

# PHOTOVOLTAIC PLANTS in LEBANON

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## About CEDRO

The United Nations Development Programme, in partnership with the Ministry of Energy and Water, the Ministry of Finance and the Council for Development and Reconstruction, initiated in October 2007 the implementation of the CEDRO project which is funded through the Lebanon Recovery Fund by means of a grant from the Government of Spain.

The CEDRO project aims at supporting the greening of Lebanon's recovery, reform and reconstruction activities through the implementation and activation of end-use energy efficiency and renewable energy applications. To achieve this, the project has worked on three levels: implementation of reference end-use energy efficiency and renewable energy demonstration projects for public sector buildings and facilities; setting up of an enabling environment for the conversion of other public sector buildings and facilities into energy efficient modalities, and the development of a national sustainable energy strategy and action plan.

To date, CEDRO has installed renewable energy systems over 100 public sites across the country: photovoltaic, microwind, commercial-scale solar hot water systems, ground source heat pump, solar street lighting, and pico-hydro. Moreover, and in support of the Government of Lebanon's objective of achieving 12% of its energy mix from renewable energy sources by 2020, CEDRO has undergone several resource assessments and studies, mainly: the National Wind Atlas of Lebanon, the National Bioenergy Strategy, Concentrated Solar Power Assessment, Hydropower from Non-River Sources, and the National Geothermal Power Assessment.

For more information, please visit our website; [www.undp-cedro.org](http://www.undp-cedro.org)

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## List of acronyms and abbreviations

DoD	Depth of discharge – percentage of discharge of a storage system
EDL	Electricité du Liban electric utility
ELV	Extra-Low Voltage
EoL	End of Life – when a product is at the end of its useful lifetime.
EPBT	Energy Payback Time – years to recover primary energy consumption
EU	European Union
GHG	Greenhouse Gases
HV	High Voltage
IRR	Internal Rate of Return
LV	Low Voltage
MW	Megawatt (s) – international unit for power
MEW	Ministry of Energy and Water (Government of Lebanon)
O&M	Operation and Maintenance
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System - geographical assessment of solar resource and performance of photovoltaic technology
RE	Renewable Energy
SBA	Solar Basic Assembly
SGSp	Solar PV Generation Sub-plant
SoC	State of charge (typically referred to batteries)
W	Watt – international unit for power
WEEE	Waste Electrical and Electronic Equipment
Wh	Watt hour – unit for electrical energy
Wp	Watt peak – In PV installations, Watt at STC

## Executive Summary

Lebanon is only just beginning the path towards more large-scale renewable energy penetration within its electricity mix. One of the more promising renewable energy options for Lebanon is that of solar photovoltaic energy, from rooftop applications to large open field solar power plants.

This study sets out the basic technical design considerations, criterion, parameters and various implications of photovoltaic power, as well as preliminary economic financial costs of PV power based on a template financial model, attached to this document.

Technical focus is placed on the following aspect of PV power development:

- (1) Characterization of plants and components, from panels, to switchgears, structures, and standards;
- (2) PV power development, such as site assessments and solar resource estimations (site selection), sizing of equipment, and design and operation parameters,
- (3) Environmental and safety considerations
- (4) Regulatory and planning requirements
- (5) Grid capacity, voltage, and frequency parameters and implications

From a financial perspective, a financial model that can be manipulated by financial experts and/or engineers can be found in the attached CD to this report. Three financial scenarios are indicated, and levelised cost of electricity achieved ranges from \$c12/kWh to \$c23/kWh, with respective payback period from 6-10 years.

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# PART A.

PV Plants: General  
Principles



# 1 Principles of PV generation

This section describes how photovoltaic (PV) technology is integrated in power plants for the generation of electricity. Several examples are presented, with an accompanying discussion on PV plant design considerations.

## 1.1 Market trends

The notion of a PV power facility has grown from milliwatts to megawatts, from extra low voltage direct current (DC) to low voltage alternating current (AC), from hand calculators to power plants and today many of the visions associated with large scale deployment of PV are now happening.

Over the past ten years there has been a rapid increase in both the scale and the number of PV power plants worldwide. The emergence of multi-MW PV plants has been concentrated in Europe, most notably in Germany, Spain, and Italy, with Japan, Korea and the U.S. adding many sites since 2003 as well [1].



Figure 1 Large PV plant in Spain (Source: PV Industry Association – ASIF [2])

The total installed capacity worldwide has grown considerably. In 2011, more than 69 GW were installed globally and could produce 85 TWh of electricity every year [1]. The increase in market demand has been driven by a combination of rising conventional electricity costs, technology advancement, environmental concern and strong government incentives to encourage

investment in grid-connected applications that represent roughly 80% of current applications, while the remaining 20% of applications are considered off-grid. As the cost of providing new electrical grid extension in rural areas is often very high, off-grid autonomous PV micro power plants are often the options that cost the lowest. This is particularly the case in remote sites and in developing countries where the public grid infrastructure is limited or the service is unreliable.

## 1.2 Plant types

There are many end uses for PV technology, with a broad catalogue of design size and complexity. A range of applications is shown in Figure 2. In all portable applications, PV offers something the grid cannot by providing electricity to non-stationary applications. Grid-tied and autonomous applications share many components although they fulfill different requirements. As an example, both grid tied and autonomous PV plants may use the same module technology, be deployed in the same climate, and yield the same energy for a hypothetical consumption or load, yet the supporting structure will be different whether they are mounted on the ground or on a building. In the case when they are associated with a building, if there is no grid, it may be expensive to extend the grid to a remote site and therefore autonomous PV plants with storage are often the best solution when compared to the traditional option of fossil-fuelled gensets or not having access to electricity at all.

If the building is connected to the grid, the PV plant is designed to be grid-dependent and to generate bulk electricity that can either be fed back to the grid or consumed by the loads as it is produced, depending on the countries' policy. The most optimal scenario is to consume as much power as possible locally, before exporting to the grid. In the case of Lebanon, where the available electricity grid is intermittent, the most adapted facility associated with a building is a dual type plant that can operate either when the grid is on in parallel mode and in an autonomous mode, with storage or in parallel with a genset (e.g. local diesel

generator), when the grid is off.

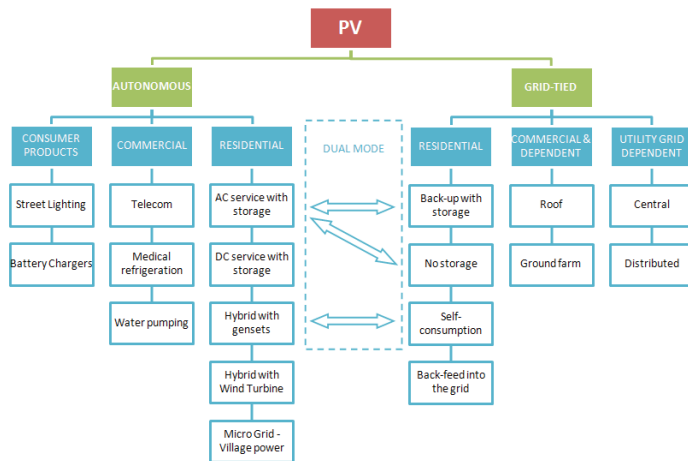


Figure 2. PV Applications Chart (Source: TTA)

The following sections describe some common PV plant types.

### 1.2.1 Small autonomous DC plants

Direct current (DC) plants are used in applications that can directly use the electricity produced by PV generators to supply DC loads. These include portable solar devices and small consumer products, very small domestic plants, water pumping, and other small applications that are typically up to 500 W and for which all loads operate with DC electricity. A simplified block diagram of a small DC plant is given in Figure 3.

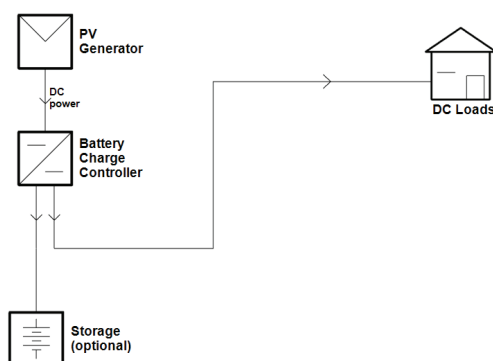


Figure 3. Diagram of a small DC PV plant (Source: TTA)

### 1.2.2 Autonomous AC plants

In autonomous AC plants, the DC electricity from the PV generator is converted to AC but there is no utility grid available. In this case, the loads operate at standard AC electricity. The inverter acts as a voltage source to supply stable AC to the loads from a battery that allows the match between the intermittent PV energy source and also the intermittent or variable consumption requirements. A simple example of this is a remote home with a plant consisting of a small solar generator on a free standing structure or on the roof, a battery for electrochemical storage and an inverter. A simplified block diagram of an autonomous PV plant providing AC service is given in Figure 4.

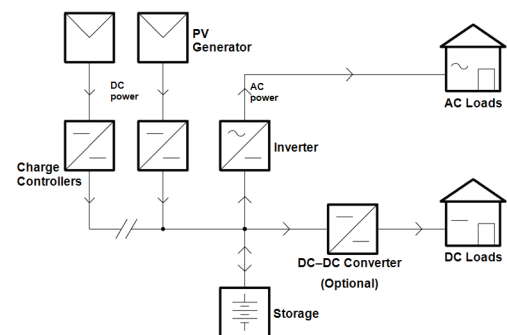


Figure 4. Diagram of autonomous PV plant with AC service (Source: TTA)



Figure 5. Autonomous AC PV micro plant (400Wp) in a rural community in Ecuador (Source: TTA)

### 1.2.3 Grid

Grid-tied plants are those in which the electricity from the PV generator is converted to AC electricity and, when connected in parallel with the utility grid, is either used on-site or injected into the grid. In general, they do not have storage capacity and the DC PV output is converted to AC by an inverter and utilized as it is generated. The inverter generates alternating current that is synchronized with the grid and stops if the grid is off or out of bounds. This is known as a grid-dependent operation. As the PV generated energy is fed to the grid it is distributed to any loads connected to it and not to any specific equipment. Depending on the point of connection to the grid these plants can either exclusively be used for commercial generation of electricity or, if connected within a consumer's distribution grid, be used to offset the load and only deliver to the grid the surplus. A simplified block diagram of a PV grid dependent plant is given in Figure 6. Figure 7, Figure 8 and Figure 9 show examples of residential, commercial, and utility scale plants.

