placed near residential areas. Small VAWT can be built on rooftops. They do not need to be pointed at the wind, thus they are appropriate for zones with ever-changing wind direction (like rooftops in residential areas).

The generator and gearbox can be placed near the ground, which makes maintenance simpler.

On the other hand, VAWT are less aerodynamically efficient, and the wide variations in force applied during each rotation make them prone to fatigue failure and thus less reliable. Their use is normally limited to small and medium-sized applications where limited space is a key factor.

(iii) **Fixed speed versus variable speed turbines.** Depending on the type of control, wind turbines are classified as constant speed or variable speed turbines.

(a) **Constant speed** wind turbines operate at almost constant speed depending on their generator and gearbox design. Their control schemes try to maximize power output by controlling the rotor torque. Constant speed wind turbines can be further classified as stall- or pitch-regulated according to their aerodynamic regulation. Constant speed wind turbines have several advantages: (i) robust, simple, and usually more reliable; (ii) more electrically efficient and do not require converters; thus, do not introduce harmonics; and (iii) have a lower capital cost than variable speed turbines. On the other hand, fixed speed turbines have a lower efficiency and present higher fluctuations in their power output, which is a major drawback in minigrids.

(b) In **variable speed** wind turbines, the rotor speed and pitch angles of the blades are controlled when the wind speed is below the nominal value. The rotor speed is controlled to target the optimum wind speed to rotor speed ratio. Variable speed turbines have the following advantages: (i) more efficient and are subjected to less mechanical stress; and (ii)as their controllers are more sophisticated, present better voltage stability characteristics. On the other hand, their electrical efficiency is lower, as they require a converter interface that converts the variable frequency current into constant frequency. This also implies some level of harmonic distortion. Variable speed turbines are more expensive. Nevertheless, the additional cost of variable speed turbines is usually compensated by their higher and stable energy production. At present, variable speed turbines dominate the market.

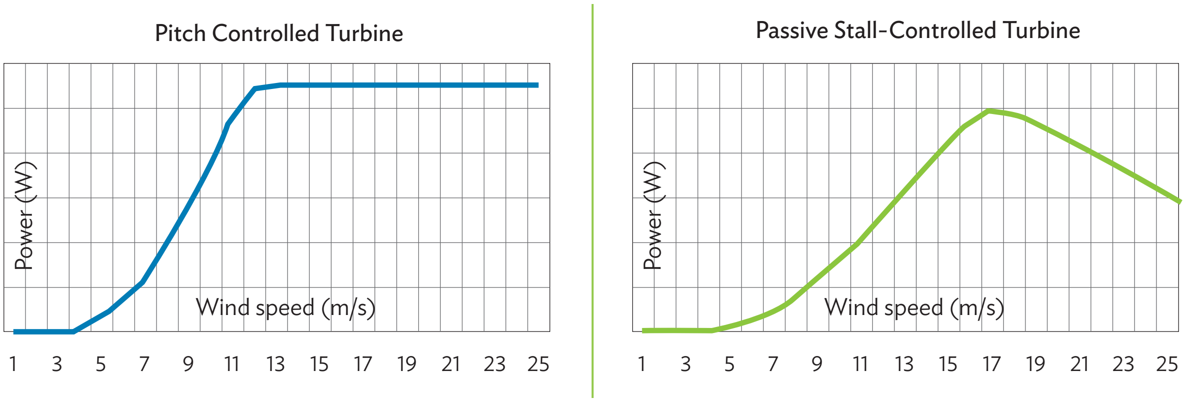
A.2.2 Power Curve

135. The power curve of a wind turbine indicates the turbine's electrical power output at various wind speeds. The shape of this curve depends on all the elements of design: the turbines (number and shape of the blades), braking mechanisms, type of transmission between the rotor and the generator, the generator, transformers, converters, etc.

136. A typical power curve for a pitch-controlled turbine has a cut-in wind speed (at which the rotor starts rotating and power starts being generated) and a cut-off wind speed (at which power output will stay constant even if wind speed increases). Active stall-controlled turbines also have similar power curves, as their control system also allows them to maintain rated power output in the high range of wind speeds.

137. For passive stall-controlled turbines, the typical power curve decreases when rated wind speed is exceeded, as they are designed with a passive aerodynamic braking mechanism whose effect is more pronounced with increasing wind speeds higher than rated speed. Typical power curves can be observed in the figure bellow.

Figure A.2-1: Typical Wind Turbines Power Curves



Pitch Controlled Turbine

Passive Stall-Controlled Turbine

kW = kilowatt, m/s = meter per second.

Source: Jose Antonio Aguado (Effergy Energia).

A.2.3 Wind Turbine Coupling in Minigrids and Siting

138. Most small wind turbines use a permanent magnet generator, which produces an AC current that is rectified into DC. This DC current can be connected to the battery and its converter with a charge controller (DC coupling), or it can be the input to a wind turbine inverter that directly transforms it into AC current at the voltage and frequency level of the grid. Medium-sized wind turbines generally use an induction generator and are more suited for AC coupling than for directly-charging batteries.

