Solar Photovoltaic (PV) Hybrid Power Plants

A Guideline Report

July 2016

REPUBLIC OF LEBANON
MINISTRY OF INDUSTRY

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For further information:

United Nations Development Programme, http://www.lb.undp.org/
CEDRO, http://www.cedro-undp.org/

Note: The information contained within this document has been developed within a specific scope, and might be updated in the future.

Acknowledgments

The United Nations Development Programme (UNDP) would like to thank the European Union for the grant that established and enabled the work of CEDRO 4. CEDRO would also like to thank all its partners including the Ministry of Energy and Water, the Ministry of Industry, the Council of Development and Reconstruction, the Lebanese Center for Energy Conservation (LCEC), and all other institutions that work closely with this project.

Foreword

Solar technology has come a very long way to become today the cheapest way to generate power. The PV-diesel configuration is an innovative approach to solar PV power integration in the Lebanese national grid, and to synchronize with self-generators during power outages. The savings on the use of fuel oil and grid electricity is remarkable. I hope this guideline report would give further confidence in this technology. The ongoing NEEREA mechanism, a highly successful and ongoing program initiated by the Central Bank of Lebanon with the support of the Ministry of Energy and Water and the Lebanese Center for Energy Conservation is still on the move with momentum foreseen for the future.

I encourage all concerned parties to tap into the resources available through NEEREA and install a PV-diesel system to save on both your own fuel bill and help, in this small yet with important way, the country in reducing its dependence on imported fuel. Get connected!

Arthur Nazarian

Minister of Energy and Water

Foreword

Energy is an integral part of modern industry. The increasing use of energy in the global industrial sector during the last decades caused real threats to the environment. Decision makers and scientists are looking for alternatives for fossil fuel as sources of clean energy.

The cost of securing energy in Lebanon is the highest when compared to other countries in the Middle East region. Most of these countries subsidize their energy consumption. The cost of energy usually constitutes a major portion of the final costs of industrial products. This fact makes Lebanese industrialists, who pay more for energy, at a disadvantage compared to their competitors.

The newly discovered offshore oil and gas reserves are very promising for the Lebanese economy, especially the industrial sector. Nevertheless, seeking energy efficiency and more sustainable sources of energy should not be overlooked. The Ministry of Industry has marked these sources, such as wind and solar energy, as major pillars within the Ministry's vision for a sustainable industrial sector. The Ministry will support all initiatives which aim to fulfil this target.

Hussein el-Hajj Hassan
Minister of Industry

Foreword

Energy efficiency counts among the most important mitigation measures of Lebanon's Nationally Determined Contribution (under the United Nations Framework Convention on Climate Change) that were presented at the COP21 Conference in Paris last December. This ambitious programme undoubtedly placed Lebanon in the group of countries that contributed the most to reach a first-ever universal, legally binding global climate deal covering all countries. This must be applauded, in particular considering the difficult situation that Lebanon has been facing for more than 4 years.

A couple of months before the Paris Declaration, the UN General Assembly adopted an ambitious and comprehensive sustainable development agenda, with 17 Sustainable Development Goals (SDG's) that seek to systematically integrate and balance economic, social and environmental objectives. By adopting this agenda, world leaders have committed to put environmental sustainability at the heart of their policies, plans and programmes. In line with these ambitions, the European Union intends to play a central role into the sustainable development agenda, thereby honouring its obligation - under the EU Treaty - to "mainstream environmental integration with a view to promoting sustainable development".

In October 2014, EU Member States agreed on updated headline targets for the EU framework on climate and energy for 2030. These include: a cut in greenhouse gas emissions by at least 40% by 2030 compared to 1990 levels; an EU-wide binding target for renewable energy of at least 27%; and an indicative energy efficiency target of at least 27%.

Considering these milestones achieved in New York and Paris, the EU's commitment from 2013 to spend at least 20% of its entire 2014-2020's budget on climate change-related projects and policies looked almost like we had a crystal ball looking into the future! Our commitment represents €180 billion in climate spending in all major EU policy areas over the 7 years in the EU and all over the world, and in particular in its neighbourhood area.

At the same time in this part of the Mediterranean, Lebanon had started reviewing its National Energy Efficiency Action Plan (NEEAP) for 2011-2015, which is now completed and updated into a NEEAP 2016-2020: An impressive achievement! The National Renewable Energy Action Plan is on its way: this is very good news indeed. Lebanon has completed its first photovoltaic farm by the Beirut River and is now working on a second one at the Zahrani refinery facilities. Solar water heaters are gradually being disseminated all over the country, energy efficiency solutions are being multiplied thanks to the efficient and attractive National Energy Efficiency and Renewable Energy Action (NEEREA) mechanism managed by the Central Bank of Lebanon...

Undoubtedly, renewable energy and energy efficiency make a lot of sense in a country where energy supply represents a real daily challenge for the citizens as well as for the economy. This is why initiatives contributing to energy savings and the generation of electricity from renewable energy sources are so important. They help to reduce the burden and must be embraced.

This national dynamics has been fostered during the past years by committed actors across the board, that is the Lebanese authorities and in particular the Ministry of Energy and Water, civil society organisations, the private sector, the donor community and UN Agencies. The impressive work done by the Lebanese Centre for Energy Conservation must be highlighted too.

Also, we as the European Union are proud of all the achieved results in the framework of our projects in the energy sector in Lebanon. In particular the CEDRO IV project which is making steady progress towards developing creative and innovative energy schemes on both municipal and industrial levels, thanks to the excellent work of the UNDP-led CEDRO team. The two studies published today on "Energy Efficiency in the Industrial Sector in Lebanon" and "Solar Photovoltaic Hybrid Power Plants for Large Institutions" are a witness of the powerful contribution of Lebanese expertise for the development of its own country.

These initiatives are done in close complementarity with other EU-funded projects, like for instance the support to the National Energy Efficiency scheme (NEEREA), where more than 100 Lebanese Small and Medium-sized Enterprises have initiated energy saving actions (€12.2 million in grants have been awarded). Some Lebanese municipalities have also benefitted from technical support to develop their first Sustainable Energy Action Plan, better known as SEAP. The EU-funded CESMED and SUDEP projects have worked to this end and are currently financing a large part of the identified actions within the SEAP.

These several promising projects under implementation across the country inspire us all. But some adjustments are needed to Lebanon's legislative framework regarding energy efficiency and renewable energy. Furthermore, there is a need for a stronger institutional setting that would foster investments and upgrade existing infrastructures. These improvements would certainly stimulate the private sector's interest and attract national and international investors, for example through innovative financing schemes including public-private partnerships. The European Union encourages Lebanese authorities to double their efforts on these important matters, and reiterates its readiness to accompany these endeavours.

Lebanon and the European Union enjoy a very strong partnership. The European Union is keen on providing the most appropriate support to contribute to Lebanon's energy autonomy and to provide an uninterrupted energy supply for all citizens at an affordable price. I hope that the current European Energy Strategy could serve as a "benchmark" for the energy sector perspectives here in Lebanon. For instance, just like many EU Member States, Lebanon could envisage improving its proper targets for 2020 as regards renewable energy, energy efficiency and the fight against greenhouse gas emissions. By doing so, future generations in Lebanon will benefit from the level of ambition and "energy" that is yielded through bringing forward the responsible and sustainable use of natural resources.

Ambassador Christina Lassen

Head of the Delegation of the European Union to Lebanon

Foreword

Innovative solutions for renewable energy integration for Lebanon are needed to both bridge the current gap in power supply facing the country and to promote cleaner sources of electricity on the long run. The United Nations Development Programme, through the European Union funded CEDRO project, has been working with commercial and industrial institutions for the complete design, supply and installation of solar photovoltaic systems that are integrated or 'hybridized' with diesel generators.

This innovative technology in Lebanon will allow industries to use solar power during electricity shortages and to decrease dependence on polluting generators and relying less on the national grid. I hope that this Guideline Report will build further confidence in this matured technology which reduces the demand for electricity from conventional fuel sources. It also increases these affordable and sustainable energy access for these industries.

Philippe Lazzarini
UNDP Resident Representative

Executive Summary

General Considerations

The electrical distribution grid of Lebanon is characterised as weak. During the daily and long-lasting blackouts, electricity is supplied by individual or neighbourhood diesel gensets, which, besides being an expensive and polluting solution, they contribute to the strong dependency on imported fossil fuels. Technological improvements in the domain of photovoltaics, electronic components and control, in combination with a strong representation of the private, public and institutional sector in the country over the last years make the hybridisation of the grid behind the metre with solar energy an interesting solution for the country's volatile grid. The solution analysed hereafter is the PV-hybrid plant consisting of solar photovoltaic and fossil fuel gensets in the generation part, electronic static conversion equipment, loads, a distribution line and, if necessary, energy storage. PV-hybrid plants interconnected to unreliable grids are still in a pilot phase but with increasing interest. Within the UNDP/CEDRO IV programme, there are five projects in Lebanon installed at the premises of the beneficiaries who co-finance the initial investment of the plant and aim to prove the technical and financial benefits of the solution.

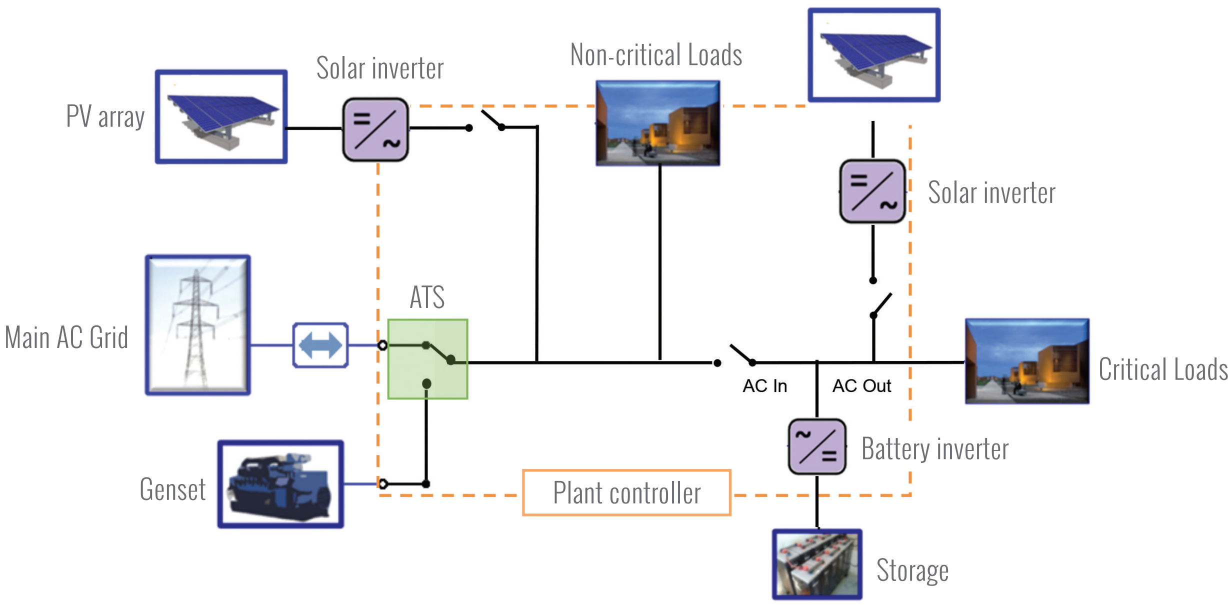

Figure A1: Overview of the PV-hybrid plant with PV and genset generation, storage and a PV plant controller

Such configuration is initially assessed under a feasibility study by estimating relevant technical, economic and environmental key performance indicators (KPIs). Technical KPIs may include the energy and power PV fraction, the annual specific PV production (kWh/kWp) and the specific diesel consumption in every hour of operation (l/kWh), while economic KPIs are the levelised cost of energy, payback period and internal rate of return, to name a few. An annual simulation of the plant is also recommended (Figure A2):

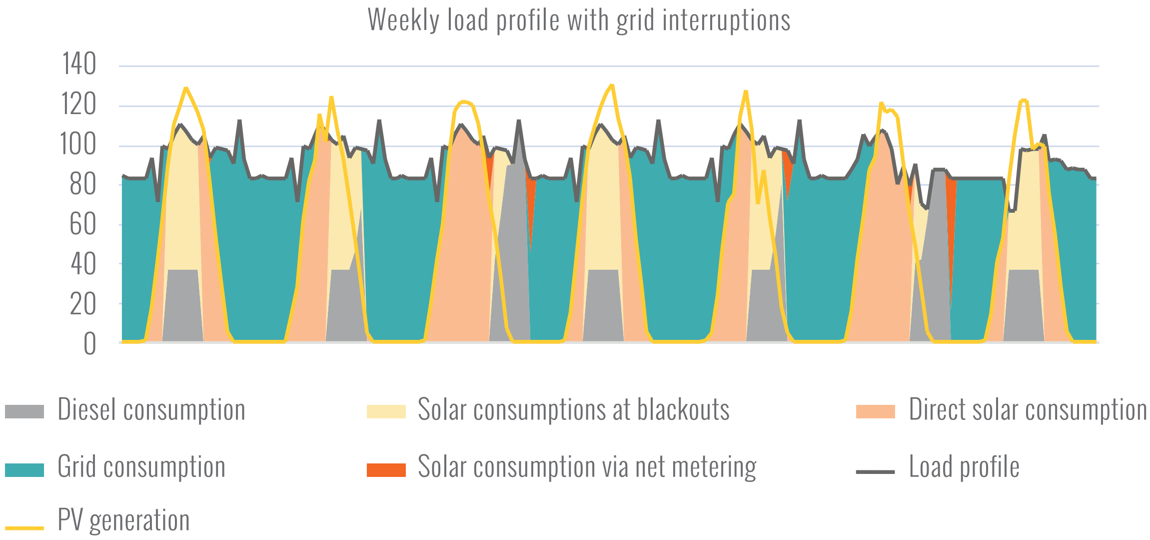

Figure A2: Sample of a weekly load profile with grid interruptions

PV-hybrid plants, or microgrids, can be classified under various criteria such as their interconnection bus (AC, DC or mixed), the quality of the main grid or the quality of service they provide. Depending on the PV fraction of energy and power, microgrid PV fraction can be characterised as low, medium or high.