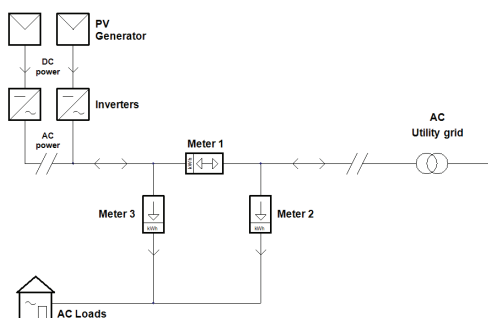


Figure 6. Diagram of a Grid-dependent plant connected outside the consumer's installation (Source: TTA)



Figure 7. Private household (Can Canal). A pioneer grid-connected PV plant in Spain, June 2001 (Source: TTA).



Figure 8. Medium scale grid-tied rooftop system (source: ICAEN [3])





Figure 9. Large scale Grid-connected PV plant with electrical production to deliver to the grid (source: TTA)

#### 1.2.4 Multi-source PV plants

Multisource or what are also called hybrid plants are terms used where PV is used in combination with one or more auxiliary sources of power. This means a second power source such as wind or hydroelectric turbines, or also auxiliary dispatchable sources such as fossil-fuelled gensets or even the utility grid. The term dual-mode is used to describe the special case of a PV multi-source plant that operates either in parallel with an external AC grid (grid dependent) or as an autonomous AC source (off-grid) when the grid power is off.

A diagram of an off-grid PV multi-source plant is shown in Figure 10.

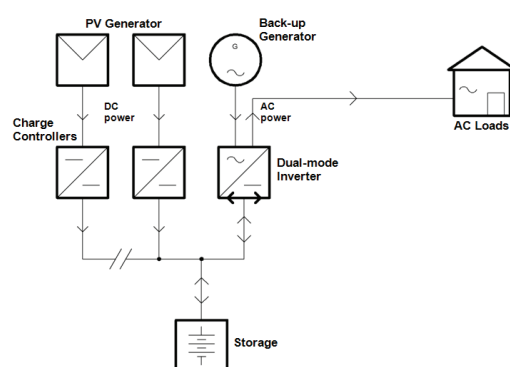


Figure 10. Diagram of an autonomous PV multi-source (hybrid) plant (Source: TTA)

Multi-source plants are usually designed to provide continuous grid equivalent electrical service during the night or during unfavorable weather conditions and with a high fraction of the energy being delivered by the solar facility. During sunny weather,

the consumer's demand is met by the PV generator and surplus generation is stored in the battery. If needed, a back-up genset can simultaneously supply both the loads and charge the battery. If adequately sized, this set up has high reliability and avoids the need for an oversized PV generator.

In the diagram shown in Figure 10, all electricity generating components are interconnected, via charge controllers or converters to a DC bus bar in parallel with the battery. An inverter converts this DC from the bus bar into standard AC to supply the loads. The battery acts as a buffer in response to the demand and also to store energy for the night time. A battery supervisory control monitors the battery state of charge and eventually disconnects the loads in case it is below a defined threshold. Prior to load disconnection, a low battery signal can be used to automatically start the back-up genset to supply AC power directly to the loads and charge the battery with a charger or a bi-directional inverter.

When the multi-source PV plant is grid-tied, the metering arrangements must comply with the local regulations governing renewable energy generation, typically a two way energy meter to account for net metering or premium (feed-in) tariffs.

#### 1.2.5 Micro-grids

Autonomous individual PV plants are used to supply single households and other facilities in remote areas or regions with intermittent grids. When several houses are clustered into a village, a residential building with several apartments or a condominium, an emerging solution is to use a larger PV plant to supply all the consumers with a standard AC single phase Low Voltage distribution grid. With a microgrid and a neighborhood plant, economies of scale are realized and investment and operation costs can be lower than the sum of the cost for the individual PV plants. However, the collective sense of responsibility in managing and paying for a jointly used limited energy resource has to be addressed. Typically, these types of micro grids have a capacity up to 100 kW but larger capacity microgrids or clustered microgrids are also possible.

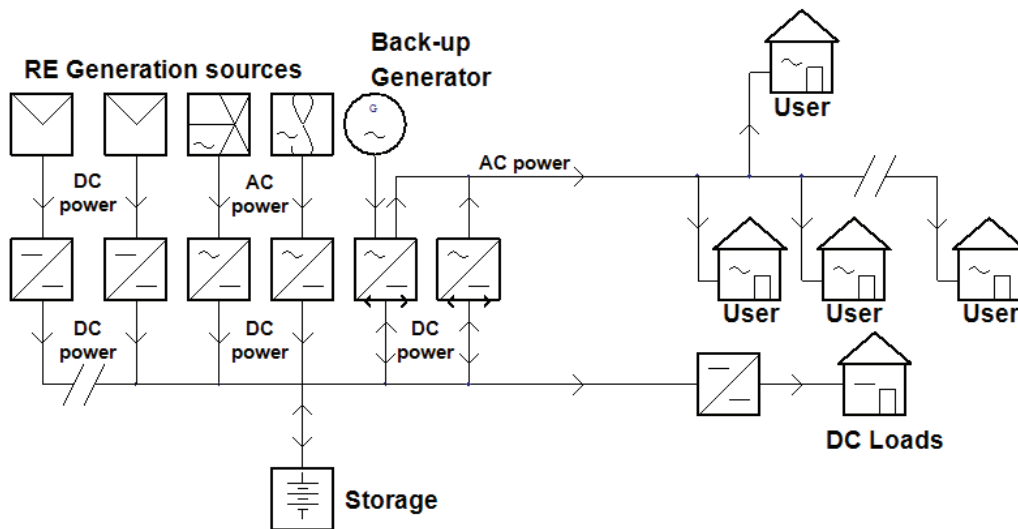


Figure 11. Generic Diagram of an autonomous microgrid (Source: TTA)

### 1.2.6 Smart grids

Another concept that is emerging is the “smart grid”. There are many definitions or visions on what features do smart grids need to incorporate, but in essence the goal in a “smart grid” is to improve the reliability of electricity distribution while incorporating distributed and variable generation sources as well as load management and storage. PV technology integrates well with this concept because of its environmental benefits and the universal nature of the solar radiation.

It is still an evolving concept that generally can consist of:

- Central and distributed sources of energy such as PV or micro wind
- Switchgear for connecting and disconnecting generators and loads
- Communications to monitor generation and loads
- Control strategy to optimally dispatch generations, loads and storage (if present)

## 1.3 Key requirements in PV plants

The best PV plants are required to objectively demonstrate adequate Performance, Safety and Reliability.

The *performance* of a plant is evaluated in terms of energy yield and its financial results. For autonomous and dual mode plants, the produced energy should supply the daily rated load at all times or within the accepted tolerance, independent of seasonal weather fluctuations. For grid-dependent plants, a performance is to feed into the grid the maximum possible energy. To achieve high performance, adequate engineering design that considers also the local grid and environmental conditions, quality of components, careful installation, acceptance testing, and maintenance are all critical aspects to address following the highest standards and state of the art.

In terms of financial results, in weak or unreliable grids, in addition to the value of the produced energy (revenue or avoided costs), the value of lost load (VOLL) should be considered. The “VOLL” is a parameter which is used to consider the cost for the unsupplied kWh. Depending on the activity, the “VOLL” can be very high, like hospitals and community centers [4].

For PV technology, as with most other renewable energy technologies, *reliability* is an essential element to consider. This is because the cost of the generated electricity is mostly affected by the payback period of the assets with low operating costs scenarios (no fuel requirements) and

the profitability of the investment which is based on long plant life and maximum energy output. PV plants are typically intended to last for a minimum of 25 years and are expected to operate at nearly their original rated performance throughout. The components in a PV plant are exposed to outdoor conditions where extremes of temperature and humidity could increase their degradation if they do not meet high quality ratings. Typically, the manufacturers' performance guarantees ensure that the annual degradation of the PV modules will be below 0.7% during a period of 25 years. Nevertheless, in some cases, higher losses could be found when measuring modules taken out of the plants. Therefore, it is recommended to perform an evaluation test after one year of installation. In the case of autonomous and dual mode plants, reliability is even more critical.

*Safety* is also an important aspect of PV plants. It is critical that it meets the local electrical code, employs components certified to internationally recognized safety standards, is properly grounded to prevent risks of electric shocks, and does not create a fire hazard. As the PV industry matures, safety measures are evolving to overcome the inexperience factor due to the relatively short history of this technology; the "shortcut" factor often caused by deadlines imposed by market incentive mechanisms; and the over competitive factor often caused by overemphasizing the lower investment cost as a design or selection criteria.

For a labor force used to either AC or to relatively safe extra low voltage autonomous DC plants, there is a gap in understanding the deadly hazards of working with DC at low voltage in large PV plants. DC at voltage up to 600 V or more from a constant current source poses an electrical risk that is not easy to tackle with traditional protective measures.

## 1.4 Characterization of plants and components

### 1.4.1 Ratings of plants and components

PV plants can be rated in several ways. The capacity of the DC PV generator (also called PV array) is stated in terms of the nominal power capacity at Standard Test Conditions (STC), namely a solar irradiance of  $1,000 \text{ W/m}^2$ , a PV cell temperature of  $25^\circ\text{C}$ , and air mass (AM) 1.5 spectrum [5]. STC are also known as "peak" DC power capacity and denoted as  $W_p$ . It is based on manufacturers' nameplate capacity values. This STC rating is based on a convenient condition not common in real conditions found in the field. It is mainly used to predict the energy production of the plant from the radiation conditions (Reference Yield) of the site. The Final Yield is 20-30% lower than the Reference Yield because of the losses related to real operating conditions, component efficiencies and availability of load or grid to which the captured energy can be delivered. The  $\text{kW}_p$  rating of a generator is simply the sum of the nameplate ( $W_p$ ) STC ratings of all the modules.