139. The siting of a wind turbine is crucial in its performance. Wind turbines must be sited far from obstacles, such as houses and trees, as these slow down wind and cause turbulences. Ideally, turbines should be placed in elevated smooth surfaces such as hills away from buildings. Rooftops are another option for small enough wind turbines.

A.3 Diesel Generator Sets

140. A diesel generator is the combination of a diesel engine with an electric generator, normally synchronous in the case of islanded systems, as they are, along with storage systems, the elements of a microgrid in charge of frequency and voltage regulation. As opposed to RE sources such as wind and solar PV, diesel generators are dispatchable sources, whose power output can be automatically regulated to match the demand. This particular characteristic makes them still essential in islanded systems, despite their high costs of operation due to prices of fuel.

141. A system based on 100% RE would require oversized solar or wind installations, and huge energy storage systems that would allow the RE system to match demand all the time. Today's prices of energy storage systems and renewable generators still do not allow to do that in a profitable way.

142. Diesel generators are the cheapest power-generating option up front for islanded systems, since their initial investment cost per rated kilowatt is much lower. On the other hand, diesel generators have much higher operation costs since they depend on the price of

fuel. Diesel generators are very compact in terms of space required for their installation, but they require space for fuel storage, and transport costs of fuel to remote areas such as islands can be very high.

Figure A.3-1: Diesel Generator Sets

2,000 kilovolt-amperes diesel generators

40 kilovolt-amperes diesel generators

Source:
Left: Cummins Manufacturer. Online available at http://power.cummins.com/
Right: Caterpillar Manufacturer. Online available at http://www.cat.com/

143. The two main control elements integrated in diesel generator sets for minigrid applications are as follows:

(i) **Automatic Voltage Regulator**. It controls generated reactive power to maintain voltage between acceptable limits.

(ii) **Electronic Governor Controller (speed governor)**. It controls generated active power to match demand by sensing frequency changes (droop control).

144. In any electrical grid, when power generation does not perfectly match demand, rotating generators slow down or speed up, and frequency values deviate from their reference values (increasing when generation exceeds demand and decreasing when generation is not enough to meet demand). In large, strong grids with the inertia of thousands of rotating generators, this effect is less pronounced. However, frequency stability is a sensitive issue for a hybrid islanded system because wind and solar PV systems have inherent fluctuating behavior due to changing wind speed and solar radiation. They also do not directly contribute to the power system inertia since they are connected to the grid via inverter and/or converter. Whenever the system's frequency is deviated from its nominal value due to any disturbance or load or generation changes, mechanisms of frequency control operate in different stages, depending on the duration of dynamics to counteract the change in frequency. The stages that happen in a time frame of 0–20 seconds are as follows [18]:

(i) **Inertial response**. Whenever there is a power imbalance in the system, diesel generators will absorb or release kinetic energy to compensate for the change in frequency, damping the rate of change of frequency. This way, the kinetic energy stored in the rotating masses of generators and motors determines the sensitivity of the system frequency toward power imbalance.

(ii) **Governor response (primary frequency control)**. After initial inertial response, the control system of the diesel generators detects the error between output and reference frequencies, and corrects the mismatch by injecting more or less fuel, adjusting the position of a valve. When there is a single diesel generator forming the grid, it can be controlled in isochronous mode. This means that the controller detects a change in frequency due to power imbalance and corrects the fuel injection until the nominal frequency is restored.

When more than one diesel generators are running in parallel, droop control is implemented for them to share the power changes. With droop control, the frequency stabilizes at a quasi-steady-state value different from the reference value according to droop characteristic of the speed governor, which is the decrease in frequency caused by a 100% increase in power output (usually set between 2.5% and 5.0%). When all paralleled generators have the same droop characteristic, they share power changes proportionally to their rated power.

145. Once the power mismatch has been corrected, the frequency stabilizes with a steady-state error with respect to the nominal frequency, a second control loop (every 30 seconds to 1 minute) shifts the droop characteristics so that the generator sets work at nominal frequency at the new active power set point.

146. To be able to quickly correct generation or consumption imbalances, diesel generators synchronized to the system must have some remaining available capacity. This immediately available generating capacity is called **spinning reserve** and must be taken into account as a function of renewable penetration and storage capacity when designing and operating hybrid RE microgrids.

A.3.1 Fuel Consumption and Efficiency Characteristic of Diesel Generators

147. Manufacturers usually give fuel consumption at four different percentage of nominal power output, usually at 25%, 50%, 75%, and 100%. These points usually fit almost perfectly to define fuel consumption as a linear function of power output. The Y-axis intercept of this linear fit represents the idle fuel consumption, which is the amount of fuel consumed to keep the generator rotating without generating any power. The slope of the fuel consumption curve (in liters per kilowatt-hour [l/kWh]) represents the extra amount of fuel consumed during an hour by the generator to increment its constant power output in 1 kW. Its normal values are in the range of 0.24–0.31 l/kWh. Logically, larger generators will have more idle fuel consumptions.