Table T1: Solar PV fraction in PV-hybrid power plants

Category	Indicative PV Annual Energy Fraction	Indicative PV Rated Capacity/ Load Ratio	Attributes
Low	< 20%	< 50%	• Genset(s) always on during duty cycle • Little or no PV curtailment • No supervisory controller needed • Low fuel reduction • Low capital costs and high internal rate of return (IRR) • No impact: low environmental benefits and low savings
Medium	20% - 50%	> 50%	• Genset(s) always on during duty cycle • Simple controller or small storage for frequency/voltage regulation • Account for spinning reserve • Substantial benefit
High	> 50%	>150%	• Genset(s) not always on • Requires sophisticated controller for grid regulation and control of electronic components • Requires batteries for PV energy time shifting • High CAPEX, low OPEX • High benefits

Category	Indicative PV Annual Energy Fraction	Indicative PV Rated Capacity/ Load Ratio	Attributes
	Autonomous > 80%		• Genset as backup/emergency • Requires sophisticated controller for grid regulation and control of electronic components • Requires batteries for PV energy time shifting • High CAPEX, low OPEX • High benefits

This categorisation defines the technical and financial aspects of the optimum solution. Low solar fraction hybrid power plants require that the genset or the main grid run constantly and simple regulation is needed without sophisticated control. Those plants have a high return on the investment but a low impact. Medium class fraction plants have a higher technical complexity and, thus, bare higher investment costs. One particularity worth taking into account is the frequency and voltage regulation; moreover the gensets should be working within their optimum set points according to the manufacturer. In high solar energy fraction plants, the genset or main grid can be used in a discontinuous way. A plant controller and batteries are additional essential components to regulate the grid and shift PV energy over time. Besides increasing quality of service and reliability, high fraction plants have considerable environmental and social benefits.

Interconnected microgrids can function under either grid-tied or autonomous mode depending on the availability of the grid. By using the appropriate electronic equipment and sophisticated control, unintentional islanding is avoided, which otherwise can provoke safety issues to the main grid. When grids are intermittent, islanding has the benefit of providing high-quality and continuous service to the user(s). In this case, the microgrid must include a controller that actively monitors spinning reserves, PV production and connected load, to dispatch PV generation when it exceeds the loads to avoid safety issues and grid instability. The available technical documentation is limited to specifications of the individual components and some technical guidelines considering the integrated solution. Two relevant standards regarding the interconnection and interoperability are the IEEE 1547 and the IEEE 2030.

Components and Functionalities

Gensets: Gensets can be characterised in various ways. Based on the design of the PV-hybrid plant the genset can: operate in case of “emergency” and charge the batteries when there is insufficient solar production; or offer a “complementary share to the energy mix” and occasionally shut down or, lastly be a source of “prime power supply” where gensets are the main energy source and PV act as a fuel-saving contributor. Depending on the genset’s rotation speed, constant or variable speed, which are typically smaller, more efficient and less polluting when supplying variable loads.

Gensets are sub-divided into four ratings, depending on the hours of duty and the output power:

Table T2: Main characteristics of genset ratings (source: ISO 8525-1)

	ESP	LTP	PRP	COP
Maximum Usage	200 h/year	500 h/year (300 h continuous)	Continuous	Continuous
Average Output Power (24 h)	70% rated power	70% rated power	70% rated power	80% – 100% rated power
Overload Availability	No	No	No	No
Ability to Operate in Parallel Applications	No	No	Yes	Yes

In any case, when designing a PV-hybrid plant, the genset or the storage technologies (electrochemical and mechanical) should provide the sufficient spinning reserve in autonomous mode and assure the supply of loads at any time.

Storage: The most mature electrochemical (battery) technologies are lead-acid, lithium-ion, flow, nickel- and sodium-based ones. Lithium-ion batteries are the most suitable for short period usage since they can efficiently discharge in the range of seconds and require a simpler recharging process than lead-acid ones. Flow batteries can also fully discharge and have a low self-discharge rate. In order to maximise the useable energy and lifetime of the battery, it is important to perform the cycling procedure within the recommended currents and to respect voltage thresholds and temperature ranges specified by the manufacturers. Moreover, batteries should be properly handled prior to installation and always stored under the recommended conditions. The following table summarises all storage-specific indicators for the four technologies described herewith.

Table T3: Comparative table of batteries' performance characteristics (ARE, 2013; IRENA, 2012)

	Deep cycle Lead-acid	Lithium-ion	Nickel-based	Sodium-based	Flow
Energy Density (Wh/kg)	25 – 50	150 – 200	20 – 80	120 – 140	-
Energy Efficiency	> 85%	> 95%	> 90%	95%	65% - 85%
Cycle Life (cycles)	2,000	5,000	3,000	4,500	1,500 – 15,000
Calendar Life (years)	> 20	> 20	25	> 10	> 10
Depth of Discharge (Practical Capacity)	80%	80%	N/A	80%	100%
Operating Temperatures (°C)	-30 to +50	-40 to +75	-40 to +60	-30 to +60	0 to +40

PV Modules: The most popular PV material is single-crystalline (c-Si) or multi-crystalline (multi-Si) silicon and such modules have reached efficiencies up to 20%. Other technologies with substantial market shares are the thin film cadmium-based modules that reveal good performance in sites with diffused radiation and high temperatures. The most important technical characteristics of PV modules are represented in a current-voltage curve.

Conversion: Conversion devices include DC-to-DC charge controllers, AC/DC rectifiers and DC/AC inverters (grid-following, grid-forming and dual-mode). Dual mode inverters operate as grid-forming inverters when the main grid is down and grid-following inverters during normal functioning of the main grid. During autonomous operation, the inverter is a back-up solution feeding the loads from an alternative source such as batteries. Once the grid is restored and its parameters return to their nominal values, the dual mode inverter becomes a current source. The dual mode inverters in the market can operate in different modes such as peak-shaving, provide reactive power and ensure feeding of critical loads. Figure A3 and Figure A4 show two inverters from different manufacturers with distinct product architecture.

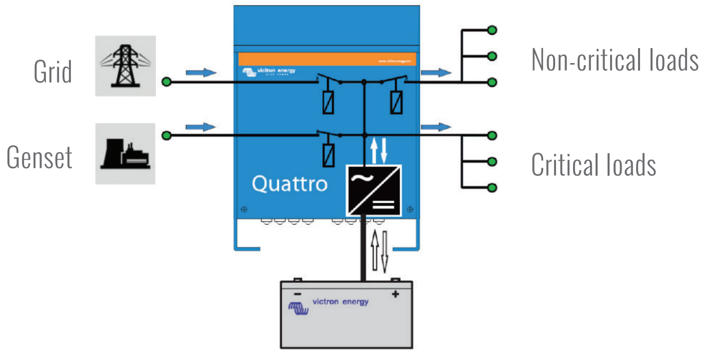

Figure A3: Dual mode inverter with internal ATS (source: Victron Energy)

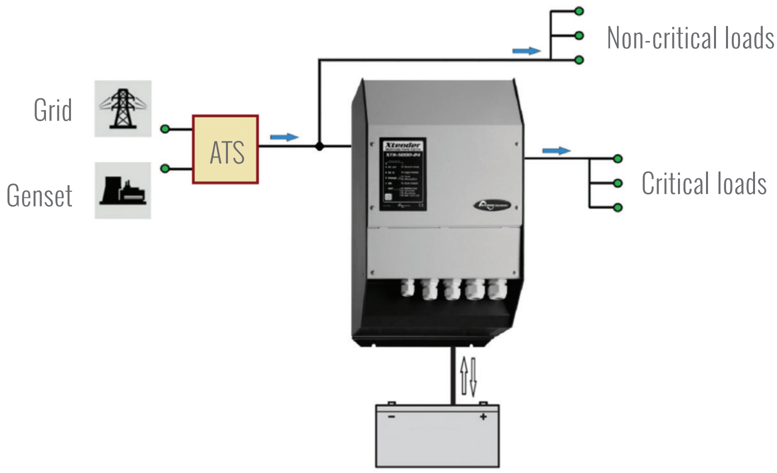

Figure A4: Dual mode inverter with external ATS (source: Studer Innotec)

PV Plant Control Unit: It is the power plant's brain and may have multiple objectives that are summarised in the table below. In addition to the control functionality, the controller may include a module for monitoring and supervision that collects data from the generation units, meteorological sensors, the loads and other equipment that display it, calculate performance indicators, generate alarms, and create databases and periodical reports.

Table T4: Main functionalities of the controller (Velasco Quesada, et al., 2015)

Objective	Description
Management of Critical Loads	The inverters have an outlet dedicated to connect the critical loads and are fed either by the batteries or directly from the genset.
Peak Shaving (or "Power Assist" or "Smart Boost")	Externally set the current limit of the inverter AC inlet once during installation; alternatively the limit can be variable in real time. The difference between the loads and the limited power from the AC inlet is provided by the battery or another current source.
Fuel Saving	When the grid is formed by the genset (e.g. during a blackout) the PV generator is limited in order to offset fuel consumption and meanwhile accounting for the operational limitations of the genset.
Management of Spinning Reserve	The disconnection of the genset(s) is always considering the spinning reserve in the grid, i.e. the operating genset(s) must be able to provide a sudden load rise by 15%-20% and a simultaneous drop from the PV generator of 60%-80%.
AC Bus Voltage Regulation	The voltage of the AC power injected into the grid is between specific set points.

Other Plant Steps

Construction: The construction of the power plant is based on the drawings and the technical specifications which constitute the final step of the design. The installation of electronic equipment is done according to the manufacturer's manual in terms of protection codes while the batteries are placed in a dry, ventilated environment. All power plant components should be easily accessible for maintenance and repair. The sensors should be located as indicated in the following table:

Table T5. Location of sensors

Sensor	Location
Solar Radiation	In the inclination plane of the PV modules
PV Panel Temperature	Below PV panel
Ambient Temperature	Outdoors, in a shaded site
Battery Temperature	Between battery arrays, attaching a battery cell

Commissioning: follows construction and the procedure should be standardised as of the norm IEC 62446. After the successful completion of commissioning, the engineer should hand in various documents such as the single line diagram, information about the PV array, earthing and overvoltage protection devices, and then, finally, hand over the plant.

Operation and Maintenance: The technical staff and the operator of the plant should be properly trained in order to understand and interpret the plant indicators and report in order to verify the correct functioning of the plant, prevent issues and correct them where needed. Such indicators include the performance ratio, autarky factor, SOC of the batteries, but also environmental ones like CO_2 emissions. The O&M plan must always be adapted to the specific plant and site, and should be prepared by or with the assistance of qualified professionals. It should include tasks organised by components and frequency of execution (at all times, weekly, monthly, trimestral, bi-annual and annual).

Table of Contents

List of Figures

List of Tables

Table of Acronyms

AC	Alternating Current
ATS	Automatic Transfer Switch
BMS	Battery Management System
CAPEX	Capital Expenses
DC	Direct Current
DG	Distributed Generation
DOD	Depth of Discharge
EMS	Energy Management System
Genset	Generator Set
GHG	Greenhouse Gases
ICT	Information and Communication Technology
IRR	Internal Rate of Return
KPIs	Key Performance Indicators
LNG	Liquefied Natural Gas
M&E	Monitoring and Evaluation
NEF	Night Energy Factor
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
O&M	Operation and Maintenance
OPEX	Operational Expenses
PR	Performance Ratio
PSH	Peak Sun Hours
PV	Photovoltaic
SCADA	Supervisory Control and Data Acquisition
SOC	State of Charge
STC	Standard Test Conditions (applied to PV cells)
UNDP	United Nations Development Programme
UPC	Universitat Politècnica de Catalunya
UPS	Uninterruptible Power Supply

1. Introduction

The United Nations Development Programme (UNDP), in partnership with the Ministry of Energy and Water, has initiated the fourth phase of the CEDRO (Community Energy Efficiency and Renewable Energy Demonstration Project for Lebanon) Programme funded by the European Union. The CEDRO IV project includes several sustainable energy sub-projects that are designed to promote renewable energy and energy efficiency technologies.

Within the EU – funded CEDRO IV project, there have been several renewable energy and energy efficiency tasks implemented in the private sector in collaboration with the public sector, in order to assist in achieving the 12 per cent renewable energy and energy efficiency targets of the Government of Lebanon and the Ministry of Energy and Water. One of the activities, Task 4, includes capacity building for the selected beneficiaries, various stakeholders and expert groups. The CEDRO IV project features, among others, the implementation of five low and medium fraction PV-hybrid pilot power plants in Lebanon with installed PV capacities ranging from 130 kWp to 300 kWp and with sophisticated control in some cases. Moreover, UNDP supports the design and implementation of four additional PV-hybrid plants in Lebanon within the EU funded MED-Solar project. This guide is partially based on this experience and the feedback obtained during the workshops and events held during the project.

PV-hybrid power plants are a reliable energy source, alternative to fossil fuel generators that are used during the national grid's frequent blackouts. Blackouts happen daily and reach up to 13 hours in some areas of the country. Moreover, the PV sector is fast approaching its maturity level in Lebanon, with many active and experienced companies, organisations and institutions designing and developing PV projects. During recent decades, the photovoltaic sector's know-how has peaked making solar energy a commercially mature option and good solution to the country's fragile energy supply.

The present document aims to provide guidelines regarding the innovative solution proposed for increasing the quality and reliability of the Lebanese grid which is the hybridisation of the grid with solar energy. New concepts have been further discussed such as the advanced PV plant controllers that aim to manage the different components of a PV plant, ensuring its operation at its most optimum set points. Additionally, the controllers' advanced algorithms allow the plants to be flexible in the sense that their objectives and functionalities are not fixed but, instead, vary according to different variables such as the presence or absence of the grid, meteorological conditions or energy demand, to name a few.

This report aims to become a practical guide for practitioners and developers of PV-hybrid power plants.

2. Overview of PV-hybrid Power Plants

2.1. General Principles and Classification

PV-hybrid power plants are electrical generation systems consisting of centralised or distributed generation units of solar photovoltaic and fossil fuel gensets, electronic solid-state conversion equipment, controller, loads, a distribution line and, sometimes, energy storage. The interconnected units are also referred to as microgrids[1] in literature and can either be interconnected to the main grid or autonomous operating in island mode, providing electricity to a single user or many. Their common feature is, nevertheless, that most of the electricity is generated and consumed within the microgrid.

Furthermore, depending on their complexity, their capacity and the level of service they seek to provide, they often include a Supervisory Control and Data Acquisition System (SCADA) and advanced computing algorithms to control the energy production. In this case, they are called smart microgrids.