From the perspective of the grid or the loads, the commonly used rating is the AC power rating used to characterize a plant. It is the maximum power that the plant can effectively deliver. In grid-tied installations it coincides with the rated continuous power capacity of the inverter (or inverters) and in autonomous plants it is usually the inverter's 30 minute power rating. These are denoted as  $W_{AC}$ . With these definitions, for grid tied plants without storage, there is an implicit assumption that the PV STC capacity is large enough to support the AC power level. The plant's AC ratings are lower than DC nameplate ratings because there are losses that are taken into account. The ratio of inverter rated capacity (AC) to PV STC capacity (DC) is called the inverter factor, and has typical values in the range of 0.80 to 0.95 for grid tied plants. In autonomous or dual mode plants, the inverter factor can reach values above 1 given that the inverter sizing will also take into account the battery capacity. Both DC and AC peak

power ratings are imprecise terms, but necessary for the general characterization of the plant. This significant difference between DC (STC) and AC (inverter) ratings can cause misinterpretation if normalized costs and yields are calculated without a clear reference whether it corresponds to one or the other.

The reference yield,  $Y_r$ , can be understood as the number of peak sun hours, this is equivalent to the incident radiation per time period (daily average, year, etc...) on a given PV generator plane divided by the reference radiation of  $1000 \text{ W/m}^2$ . The generator yield,  $Y_a$ , is a normalized value or DC kWh per nominal capacity at STC ( $\text{kW}_p$ ) per time period. The final yield,  $Y_f$ , is a normalized value of kWh actually produced and delivered per nominal  $\text{kW}_p$ . The performance ratio, PR, is the ratio of final yield divided by reference yield. On the other hand, the annual plant factor is the equivalent hours of operation at the rated AC capacity.

Energy yield ratings of PV plants are valuable to estimate the amount of energy that a given plant will produce in a given period of time (day, month or year). The energy yield can be estimated through simplified calculations or with a simulation of the performance of all of the components as they are in a design using the weather conditions at the installation site as input. Typically, recorded first year energy yield can be adjusted annually to include the effects of component aging. This estimate can be used directly in grid-tied plants that are able to export to the grid all their production. Nevertheless, for autonomous and back up applications or pure grid tied plants that are connected to weak or unreliable grids, the generation is curtailed by the inability to export all the production if the demand is lower.

The monitored generation for one PV installation of 108 kWp is shown in Figure 12. The result is compared with the average of the generated electricity for the last 3.5 years (Table 1).

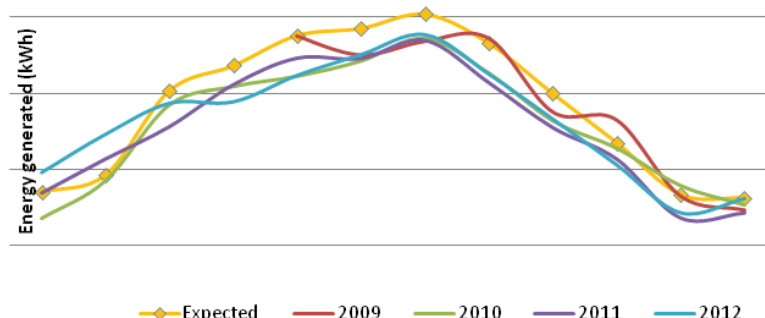


Figure 12. Yearly electricity generated vs. average for the last 3.5 years for a 108 kWp PV plant in Girona, Spain (Source: TTA, based on the results of a real PV plant monitored with REFUlog – [www.refulog.com](http://www.refulog.com))

The final generation varies from year to year and it is often below expectations. The year with the highest yield has fallen over 3% short of the 169,835 kWh/year expected, as shown in the Table 1.

	Average	2009 (May-Dec)	2010	2011	2012
Energy generated (kWh/year)	169,828	115,820	154,951	153,661	158,346
Variation (%)		5,6%	-1,7%	-2,6%	0,4%

Table 1. Variation in the yearly energy generation vs. the average

The more relevant aspect to take into account is the variability of the resource. Although solar energy is a relatively predictable resource, calculations are based on long terms average values and there are variations from one year to another. If these variations are observed on a monthly basis the tolerance is even higher. This should be taken into account when planning the cash flow revenue of the plants.



### 1.4.2 Components

Simplicity is one of the assets of PV technology when compared to other electricity generation technologies. From the point of view of maintenance, this advantage can offset the complexity associated with the fact that the plants are distributed amongst several sites. The general criteria used for the concept engineering and to select the components meet at least the following three main requirements:

- To design all the facilities with a modular concept so that spare parts inventory is compatible with all of them.
- To keep the size of the components within the size and weight to be transported by a light truck and handled by two people.
- To meet internationally recognized technical standards and state of the art performance.

PV plants consist of a set of components engineered to statically convert solar radiation into electricity and convert its characteristics to deliver it in a condition that can supply the intended application. The specific components vary from one application to another but some components are common to most applications and are described in the following paragraphs.

#### 1.4.2.1 Generation: PV Modules

PV generator power capacity is rated in Watts (DC) at STC. Relatively few PV module types now dominate the market. Crystalline cells are the major constituent of the PV modules, with encapsulate, cell tabbing, front and rear cover sheets, framing, and connection boxes. These have the highest efficiencies commercially available and are manufactured either from single-crystal (c-Si) or multi-crystalline silicon (multi-Si) and account for approximately 85% of the commercial market. The rest is made up of various thin films of silicon or CdS/CdTe (cadmium sulfide/cadmium telluride) [6] (See Figure 13 for historical evolution of PV technologies overview).

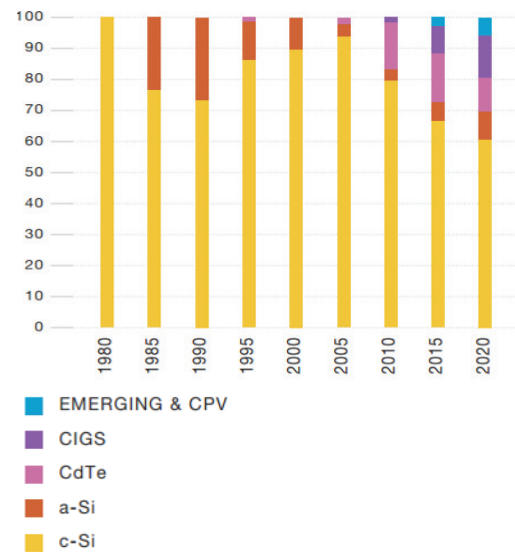


Figure 13. EPIA evolution of technology market share and future trends; % (Source: EPIA [6])

Significant increases in production of c-Si and multi-Si based modules have occurred over the past few years thanks to very aggressive market incentives in several countries resulting in a decrease in prices which significantly reduces the overall plant cost.

The cost of thin-film PV modules has also dropped in recent years. Thin-film modules are generally less efficient than crystalline silicon and require more space for a given capacity but can have a higher yield under certain environmental conditions like diffuse radiation or high operating temperatures. The amount of thin-film modules being installed is also growing rapidly, particularly on ground-mounted plants where space availability is not a limiting factor. Thin film modules are seldom used in applications with space limitations such as roof-mounted plants.

PV modules are characterized by their electrical and physical specifications. The physical characteristics are: size, weight, cover material, packaging, mounting requirements, and grounding methods. The electrical characteristics are: power capacity rating,  $V_{OC}$ ,  $I_{SC}$ ,  $V_{MP}$ ,  $I_{MP}$ , fill factor, maximum voltage rating, temperature coefficients, and efficiency. Visual appearance, color, and flexibility are also relevant especially in some building integrated designs.

The PV modules electrical conditions are typically represented by its current – voltage characteristic curve. This curve describes the energy conversion capability under certain conditions of irradiance and temperature. In Figure 14 the current/voltage curves for a tandem thin-film ( $\mu\text{Csi} - \text{a-Si}$ ) PV module with 128 Wp capacity under different irradiance conditions is shown.

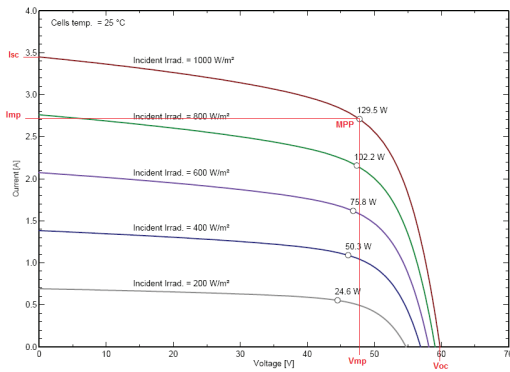


Figure 14. Current-Voltage curves of a PV tandem thin-film module of 128 Wp (Source: TTA, based on data from PVsyst)

The MPP (Maximum Power Point) is where the PV generation is at its maximum.  $V_{MP}$  and  $I_{MP}$  are the voltage and current at this point. Moreover, the  $V_{OC}$  (Open Circuit Voltage) and the  $I_{SC}$  (Short-Circuit Current) are the maximum voltage and current from a PV module.  $V_{OC}$  occurs when the net current through the device is zero.

The  $I_{REVERSE}$  is the current a module can withstand in the reverse direction to normal without damage to the module. This rating is obtained from the manufacturer at expected operating conditions.

The FF (Fill Factor) of a solar cell is defined as the ratio of the maximum power to the product of  $V_{OC}$  and  $I_{SC}$ . It is used as a performance indicator: If the current-voltage curves of two devices have the same values of  $V_{OC}$  and  $I_{SC}$ , the module with higher FF will produce more power.

Temperature affects the PV module behavior. The temperature coefficients define the decrease of the efficiency with the increase of the operating temperature. In Figure 15 five current-voltage curves for different temperature conditions are shown.

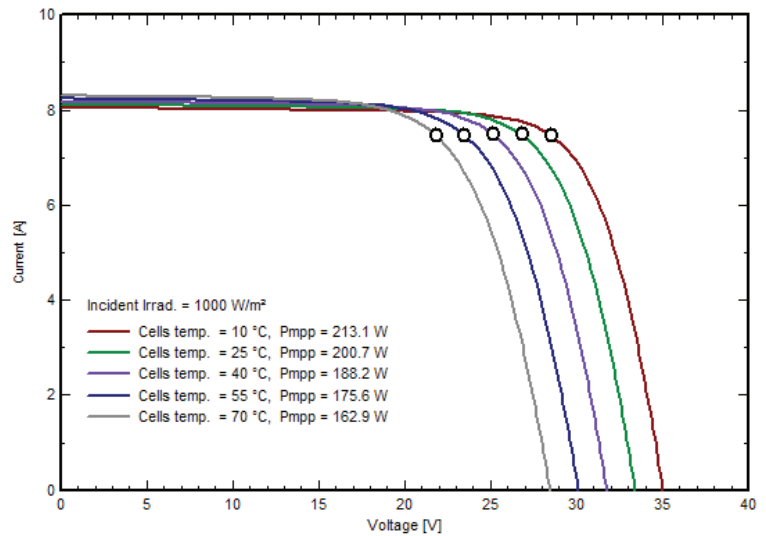


Figure 15. Current-voltage curves for a 200Wp polycrystalline PV module under different temperature conditions. The temperature coefficient of the represented module is  $-0.41\%/^{\circ}\text{C}$  (Source: PVsyst)

The PV generator is considered as a mechanically and electrically integrated assembly of PV modules, and other necessary components, to form a DC power supply unit. Within a PV generator the modules are distributed in series called strings. Usually a PV generator is composed by more than one string. The final PV generator layout is defined depending on climate conditions, module, battery charge controller and/or inverter type.