148. Efficiency of a diesel generator (η) represents the amount of chemical energy on the fuel that gets finally converted into electric energy by the generator. This parameter is given by

$$\eta = \frac{Energy\ Output}{Energy\ in\ the\ fuel} = \frac{Energy\ Output}{HV \cdot Fuel\ Consumption}$$

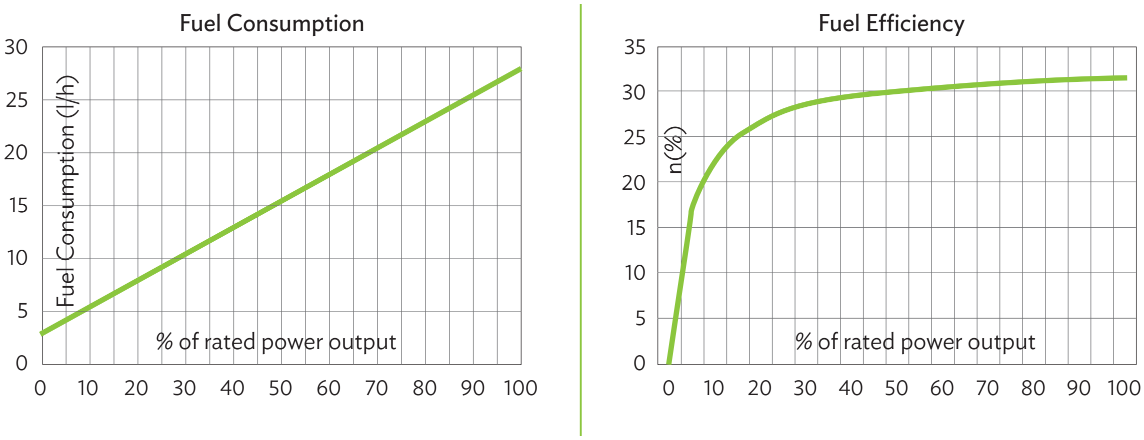
where HV is the heating or combustion value of fuel. There is no agreement on whether to use the high or low heating value. In any case, the value used should be specified.

149. If we assume fuel consumption to be linear, then efficiency, as a function of power output, is as follows:

$$\eta(\%) = \frac{100 \cdot \mathrm{P} \cdot \Delta\mathrm{t}}{\mathrm{HV} \cdot (a \cdot P + b)}$$

- P is the power output (kw).
- Δt is 1 hour.
- HV is the combustion value (approximately 44 megajoules per kilogram or 12.2 kilowatt-hours per kilogram).
- a is the slope of the linear fuel consumption curve.
- b is the Y-axis intercept of the fuel consumption curve.

Figure A.3-2: Fuel Consumption and Efficiency



Fuel Consumption

Fuel Efficiency

l/h = liter per hour.

Note: Fuel consumption/efficiency is given as a function of generated power of a 200-kilovolt-ampere diesel generator. Slope of the fuel consumption curve a = 0.25 l/h•kW, and idle consumption b = 3 l/h.

Source: Jose Antonio Aguado (Effergy Energia).

150. The closer to its rated power output, the more efficient a diesel generator gets. Under 25%–30% of rated power, efficiency quickly decreases.

A.3.2 Lower Limit on Output Power

151. Low efficiency is not the only reason why diesel generators should not be operated at very low percentages of their rated power. At loads under this percentage, fuel cannot burn completely due to low cylinder pressure and a carbon laydown occurs. Low cylinder pressure results in poor piston ring sealing because this relies on the gas pressure to force them against the oil film on the bores to form the seal. Due to this poor sealing, combustion gases enter in contact with the lubricating oil on the cylinder walls, burning it, and creating a glaze that removes the effect of the honing marks on the cylinders, causing poor lubrication.

152. Unburned fuel leaks and mixes with the lubricating oil, and injectors of the engine end up clogged with soot, which leads to even poorer combustion causing the engine to enter a fast degrading cycle. At low pressures, the temperature inside the pistons is also lower and water condenses, forming acids with some combustion by-products that mix with the lubricating oil, which further increases wear. In summary, prolonged periods of operating the generator with very low loads will permanently damage the generator.

153. For this reason, depending on the load profile and the RE penetration, it is often necessary to include diesel generators with different rated powers in minigrids, so that when the power required from diesel generators is low, larger generators can be switched off and smaller generators can supply that power more efficiently.

154. Some companies are starting to commercialize generator sets that can run efficiently under low load conditions for extended periods with minimum carbon buildup, and have good load following capability at low load. Another alternative for low-load operation is a variable speed generator set with a power electronic converter to interface with the grid. In this way the problems of fixed-speed low load operation are avoided. On the other hand, this solution adds cost and complexity. The size of commercially available variable speed generators is also limited.

A.3.3 Diesel Generators Classifications

155. According to the type of operation they are designed for, diesel generators are classified under three ratings in the standard ISO 8528-1.

156. **Standby power rating.** Standby power generators are specially designed to provide emergency energy during a power outage. No overload capability is available in standby rated generators. The design of these generators only considers short periods of operation for critical loads.

157. **Prime power rating.** Prime power applications are divided into two categories:

(i) **Limited running time:** In this case, the diesel generators operate a reduced number of hours (less than 1,000 hours per year). This type does not fit in most minigrid applications.