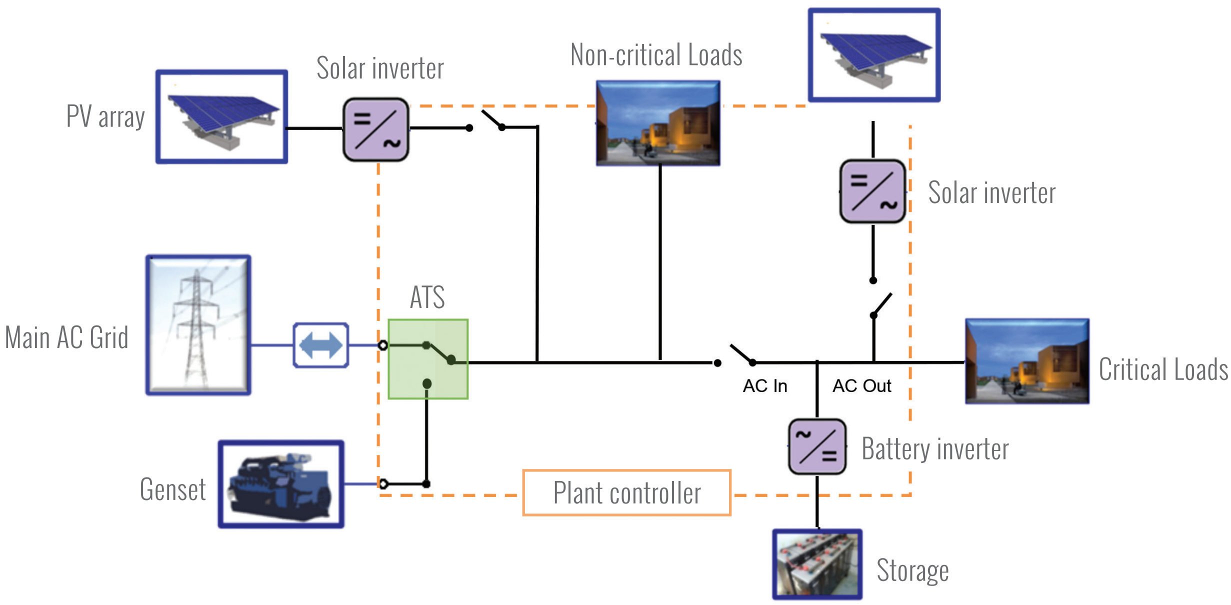

Figure 1: Architecture of a grid and genset inter-connectable PV plant

A qualitative distinction of microgrids can be done in various ways depending on their load power capacity, architecture, interconnection bus and renewable energy fraction, etc. For instance, Lilienthal (Lilienthal, 2013) suggests microgrid categorisation according to their capacity and whether they are connected to a reliable or intermittent/unreliable grid or not, as shown in Figure 6. According to this categorisation, Type 1 includes critical loads such as health clinics that need reliable and uninterruptible services. Type 2 are microgrids connected to unreliable grids; in this case, renewable energy technologies are used in order to replace or offset fuel consumption that is otherwise feeding the loads during blackouts. Type 3 includes large, isolated microgrids that allow multiple generation in parallel without a defined limit of installed capacity while Type 4 are smaller scale microgrids, usually with fewer energy sources (Walker, 2014). The present guidelines focus on the Type 2 microgrids, where a PV generator is behind the metre and hybridises both the main grid when it is energised and the fossil fuel gensets during blackouts.

[1] *Instead of "microgrids", some experts also use the term "mini-grids" but in this report the term "microgrid" will be used.*

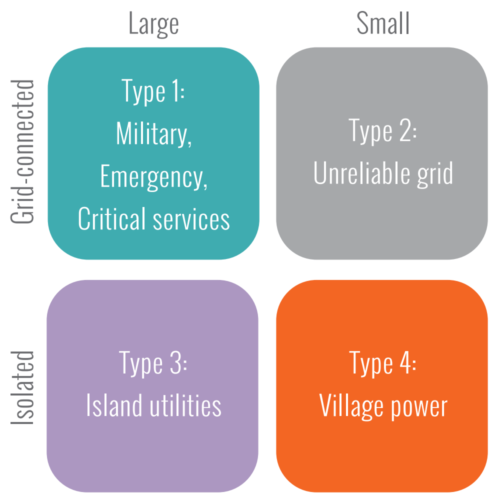

Figure 2: Microgrid classification (source: HOMER Energy)

From the design and operation point of view, the most relevant categorisation is done according to the level of solar energy generation (or other renewable energy technology) of the microgrid (see Table 1). When combining PV generation, grid supply and fossil fuel genset for example, the fraction of solar energy generated with respect to the total (a.k.a. PV fraction) can be low, medium or high. This categorisation also has implications on the requirements on the control and technological complexity needed in each case in order to ensure reliability and performance.

Table 1: Solar PV fraction in PV-hybrid power plants

Category	Indicative PV Annual Energy Fraction	Indicative PV Rated Capacity/ Load Ratio	Attributes
Low	< 20%	< 50%	• Genset(s) always on during duty cycle • Little or no PV curtailment • No supervisory controller needed • Low fuel reduction • Low capital costs and high internal rate of return (IRR) • No impact: low environmental benefits and low savings
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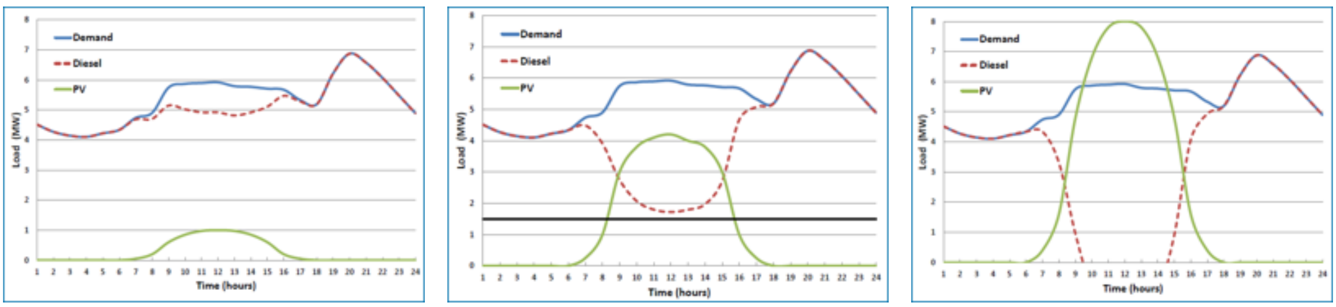
	Autonomous > 80%		• Genset as backup/emergency • Requires sophisticated controller for grid regulation and control of electronic components • Requires batteries for PV energy time shifting • High CAPEX, low OPEX • High benefits

The rate of the renewable energy fraction has a great impact on the final solution selected in technical, economic and environmental aspects. Low solar fraction hybrid power plants require that the genset or the main grid run constantly and a simple control is needed; solution similar to classical grid-tied PV power plants (see Figure 3-a). The grid is formed by the genset that is always on and the PV generator offsets fossil fuel consumption during sunny hours. The genset operates within its acceptable capacity range. Those plants have a high return on investment but a low impact.

Medium class PV fraction plants have a higher technical complexity and, therefore, bare higher investment costs and need more sophisticated control. A particularity worth taking into account is the frequency and voltage regulation in addition to that genset(s) work within their optimum power range points[2].

In high solar energy fraction plants, the genset or main grid can be used in a discontinuous way (see chapter 3.2 for genset functionalities) with sophisticated equipment to control and dispatch energy sources and loads, remotely monitor the plant, etc. A plant controller and batteries are additional essential components. The genset can occasionally shut off while solar generation and storage feed the loads. In this case, the AC grid is formed by the battery inverter (also called dual-mode, grid-forming or voltage source inverter) by setting the voltage and frequency (see Figure 3-c). Besides increasing quality of service and reliability, high fraction plants have considerable environmental and social benefits including significant mitigation of greenhouse gases (GHG), fossil fuel independency, energy security and reliability.



(a) (b) (c)

Figure 3: Simulation of a low (a), medium (b) and high class (c) fraction levels of PV (source: UPC)

[2] *The minimum recommended part load of the genset varies amongst the manufacturers and should be verified during project design.*

2.2. *Current Status of PV Hybrids*

Even though solar energy technologies are considered to be a mature sector with many active and experienced companies in the field, the concept of PV-hybrid plants for intermittent grids is new and at the beginning of its learning curve. At the moment, there are many PV-hybrid pilot projects implemented worldwide, testing state-of-the-art technologies and innovative functionalities and demonstrating their key benefits. The initial costs are still high and often shared amongst the private investors and national or international agencies offering market incentives in the form of subsidies, rebates or loans. Nevertheless capital expenses are falling and their associated marginal O&M costs of hybridising the internal grid with solar are very low. Before the design of a project, it is recommended to conduct a preliminary study and evaluate the benefits of the plant, simulate the plant and calculate relevant key performance indicators (KPIs), technical, economic and environmental. A sample of such a feasibility study can be found in Annex 1.

For the time being, the technical documentation regarding PV-hybrid plants as integral solutions is limited to some technical guidelines. There are some standards published by IEEE, IEC and German organisations VDE and DIN about solar energy projects in general, PV cells, modules and generators, electricity converters, batteries, project planning, safety and implementation (see Annex 2 for a reference list). Furthermore, there are some guidelines dealing with the interconnection and interoperability of PV-genset-grid hybrid plants. Each project developer should establish the applicable standards and engineering criteria to be fulfilled.

The IEEE 1547-series "Standard for Interconnecting Distributed Resources with Electric Power Systems" provides, amongst others, performance, operation and safety standards when interconnecting distributed generation (DG) to the utility grid. In the context of smart grids with two way energy flows, intelligent information and communication technology (ICT) and energy management and controlling systems, the IEEE 2030 provides definitions and guidelines for the interoperability of DG and the end-users' loads. According to this standard, interoperability is defined as "the capability of two or more networks, systems, devices, applications, or components to externally exchange and readily use information securely & effectively." Figure 8 illustrates the relations amongst the three concepts that define and enable the smart grid through interoperability: electric power, communications and information.

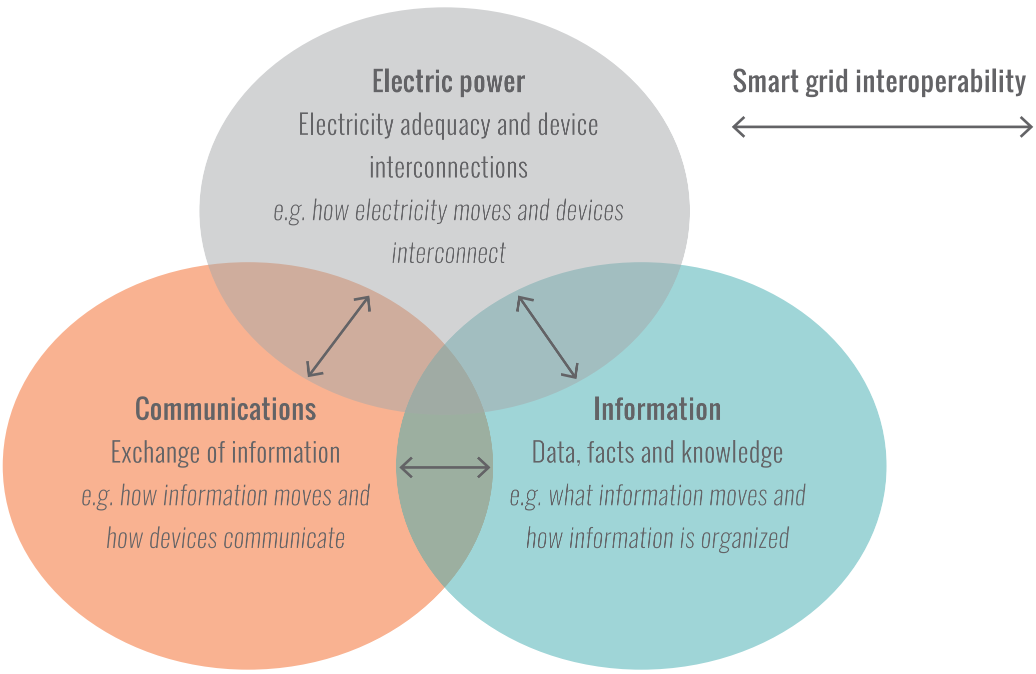


Figure 4: Relations amongst electric power, communications and information in the smart grid (Basso, 2014)

3. Components of PV-hybrid Microgrids

3.1. Main Electrical Distribution Grid

3.1.1. Characterisation and the Case of Lebanon

Electrical distribution grids have different levels of reliability and can be characterised as either strong/stiff or weak. "Weak" is the grid with large source impedance and unstable voltage levels compared to the standardised values. One indicator of the weakness of the grid is the inertia constant which determines the ability of the grid to control the voltage and frequency levels (San Martin, et al., 2015). Furthermore, the lowest the voltage range within which the grid operates, the weakest the grid and the lowest the short-circuit power is. Normally when solar energy is injected into the main grid, the grid voltage rises whereas when there is a deficit of generation, the grid voltage drops.

In the case of Lebanon, the national grid infrastructure was significantly damaged during the civil war and it has yet to be completely recuperated and adjusted to growing demand and requirements. Given the fact that electricity demand is higher than production, scheduled load shedding blackouts are frequent and in some occasions can reach 13 hours per day and they are expected to increase (Fardoun, et al., 2012); the daily average of blackouts is 5.2 hours. During these periods, electricity is mainly supplied by individual or neighbourhood diesel gensets or in cases such as Jbeil (EDJ) and Zahle (EDZ) concessions have their own centralized generators and supply power to their subscribers during blackouts.

3.1.2. Interconnection of Renewables to the Main Grid

In order to increase the reliability of the grid and make it stiffer, Bindner (Bindner, 1999) proposes grid reinforcement or integration of renewables with storage and control strategies. Such strategies include voltage peak limitation, maintenance of voltage levels between permitted ranges and control of the power of the renewable energy fed into the grid.

Interconnecting solar power plants behind the metre can mitigate issues regarding the quality of supply and enhance energy security for the grid's clients especially when the consumer load coincides with solar energy production. When the grid is intermittent and fossil fuel gensets operate during power outages, electricity produced by the PV generator offsets fossil fuel consumption when the gensets are on. Additionally, in high fraction PV-hybridisation, any surplus power not consumed directly by the consumer can offset the electricity demand from the main grid through a net-metering arrangement with the utility provider.

Interconnected microgrids can operate under either grid-tied or autonomous mode, depending on the availability of the grid. Unintentional islanding could cause safety issues to the main grid, but unintentional islanding is easily avoided by incorporating anti-island functionalities to the plant's design. This protection is usually embedded in the inverters. When grids are intermittent, intentional islanding has the benefit of providing high quality, continuous service to the user(s). In this case, the microgrid must include control functions to maintain grid stability and curtail PV generation when it exceeds the loads.

Interconnection of the PV generator can be done in both low and medium voltage grids, depending on the capacity size and the location of the site. The transmission grid in Lebanon consists of high-voltage lines of 66 kV, 150 kV and 220 kV; the distribution grid consists of medium-voltage lines of 5.5 kV, 11 kV, 15 kV, 20 kV and 33 kV and finally the low voltage grid is 380/220 V at 50 Hz.