The output voltage (i.e. open circuit voltage or MPPT voltage) of the PV generator is calculated as the product of the number of modules in series and the voltage of one module, while the output current (i.e. short-circuit current or MPPT current) of the PV generator is calculated as the product of the number of strings and the current of the module.

When the maximum voltage and current of a module, string or PV generator is calculated, one may consider safety factors of 1.2 for voltage and 1.25 for current multiplied by the extreme values of  $V_{OC}$  and  $I_{SC}$ .

#### 1.4.2.2 Conversion: Inverters

Inverters are another key component that impacts plant cost, design and

performance. Inverters electronically convert the electrical characteristics of a DC power source to the suitable conditions for AC loads, or to be injected into the distribution grid.

#### 1.4.2.2.1 Grid-tied inverters

The PV generator is electrically wired to the inverter through a junction box and a DC switch. Similarly, an AC switch is placed between the output of the inverter and the AC grid. There are also over-current protection devices on both the AC and DC sides and additional protection is often also added for transient surge suppression such as lightning induced voltages. The inverter operates at high frequency in a manner that absorbs power from the PV generator at its maximum power point and converts it into an AC current at the grid's frequency and voltage. The inverter's control drives the internal transistors, tracks the maximum power point (MPPT), ensures grid interface requirements, provides metering of input and output, and interfaces with the operator and overall plant monitoring and data loggers.

There are different standards from country to country (and sometimes from utility to utility within the same country) to adapt the requirements to the particular condition. The European general practice is to keep PV inverters connected during minor faults in order to support the grid riding through voltage dips and operating at variable reactive power levels to maintain normal grid voltage. In Lebanon, a set of adapted settings to the Lebanese grid have been proposed by the UNDP-CEDRO project and are shown in Table 2. Additionally, a new IEC standard that is attempting to provide some common requirements is IEC 62109 "Safety of power converters for use in photovoltaic power systems".

Another consideration concerning inverters is the rating of their enclosures. Some inverters are rated for only indoor environments such as IP 20. For outdoor environments enclosure ratings such as IP 55 and IP 65 are used. Inverters have to be installed according to their environmental protection rating and ambient temperature range.




RECOMENDED SETTINGS FOT INTERCONNECTED NET METERED RENEWABLE ENERGY MICRO POWER PLANTS WITH INVERTERS							
TYPE OF PLANT	REFERENCES DIAGRAM (SINGLE PHASE)	RATED CURRENT	DISCONNECTION MEANS	VOLTAGE TOLERANCE	FREQUENCY TOLERANCE	TRIP DESCONNECTION TIME	DC INJECTION
<b>B1: Grid dependent</b>		Nominal power  (≤subscribed demand)	-Inverter embedded stop function -Inverter external switch -External Transfer switch	> 0,80 Um < 1,15 Um	> 45 Hz < 55 Hz	< 2s	< 0,5% ac current in nominal power*
<b>B2: Dual mode Grid dependent / autonomous</b>		Power 30 min  (≤subscribed demand)	-Inverter internal transfer synchronizing switch -Inverter manufacturer external transfer synchronizing switch	> 0,70 Um < 1,15 Um	> 45 Hz < 65 Hz	< 20ms	* Apply for transformerless inverter - directive PD 1663/2000 or similar
<b>A: Autonomous</b>		<b>NOT POSSIBLE</b>					

Table 2. Recommended settings for grid tied grid dependent (B1) and grid tied dual mode (back-up) (B2) for Lebanon (Source: CEDRO, TTA)

For grid-tied operation, the inverter is grid dependent and it controls the current into the grid to meet the requirements for interaction functionality. These requirements are quickly evolving and constituting significant research discussions in many countries. These standards include a voltage and frequency window and requirement for "anti-islanding" to ensure that the inverter disconnects from the utility grid if not under the specified conditions.

A ventilated, shaded area such as the north side of a building is a good place to install an inverter outdoors. Inverters located indoors are better protected from a harsh environment but add a small source of waste heat.

An important characteristic of an inverter is its efficiency curve. Inverter efficiency varies with the operating power level and also varies with the DC PV input voltage. A number of standards have been developed

to provide representative weighted-average efficiency for various climates. These are selected to reflect the frequency of solar resource conditions and the most widespread are those established by the California Energy Commission (CEC) and those more commonly termed “European” weighing. These characterization methods weigh the inverter efficiency at various power levels and therefore, the same unit will have different weighed-average efficiency ratings. Figure 16 shows a typical inverter efficiency curve.

Table 3 lists the weighting factors for both of the methods. The CEC efficiency rating reflects more closely the Lebanese radiation conditions than the so called “European” conditions that are based on conditions in Germany.

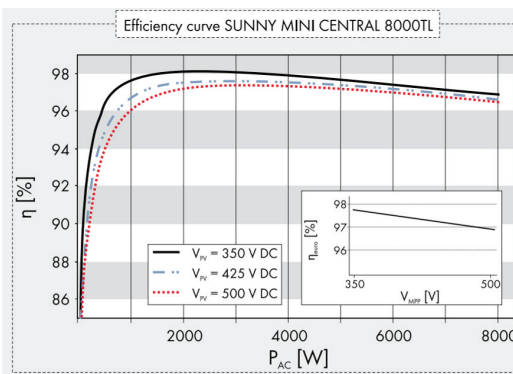


Figure 16. Example of inverter efficiency curve for an 8 kW grid-tied inverter with CEC efficiency of 98% (Source SMA [7])

Inverter Power Level	Weighting Factor CEC	Weighting Factor “Europe”
5	0.00	0.03
10%	0.04	0.06
20%	0.05	0.13
30%	0.12	0.10
50%	0.21	0.48
75%	0.53	0.00
100%	0.05	0.20

Table 3. CEC and “European” efficiency weighting factors

#### 1.4.2.2.2 Autonomous inverters

Autonomous inverters, also known as off-grid or battery inverters are capable of accurately controlling the output AC

voltage that is supplied to the loads. They effectively form the grid. Since there are load variations, this requires a dynamic response and electricity buffer storage (i.e., battery) to withstand transients and to ensure stability. The sizing of the inverter for autonomous operation is critical for efficiency and reliability. It must provide for any surges that the load may require (5” power rating) and, at the same time, have a high efficiency at low marginal power, which is the most frequent operating condition. Some inverters can also operate in reverse mode acting as a battery charger when connected to an AC source.

The first consideration in the selection of an inverter for PV plant with storage is that it is compatible with the DC bus bar voltage range and that it has the required response capabilities to maintain voltage and frequency output even with significant fluctuations of the load that it supplies. The DC operating voltage range of the battery must be within the allowed input DC voltage range of the inverter. Some inverters may incorporate a low voltage load disconnect function to protect the battery from over discharge.

The inverter must supply the loads a similar standard voltage and frequency to the utility grid and, as a general rule, most good performing inverters provide a sinusoidal wave output typically 230 V<sub>AC</sub> at 50 Hz for single-phase loads. Sets of three single inverters can be combined to form three phase grids if they have been designed with that feature.

The second consideration is the surge and continuous power rating. The power rating of the inverter should cover the maximum power required by the loads.

In autonomous applications with storage, the main operating parameter is the consumption profile of the site (hourly consumption), thus any rating methodology to establish the weighted average efficiency must be related to the particular load characterization.

Different methodologies are developed in order to calculate the average inverter’s efficiency. As an example, Vallvé et al.

(2010) designed a simplified estimation method for the calculation of the inverter's weighted efficiency in a PV hybrid plant. The weighing factors were calculated for three idealized load profiles [8]:

Category A: essential consumption dominated by lighting and communication needs. Most of the demand is consumed during the evening at relatively low battery voltage.

Category B: households with small and medium demand and a load profile that also has appliances with higher power requirements and a base load, usually associated to food refrigeration. Part of the load is during the daytime at relatively high battery voltage.

Category C: households and small businesses with medium to high demand profile similar to B but with

higher daily load.

For these categories one can establish idealized load profiles from which the normalized hourly power histograms for power levels corresponding to a % of Daily demand in AC,  $D_{dac}$ , were calculated and represented in Figure 17.

Finally, to estimate the DC load to be used in sizing a PV hybrid plant taking into account the inverter energy efficiency, and for applications represented in categories A, B or C, is as follows:

- Estimate or know the average Daily AC Demand,  $D_{dac}$  and the load category. Then,

$$L_{dck} = t_{id} \cdot L_{id} + \frac{D_{dac}}{\eta_{inv}}$$

- For category A, the inverter weighted efficiency is:

$$\eta_{inv,A} = 0.44 \cdot \eta_{1\% \cdot D_{dac}} + 0.22 \cdot \eta_{3\% \cdot D_{dac}} + 0.22 \cdot \eta_{10\% \cdot D_{dac}} + 0.12 \cdot \eta_{20\% \cdot D_{dac}}$$

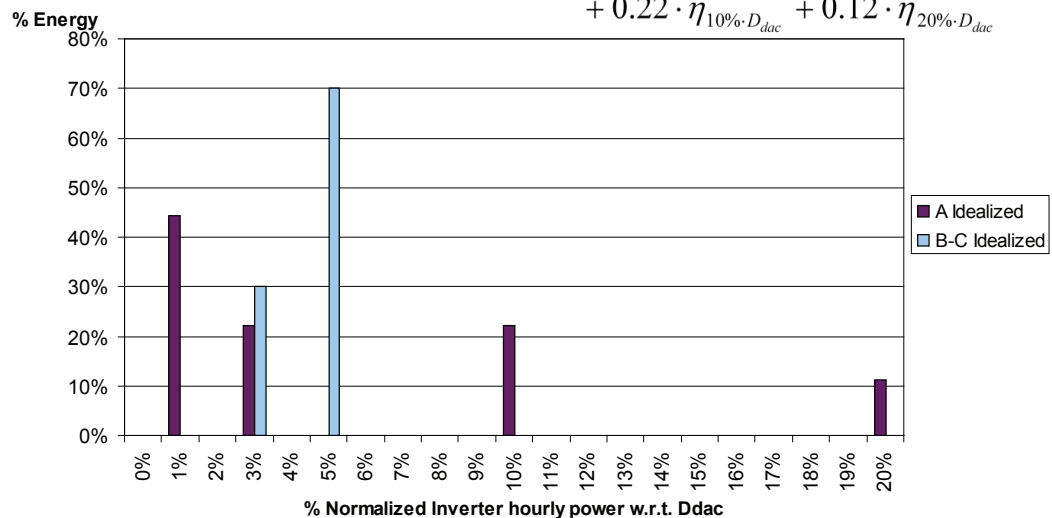


Figure 17. Power histograms for demand categories A and B-C (Source: [8])

For load category A, approximately 90% of the energy is consumed when there is no PV generation whilst in categories B and C, the ratio is closer to 65%.