(ii) **Indefinite running time:** In this case, the diesel generators are not designed to provide maximum power continuously over long periods. They properly integrate in minigrids, in which RE power output forces generators to operate at low load factors during some periods.

158. **Continuous power rating (base load).** Under this operation mode, the generator supplies energy to a constant demand. These generator sets operate at high rating levels usually beyond 75%. They are not designed to constantly change power output or to operate at low loads. This is the right type of generator to provide continuous base generation in hybrid islanded grids.

159. On the other hand, diesel generators can be three-phase or single-phase. Three-phase generators for the same voltage and power rating are more compact and least costly than single-phase generators. For that reason, single-phase generators of rated powers over 30 kW are not common.

A.4 Electric Battery Storage Systems

160. Electric energy in minigrids can be stored in different ways: as mechanical potential energy in flywheels and small pump-hydro plants, or as chemical energy in batteries. This document covers only the latter. The batteries themselves are only a part (and the most

costly) of the battery electric storage system (BESS) that also comprises monitoring, control, and power conversion systems.

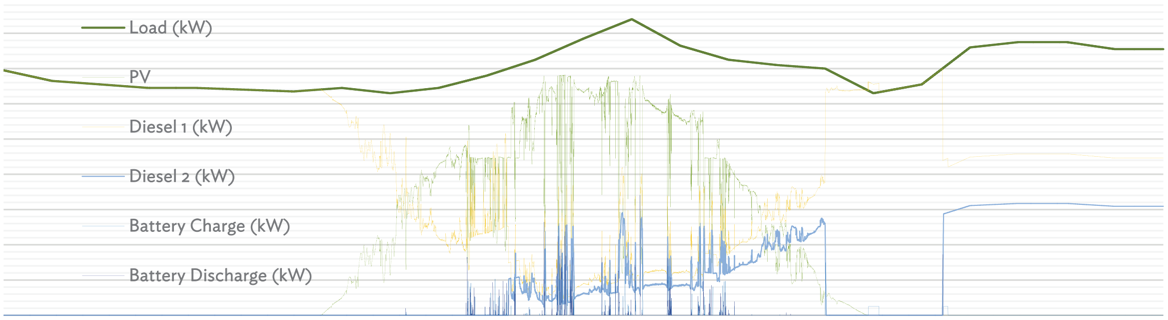
A.4.1 Roles of Battery Storage in Minigrids

161. Energy storage has two main functions in islanded minigrids, and for both of them, the need for storage increases with RE penetration:

(i) **Grid support (short-term power compensation)**. As opposed to large utility grids, where individual loads and generators represent a very small fraction of the total generation or consumption, and power flows are quickly compensated by the inertia of rotating machines and their control systems, maintaining the balance between power generation and consumption is a much bigger challenge in islanded minigrids. In these small grids, connection and disconnection of single loads can represent a large percentage of the total consumption that one or two diesel generators might not be able to cover fast enough. This problem is even more evident as we aim to increase RE penetration. Passing clouds and changes in wind speed, at times when renewable generation represents a large percentage, could make generation suddenly drop by 70% in just a few seconds. The combination of a battery storage with properly controlled converters allows to compensate for such sharp fluctuations in generation and demand in the range of milliseconds. For grid support purposes, the limiting characteristic is the maximum power of charge and discharge. A maximum power implies a capacity that relates by the maximum rate of power to nominal capacity ratio that the batteries can withstand without drastically reducing their life span.

An example of the battery power profile in grid support operation mode can be seen in the Figure A.4-1 for a minigrid with two diesel generators and high solar PV penetration. The battery instantly compensates fluctuations in solar PV generation caused by clouds and returns to rest state when the controllers of the diesel generators (with slower dynamics) restore the power balance again.

Figure A.4-1: Battery Power Profile in Grid Support Operation



kW = kilowatt, PV = photovoltaic.

Source: Jose Antonio Aguado (Effergy Energia).

(ii) **Load following or load shifting (long-term energy management)**. Battery storage can also be used to store the excess of renewable generation at periods of low demand and high generation, instead of curtailing it with the inverters or dissipating it in dump loads. This stored energy can be later discharged in periods of higher demand or lack of RE generation, thus saving fuel. If the configuration of the minigrid allows operation without a rotating machine, it can result in periods of functioning without a diesel generator running, leading to reduced operation costs.

A.4.2 Main Battery Characteristics

162. The fundamental variables that define suitability of a storage device for minigrid applications are the following:

(i) **Energy storage capacity.** Storage capacity is the amount of energy that can be stored in the battery. Manufacturers can provide this number in kWh or in ampere-hours (Ah) at nominal voltage. In lead-acid batteries, due to rate effect, actual observed capacity is not exactly a constant value and would depend on the way the battery is discharged. Actual capacity decreases as speed of discharge increases. When weight and/or space are a limitation, energy density, defined as capacity over mass (watt-hour per kilogram [Wh/kg]) or volume (watt-hour per cubic meter [Wh/m^3]) is also a factor to consider.

(ii) **Maximum charge and discharge rates**. These are measures of how fast a battery can be charged and discharged; they can be expressed in kW or in ampere (A) at nominal voltage. Again, the real behavior of batteries is nonlinear, and the maximum power that can be extracted from them depends on factors such as state of charge. For high-level calculations, it is acceptable to use nominal values. Charging rate is lower than discharging rate for most technologies.