A further feature in PV-hybrid plants is the interconnection bus bar of the main components which can either DC, AC or mixed AC/DC. DC bus is often preferred by designers in high solar fraction plants with storage when the load profile peaks at evening or night times and solar energy production does not coincide with electricity consumption. On the contrary, it is more common to use an AC-coupled concept with distributed generation, daytime load profiles or low and medium solar fraction. The mixed AC/DC configuration, where PV generators are coupled in both AC and DC bus, may be a good alternative that compensates for the drawbacks of both other options.

Figure 5 is a generic illustration of hybrid power plants. In case (a) the DC output of PV generators is coupled with the DC bus bar through a PV charge controller (typically MPPT); other generators are also coupled with the DC bus using power converters. In the case of a DC bus, energy is either stored or fed into the loads through a dual mode inverter. AC coupling is done by converting the DC solar energy to AC through a solar (or grid) inverter (case (b)), whereas case (c) is a combination of (a) and (b) of Figure 2.

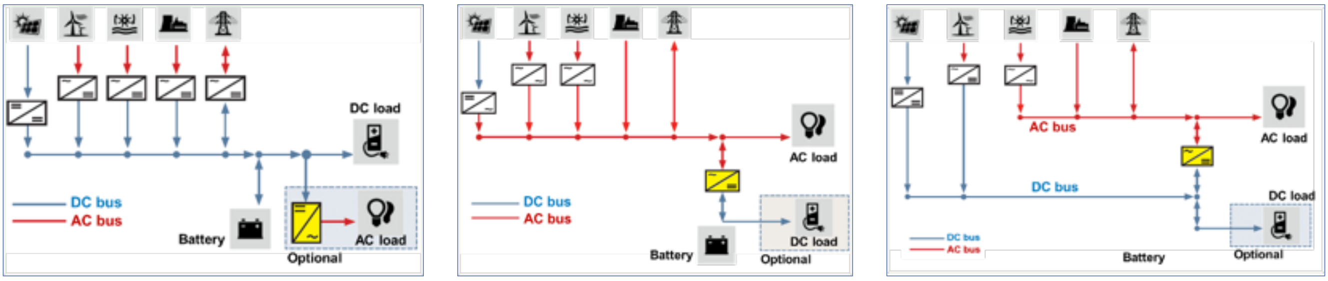


Figure 5 : Configurations with a DC (a), AC (b) or mixed AC/DC (c) coupling (source: UPC)

3.2. Fossil Fuel Generator Sets

Generator sets (or gensets) fuelled by diesel, gasoline, bio-diesel, natural gas, etc., in a single unit configuration or several in parallel, supply AC electrical power. When characterising gensets, three types of classifications can be made:

1) Type of Role/Duty of the Genset in the Microgrid:
Gensets have three main roles when functioning in a microgrid concept: "emergency" when the genset is to occasionally support the charging step of the battery in case there is insufficient solar production (for high solar fraction microgrid); "complementary share to the energy mix" (for medium fraction class) where they are not operating continuously; and "prime power supply" where PV acts as a fuel-saving contributor and gensets are the main energy source (for medium and low fraction microgrids).

2) Operating Regime of the Genset:
Gensets have four ratings:

- Emergency Standby Power (ESP):
- Limited Time Running Power (LTP)
- Prime Running Power (PRP)
- Continuous Operating Power (COP)

According to the standard ISO 8528-1:2005, "PRP is the maximum power that a generating set is capable of delivering continuously while supplying a variable electrical load when operated for an unlimited number of hours per year." When sizing the genset, it should be taken into consideration that the average power output of the genset should be below 70% of the PRP. Under the ESP mode, the genset delivers high power for limited hours per year. The main characteristics of those ratings for gensets are summarised in the Table 2:

Table 2: Main characteristics of genset ratings (source: ISO 8525-1)

	ESP	LTP	PRP	COP
Maximum Usage	200 h/year	500 h/year (300 h continuous)	Continuous	Continuous
Average Output Power (24 h)	70% rated power	70% rated power	70% rated power	80% – 100% rated power
Overload Availability	No	No	No	No
Ability to Operate in Parallel Applications	No	No	Yes	Yes

3) Rotation Speed:
Another classification of gensets can be done according to their rotational speed. There are constant speed gensets (from 500 rpm the low speed ones to 3,000 rpm the high speed ones, to produce a constant 50 Hz grid frequency) and variable speed gensets that operate from 800 rpm to 3,200 rpm for 50 Hz grid frequency. There are also variable speed gensets with DC outputs that can be coupled with the DC bus bar. In variable speed gensets, the engine speed is controlled and an electronic power converter adjusts and stabilises the electrical output parameters. The engines are smaller than those in constant speed gensets and more suitable for smaller hybridisation applications since they can supply low loads or variable loads more efficiently than the constant speed gensets. Moreover, running on low speeds prolongs their lifetime and reduces emissions (Nayar, 2010).

In applications where high reliability is needed (low risk of temporary disconnection), the plant's control strategy has to constantly account for the spinning reserve, or the "unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power" (Rebours & Kirschen, 2005). When in autonomous mode, the PV-hybrid plant should be capable of feeding the loads at any time, even in extreme cases where there is a sudden drop of PV generation (e.g. from a sudden cloud, or temporary disconnection) or a surge of demand or both.

There are two strategies in order to account for the spinning reserve: have the genset(s) on constantly at relatively low load or add storage, such as batteries or mechanical storage (flywheels). In order to choose the optimum option, it is recommended to compare the operating cost of the wasted fuel versus the investment cost of storage.

3.3. Electrical Energy Storage (EES)

3.3.1. Applications
Electricity storage can serve a large variety of renewable energy applications according to the technology, size and operating conditions. Its functionalities include PV energy time shifting, peak shaving, PV ramp rate control, energy backup, grid stabilisation and voltage/frequency regulation. Table 3 summarises the functionalities of the storage systems for renewable-based applications and their running times:

Table 3: EES functionalities for renewable-based applications (adapted from (Fuchs, et al., 2012))

Duration of Power Supply	"Seconds to minutes" < 0.25 h	"Daily" 1 h - 10 h	"Weekly to monthly" 50 h - 500 h
Applications	• Primary/Secondary frequency control • Spinning reserve • Voltage control • Black start capability • Peak shaving • Island grids • Uninterruptible power supply	• Tertiary frequency control • Standing reserve • Load levelling • Island grids • Residential storage systems • Uninterruptible power supply	• Storage for "dark calm" periods • Island grids

There are various energy storage options like flywheels, pumped hydro, compressed air, power-to-gas or hydrogen, however the focus of the present guidelines is on electrochemical storage technologies (batteries) which are frequently used in interconnected solar-based hybrid plants. The most widely used technology is lead-acid, but alternatively lithium-ion and flow batteries, nickel and sodium-based are also used. From those, lead-acid batteries, either flooded or valve-regulated ones, dominate the market of solar applications due to their robustness and deep cycling applications. Lithium-ion, on the other hand, are most suitable for short period applications like peak shaving, since they can efficiently discharge in a range of seconds. Additionally, lithium-ion batteries have a more simple recharging process than lead-acid ones that require a multi-phase charging process. Flow batteries, the most popular of which are the vanadium redox ones, can also fully discharge without a negative effect on their lifetime and have a low self-discharge rate; however, they have lower efficiencies than lithium-ion. The following table summarises all storage-specific indicators for the four technologies described herewith.

Table 4: Comparative table of batteries' performance characteristics (ARE, 2013; IRENA, 2012)

	Deep cycle Lead-acid	Lithium-ion	Nickel-based	Sodium-based	Flow
Energy Density (Wh/kg)	25 - 50	150 - 200	20 - 80	120 - 140	-
Energy Efficiency	> 85%	> 95%	> 90%	95%	65% - 85%
Cycle Life (cycles)	2,000	5,000	3,000	4,500	1,500 - 15,000
Calendar Life (years)	> 20	> 20	25	> 10	> 10
Depth of Discharge (Practical Capacity)	80%	80%	N/A	80%	100%
Operating Temperatures (oC)	-30 to +50	-40 to +75	-40 to +60	-30 to +60	0 to +40

Lead-acid batteries are still the most popular technology for renewable applications and UPS's mainly because of their lower costs, simple connection to the DC bus bar, electrical safety and reliability. Nevertheless, there are many types of batteries within the lead acid family and selecting the most suited to a particular application needs careful analysis. Lithium-ion batteries are considered potential alternatives to particular applications due to their high density and longer lifespan (UNDP/CEDRO, 2013). Furthermore, their use in the automotive sector, as well as the entrance into the Li-ion market of big players may drop their prices considerably.

3.3.2. Cycling

Batteries are recharged using a charge controller which can be an independent device (in DC coupling) or integrated into the battery inverter (AC coupling). Lithium-ion batteries and some nickel-based ones require an additional integrated battery management system (BMS). In order to maximise the useable energy and lifetime of the battery, it is important to perform the cycling procedure within the recommended currents and to respect voltage thresholds and temperature ranges specified by the manufacturers. Moreover, batteries should be properly handled prior to installation and always stored under the recommended environmental and charge conditions.

For optimum performance, lead-acid batteries should operate between 10ºC and 30ºC; below or above those thresholds, their useful capacity drops according to a correction factor that is specified by the manufacturer. The following graph illustrates the effect of temperature on the depth of discharge (DOD) and on cycle life. A battery typically operating at 30ºC and discharging at 70% will have a lifetime of about 1,500 cycles. For example, in an application where the battery completes on average one cycle every two days, and assuming that it has been handled properly, it will need to be replaced after approximately eight years.

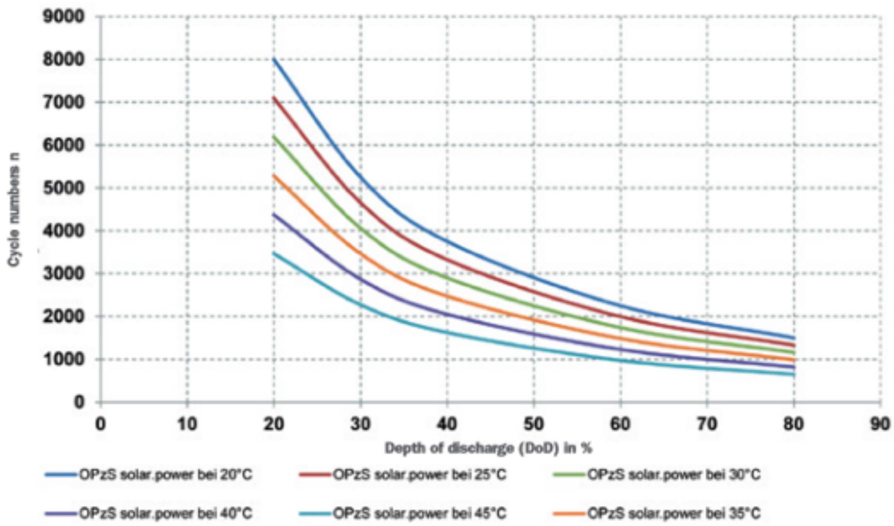


Figure 6: Lifetime of OPzS batteries (in cycles) for different temperatures and DOD levels (source: Hoppecke)

3.4. PV Modules

PV modules connected in series together with other components, like the structure and cabling, make up the PV generator that supplies DC power. PV modules are rated in watts at standard test conditions (STC) (Symbol: W_{STC} or W_P). The most popular technology is single-crystalline (c-Si) or multi-crystalline (multi-Si) silicon modules that have reached efficiencies of up to 20%. Other technologies with substantial market shares are thin film silicon modules that show good performance in sites with diffused radiation and high temperatures, and the thin film cadmium-based modules like cadmium sulphide (CdS) and cadmium telluride (CdTe).

Besides the rated STC capacity, typically from 200 up to 300 Wp per module (noting that the most commonly used ratings in Lebanon are 315 and the 320Wp), the most important technical characteristics of PV modules are their open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum power voltage (V_{MP}) and maximum power current (I_{MP}), the fill factor, temperature coefficients and efficiency (UNDP/CEDRO, 2013). Those characteristics can be represented by a current-voltage curve and power curves, as shown in Figure 7. The power is the product of the current at a given voltage and the maximum power point (MPP) happens at the voltage that gives the maximum power for a given operating temperature and incident radiation.

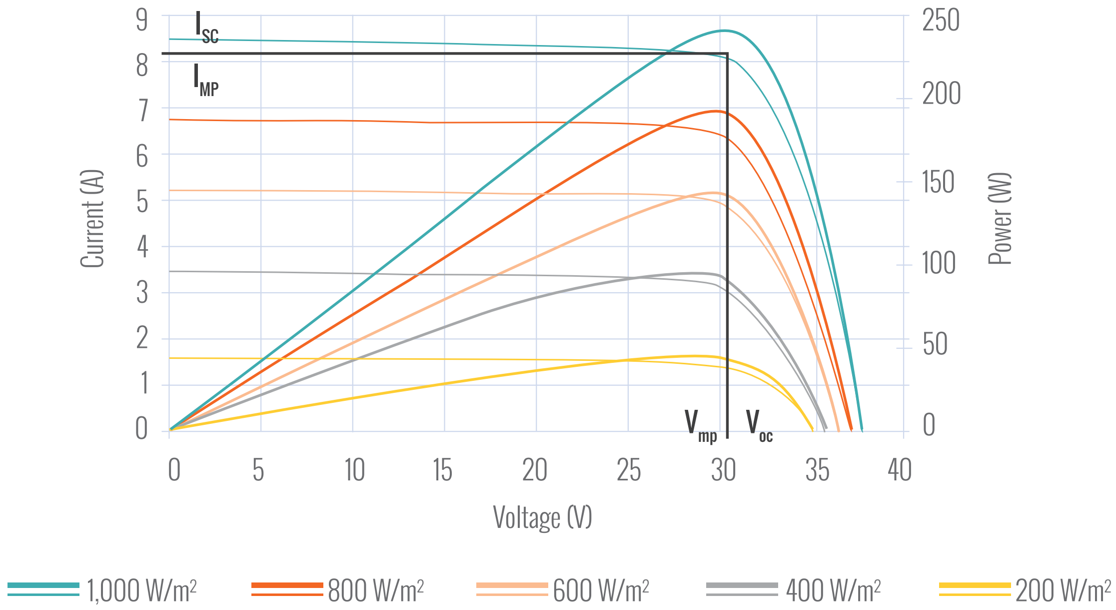


Figure 7: Combined I-V and power output curve of a 245 WP polycrystalline module at AM 1.5 and 25ºC (source: Suntech)

The temperature coefficients are used in order to correct the operating yield with respect to STC.