Table 4 shows the weighing factors for the profiles defined.

Category	No load time (idle)	Power level (% of Daily demand in AC)										
		1%	3%	5%	10%	15%	20%	25%	30%	50%	75%	100%
A	6h	0.44	0.22	-	0.22	-	0.12	-	-	-	-	-
B and C	0h	-	0.30	0.70	-	-	-	-	-	-	-	-

Table 4. Weighing factors to calculate average energy efficiency of inverters for autonomous and back up electrification (Source: Vallvé et al. (2010) [8]).

- For profiles B and C, the inverter weighted efficiency is:

$$\eta_{inv,B-C} = 0.30 \cdot \eta_{3\% \cdot D_{dac}} + 0.70 \cdot \eta_{5\% \cdot D_{dac}}$$

Where  $L_{dcc}$  is the daily energy load in DC (in Wh),  $t_{id}$  is the daily idle time (in hours),  $L_{id}$  is the idle inverter consumption (for no load periods, in W),  $D_{dac}$  is the daily average demand (Wh) and  $\eta_{inv}$  is the weighted inverter efficiency for that particular application and category (adimensional).

The inverters for autonomous or back up electrification can be rated for average energy efficiency, but only for each particular site demand conditions.

#### 1.4.2.2.3 Dual mode inverters

A Dual Mode inverter has the special feature that it can operate both as a grid dependent inverter (Current Source Inverter) and also, when the grid is down, as an autonomous inverter (Voltage Source Inverter).

Its main purpose is to offer a back-up solution when the grid goes down, i.e. feeding the load from an alternative power

source, such as batteries. Then when the grid is back, the dual inverter synchronizes and a transfer switch connects it seamlessly to the grid while, at the same time, switching to grid dependent mode.

The transfer relay that disconnects and reconnects the inverter to the grid can be either internal or external. The dual inverter accepts a wider fluctuation of grid voltage and frequency than a purely grid-dependent inverter. Unintentional islanding while connected to the grid is avoided by the transfer relay.

In the case of Lebanon, the country suffers regular power cuts due to the energy shortage. Given this context, the PV plants installed within the CEDRO project have been designed to be used as back-up to cover the energy demand at least during the power cuts of the grid. When there is grid supply, the PV generation helps to reduce the consumption from the utility grid by supplying the load of the facility and charging the battery, as well as back-feeding to the grid any excess power. During the power cuts, power is taken from the DC side (PV generator and the battery) to fill the gap and provide back-up electrical

Opening of the transfer relay			
	CEDRO settings	Factory min value	Factory max value
Grid Voltage min	165 V	50 V	230 V
Grid Voltage max	270 V	235 V	290 V
Grid Frequency min	35 Hz	35 Hz	50 Hz
Grid Frequency max	85 Hz	50 Hz	85 Hz
Delay in the opening	8 s	0 s	30 s
Closing of the transfer relay			
	CEDRO settings	Factory min value	Factory max value
Grid Voltage min	175 V	60 V	230 V
Grid Frequency min	35 Hz	35 Hz	50 Hz
Grid Frequency max	85 Hz	50 Hz	85 Hz
Delay in the closing	0 min	0 min	
Other			
	CEDRO settings	Factory min value	Factory max value
Time of interruption	20 ms	1 ms	40 ms
Current Max of transfer relay	50 A	-	-

Table 5. Settings for a dual type inverter in the CEDRO project (Source: CEDRO, TTA)\*

\*Table 5. Other manufacturers offer dual type inverters with external relays such as, for example, SMA's Sunny Backup.



supply to the essential loads whilst the non-essential loads remain disconnected until the grid is available again. In the CEDRO demonstration sites, Studer Innotech XTM 4000-48 dual inverters have been used that have an internal transfer/synchronization relay with the settings in

#### 1.4.3 Switchgear and electrical accessories

Switchgear and electrical accessories includes all the cabling, circuit breakers, grounding connections, switchgear, and metering. These components are mounted outdoor and must be capable to withstand rain, extreme temperatures, corrosion and exposure to UV radiation. All electrical equipment has to be rated for the voltage class (LV, ELV) and current (AC, DC) it will be subjected to. Cabling for PV generators is available in several grades of temperature and voltage class, UV resistance, and wet conditions.

#### 1.4.4 Energy storage

Energy storage is needed for autonomous and back up applications to partially store solar-generated electricity and to be able to match the load and the generation profiles thus delivering an uninterrupted service. While a variety of battery technologies are increasing their share of the market, lead-acid technology still remains the more common commercial form of electrochemical reversible storage. Lead-acid batteries are available as open vented or sealed, with absorbed glass mat (AGM) or gel electrolyte. Batteries should not be fully discharged and their practical capacity is the difference between the rated capacity and the manufacturer's mandatory residual charge. For most applications, a deep-discharge flooded lead-acid technology is used for long durability and cycle life. These types of batteries have to be periodically charged, as often as possible, to their full state of charge (SoC) and if properly designed, sized, and maintained, they can attain service lives of 10 years or more.

Batteries make up for the periods when there is load and not sufficient solar irradiation, such as during the night or

during cloudy weather. The match between daily and seasonal load profiles and PV generation profiles establish the patterns of charge and discharge duty cycles that influence storage sizing and design. In a typical daily duty cycle in an autonomous plant, the battery is charged during the day and is discharged during the night with a shallow cycle. If there is a sequence of cloudy days the battery is discharged with a deep cycle (see

Figure 18). These cycles are the main parameters that affect the lifetime of a well-kept battery, although other parameters such as battery temperature, current, and voltage are significant as well.

Figure 18 clearly shows, for an autonomous residential application, that a high SoC is easy to maintain in the summer and more difficult during the winter. The seasonal extremes range from a low of 20% in the winter to 100% in the summer with an annual average of about 70%. During winter, the battery charge controller's disconnect function occasionally sheds loads to avoid battery damage. Typically on a monthly basis, the battery should become fully charged at least 30% of the days and preferably more to assure long life and adequate equalization. Depending on how carefully the user manages the PV plant, the battery may frequently suffer long periods of intermediate state of charge without reaching full charge even under average irradiation conditions: This presents an additional stress which shortens battery lifetime. In back-up applications, cycling of the battery takes place only during the periods of blackout and battery capacity can be smaller than for a similar fully autonomous application.

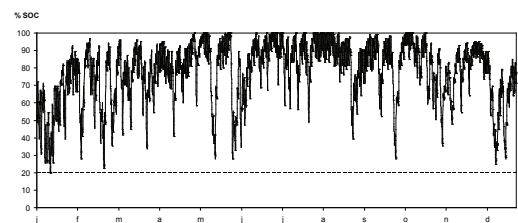


Figure 18. Data on Battery State of Charge (SoC) for one year in a PV-autonomous plant supplied a remote household in Mediterranean climate. Note combination of shallow and deep discharge cycles (Source: TTA).

Alternative types of batteries for PV applications are currently under research and validation, see for example IRENA's report on "Electricity Storage and Renewables for Island Power" [9].

The selection of one of these technologies depends on the requirements regarding performance, lifetime, safety and cost for a given application, all having a high recyclability.

Recent progress suggests that Lithium (Li) ion batteries are the best placed alternatives to eventually replace lead acid for some applications, given their much smaller size and weight (7 to 10 times less), higher efficiency (near 100%), higher durability and reliability (>3,000 cycles with a 80% depth of discharge) and maintenance-free that offset their comparatively higher costs [10]. Moreover, the market for Li-ion batteries is expected to rapidly develop thanks to the electric vehicle industry.

#### 1.4.5 PV battery charge controllers

The battery is the most fragile part of the PV installation and the control over it will greatly affect its duration. The charge control functionalities are to control the DC current from the PV generator into the battery and from the battery to the loads. These may be embedded into a specific device - the battery charge controller (BCC) - or partially or totally integrated with other components such as the inverter.

The design of an autonomous PV plant for high supply reliability and a high solar fraction (> 90 %) implies an oversized PV generator because it is sized to meet worst case average conditions. Consequently, it can yield more energy than needed during certain periods of the year. When the battery is already full and there is no grid or load to absorb the power, the PV generation has to be curtailed to avoid overcharging the battery. The battery charge controller

Battery Technologies	Characteristics
Lithium based (Li)	High energy density, small and light
Nickel based (Ni)	Proven off-shore & harsh environments, long life
Lead based (Pb)	Proven in application, lower cost
Sodium based	High energy density

Table 6. Specific attributes of different battery types (Source: EuroBat [10])

Also Ni-Cd technology is used for energy storage in PV. It is an advanced, easy to charge and robust battery technology, suitable for all industrial applications under extreme environmental conditions (usable at extreme low and high temperatures from -50°C up to +60°C). At the same time, the Ni-Cd battery technology provides medium acquisition costs and also low life cycle costs for the operator. Ni-Cd batteries are recycled in established recycling facilities with a close to 100% recovery of Cd, which is re-used for battery manufacturing purposes [10]. Ni-Cd batteries have a high number of operating cycles at low DoD (depth of discharge) (4.800-6000 cycles at 33% DoD), but low at very high DoD (300 – 500 at 100% DoD) and around 1000 – 1500 cycles at typically 80% DoD [11]. The efficiency of Ni-Cd batteries is lower than the Li-ion batteries and close to the Lead-Acid's (0.65 -0.85) [11].

essentially manages the flow of current into the battery as needed; it allows current to flow to the loads, maintains the photovoltaic generator at its maximum power point (in the case that this feature is included), provides disconnect capability to prevent over-discharge of the battery by either disconnecting or disabling certain components and provides an interface with the user. In Lebanon's back up application, the surplus PV generation is only curtailed during blackouts because, when the grid is available, it is back fed to the grid, which then actually becomes a virtual storage for consumption at a later moment under a net metering agreement with the electrical utility.