(iii) **Lifetime**. It is a measure of how long a battery can work properly. This information is usually given as the number of cycles of a certain depth of discharge that the battery can withstand, or as the total amount of energy that can circulate through the battery before failure, normally defined as 20% decrease in capacity. The last criterion is referred to as lifetime energy throughput, which could not accurately predict lifetime. Despite this, it is frequently used for project simulations due to its simplicity and for lack of better criteria. Temperature changes caused by environmental conditions and high charging or discharging rates have a big impact on life span that this criterion cannot take into account. There are no standard methods to predict life span as a function of battery operation. This is a hot topic of research, given that one more replacement of the battery bank can make an important difference in the cost of a minigrid project. Besides the wear caused by frequent use, batteries (some technologies more than others) will also see their performance decrease due to aging (especially in harsh ambient temperature), that is commonly referred to as a calendar life.

(iv) **Operating temperature range.** Batteries have an optimal temperature at which they can operate, a range of allowed temperatures in which the battery functions in a derated way, and a temperature range outside of which the batteries will be permanently damaged. This information is valuable depending on the climate conditions of the minigrid and will sometimes be the decisive factor that tips the scales in favor of one technology over another.

(v) **Roundtrip efficiency**. In the process of transforming electrical energy into chemical energy that gets stored in a battery and vice versa, some amount of energy is lost. The energy that can be discharged from a battery will always be less than the energy charged into it. The importance of these losses can be expressed as the percentage of energy that can be discharged from the battery over the energy used to charge it:

η_roundtrip (%)=100•energy_discharged/energy_charged

(vi) **Initial investment**. Total capital cost of the battery installation will also depend on other factors such as transport, local labor rates, etc. Capital costs, other than the battery bank itself, include converters, safety equipment, a control system that allows the operator to monitor and control the state of the battery remotely. The battery is a critical device, which highly impacts the overall cost over the lifetime of the system.

(vii) **Operation and maintenance costs**. Some batteries require more maintenance than others to stay at good performance. Many factors affect the amount of money that has to be spent to provide a good maintenance: type of technology, availability of local skilled operators, size of the installation, temperature and humidity conditions, etc.

163. Although some standards pertinent to batteries for RE applications exist (such as the IEC-61427), there is still a lack of defined standards that manufacturers have to follow when providing performance data. For this reason, battery selection is a task that should ideally be guided by experts in the field.

A.4.3 Electric Battery Technologies

164. Lead-based, lithium-based, nickel-based, or sodium-based batteries can be used subject to particular system requirements. Usually, batteries with lowest capital expenditure are not the most cost-effective alternative over the project lifetime and might not be optimized for the performance requirements of the minigrid [4].

165. A system's specific technical and environmental requirements are the main drivers for the selection of battery technology for off-grid or minigrid RE systems [19]. A brief description of several commercially available technologies is provided.

166. **Lead acid.** Lead acid is the oldest type of battery, and it comprises a wide range of models, which allows adaptation to every minigrid application. As of today, they are still the least expensive type of battery. There are two main types of deep-cycle lead-acid batteries: wet cell batteries and valve regulated. Wet cell lead-acid batteries (or flooded lead-acid batteries) use distilled water as a part of the electrolyte, which needs to be replaced around two to three times a year.

167. It is commonly accepted that lead-acid technology has already reached its maximum development and that no significant improvements in capacity or lifetime will be made. In summary, their main advantage is their low cost, but they are rather short-lived in terms of cycles compared with other technologies. Therefore, a battery bank of lead-acid batteries would need to have a higher capacity than other technologies to achieve a similar life span for the same application. They also usually have lower roundtrip efficiencies than other

batteries, and their recommended minimum state of charge is about 30%–40%, which makes their effective capacity lower.

168. **Nickel-based batteries**. Nickel–cadmium (Ni-Cd) and nickel–metal hydride (Ni-MH) batteries have been used for several decades as an alternative to lead-acid batteries, although they are more expensive. They have a longer expected life span and resistance to harsh conditions. Their main advantages are as follows:

(i) Long calendar life (typically over 20 years) and higher cycle life than lead-acid batteries.

(ii) Robustness and reliability since they are very resistant to extreme temperatures and good at taking mechanical and electrical abuse.

169. Under severe environmental conditions, Ni-Cd batteries represent an excellent option for rural electrification. Although up-front costs are slightly higher compared with that of other technologies, their robustness could be competitive in certain applications. Although Ni-HM batteries are more expensive, some characteristics might make them more suitable than Ni-Cd batteries, such as higher energy density (important when space is a limitation) and no need for conditioning to avoid memory effect.[4] Another important consideration is that cadmium is a toxic heavy metal, which is an issue from an environmental point of view.

170. **Lithium-ion batteries** are the most widespread in portable electronic devices as well as electric vehicles due to their high energy density and superior cycling capabilities. Their main disadvantage has been their higher cost; however, prices, which have decreased greatly over the past 2 years, are expected to continue to decrease. Their main characteristics are the following:

(i) high roundtrip efficiency;

(ii) maintenance-free design;

(iii) long calendar and cycle lifetime; and

(iv) high energy density (low weight and more compact).