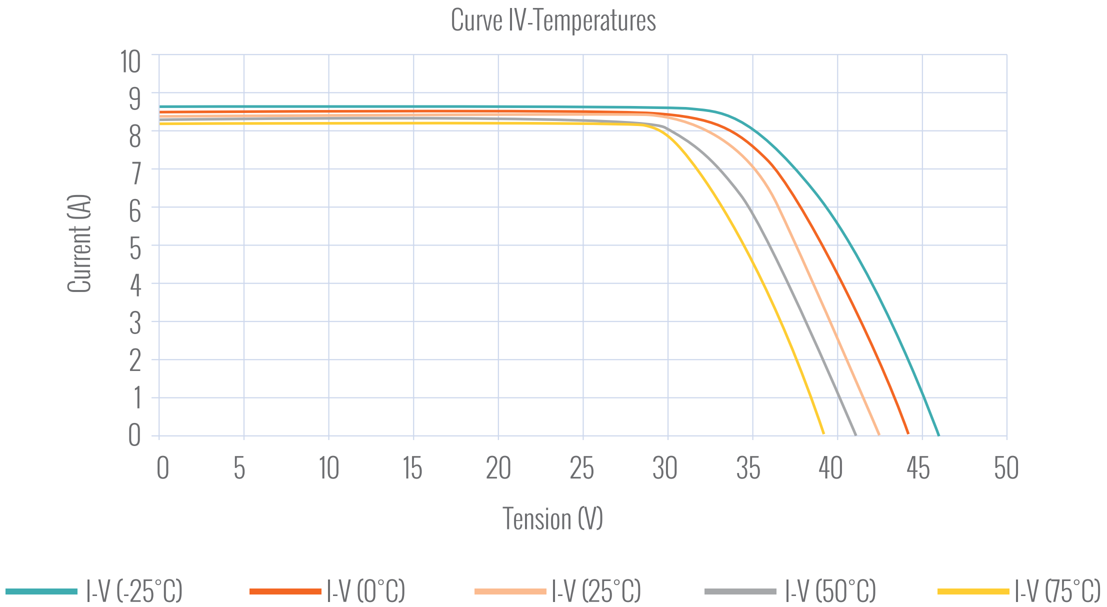


Figure 8: I-V curve for different temperatures of a 300 Wp polycrystalline module (source: Solar Innova)

3.5. Conversion

The conversion of PV electricity to forms that can be fed into other components, such as batteries, loads or the main grid, is done through different kinds of power electronics. Depending on the application, conversion devices can be DC-to-DC PV battery charge controllers, DC/AC inverters and AC/DC rectifiers. There are different types of inverters such as grid-following, grid-forming and dual-mode ones and they can be found in single-phase or three-phase configurations. Power conversion equipment has enclosure ratings that should be respected when deciding where they will be installed. For example, equipment with IP 20 should only be installed indoors, while an IP 55 or higher means that the equipment can be installed outdoors.

3.5.1. PV Charge Controllers

Battery charge controllers ensure the optimum recharge of the batteries and protect them from over discharge to achieve their expected lifetimes. In configurations where the PV generator is DC coupled to the battery, they convert and control solar power. Charge controllers are responsible for setting the recharging and discharging current and voltage. Often, they include a maximum power point tracking (MPPT) algorithm for optimum performance. For very small installations, there are simple on/off charge controllers, or controllers with pulse width modulation (PWM) technology but without an MPPT.

Battery charge controllers have an estimated lifetime of 5-10 years; maximum currents at the entrance and the exit of typical charge controllers available in the market range between 4 and 80 Amps. Charge controlling functionalities are also embedded into battery (or grid-forming) inverters for autonomous applications, known as inverter/chargers. This allows the battery to be charged from an AC source (genset or the main grid).

3.5.2. Grid-dependent Inverters

Grid-dependent (also called grid-tied, grid-following, current-source or solar) inverters convert DC current from the PV generator to AC and feed it into an AC grid. Their operation depends on another AC source, such as the main grid, a genset or a grid-forming inverter; they shut down when this AC source is down or when the grid's parameters are outside the pre-set voltage and frequency ranges. The trip time to switch off is around one second; they reconnect when grid parameters' thresholds are restored within permissible values (Vallvé, 2012).

Solar inverters also include the functionality of MPPT and more commonly now multi-MPPT which allows the connection of strings with different orientations and/or tilts to the same inverter, without affecting the overall performance of the array. Some solar inverters can integrate a transformer while others cannot. Additional functionalities include grid stabilisation (voltage and frequency) with batteries and reactive power support (Mueller-Stoffels, et al., 2013). Their efficiency is not linear but increases logarithmically until it reaches its highest values of around 98% at 30% part load. They are available in the market at capacities from a few kW to 3 MW.

3.5.3. Autonomous Inverters

Unlike grid-following inverters, autonomous (or grid-forming or voltage-source or battery) inverters create the AC grid and operate in autonomous grids or as backup for critical loads in grids when the grid fails. Moreover, the drop control function allows battery inverters the possibility to change grid frequency depending on the state of charge (SOC) of the battery and thus curtail the production of the solar (grid following) inverters.

Two important characteristics of battery inverters are their continuous power and the surge power (5 seconds) rating. Capacities of grid-forming inverters found in the market range from a few tens of watts up to 200 kW. While their output follows the loads, it is important that their efficiency level is high, especially at partial load and very low no-load self-consumption.

3.5.4. Dual mode Inverters

Dual mode inverters are a combination of the above; they can operate as grid-forming inverters (voltage source) when the main grid is down and as grid-following inverters (current source) when tied to an energised grid. During autonomous operation, the inverter is a back-up solution feeding the loads from the battery. Once the main grid's parameters return to their nominal values, the dual mode inverter synchronises and becomes a current source. When in grid-tied mode, the output of the inverter towards the loads has the same voltage and frequency values as the grid (from the main grid or gensets). The change between modes happens through a dual mode transfer relay, that can be embedded in the inverter or not and the switching time between modes is usually below 20 msec. The dual mode inverters in the market can operate in different modes such as peak shaving or critical load feeding.

In addition to the dual mode transfer relay, the configuration of a PV-hybrid plant includes an automatic transfer switch (ATS) to switch between the main grid and genset(s). The ATS can be either integrated to the dual mode inverter, which has two AC inlets (Figure 9) or outside of it when the inverter has one AC inlet (Figure 10).

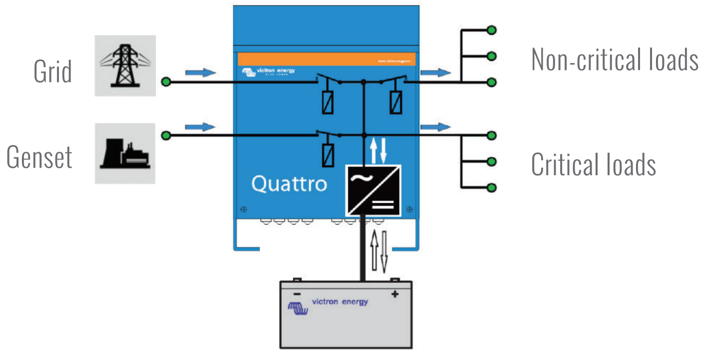


Figure 9: Dual mode inverter with internal ATS (source: Victron Energy)

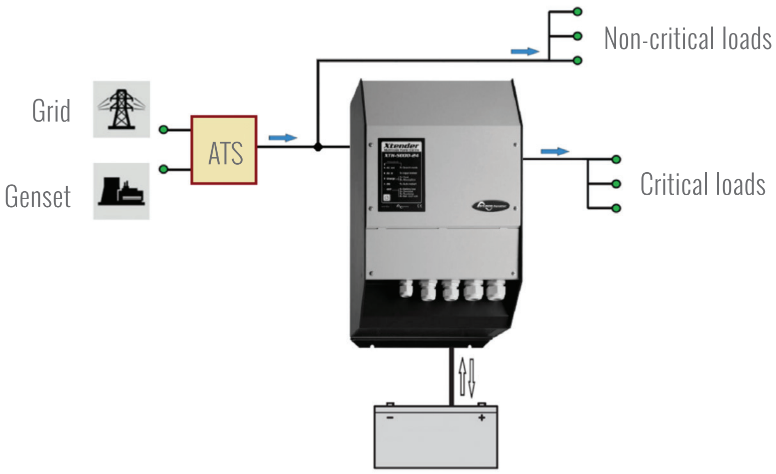


Figure 10: Dual mode inverter with external ATS (source: Studer Innotec)

3.6. PV Plant Control Unit

PV plant control units are able to make intelligent decisions in order to ensure optimum integration of renewable energy or other objectives. This is done through direct communication with solar and battery inverters, the genset and the ATS (Velasco Quesada, et al., 2015). Table 5 presents a list of the main functionalities of a PV plant controller.

Table 5: Main functionalities of the controller (Velasco Quesada, et al., 2015)

Objective	Description
Management of Critical Loads	The inverters have an outlet dedicated to connect the critical loads and are fed either by the batteries or directly from the genset.
Peak Shaving (or "Power Assist" or "Smart Boost")	Externally set the current limit of the inverter AC inlet once during installation; alternatively the limit can be variable in real time. The difference between the loads and the limited power from the AC inlet is provided by the battery or another current source.
Fuel Saving	When the grid is formed by the genset (e.g. during a blackout) the PV generator is limited in order to offset fuel consumption and meanwhile accounting for the operational limitations of the genset.
Management of Spinning Reserve	The disconnection of the genset(s) is always considering the spinning reserve in the grid, i.e. the operating genset(s) must be able to provide a sudden load rise by 15%-20% and a simultaneous drop from the PV generator of 60%-80%.
AC Bus Voltage Regulation	The voltage of the AC power injected into the grid is between specific set points.

The PV plant controllers function in a multi-level hierarchy scheme by continuously detecting failures, conducting the diagnostic and reconfiguring the parameters in real time to ensure that the objective will be met. Besides the controlling part, they may include a module for the monitoring and supervision of the power plant and its parameters. The monitoring module collects data from the generation units, the meteorological sensors, the loads and other equipment. This collected data is displayed in monitors in real time, is used as input for the calculation of performance indicators (such as the performance ratio, the solar yield and the solar fraction), generates alarms as well as creates databases and periodical reports.

Depending on the source that forms the grid in each instance (genset, main grid or the battery inverter), the PV plant controller operates under four modes, each with its own functionality:

Table 6: Operation modes of the energy management system

Mode	AC source	Functionalities
1	Main grid	• Grid power control • Grid energy control • Back feed to grid • Load management • Reactive power control • Battery charge control
2	Genset	• Diesel Power Assist • Fuel reduction • Load management • Spinning reserve management • Reactive power control • Battery charge control
3	Dual mode inverter	• Battery charge control • Load management
4	None	• Battery charge control • Load management

4. Plant Sizing and Design

This chapter presents the main considerations to be taken into account when sizing and designing a PV-hybrid plant. First of all, the main objective of hybridisation has to be defined, since this will determine the restrictions concerning the installed capacities. For example, the PV capacity of a PV generator designed for fuel saving will be different than the capacity when aiming for a high solar fraction autonomous plant.

4.1. Site and Resource Assessment

The initial step of the plant design is to evaluate that the site is adequate for the generation of solar energy and can serve the objective of the plant in terms of space availability for the PV modules and electronic equipment as well as solar resources throughout the year. To limit the technical losses, it is recommended to place the electronic equipment (battery charge controllers and inverters), the gensets and the battery into a "technical room" close to the PV generator.

Since the PV modules are rated in STC at 1 kW/m², the real in plane solar radiation is needed to estimate solar production under real climate conditions. The solar radiation received per unit area depends on the inclination of the surface; depending on the angle of the PV modules and the season of the year, the modules will produce a different yield. The daily solar radiation is symbolised by the letter H and measured in kWh/m²/day or peak sun hours (PSH).

If a ground solar radiation sensor or satellite measurements are not available, there are various alternative sources of data widely recognised for their accuracy, such as NASA, Metosat or PVGIS. PVGIS[3] gives monthly average solar radiation values for any orientation and azimuth and can be used to optimize the selected arrangement at specific site coordinates.

Table 7: Monthly solar irradiation for Beirut, at a horizontal plane, due South at the yearly optimum inclination angle, at 20⁰ and 10⁰ in Wh/m²/day, retrieved by PVGIS*

Month	H_h	H_{opt} (30o)	H (20o)	H (10o)
Jan	2,680	3,990	3,630	3,190
Feb	3,560	4,780	4,470	4,060
Mar	5,350	6,350	6,160	5,820
Apr	6,350	6,660	6,710	6,600
May	7,620	7,240	7,540	7,660
Jun	8,440	7,610	8,080	8,350
Jul	8,160	7,540	7,940	8,140
Aug	7,420	7,500	7,660	7,630
Sep	6,200	7,110	6,970	6,600
Oct	4,790	6,290	5,930	5,420
Nov	3,370	5,010	4,570	4,020
Dec	2,550	3,940	3,550	3,080
Year	**5,550**	**6,180**	**6,110**	**5,900**

* For the given example of Beirut, the parameters are: Location: 33°53'19" North, 35°29'43" East, Elevation: 95 m above sea level. Optimal inclination angle is 30⁰

[3] *http://re.jrc.ec.europa.eu/pvgis/*

Table 7 shows how annual total results of the radiation in Mediterranean countries for different angles do not have a large variation among them (from 5,900 Wh/m²/day at 10º to 6,180 Wh/m²/day at 30º). This small difference in radiation is particularly due to the latitude of the region, where the optimum angle changes throughout the year, which is revealed in Figure 11. In this example, it should be noted that if the aim were for a uniform monthly contribution rather than annual maximum, 30º or even higher may be a better option.