There are different techniques to control the charging of the battery, either using the measurement of voltage or using the measurement of input/output current.



The voltage measurement is simpler and charge controllers for small installations use this parameter. In medium and large installations, control is based on the measurement of voltage and current, and in some cases, a historical record of the battery cycles. The most widely used charge controllers are the ones that control the DC current.

PV battery charge controllers for lead-acid batteries can be of several types:

- Series controllers, which include a switch between the PV generator and the battery in order to stop the charging
- Shunt or parallel controllers, which short-circuit the generator current at the end of the load
- Charge controllers with internal high frequency conversion that allows absorbing power from the PV generator at its maximum power point (MPPT) for increased performance

Also, there are several types of control strategies. In the “on-off” controllers, the charging current is completely interrupted when the “end of charge voltage” is reached while in charge controllers with Pulse Width Modulation (PWM), the charging current is gradually reduced in order to maintain the equalization voltages.

In autonomous installations, abnormal situations may occur. The most potentially dangerous situation for both the charge controller and for the loads is the operation without battery, which can happen accidentally if the protection fuse breaks. In order to avoid this problem, the charge controller must be able to withstand any situation of “non-battery” and protect the loads.

To select an appropriate charge controller, the input current (from the PV generator) and the output current (from the battery through the controller to the loads) should be considered. It is advised to multiply the current values by a safety factor of 1.25. The final size of the charge controller is selected by the calculated maximum DC current.



Figure 19. PV installation functionally integrated into the building façade. Library in Mataró, Spain (Source: TTA)



Figure 20. Ground mounted PV system in a rural environment in Spain (Source: TTA)

For PV generators in buildings there are several solutions ranging from simple add on concepts to sophisticated architectural integrations. With *physical integration*, the building is used to support the frame of the modules saving some of the structural costs and adding value to the roof of a building that is already exposed to sunlight; by *visual integration* one adds to the previous concept the fact that the PV generator purposely impacts on the intended appearance of the building; and with *functional integration*, PV cells can be embedded into PV roofing tiles or modules can take the form of roofing, shingles, windows, awning, or skylights and may also include other construction components functions (see Figure 19).

Many commercial roofs are flat and not normally designed to withstand additional overloads. A ballasted structure with concrete blocks is a practical solution to support the PV generator but the building's capacity to withstand additional load should be assessed (see Figure 21). Another option is to fasten it to the roof surface but one must take into consideration the existing waterproofing and thermal protection

(see Figure 23 and Figure 24). In a tilted roof the modules can be fastened to the roof structure with a rack or frame (see Figure 22). Carports are also a good option for commercial applications where the

additional cost of higher structures can be offset by the benefit of providing shade for cars, while, furthermore, not necessitating the requirement for additional land.



Figure 21. Ballasted structure with concrete blocks on flat roof. Installation in the army barracks site done within the CEDRO project (Source: CEDRO project site)



Figure 22. PV modules fastened to the tilted roof structure. Installation done within the CEDRO project (Source: CEDRO project site)

#### 1.4.6 Structures

PV generation needs important surfaces exposed to sunlight where PV generators can harvest it. Structural solutions differ depending on the application, such as ground mounted, or integrated into a built environment such as pergolas and building's rooftops, or façades.



Figure 23. Structure anchored to the roof. Installation done within the CEDRO project (Source: CEDRO project site)



Figure 24. Anchored structure. Installation in Kfor done within the CEDRO project (Source: CEDRO project site)

For ground-mounted PV generators, the structures can be anchored to a foundation ranging from ballast blocks on the ground (see Figure 21), to poured concrete, to driven piles or helical screws. Ground mounted structures can either be fixed or track the sun's direction moving on one or two axes. Tracking structures can boost annual radiation by up to 30% - 45% relative to a fixed optimum angle surface [12]. This increase has associated additional costs since the structures are more expensive to purchase and maintain and also require more area to avoid row to row shadowing. Given the current module costs reductions, in general, the additional yield obtained does not seem to make up for the extra costs and complexity of tracking structures. This reality must be constantly monitored however as costs of modules and structures will change.

#### 1.4.7 Standards

The applicable codes and standards often cross beyond electrical and PV design practices into disciplines such as building codes and civil engineering standards, land use, and so on, both at national and international levels. The international standards that typically may be

relevant to PV technology and can be considered in the design and procurement aspects of PV plants are given in Table 7.

Components	International Standard
Solar Cells and modules	<ul style="list-style-type: none"> <li>• IEC 60891 ed2.0: Photovoltaic devices - Procedures for temperature and irradiance corrections to measured I-V characteristics</li> <li>• 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.</li> <li>• IEC 61215 ed2.0: Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval</li> <li>• IEC 61345 ed1.0: UV test for photovoltaic (PV) modules</li> <li>• IEC 61646 ed2.0: Thin-film terrestrial photovoltaic (PV) modules - Design qualification and type approval</li> <li>• IEC 61701 ed2.0: Salt mist corrosion testing of photovoltaic (PV) modules</li> <li>• IEC 61730: Photovoltaic (PV) module safety qualification - IEC 61730-1 ed1.0: Requirements for construction; IEC 61730-2 ed2.0: Requirements for testing</li> <li>• IEC 61829 ed1.0: Crystalline silicon photovoltaic (PV) array - On-site measurement of I-V characteristics</li> <li>• IEC 61853 – 1 ed1.0: Photovoltaic (PV) module performance testing and energy rating - Part 1: Irradiance and temperature performance measurements and power rating</li> <li>• 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</li> <li>• EN 50380: data sheet and nameplate information</li> </ul>
Charge controllers and inverters	<ul style="list-style-type: none"> <li>• IEC 61683 ed1.0: Photovoltaic systems - Power conditioners - Procedure for measuring efficiency</li> <li>• IEC 62093 ed1.0: Balance-of-system components for photovoltaic systems - Design qualification natural environments</li> <li>• IEC 62103 ed1.0: Electronic equipment for use in power installations</li> <li>• 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</li> <li>• IEC 62116 ed1.0: Test procedure of islanding prevention measures for utility-interconnected photovoltaic inverters</li> <li>• IEC 62509 ed1.0: Battery charge controllers for photovoltaic systems - Performance and functioning</li> <li>• VDE 0126-1-1: Grid protection – Automatic disconnection device between a generator and the public low-voltage grid</li> </ul>

Storage and other components	<ul style="list-style-type: none"> <li>• 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: Valverements</li> <li>• 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</li> <li>• IEC 62093 ed1.0: Balance-of-system components for photovoltaic systems - Design qualification natural environments</li> <li>• IEC 62103 ed1.0: Electronic equipment for use in power installations</li> <li>• 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</li> <li>• IEC/TS 62727 ed1.0: Photovoltaic systems - Specification for solar trackers</li> <li>• NFC 58 510: Lead-acid Secondary Batteries For Storing Photovoltaic Generated Electrical Energy</li> <li>• IEEE 937: Recommended Practice for Installation and Maintenance of Lead-Acid Batteries for Photovoltaic (PV) Systems</li> <li>• IEEE 1144: Recommended Practice for Sizing Nickel-Cadmium Batteries for Photovoltaic (PV) Systems</li> <li>• IEEE 1145: Recommended Practice for Installation and Maintenance of Nickel-Cadmium Batteries for Photovoltaic (PV) Systems</li> <li>• IEEE 1361: for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic (PV) Systems</li> </ul>
Planning, safety and implementation	<ul style="list-style-type: none"> <li>• 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</li> <li>• IEC 61000: Electromagnetic compatibility (EMC). IEC 61000-4: Testing and measurements techniques</li> <li>• IEC 61724 ed1.0: Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis</li> </ul>

	<ul style="list-style-type: none"> <li>• IEC 61725 ed1.0: Analytical expression for daily solar profiles</li> <li>• IEC 61727 ed2.0: Photovoltaic (PV) systems - Characteristics of the utility interface</li> <li>• IEC 62108 ed1.0: Concentrator photovoltaic (CPV) modules and assemblies - Design qualification and type approval</li> <li>• IEC 62124 ed1.0: Photovoltaic (PV) stand alone systems - Design verification</li> <li>• IEC 62253 ed1.0: Photovoltaic pumping systems - Design qualification and performance measurements</li> <li>• 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;</li> <li>• IEEE 928: Recommended Criteria for Terrestrial Photovoltaic Power Systems</li> <li>• IEEE 1374: Guide for Terrestrial Photovoltaic Power System Safety</li> <li>• IEEE 1526: Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems</li> <li>• 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</li> </ul>
General standards	<ul style="list-style-type: none"> <li>• IEC 61702 ed1.0: Rating of direct coupled photovoltaic (PV) pumping systems</li> <li>• IEC 61725 ed1.0: Analytical expression for daily solar profiles</li> <li>• IEC/TS 61836 ed2.0: Solar photovoltaic energy systems - Terms, definitions and symbols</li> <li>• IEC/PAS 62111 ed1.0: Specifications for the use of renewable energies in rural decentralized electrification</li> <li>• 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);</li> <li>• IEC 62446 ed1.0: Grid connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests and inspection</li> <li>• 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.</li> <li>• DIN 5043-2: Radioactive luminescent pigments and paints; method of measurement of luminance and designation of luminescent paints.</li> </ul>

Table 7. International standards considered for PV devices and installations



## 2. Institutional and developer aspects of PV plants

### 2.1 PV Plant development steps

A couple of steps should be followed for the correct development or deployment of a PV plant.

grid. Bear in mind that PV plants are initial capital intensive investments with operational lives of at least 25 years and these aspects need to be carefully assessed under present circumstances but also, and most importantly, in light of any possible policy change in the short, medium and long term.