171. These characteristics were often enough to make up for their higher price (twice as expensive as lead-acid batteries) in minigrids for rural electrification.

172. Different geometry can be found in lithium-ion cells such as cylindrical, prismatic, or pouch cells. There are also several different lithium-ion chemistries, each depending on the material choices of anode (graphite, carbon, lithium, titanate) and cathodes (lithium-manganese-oxide, nickel–cobalt–aluminum, lithium-iron-phosphate, lithium–cobalt-oxide).

173. Each lithium-ion technology offers different compromises between different performance characteristics (cycle life, temperature resistance, etc.), and therefore the ideal choice would depend on the application. Usually, lithium titanate batteries offer the best

---

[4] Decrease in effective capacity when the batteries are repeatedly recharged after a partial discharge, which is noticeable in Ni-Cd batteries.

performance in terms of cycle life and energy density but, nowadays, they are considerably more expensive than other lithium-ion technologies.

174. This technology requires a battery management system to avoid overcharge, perform cell balancing, and monitor cell temperature. Usually, LIB manufacturers offer within this technology remote monitoring of certain battery parameters such as state of charge, power profile, battery degradation, among other operating conditions.

175. **Molten salt-based batteries,** such as sodium sulphur and sodium nickel chloride, use molten salt as an electrolyte. Sodium sulfur batteries are more suited for large grid storage applications than for minigrids. Sodium nickel chloride batteries are a recent technology and their use for minigrid stability is under research. Some relevant features of this technology are the following: can easily support high temperature, almost maintenance-free, and less sensitive to site conditions.

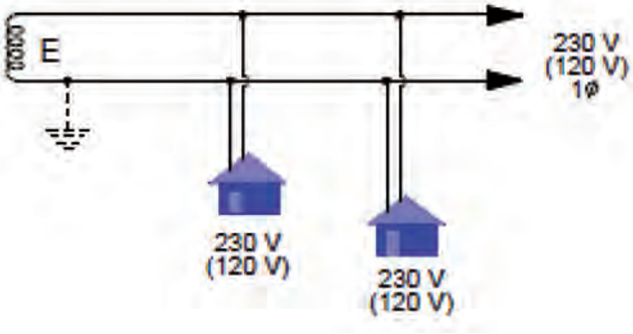
176. **Hybrid (battery/ultracapacitors) storage systems** use a combination of both technologies. Ultracapacitors are high-capacity electrochemical capacitors that can be charged or discharged at rates only limited by the power electronics of the converters. This characteristic becomes even more interesting when combined with batteries in grid support applications. In this type of application, the battery needs to instantly compensate power mismatches until other slower controllers can restore the balance. Combining batteries and ultracapacitors in an intelligent-controlled device allows the reduction of battery capacity as the ultracapacitors can provide these short power bursts.

A.5 Electrical Distribution Network

177. In cases where there is no usable preexisting distribution grid, the most suitable line configuration needs to be determined. In isolated communities, the vast majority of loads will be single-phase loads; thus, three-phase distribution is not necessarily imposed and converters could be used for the few motors requiring three-phase supply in the community. Different single-phase and three-phase configurations are possible. The best configuration will depend on the size of power demand, the amount and location of consumers and generators, etc. The power level, at which a three-phase configuration becomes more economical than single phase, is site-specific based on those factors. Several configurations are described below.

178. **Single-phase, two-wire configuration:** This is the simplest configuration: generators and consumers are all connected to the same AC phase. One of the two conductors can be grounded. To receive electricity supply, all consumers need to do is tap those two wires. In this aspect, it is more straightforward to design than other configurations, as there is no need to balance loads between phases. Voltage drops and power losses in single-phase systems are higher than in three-phase distribution. However, in small minigrids with low power levels, the minimum size of the conductors might be constrained by mechanical resistance reasons, leaving voltage drop and power losses within acceptable values. In such cases, the increased current-carrying capacity offered by a more expensive three-phase distribution system would not be necessary.

Figure A.5-1: Two-Wire, Single-Phase Distribution

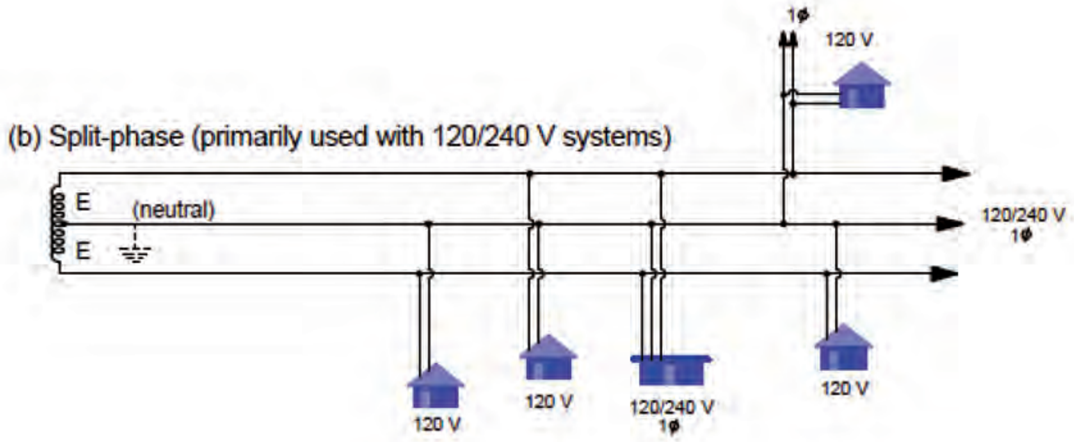


E = electric voltage (electromotive force), V = volt.