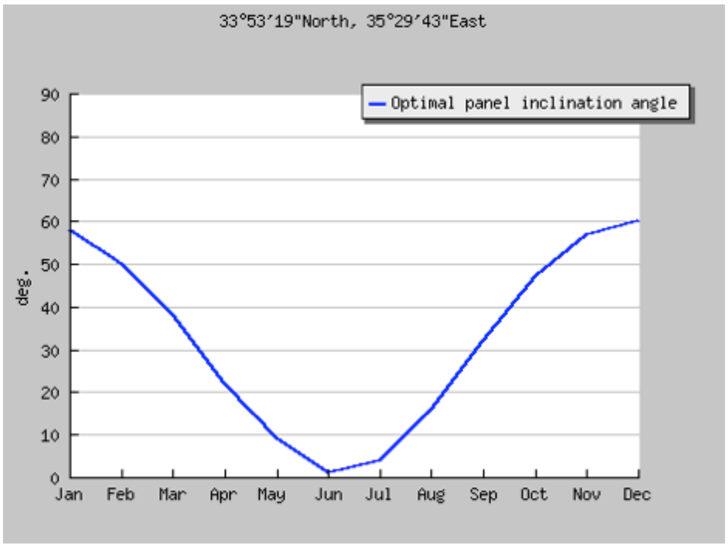


Figure 11: Optimal panel inclination angle per month for Beirut (source: PVGIS)

4.2. Shadow Analysis

In sites with limited space availability, it is very important to account for partial shading when sizing the PV generator. Shading losses should not exceed 4% per year. In order to avoid such losses, the design of multiple row PV generators should respect the pitch (d) of the modules, i.e. the distance between the two rows or an array and any obstacle of height h, as seen in Figure 12. This method guarantees a minimum of four hours of sunshine at noon during the winter solstice and the distance is calculated by the following formula:

d = h . k

Where k is a non-dimensional factor given from the equation:

k = 1/ tan (61° - latitude)

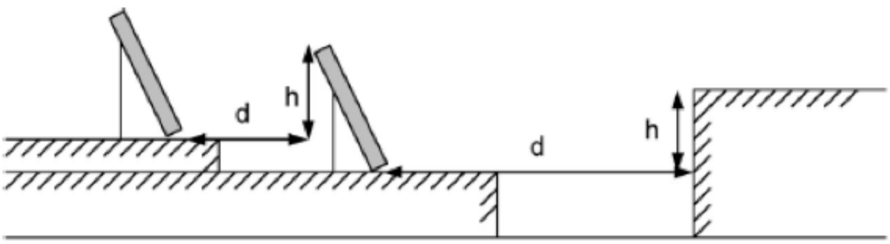


Figure 12: Variables to calculate the minimum distance between PV arrays (IDAE and CIEMAT, 2002)

4.3. *Sizing and Design of PV-hybrid Plants*

The sizing methodology of the PV generator and other components depends on various parameters such as the desired solar fraction or whether it is an autonomous unit or grid-connected. The components' capacity depends on site-specific restrictions, budget limitations and the objective of the PV hybridisation.

4.3.1. Sizing Strategies

There are general design recommendations; the optimum orientation of a PV array in the Mediterranean region throughout the year is to face south. However, the selected orientation depends on other considerations such as the consumer's load profile. For example, if the load profile peaks in the morning, the panels can be oriented towards the east. The optimal inclination angle is also relevant to the season; if the PV generator is designed to produce more energy during winter, then the panels' angle should be higher than the optimal angle for the whole year; the contrary is true if the consumption is higher in summer.

Besides the load profile and its seasonality, PV plant developers may also need to consider the solar fraction they want to achieve when selecting the installed capacity of the PV generator, its tilt and its orientation. Given the decreasing costs of PV panels, it is sometimes worth considering oversizing the PV generators and placing them at a lesser optimum angle to gain additional yield on an annual basis at the expense of losing some performance, rather than avoiding shadows all year long. For example, there are some innovative mounting designs that target maximising the occupancy of limited-space roofs, rather than producing solar energy under optimum orientation and inclination. Under such configurations, the total yield of the PV generator can be higher but always "sacrifices" the individual yield of the panel. One example is the East-West double-tilt mounting structure for panels that results in a high power density design that can be an option for flat roofs or roofs with low slopes.

In low solar fraction plants, all available PV energy is produced and consumed and there is no curtailment. The design objective should, therefore, be to maximise the PV yield by selecting the appropriate orientation. The previous chapter 4.1 shows that there is enough tolerance in selecting tilt and orientation in latitudes in Lebanon.

In grids with medium and high fraction the choice of the tilt and orientation is more complicated. Depending on the load profile of the demand, curtailment is unavoidable. Therefore, the sizing of the plant should take into account this curtailment and intend to minimise it in order to limit the costs of the plant.

4.3.2. Design Considerations per Component

Sizing the components' results in rough estimations of the capacities required, but the final design will be influenced by the available products in the market, the connection of the equipment and the site-specific climatic conditions. For example, the operating voltage is inversely proportional to the ambient temperature so high temperatures have negative effects on the yield of the PV generator. Therefore, to produce the same kWh of solar energy with a given solar radiation, the PV generator should be larger in warm sites than in colder ones.

4.3.2.1. PV generator

In a complete autonomous plant with PV, storage and a genset, the main design factor relating to the size of the plant is the daily energy demand (in kWh/day). Using a simplified method, the rated PV STC capacity (kWp) is calculated by the formula:

$$C_{PV}\,[kW_p] = \frac{\text{Solar fraction [\%] x Demand [kWh/day]}}{\text{PR} \times \text{PSH[h/day]}}$$

Solar fraction is the ratio of energy demand covered by the PV generator over the total energy demand; the PSH is the average daily radiation at the selected PV plant in the darkest month (conservative sizing method) and PR is the average performance ratio of the plant. PR is the normalised ratio of the produced solar energy to the available solar energy and depends on the overall module and plant efficiency and captured losses. In autonomous plants it is estimated at around 40% - 65% depending on whether the PV generator is oversized or not. If the generator is oversized and its production is often curtailed , then the PR is lower. As a reference, in grid-connected plants that dispatch all the production, the PR is in the range of 65% - 80%.

When considering PV-hybrid plants that are interconnected with the main grid, a distinction should be made based on the quality of the grid. If the main grid is strong where no periodic interruptions occur and there is net-metering with the utility, then the main technical considerations are the specifications of grid interconnection and the total demand at the facility.

If the main grid is intermittent and the PV system is designed to offset fuel consumption during blackouts (fuel-saving functionality with no batteries), the selection of PV capacity should respect the technical limitations imposed by the genset. For example, according to its manufacturer, if the genset's minimum part load is 30%, then the ratio of PV power to the load should not exceed 60%. This allows accounting for the spinning reserve, the operation point of the gensets within the recommended range and protecting the equipment in case of a sudden drop of demand (e.g. reverse power to the genset).

The PV generator creates DC electricity and consists of a number of PV modules connected in parallel, series or both. The set up depends on the desired current and voltage of the whole generator, in ideal cases when there is no or minimal voltage and / or current mismatch:

- When connected in parallel, the voltage of the array is equal to the voltage of the individual panels, while the current of the array is the sum of the individual currents.
- On the contrary, when the PV modules are connected in series (strings), the voltage of the generator is the sum of the voltage of the individual voltages while the total current is the current produced by one panel.

Every inverter permits a specific range of voltages coming from the PV generator. The operating voltage depends on the temperature of the modules and the estimated voltage in both the highest and lowest temperatures (usually 55ºC and 10ºC respectively) should be within this range of the inverter in order to avoid any production losses and the open circuit voltage should remain below the inverter's maximum voltage at the lowest temperature.

PV structures can be mounted on the ground or on the roofs. The PV panels are either directly attached to the structure or through rails. The structure can be anchored or ballasted and should always be able to withstand high wind velocities, the seismic activity of the site or other extreme environmental conditions.

4.3.2.2. Batteries

The battery's practical (or useful) capacity should be sufficient in order to feed at least the priority loads (or total loads depending on the application). Batteries can be directly charged by the sun, the main grid (when grid-connected), or the genset (during blackouts). The installed capacity in kAh is derived from the following formula:

$$C_{bat}\,[kAh] = \frac{\text{Demand [kWh/day] x Autonomy [days]}}{\text{U(V) x DOD}}$$

Depending on the application and the solar share, the demand to be fed by the batteries can be the priority loads, the total loads or the evening/night loads. The depth of discharge (DOD) depends on the battery technology; in lead-acid batteries, it can be up to 75%. U(V) is the operating voltage (usually 24 V or 48 V) and, finally, the autonomy depends on each project developer and the application. For backup purposes, this application is usually 2-3 days, while for grid stability, it is around 15-30 minutes.

Battery faraday capacity is given in Ah under a given discharge rate; i.e. it is the current that can be taken from the battery during a specific number of hours. The capacity rate is given for a discharge duration of 10 hours (C_{10}) or 20 hours (C_{20}). There are some empirical relationships between capacities for different discharge rates:

$C_{100}/C_{20} \approx 1.25$

$C_{40}/C_{20} \approx 1.14$

$C_{20}/C_{10} \approx 1.17$

The accurate capacity of the batteries depends on the Peukert coefficient k, which is related to the battery technology, and is derived by the following formula:

$$C_t = t \cdot I^k$$

Where t is the discharge time and I is the current. Typical ranges of the Peukert coefficient for different lead-acid battery types are:

AGM	1.05 - 1.15
Gel	1.10 - 1.25
Flooded	1.20 - 1.60

Each electrochemical cell has a nominal voltage of 2 V, following the same concept as PV modules; there should be 24 cells connected in series in order to achieve a 48 V battery.

4.3.2.3. Solar Inverters

The sizing of solar inverters is figured out through the nominal inverter-PV array power ratio:

$$\text{Power ratio} = \frac{\text{Inverter maximum input power}}{\text{PV rated capacity}}$$

This ratio is usually less than 1; for northern European zones it is approximately 0.7-0.8, whereas for Mediterranean countries is 0.9-0.95.

4.3.2.4. Battery Inverters

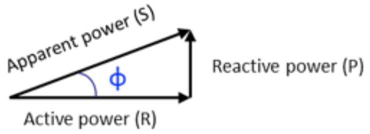
DC/AC inverters that supply loads from batteries should be designed in such a way where they can supply the demand peaks at all times. An empirical way to size an inverter from daily energy data is:

$$C_{inv}\ [kW] = k \times \text{Demand}\ [kWh/day]$$

In this formula, k is a correlation factor between the daily peak power and the energy demand of the consumer. For residential profiles, this correlation factor is around 0.2 and it increases in case the consumer has industrial loads with high nominal power.

Inverters' rated capacity is often given in VA (volt-amperes), or the real power they can supply. The relation between the real power and the active power (in kW) is defined by the power factor, a dimensionless number that takes values from -1 to 1, where 1 means that all real power is active power. The power factor is usually 0.8 to 0.9 and the deviation from 1 is due to the existence of reactive loads such as capacitors and inductors. The power factor is given by the equation:

$$PF = \cos\varphi = \frac{R}{S}$$



Other considerations when sizing and designing the inverter are:

- For a battery inverter, the operating voltage of the batteries is within the voltage range acceptable by the inverter
- It supplies the loads with similar standards to the main grid (e.g. 230 VAC and 50 Hz)
- The efficiency of an inverter drops considerably when it operates below the 10% of its nominal capacity (see Figure 13), thus, they should not be oversized.

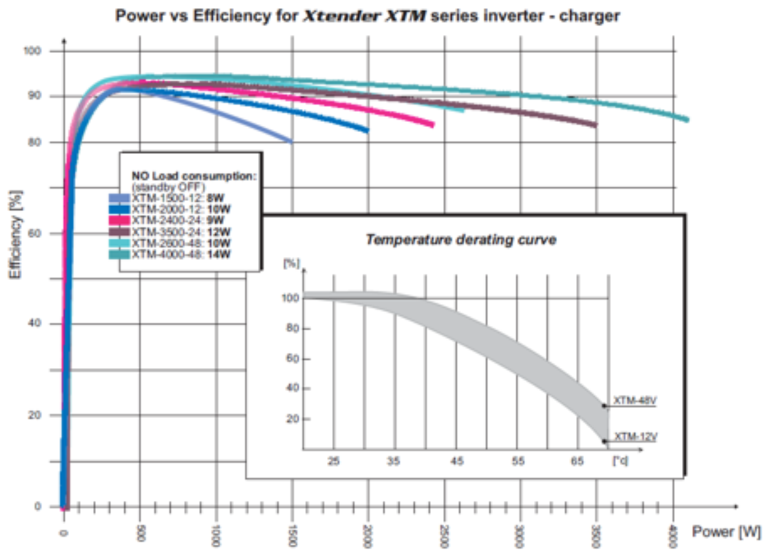


Figure 13: Efficiency derating curve of a dual mode inverter (source: Studer Innotec)

The DC/DC PV charge controller should be sized in order to absorb the maximum DC current produced by the PV generator, increased by a safety factor of 20%.

4.3.3. Wiring

The cables in a PV-hybrid plant should be able to carry the maximum current under the worst case scenario of highest temperature at full load and at steady state. Sizing of both the DC and AC wires is important in order to avoid unnecessary losses caused by voltage drops, maintain low temperatures and eliminate risks of fire and short circuits. The cable covers should be resistant to degradation by sunlight, especially when they are exposed to temperatures above 30ºC. A reference for a maximum voltage drop recommended is given in Table 8.

Table 8: Maximum voltage drop for wire sizing (UNDP/CEDRO, 2013)

Wiring	Recommended Maximum Voltage Drop (%)	Reference Power
PV modules to PV inverter	3	STC capacity
PV generator to PV charge controller	2	STC capacity
Charge controller to battery	2	STC capacity
Battery to autonomous or dual mode inverter	1	Inverter 30' rating
Autonomous or dual mode inverter to loads	5	Inverter 30' rating
Autonomous or dual mode inverter to main grid	1	Inverter rating

Some sources recommend a less flexible max voltage drop value of 1.5% both at the DC and AC sides, and this is currently being applied in DREG's demonstration projects.

The cable from the PV generator should be able to provide the 130% or 125% of the ISC depending on whether it has an overcurrent protection or not. The minimum required cross section of the cable (in mm^2), which is either made from aluminium or copper, is calculated by using the following formula:

$$S = 2 \frac{L \times I}{\sigma U}$$

L is the wiring length (in m), I the current (in A), σ the conductivity of the metal ($5.95 \times 10^7 (\Omega \cdot m)^{-1}$ for copper and $3.50 \times 10^7 (\Omega \cdot m)^{-1}$ for aluminium) and U is the voltage drop.

Table 9 gives reference magnitudes of allowed maximum currents:

Table 9: Maximum currents allowed for specific cross sections of bipolar Cu cables insulated with rubber or PVC at 27ºC (source: UPC)

S (mm^2)	I (A)	S (mm^2)	I (A)	S (mm^2)	I (A)
0.75	8	**4.0**	25	**25**	78
1.0	10.5	**6.0**	32	**35**	97
1.5	13	**10**	44	**50**	115
2.5	18	**16**	59	**70**	140

AC and DC cables have colour codes that are shown below:

Circuit	Colour	Explanation
DC	Red	Positive pole
	Black	Negative pole
AC	Black, Brown or Grey	Phases
	Blue	Neutral
	Yellow & Green	Grounding

5. Construction and Commissioning

The construction of the power plant is based on the drawings and technical specifications, which are the final step of the design. The installation of electronic equipment is done based on the manufacturer's manuals in terms of protection codes while the battery is stored in a dry, ventilated environment. All power plant components should be easily accessible to maintenance and repair, if needed.

Apart from the basic components, it is very important to place the different sensors in the appropriate place. Table 10 includes an example of the most important sensors in a PV-hybrid plant. There can be additional sensors, such as the genset-related ones that measure the lubricant temperature, oil pressure, the water temperature, etc.

Table 10: Important sensors in a PV-hybrid plant

Sensor	Location
Solar Radiation	In the plane of the PV modules
PV Module Temperature	Below PV panel
Ambient Temperature	Outdoors, in a shaded and ventilated location
Battery Temperature	Between battery cells, attached to a battery cell

Sensor measurements are used from the PV plant controller's algorithm in order to execute the different functionalities it is designed for. Besides sensors, the communications equipment should be properly installed to ensure bi-directional communication between the controller and the components of the plant.