Recent experiences in regulated PV markets (e.g. Spain) have shown that the regulatory framework may be subject to important modifications due to political, financial or even collateral factors.

### PV Development steps

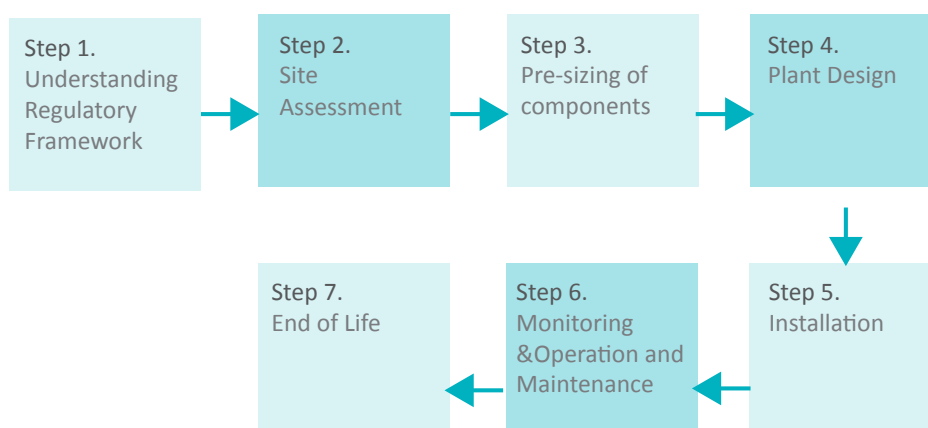


Figure 25. PV plant development steps

#### 2.1.1 Understanding regulatory framework

The first step in any PV plant investment consists in a clear understanding of the relevant legal and administrative requirements, and their possible evolution with time. Grid connected PV generation can be exploited in several ways depending on the underlying nature of the electricity sector and the (present and future) energy policies set up. A major decision is whether the produced energy is for self-consumption or to be sold to the electric utility under some long term purchase agreement.

The general key aspects that any PV plant developer must ascertain are grid connection conditions, electricity revenue regimes, and transaction procedures related to electricity injection into the

Hence, a regulatory risk analysis under several scenarios is a sound exercise to carry out, to help pinpoint those aspects that may more critically affect the feasibility of a given PV development and address them conveniently in throughout the PV plant design chain.

#### 2.1.2 Site assessment and solar resource

Prior to the design stage, it is essential to assess the site to ensure that it meets the requirements of space availability, clear exposure to solar radiation, climate, orientation and tilt of the plane foreseen for the PV modules (esp. for facade or a roof), and also the possible locations for the electronic equipment.



Figure 26. Grid-connected PV generator integrated on roof according to the space available and characteristics of the location (Source: TTA)



Figure 27. PV installation integrated on space available (on roof and façade) Spain (Source: TTA)

A PV installation integrated into a building can also provide some energy efficiency and comfort measures (i.e., reduce the heat load by placing rows of PV modules as eaves above windows to shadow them during the summer or to use the PV modules in a pergola covering part of the roof to reduce the intensity of solar induced cooling load) (more detailed information can be found in section 2.1.2.5 “Roof and ground mounting considerations”).

Furthermore, the adequacy of road accesses to the proposed site must be assessed; eventual civil works will increase the cost of the PV plant development.

#### 2.1.2.1 Resource at the selected Location

The sun paths throughout the year are dictated by the latitude and longitude and, together with cloudiness and atmospheric conditions, will define the solar energy

resource expressed as kWh/m<sup>2</sup>/day or its equivalent term sun peak hours.

Weather resource data can be obtained mainly in two different ways: from ground based meteorological stations or by satellite (geostationary or polar-orbiting) measurements and simulations based on both sources to assess it for different orientations and tilts. Some well-known available online web applications exist such as the PVGIS<sup>1</sup> use data from the European Radiation Atlas in their first databases, which are then interpolated until they cover the desired surface resolution. New databases that are being incorporated in such applications come from satellite databases like Meteosat. Although satellite based data is not as accurate as ground measurements, it offers the best coverage and regular calculations for large territories and long periods of time.

Other reference source that has sufficient accuracy for most designs in Lebanon is Solar-MED-Atlas<sup>2</sup> – which provides the global horizontal irradiation (GHI) and direct normal irradiation (DNI) (see Figure 28 for the solar resource map of Lebanon).

In October 2011, AF-Mercados EMI; TTA and IDRC performed an *Assessment of Renewable Energy Sources* in Palestine for The Palestinian National Authority and The World Bank [13]. Within the assessment, solar data (global irradiation<sup>3</sup> at a 0° (horizontal)) obtained from several ground meteorological observation stations around the country<sup>4</sup> was compared to the solar satellite data obtained from the Helioclim 3 databases<sup>5</sup>. The ground data was based on measurements that were taken for several years at different sites,

1 PVGIS (Photovoltaic Geographical Information System) is developed by the Institute for Energy and Transport of the Joint Research Center of the European Commission (<http://re.jrc.ec.europa.eu/pvgis/>) [last accessed May 2013]

2 <http://www.solar-med-atlas.org> [last accessed May 2013]

3 Global irradiation is the sum of the radiation coming directly from the sun to the surface and the diffuse radiation that has been reflected by the atmosphere and clouds

4 Measurements taken for several years at different places in Palestine, provided by the Energy Research Center (ERC) of the University of An-Najah (<http://www.najah.edu/page/149>)

provided by the Energy Research Center (ERC) of the University of An-Najah<sup>6</sup>. In addition, monthly averages from ground stations were compared with data values from the Helioclim and PVGIS databases. The comparison showed that the annual average differences did not exceed 4%.

It was concluded that the solar data obtained from those databases is an

acceptable basis for sizing and calculation of the yield for PV plants. The results of the study could be extrapolated to Lebanon.

Taking Beirut as a reference site and using PVGIS to obtain irradiation values

for different tilts we can state that, on average, **Lebanon has a solar Global Horizontal Irradiation of 5.3 peak sun hours, which yearly stands for about 1,934 peak sun hours.**

According to the study, in the case of Concentrated Solar Power (CSP) technology, which uses the Direct Normal Irradiation (DNI), it is recommended to obtain the data (irradiation and temperature) by collecting ground measurements for a minimum of one year for each specific site.

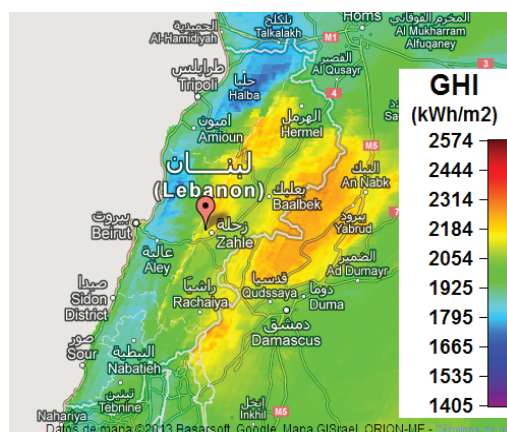


Figure 28. Solar resource map (Source: Solar-Med-Atlas)

Month	$H_n$	$H(23^\circ)$	$G(30^\circ)$	$G(45^\circ)$
January	2610	3610	3830	4140
February	3470	4400	4590	4790
March	4680	5380	5470	5450
April	5870	6160	6110	5770
May	7270	7130	6930	6240
June	8150	7730	7430	6520
July	7900	7610	7360	6530
August	7200	7380	7260	6720
September	6130	6880	6950	6810
October	4580	5690	5890	6080
November	3200	4370	4620	4970
December	2390	3390	3620	3960
Daily Average (Wh/m <sup>2</sup> day)	5300	5820	5840	5670
Sun peak hours (daily average)	<b>5.30</b>	<b>5.80</b>	<b>5.84</b>	<b>5.67</b>
Sun peak hours (yearly average)	<b>1,934</b>	<b>2,124</b>	<b>2,132</b>	<b>2,070</b>

Table 8. Global irradiation received at different tilts for Beirut (Source: PVGIS HELIOCLIM)

<sup>5</sup> Helioclim databases last accessed May 2013; available at: <http://www.helioclim.org>

<sup>6</sup> <http://www.najah.edu/page/149>



### 2.1.2.2 Orientation and Tilt

There are general rules of thumb to consider when choosing the orientation of a fixed PV generator. Empirically, for maximum yearly yield in the Mediterranean regions, it is recommended to have the surface facing south and tilted at approximately 5-10 degrees less than the local latitude. On the other hand, for self-consumption, both back up and autonomous, optimum tilt is 5-10 degrees more than the local latitude.

Other factors that can be considered to choose the orientation are convenience (for example using the slope of an existing roof may be less expensive and make up for the loss of performance in comparison with the optimum slope); minimizing the shade effect in multiple row configuration; shading from landscape and trees and surrounding buildings; consistent morning fog or afternoon showers; and sensitivity to required priority time of generation (for example in the PV back up plants for schools and municipal buildings developed within project CEDRO in Lebanon, the PV modules face 20° east to favor more generation during the opening hours of the facilities – in the morning).

Table 8 shows global irradiation monthly values for different angles at South orientation for Beirut. Based on this a tilt of 30° is recommended for maximum yearly yield; 23° for maximum yearly yield when we have space limitations and multiple rows (see section 2.1.2.3); and 45° for autonomous and back up applications where the objective is to compensate the difference in irradiance between summer and winter.



Figure 29. PV installation on the roof of El Tleile public school developed within the CEDRO project. The PV modules face 20° east and 45° tilt (Source: CEDRO site)

### 2.1.2.3 Impact of partial shading

Even partial shading on the surface of a PV module has a surprisingly high impact on its output power due to the series connection between the PV cells, which causes that the current on the entire string to be determined by its weakest cell. **A partial shade on less than the 6% of the surface of a PV generator may reduce its output by over 70%** [14]. Partial shading can be caused by trees, walls, rooftop equipment, or adjacent rows of modules.

Partial shading is difficult to model yet it should be easy to avoid once a site assessment is done. Some sophisticated simulation software can model both near-field and horizon effects while other tends to treat it as a constant loss factor.