Source: World Bank. Energy Sector Management Assistance Programme. 2000. *Mini-Grid Design Manual*. Washington, D.C.

179. **Single-phase, three-wire (split phase) configuration:** This configuration is primarily used in systems in which the nominal distribution voltage is 120 volts. It requires a third conductor and for generators to have their output voltage split, e.g., 120 volts-0-120 volts. If the loads are balanced between the two split phases, the line capacity with a third conductor is four times as much as in the two-wire configuration. When the split phases are unbalanced, which is usually the case in minigrids, this capacity increases with respect to the two-wire configuration decreases.

Figure A.5-2: Three-Wire, Single-Phase Distribution



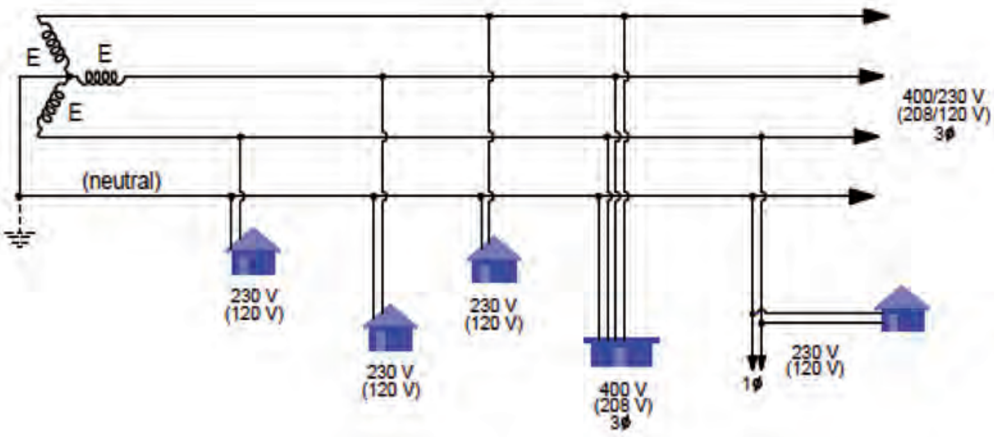
E = electric voltage (electromotive force), V = volt.

Source: World Bank. Energy Sector Management Assistance Programme. 2000. *Mini-Grid Design Manual*. Washington, D.C.

180. **Three-phase:** Three-phase distribution is theoretically the most economical configuration in terms of conductor size when considering the same voltage drop and losses constraints. In bigger minigrids, where there are large consumers or significant industrial activity that requires three-phase motors, three-phase distribution makes more sense than single phase. However, efforts should be made while planning the distribution line to balance loads between phases at peak time as much as possible to minimize losses. Three-phase generators have a de-rating in their total power output capacity when the phases are not balanced.

181. **Three wires and neutral (wye connection)** is the most used configuration for three-phase distribution as the current is transmitted at a voltage 1.73 times higher than with a delta connection. This means that the required current for the same power decreases in the same factor and that power losses in distribution are three times lower than with a delta configuration, when the loads are balanced. The neutral conductor can be grounded, although it is not always necessary or convenient to do so.

Figure A.5-3: Three-phase, Wye Distribution

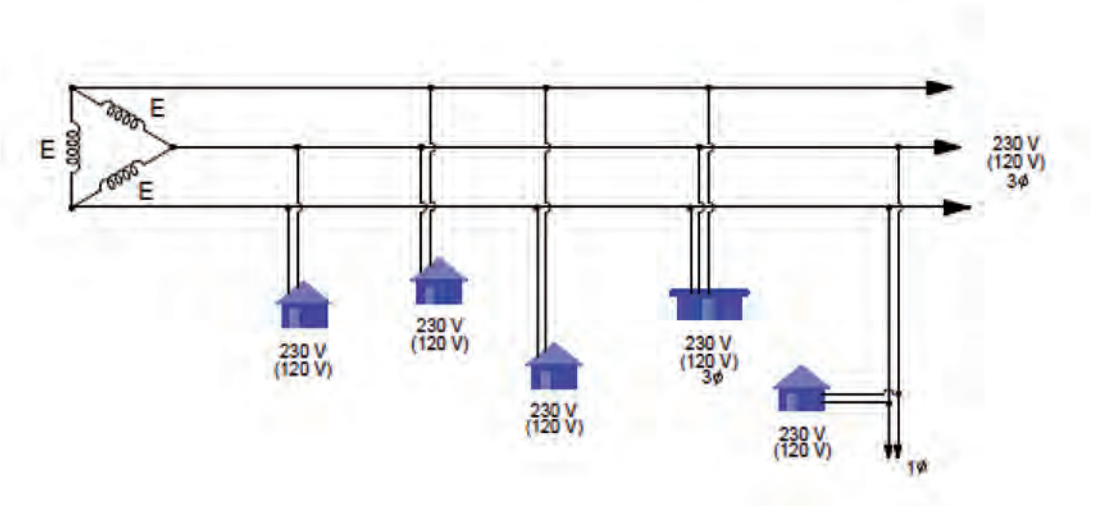


E = electric voltage (electromotive force), V = volt.