During the installation of the PV generator, special care should be given to the grounding of the metallic structure and its solid mounting to the ground to protect the PV generator from extreme, site-specific conditions.

After the equipment is installed, a series of verification tests should be performed in order to ensure that the equipment functions are as specified and the components communicate correctly amongst them. A complete list of commissioning tests according to the standard norm IEC 62446 is provided in Annex 3.

Moreover, the engineer should provide a series of documents that include:

1. Single line diagram
2. General specifications of the PV generator arrays: module types, total number of modules, number of strings, modules per string
3. PV String information: String cable specs (size and type), string over-current protective device specs (type and voltage/current ratings)
4. PV generator electrical details: main DC cable specifications (size and type), combiner junction box locations, generator over-current protective devices
5. Earthing and overvoltage protection: details of all earth/bonding conductors (size and connection points), details of any connections to an existing lighting protection system, details of any surge protection device installed
6. AC part: AC isolator location, overcurrent protecting device (location, type and rating), residual current device (location, type and rating)

The final step is the hand over and project completion.

6. Operation & Maintenance

6.1. Indicators

The PV plant controller includes a module for monitoring that can generate informative reports. These reports can be used by the technical staff of the plant or the operator in order to verify the correct operation of the plant, prevent issues and correct them were needed. These reports may consist of graphical visualisation of the energy flow and performance indicators. Some of the most important indicators calculated over a specific time period are:

- The reference yield of the PV generator: represents the number of peak sun hours or the solar radiation that a site would receive the sun's reference irradiance G (=1 kW/m^2). is the total in-plane irradiance. The reference yield depends on the location and orientation of the PV generator.

$$Y_R = \frac{I(kWh/m^2)}{G\ (kW/m^2)}$$

- The performance ratio of the PV plant (or sub plant) accounts for all losses incurred due to capture and conversion of energy and is calculated using the following formula:

$$PR = \frac{\text{Final Yield}}{\text{Reference yield}}$$

Other indicators can include the renewable energy fraction, the autarky factor (the ratio of the energy consumption self-generated by the consumer) or environmental factors like CO_2 emissions.

Alarms can facilitate the operation. Alarms are generated when parameters or indicators are outside pre-set thresholds or to inform about the status of the grid or to communicate component-specific alerts, such as low SOC of batteries.

6.2. Common Faults

When considering photovoltaic installations, there are some faults and errors that occur frequently and can be identified by the analysis of the indicators. For example, a lower than expected performance ratio can be caused by plant conditions like, for instance, oversizing of the PV generator and, thus, frequent curtailment, excessive component losses, wrong reading of the radiation sensor or physical degradation of the panels (cracks, strains, etc). Also, it can be caused by external conditions such as instability of the main grid or the genset grid and, thus, frequent unplanned disconnections of PV generation. In general, wrong readings of the temperature and radiation sensors can cause wrong charging voltage of the batteries or MPP tracking; as a result, all sensors should be periodically revised and calibrated.

Common issues concerning the plant controller can be a failure in the remote monitoring (bad internet connection, problems with Ethernet cables, loss of signal, etc) or there might be a required reset. Another source of problems can be the initial configuration of the equipment that can cause conflicts among the equipment, therefore a revision of the variables should be done.

Other commonly occurring faults can be undersized cables that need reinforcement in order to limit the component losses or module failures like a burned junction box and bad soldering of the connectors, which can cause damage to the EVA and backsheet of PV modules[4]. A fault that appears at hydrogenated amorphous silicon modules is the Staebler-Wronski effect that can cause a 15-25% reduction in the yield over the first 1,000 hours of exposure to the sun. The light-induced degradation causes silicon-based cells to lose up to 3% of their efficiency. Other issues include panel discoloration, corrosion or delamination, which can be caused by water fraction, light decoupling or degradation of the EVA encapsulant and can cause electrical risks and an efficiency drop. As a common practice, it is recommended to consider a half to one percent of annual panel degradation when sizing the system.

6.3. Maintenance

The hybridisation of fossil fuelled plants with PV adds minor tasks to the existing maintenance procedures therefore making the additional O&M costs marginal. The maintenance of the PV-based plants can be divided amongst surveillance, preventive and supervision level. The surveillance levels consist of basic up-keeping actions to be performed by the operator's local service (technicians and keepers), such as the cleaning of the modules, removing soiling, visual inspection of components and registration of alarms and incidences. The professional maintenance staff carries out the preventive level and its purpose is to verify that the measured values and indicators are within the allowed ranges. Finally, an administrator or an evaluator who is responsible for data assessment of periodical evaluation reports with relevant indicators of the plant's performance conducts the supervision or evaluation level.

The O&M plan must always be adapted to the specific plant and site, while it should be prepared by or with the assistance of a qualified professional. It should include tasks organised by components and frequency of execution (at all times, weekly, monthly, trimestral, bi-annual and annual).

Finally, the plant should be insured from unexpected damage such as natural conditions (fire, lightning, storm, and snow), water damage and flood, short-circuits, overcurrent and overvoltage, explosion, errors during construction or installation, material errors, subsidence, landslide, rockslide, theft and vandalism, operating error and negligence. Insurance will not need to cover earthquakes, war, terrorism, nuclear accidents/radiation or radioactive substances, internal unrest, normal operational or premature wear, corrosion, existing deficiencies.

[4] *Soldering is the process of creating permanent connections among the electronic components and connectors of the modules. Poor soldering can cause high resistance, increased temperatures and permanent damages at the modules.*

7. Discussion & Conclusion

The present guidelines address various aspects related to PV-hybrid plants, autonomous and interconnected to strong or weak grids, including a universal understanding of the plants and their classification, the components and their functionalities, but also related to simplified procedures such as the sizing and design of components, the construction, commissioning, operation and maintenance of the plants.

The integration of (distributed) renewable energy in weak grids can demonstrate various benefits for the grid itself as well as the owners of the facilities. Benefits include the reduction of fossil fuel use and associated GHG emissions, the improvement of grid reliability and limitation of power outages, protection of critical loads, independence of foreign supply, and increased energy security coupled with a fixed energy cost which is immune to future tariffs' and fossil fuel costs' increases. In Lebanon more specifically, the PV-hybrid plants can match supply with demand, alleviate the consumers from high operating costs of the gensets and increase the national renewable energy share. Furthermore, obtaining a clear understanding of the renewable energy based plant, its design, operation and maintenance procedures can decrease both capital and running costs derived from oversizing, frequent replacement of components and inefficient operation.

However, besides the description of the benefits associated with the PV-hybrid plants, the argument with beneficiaries should include a series of technical and economic indicators, which can either be calculated and demonstrated in tables or visualised in graphs. As common practice, prior to the detailed project design, a feasibility study is conducted that includes the indicators and simulation results, among others.

Additional information about PV-hybrid plants for the technical staff can be found in:

- Basso, T., 2014. IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability with the Electrical Grid, s.l.: NREL.
- CEDRO, 2016. Guidelines on Net Metering, s.l.: UNDP/CEDRO
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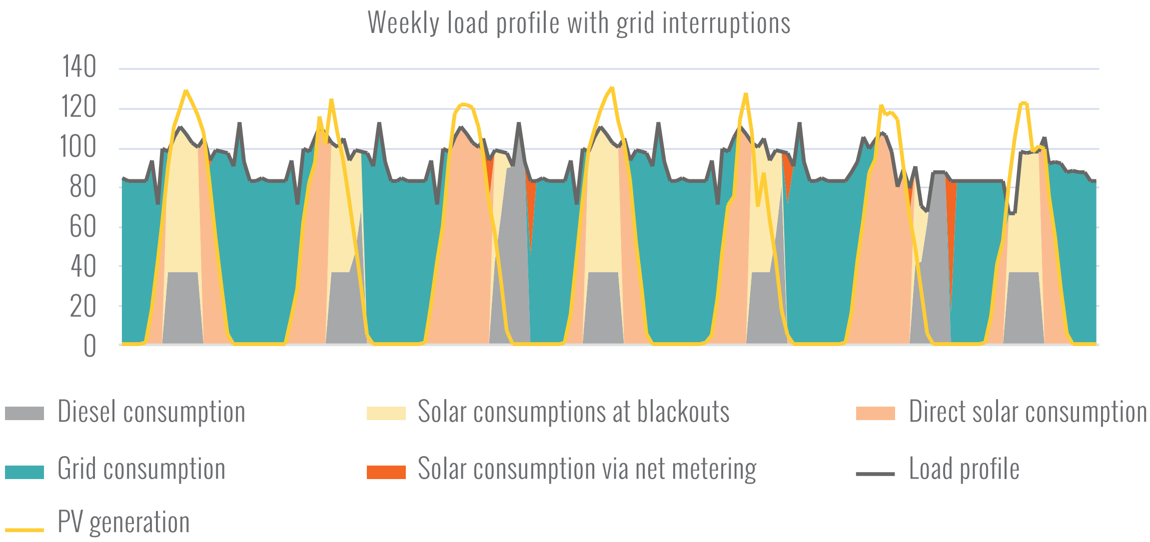
Available at: http://microgridnews.com/microgrid-categories-quality-standards-training-capacity-building/
[Accessed 14 January 2016].

Annex 1 – Sample of a Feasibility Study

The present sample is based on a detailed study conducted for a factory in Lebanon. Its objective is to assess the impact of a proposed PV-hybrid plant connected to the internal grid of the facility and to explore the sensitivity of partial subsidies to the investment costs. This case consists of a PV generator, diesel genset(s) and the main intermittent grid. During normal functioning of the national grid, the PV plant offsets part of the demand and, in the case of instantaneous surplus, exploits the net-metering scheme by injecting to the grid all excess electricity that is not directly consumed by the loads. This electricity is credited to be consumed when solar production is low or demand is high without any extra charges. During national grid blackouts the PV offsets diesel consumption. If solar production exceeds demand, the output of the PV panels is controlled and curtailed in order to avoid back feeding into the diesel genset and to ensure sufficient spinning reserve to guarantee continuity of service.

The main result of the simulation is a graph of the different energy flows of the PV-hybrid plant including:

- The electricity consumption from the main grid (red)
- The electricity consumption from the genset during blackouts (green)
- The solar electricity directly consumed during grid supply (orange)
- The solar electricity directly consumed during genset supply (yellow)
- The solar electricity consumed via the net metering scheme (fed to the grid when production is higher than demand and recuperated from the grid when the production is lower) (blue)



FigureA1-1. PV-hybrid plant operation during a random week with persistent grid interruptions (source: TTA)

Moreover, the distribution of sources in the first year of the project and the renewable energy fraction are good indicators of the performance of the plant.

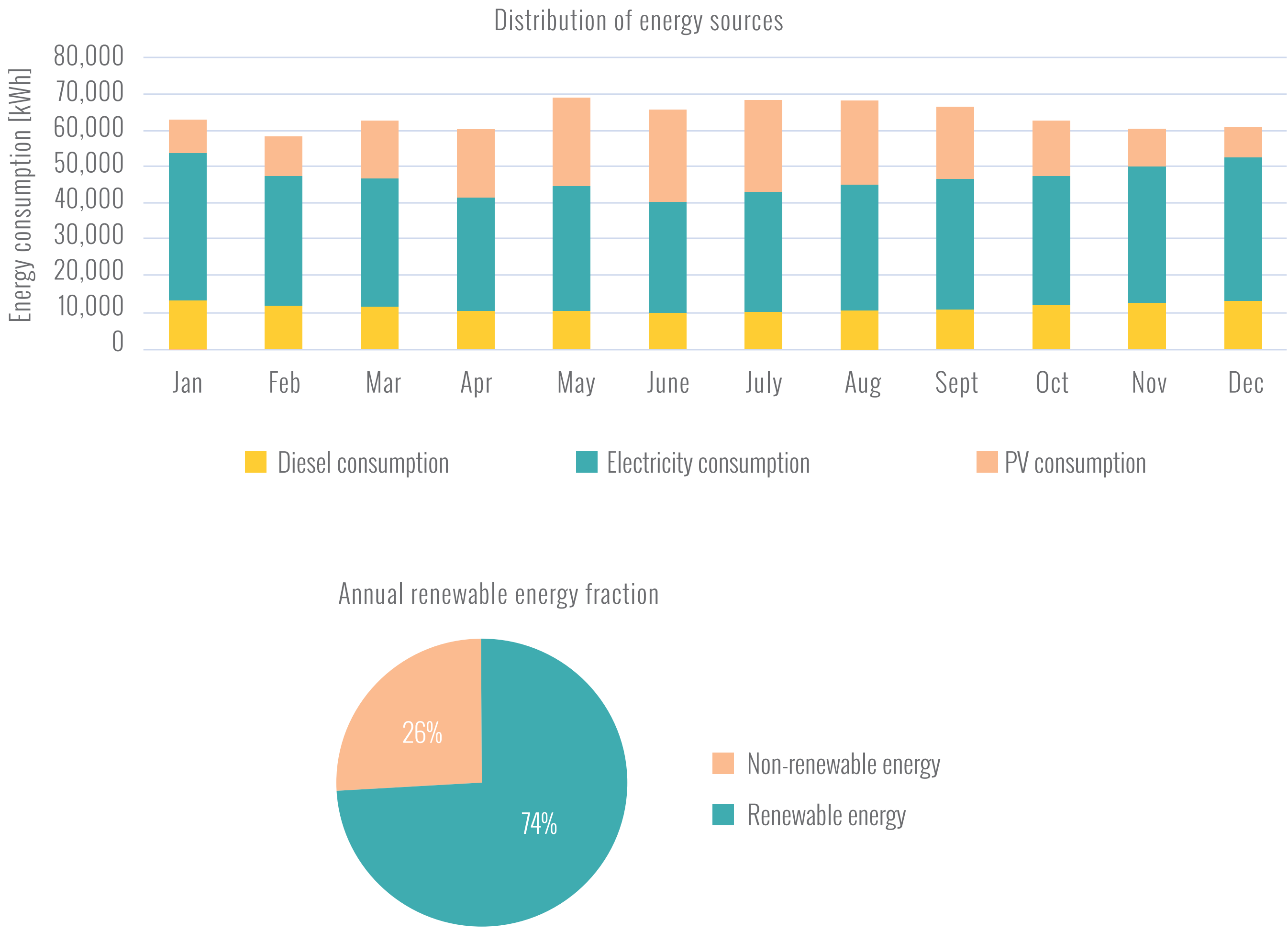


Figure A1-2: Monthly and annual renewable energy fraction of the plant (source: TTA)

The economic viability of the PV-hybrid plant can be demonstrated by the calculation of various financial indicators such as the payback period, the net present value (NPV) and internal rate of return (IRR). Furthermore, a feasibility study can include the comparison of the levelised cost of electricity (LCOE) before and after the implementation of the solar-based plant, as shown in the LCOE cost breakdown graphs for a plant of 240 kWp

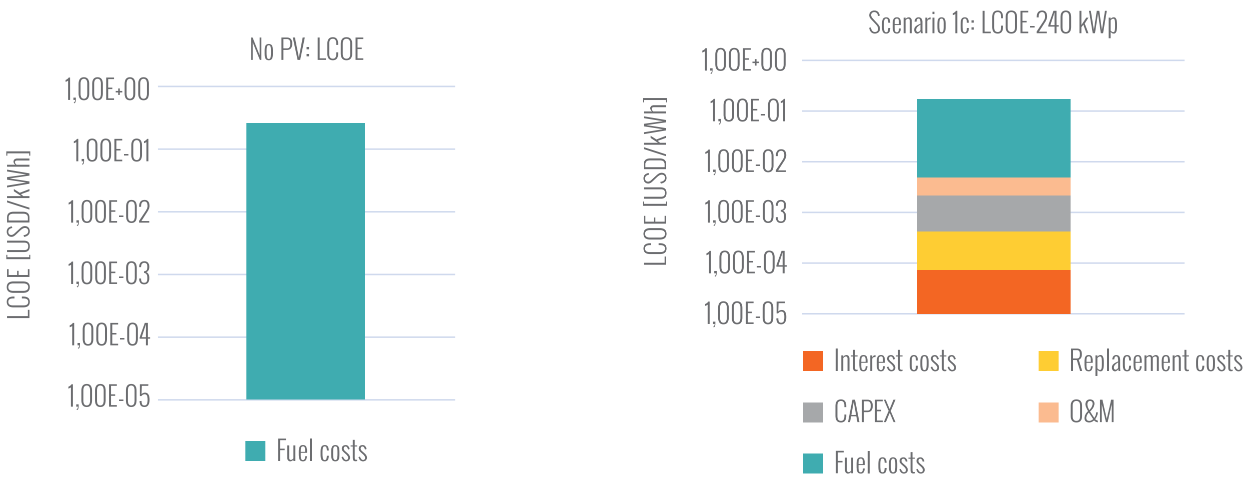


Figure A1-3. Cost breakdown of LCOE without (left) and with the PV-hybrid plant (right) (source: TTA)

Annex 2 - International Standards for PV-hybrids

The table below provides a reference list of international standards typically used in PV-hybrid plants.

Components	Components International Standard
Solar Cells and Modules	• IEC 60891 ed2.0: Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics • IEC 60904: Photovoltaic devices - IEC 60904-1 ed2.0: Measurement of photovoltaic current-voltage characteristics; IEC 60904-2 ed2.0: Requirements for reference solar devices; IEC 60904-3 ed2.0: Measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data; IEC 60904-4 ed1.0: Reference solar devices - Procedures for establishing calibration traceability; IEC 60904-5 ed2.0: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method; IEC 60904-7 ed3.0: : Computation of the spectral mismatch correction for measurements of photovoltaic devices; IEC 60904-8 ed2.0: Measurement of spectral response of a photovoltaic (PV) device; IEC 60904-9 ed2.0: Solar simulator performance requirements; IEC 60904-10 ed2.0: Methods of linearity measurement. • IEC 61215 ed2.0: Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval • IEC 61345 ed1.0: UV test for photovoltaic (PV) modules • IEC 61646 ed2.0: Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval • IEC 61701 ed2.0: Salt mist corrosion testing of photovoltaic (PV) modules • IEC 61730: Photovoltaic (PV) module safety qualification - IEC 61730-1 ed1.0: Requirements for construction; IEC 61730-2 ed2.0: Requirements for testing • IEC 61829 ed1.0: Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics • IEC 61853 – 1 ed1.0: Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating • IEC/TS 62257-7 ed1.0: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 7: Generators; IEC/TS 62257-7-1 ed2.0: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 7 - 1: Generators - Photovoltaic generators • EN 50380: data sheet and nameplate information
PV Module Temperature	• IEC 61683 ed1.0: Photovoltaic systems - Power conditioners - Procedure for measuring efficiency • IEC 62093 ed1.0: Balance-of-system components for photovoltaic systems - Design qualification natural environments • IEC 62103 ed1.0: Electronic equipment for use in power installations • IEC 62109: Safety of power converters for use in photovoltaic power systems • IEC 62109-1 ed1.0: General requirements; IEC 62109-2 ed1.0: Particular requirements for inverters • IEC 62116 ed1.0: Test procedure of islanding prevention measures for utility interconnected photovoltaic inverters • IEC 62509 ed1.0: Battery charge controllers for photovoltaic systems -Performance and functioning • VDE 0126-1-1: Grid protection – Automatic disconnection device between a generator and the public low-voltage grid

Components	Components International Standard
Storage and Other Components	• IEC 60896-11 ed1.0: Stationary lead-acid batteries - Part 11: Vented types - General requirements and methods of tests; IEC 60896-21 ed1.0: Stationary lead acid batteries - Part 21: Valve regulated types - Methods of test; IEC 60896-22 ed1.0: Stationary lead-acid batteries - Part 22: Valve regulated types • IEC 61427: Secondary cells and batteries for renewable energy storage – General requirements and methods of test Project IEC 61427-1 ed1.0 (Pre-release of the official standard): Photovoltaic off-grid application • IEC 62093 ed1.0: Balance-of-system components for photovoltaic systems - Design qualification natural environments • IEC 62103 ed1.0: Electronic equipment for use in power installations • IEC/TS 62257-8-1 ed1.0: Recommendations for small renewable energy and hybrid systems for rural electrification - Part 8-1: Selection of batteries and battery management systems for stand-alone electrification systems – Specific case of automotive flooded lead-acid batteries available in developing countries • IEC/TS 62727 ed1.0: Photovoltaic systems - Specification for solar trackers • NFC 58 510: Lead-acid Secondary Batteries For Storing Photovoltaic Generated Electrical Energy • IEEE 937: Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems • IEEE 1144: Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems • IEEE 1145: Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic (PV) Systems • IEEE 1361: for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems
Planning, Safety and Implementation	• IEC 60364-7-712 ed1.0: Electrical installations of buildings - Part 7-712: Requirements for special installations or locations - Solar photovoltaic (PV) power supply systems • IEC 61000: Electromagnetic compatibility (EMC). IEC 61000-4: Testing and measurements techniques • IEC 61724 ed1.0: Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis • IEC 61725 ed1.0: Analytical expression for daily solar profiles • IEC 61727 ed2.0: Photovoltaic (PV) systems - Characteristics of the utility interface • IEC 62108 ed1.0: Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval • IEC 62124 ed1.0: Photovoltaic (PV) stand alone systems - Design verification • IEC 62253 ed1.0: Photovoltaic pumping systems - Design qualification and performance measurements • IEC/TS 62257-3 ed1: Recommendations for small renewable energy and hybrid systems for rural electrification – Part 3: Project development and management; IEC/TS 62257-4 ed1.0: Recommendations for small renewable energy and hybrid systems for rural electrification – Part 4: System selection and design; IEC/TS 62257-5 ed1.0: Recommendations for small renewable energy and hybrid systems for rural electrification – Part 5: Protection against electrical hazards; IEC/TS 62257-6 ed1.0: Recommendations for small renewable energy and hybrid systems for rural electrification – Part 6: Acceptance, operation, maintenance and replacement; • IEEE 928: Recommended Criteria for Terrestrial Photovoltaic Power Systems • IEEE 1374: Guide for Terrestrial Photovoltaic Power System Safety • IEEE 1526: Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems • IEEE 1547: Standard for Interconnecting Distributed Resources with Electric Power Systems. IEEE 1547.1: Standard for Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems

Components	Components International Standard
General Standards	• IEC 61702 ed1.0: Rating of direct coupled photovoltaic (PV) pumping systems • IEC 61725 ed1.0: Analytical expression for daily solar profiles • IEC/TS 61836 ed2.0: Solar photovoltaic energy systems - Terms, definitions and symbols • IEC/PAS 62111 ed1.0: Specifications for the use of renewable energies in rural decentralized electrification • IEC 62257: Recommendations for small renewable energy and hybrid systems for rural electrification. IEC/TS 62257-1 ed1.0: General introduction to rural electrification; IEC/TS 62257-2 ed1.0: From requirements to a range of electrification systems; IEC/TS 62257-7-3 ed1.0: Generator set - Selection of generator sets for rural electrification systems; IEC/TS 62257-9-1 ed1.0: Micropower systems; IEC/TS 62257-9-2 ed1.0: Microgrids; IEC/TS 62257- 9-3 ed1.0: Integrated system - User interface; IEC/TS 62257-9-4 ed1.0: Integrated system – User installation; IEC/TS 62257-9-6 ed1.0: Integrated system – Selection of Photovoltaic Individual Electrification Systems (PV-IES); • IEC 62446 ed1.0: Grid connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests and inspection • ISO 9845-1: Solar energy - Reference solar spectral irradiance at the ground at different receiving conditions - Part 1: Direct normal and hemispherical solar irradiance for air mass 1.5. • DIN 5043-2: Radioactive luminescent pigments and paints; method of measurement of luminance and designation of luminescent paints.

Annex 3 - Commissioning Protocol

Before starting any PV system testing:

- Check that non-current carrying metal parts are grounded properly
- Ensure that all labels and safety signs specified in the plans are in place
- Verify that all disconnect switches in the distribution box are in the open position and tag each box with a warning sign to signify that work on the PV system is in progress

PV array:

- Verify that all circuit breakers are open and that no voltage is present at the output of the distribution box
- Visually inspect all plugs and receptacle connectors between the modules to ensure they are fully engaged
- Check that strain reliefs/cable clamps are properly installed on all cables and cords by pulling on cables to verify
- Check to make sure all panels are attached properly to their mounting brackets and nothing catches the eye as being abnormal or misaligned
- Visually inspect the array for cracked modules
- Check to see that all wiring is neat and well supported

PV array circuit wiring

- Check that switch is open, when working on the DC side of the inverters
- Verify polarity of each string and verify that both the positive and negative string connectors are identified properly.

AC inverter

- Check all internal protections are closed before commissioning
- Check humidity or water inside the inverter and close the door
- Check anti-islanding protection

AC wiring

- Verify that the only place where the AC neutral is grounded is at the main distribution box
- Verify that all cables are properly connected to the main distribution box

Batteries

- Verify the electrolyte level
- Revise connections between batteries and charge controllers, inverters, meanwell source, grounding and among batteries
- Revise battery room: space between them, polarity of the battery cells, cabling, stability of the structure, earthing of the room, available material for battery connections, sufficient electrolyte and distilled water
- Start the charging process of the battery according to manufacturer

Annex 4 - Plant Maintenance Checklist

At all times:

SUBSYSTEM	O&M LEVEL	DESCRIPTION	COMMENTS
0 - General	Basic	Existence and availability of O&M checklists and plan	
0 - General	Basic	Availability and updating of O&M book records (O&M book)	All maintenance (corrective and preventive) actions must be registered
0 - General	Professional	Existence and availability of as-built drawings	Should be provided by the system installation contractor
0 - General	Professional	Existence and availability of technical documentation and manuals in specified languages	Should be provided by the system installation contractor
0 - General	Professional	Existence and availability of the monitoring and evaluation (M&E) plan	Should be provided by the system installation contractor Should define 2 levels (Basic, Operational) + 1 Extended for advanced or exhaustive monitoring
0 - General	Professional	Availability and updating of M&E reports (M&E book)	Bi-annual and yearly monitoring reports must be registered in the M&E book
0 - General	Basic	Access to solar collectors, tanks and control rooms is restricted only to maintenance and authorised personnel	

Trimestral:

SUBSYSTEM	O&M LEVEL	DESCRIPTION	COMMENTS
1 - PV Generator and Roof	Basic	Cleaning of eventual dusty or soiled panels	Frequency should be increased to monthly when climate is very dry or dusty
1 - PV Generator and Roof	Basic	Visual check for cracks, hot spots, colour defects in PV panels	
1 - PV Generator and Roof	Basic	Sealant around roof fractions should be in good condition.	
1 - PV Generator and Roof	Basic	Visual check all nuts and bolts fixing the panels to any support structures for tightness, absence of corrosion in metallic parts	

SUBSYSTEM	O&M LEVEL	DESCRIPTION	COMMENTS
1 - PV Generator and Roof	Basic	Verify the reference photocell and the temperature sensor condition (tight fixation, good contact, wire continuity)	
1 - PV Generator and Roof	Basic	Visual check the wiring good condition	
2 - Battery	Basic	Check the battery density and voltage (each cell)	Register 6 cells readings each trimester, so that the whole bank is checked every year
3 - Plant Controller	Supervisor Consultant	Download monitoring data, check raw data for eventual errors or inconsistencies	

Bi-annual:

SUBSYSTEM	O&M LEVEL	DESCRIPTION	COMMENTS
1 - PV Generator and Roof	Basic	Prevent eventual vegetation growth that may produce shading.	
1 - PV Generator and Roof	Professional	Check the panels and wiring condition, fulfilment of operating specifications	If generation from panels is lower than specifications, perform cabling verification test
2 - Battery	Professional	Check good condition of wiring and terminals (including earthing), tight connections, free of dust.	
3 - Plant Controller	Supervisor Consultant	Analyse monitoring data and prepare evaluation reports (bi-annual, yearly and aggregate). Draw conclusions and recommendations on basic and operational parameters.	
3 - Plant Controller	Supervisor Consultant	If 3rd level monitoring is set, analyse complete monitoring data, prepare evaluation reports (bi-annual, yearly and aggregate) and draw conclusions / recommendations	
4 - Inverter	Professional	Check inverter state: operation, displays, alarms, verification of modes of operation, etc.	Check inverter performance under each mode of operation, fulfilment of specifications

SUBSYSTEM	O&M LEVEL	DESCRIPTION	COMMENTS
5 - DC Distribution and Protections	Professional	Check good condition of wiring and terminals (including earthing), tight connections, free of dust.	
5 - DC Distribution and Protections	Professional	Check good condition of the LV connection board - metre, switches, wiring and terminals (including earthing), tight connections, free of dust.	
7 - AC Connection to Grid	Professional	Check good condition of the LV connection board - metre, switches, wiring and terminals (including earthing), tight connections, free of dust.	

Annual:

SUBSYSTEM	O&M LEVEL	DESCRIPTION	COMMENTS
0 – General	Professional	General check-up of all elements and operating conditions	Annual independent general maintenance test
1 - PV Generator and Roof	Basic	Visual check for shading of the collectors during the day (mid-morning, noon, and mid-afternoon)	