Source: World Bank. Energy Sector Management Assistance Programme. 2000. *Mini-Grid Design Manual*. Washington, D.C.

182. **Delta configuration** is much less frequently used for this reason. However, it is a more robust configuration when dealing with highly unbalanced loads as each one of the three conductors supplies the load of two phases. In this way, the overload capacity of each single phase is higher than in wye connected systems.

Figure A.5-4. Three-Phase, Delta Distribution



E = electric voltage (electromotive force), V = volt.

Source: World Bank. Energy Sector Management Assistance Programme. 2000. *Mini-Grid Design Manual*. Washington, D.C.

REFERENCES

[3] Alliance for Rural Electrification. 2011. *Rural Electrification with Renewable Energy. Technologies, Quality Standards and Business Models*. Brussels.

[14] Alliance for Rural Electrification. 2014. *Hybrid Minigrids for Rural Electrification: Lessons Learnt.* United States Agency for International Development.

[16] Australian Business Council for Sustainable Energy. *Solar PV Systems: Users Maintenance Guide.*

[15] Battery University, Cadex Electronics Inc. [online]. Available at http://batteryuniversity.com/. (accessed June 2016).

[12] C. W. E. Association. 2016. CanWEA [online]. Available at http://canwea.ca/ (accessed June 2016).

[8] Clean Energy Solution Center. 2015. *Tools for Minigrid Practitioners.*

[19] EUROBAT. 2013. *Battery Energy Storage for Rural Electrification Systems Guidance Document.* The Association of European Automotive and Industrial Battery Manufacturers.

[9] Homer Energy. 2017. Software for Microgrid and Distributed Generation Power System Design and Optimization. [online]. Available at http://www.homerenergy.com/

[1] International Energy Agency. 2016. *World Energy Outlook 2016.*

[4] International Renewable Energy Agency. 2016. *Innovation Outlook: Renewable Mini-grids*. Abu Dhabi.

[7] L. Landberg et al. 2003. *Wind Resource Estimation—An Overview. Wind Energy.* July.

[6] M. Sengupta et al. 2015. *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications.*

[5] National Renewable Energy Laboratory, Renewable Resource Data Center. 2017.

[20] NREL. 2016. System Advisor Model. [online]. Available at https://www.nrel.gov/analysis/sam/help/html-php/index.html?mtf_lcoe.htm

[18] P. Gugale et al. 2014. *Development of Network Dimensioning Guidelines for Renewable Island. In Innovative Smart Grid Technologies Conference Europe (ISGT-Europe),* 2014 IEEE PES.

[21] P. Kundur. 1994. *Power System Stability and Control.* McGraw-Hill.

[17] R. Arghandeh and Y. Zhou. 2017. *Big Data Application in Power Systems.* Elsevier Science. p. 500.

[13] S. Clarke. 2003. *Electricity Generation Using Small Wind Turbines at Your Home or Farm.* Rural Environment/OMAFRA.

[2] United Nations. 2017. Sustainable Energy for All. http://www.se4all.org/

[11] United States Agency for International Development. 2013. *Solar PV System Maintenance Guide.*

[10] W. Brooks and J. Dunlop. 2013. *PV Installation Professional Resource Guide.* North American Board of Certified Energy Practitioners.

[22] World Bank. Energy Sector Management Assistance Programme. 2000. *Mini-Grid Design Manual.* Washington, D.C.

Deployment of Hybrid Renewable Energy Systems in Minigrids

Despite significant economic growth in Asia in recent decades, millions of people in rural Asia still lack access to electricity. In response, the Asian Development Bank is working to foster universal access to energy by developing small hybrid renewable energy systems in rural Asian areas. This publication highlights the experiences of ADB's pilot projects to achieve access to electricity and energy efficiency in five developing countries in Asia. It provides technical guidance and recommendations for the effective deployment of similar systems in minigrids in remote rural locations and small isolated islands.

About the Asian Development Bank

ADB's vision is an Asia and Pacific region free of poverty. Its mission is to help its developing member countries reduce poverty and improve the quality of life of their people. Despite the region's many successes, it remains home to a large share of the world's poor. ADB is committed to reducing poverty through inclusive economic growth, environmentally sustainable growth, and regional integration.

Based in Manila, ADB is owned by 67 members, including 48 from the region. Its main instruments for helping its developing member countries are policy dialogue, loans, equity investments, guarantees, grants, and technical assistance.

ASIAN DEVELOPMENT BANK
6 ADB Avenue, Mandaluyong City
1550 Metro Manila, Philippines
www.adb.org