In multi-row PV generators, row to row shading should be assessed to minimize yield losses. For a given site, the main design parameters include: row spacing, PV generator orientation (azimuth and slope), and module layout (vertical or horizontal). Annual shading losses should be limited to 2-4%. In practice, in Lebanon, this means spacing rows such that the setback ratio is at least 2:1. The setback ratio (SBR) is defined as the horizontal distance between rows,  $b$ , divided by the vertical distance between the high and low sides of adjacent rows,  $a$ . As shown in Figure 30, the SBR, the critical shade angle ( $\alpha$ ), the ground cover ratio (GCR), and the PV generator tilt ( $\beta$ ) are all related. The GCR is defined as the PV generation surface divided by the ground area, or in continuous rows, as the module width,  $c$ , divided by the row spacing,  $d$ .

$$\text{SBR} = b/a$$

$$\alpha = \tan^{-1}(1/\text{SBR}) = \tan^{-1}(a/b)$$

$$\text{GCR} = c/d = (\cos(\beta) + \text{SBR} \cdot \sin(\beta))^{-1}$$

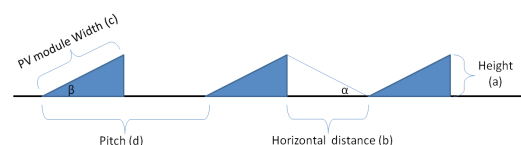


Figure 30. Row spacing at slope angle  $b$  (Source: TTA)

Figure 31 illustrates how design geometry can affect losses caused by inter-row shading for multiple row PV generators<sup>7</sup>. The example showed is situated in Beirut, Lebanon; the generator has a setback ratio of 2:1, which corresponds to a noon time critical shade angle, or constant limit angle, of  $26.5^\circ$  for a south-facing surface. The upper green line represents the output as a function of tilt angle for a single row and shows an optimal tilt angle of  $27^\circ$  (which happens to be  $6^\circ$  less than the  $33^\circ$  latitude at Beirut). The black line below represents the output for a realistic PV generator with a constant setback ratio of 2:1 for any choice of tilt angle and the squares in blue shows the GCR. An interesting conclusion is that the optimal angle for this example is around  $23^\circ$  that is several degrees less than might otherwise be selected in a single row arrangement.

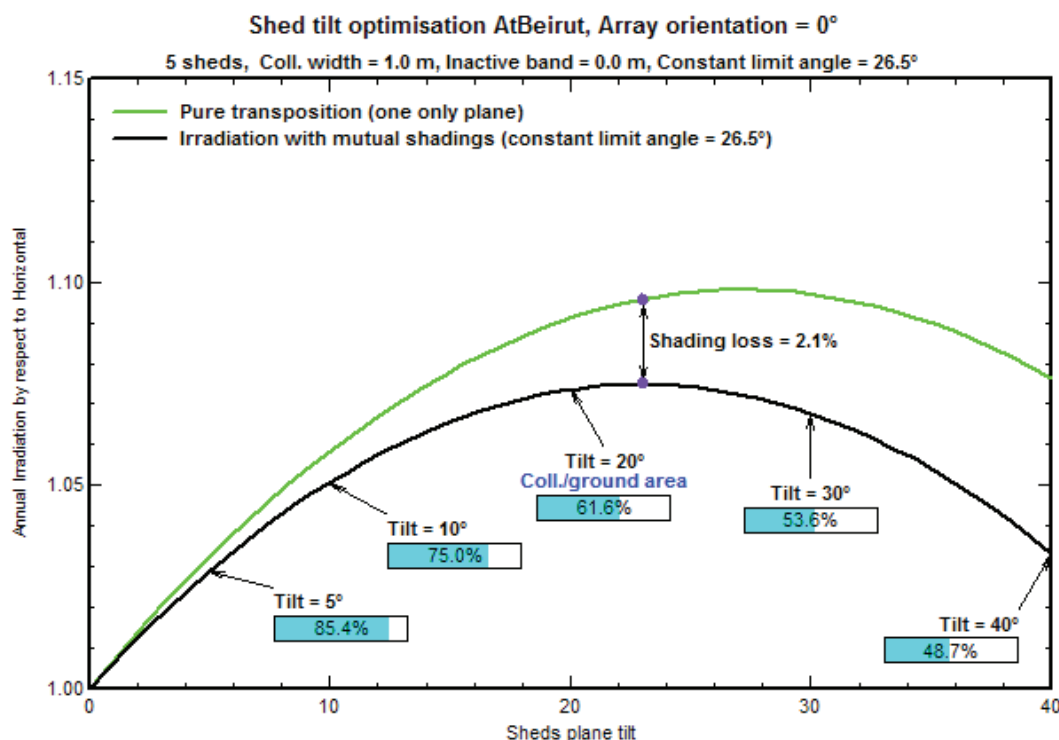


Figure 31. Beirut, Lebanon, optimal tilt angles for one unshaded row and for multi-row shading, for a constant setback ratio of 2:1 (Source: PVSyst by using data from Solar-MED-Atlas)

As another example, the same simulation is done with a different setback ratio (1.5:1), which corresponds to a constant limit angle, of  $35.2^\circ$  for a south-facing surface. As shown in Figure 32, the shading loss by using the indicated SBR is almost 5%, while using the 2:1 the shading loss was around the 2%.

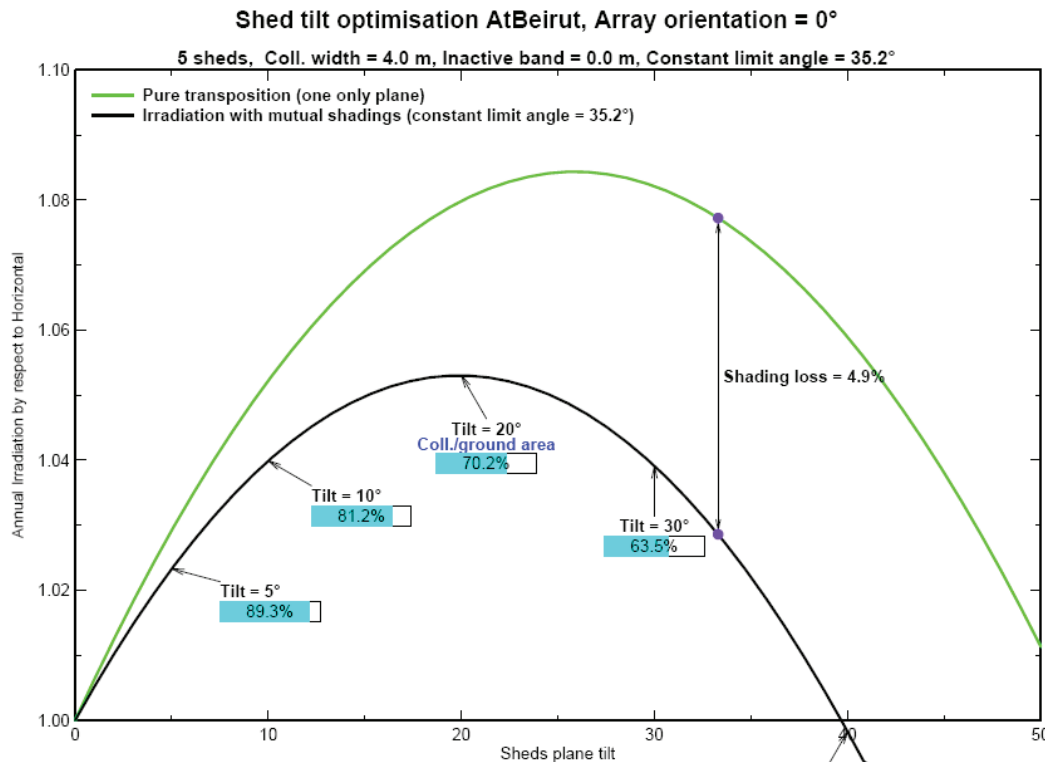


Figure 32. Beirut, Lebanon, tilt angles for one unshaded row and for multi-row shading, for a constant setback ratio of 1.5:1 (Source: PVsyst by using data from Solar-MED-Atlas)

Row to row shading will usually occur only for a short period of the year, but if it is significant, then the choice between vertical vs. horizontal module orientation of crystalline modules becomes important. Shade bands are projected along the lower edge of rows and it is advantageous to mount the modules in a horizontal direction so that the current can bypass through the bypass diode the shaded series of cells without losing the entire output.

Most thin-film modules are less sensitive to partial shading and reductions in output that are more nearly linearly proportional to the shaded fraction of total generator surface.

The ground cover ratio (GCR), or the active PV generator surface relative to the ground footprint area, is significant in terms of shade impacts. Most fixed orientation PV generators at tilt angles optimized for maximum annual yield will have GCRs in the 0.4 to 0.6 range, meaning that the total area of the PV modules is about a 40-60% of the total land acquired. Horizontal 1-axis trackers can achieve shade losses comparable to fixed tilt PV generators with

only slightly less dense GCRs, typically in the 0.35-0.5 range. Tilted 1-axis and 2-axis tracking PV generators generally need to be spaced at GCRs in the 0.20 range or less in order to achieve comparably low annual shading losses of about 2% [15],[16].

#### 2.1.2.4 Impact of dust

The yield of the plant can be reduced by dust, leaves and bird droppings on to the module surface. If the site is exposed to dusty conditions scheduled washing of the PV modules should be considered and compared against the relative financial losses associated with the expected decrease in yield. A single washing in the middle of the dry season and another one at the end can significantly reduce annual dust losses [17].

#### 2.1.2.5 Roof and ground mounting considerations

The option of mounting a PV generator on the roof of a building or on the ground is conditioned by its size and multiple considerations. In addition to the building's orientation and available surface, the

decision is affected at least by some of the following characteristics:

- Surface type (tiles, metal, inverted roof, waterproofing, concrete, etc.)
- Basic condition and strength (live load and wind load limitations)
- Accessibility (equipment installation and service access)

For ground mounted PV generators, some typical considerations are:

- Soil type
- Drainage
- Vegetation control
- Security

Shade structures and pergolas are a special case of structural solutions for ground and roof mounted PV generators that have been successfully used in urban settings as well as in carports. In addition to the generation of electricity it offers the benefits of providing shade and using space that has been committed to other forms of development. Often the higher cost of the elevated structure is offset by the additional functionalities it offers.



Figure 33. Urban Pergola (canopy) in Barcelona, Spain (Source: TTA)



Figure 34. Roof mounted shade structure in Barcelona, Spain (Source: TTA)

### 2.1.2.6 Interconnection to the grid

The power generated at a PV plant can either be consumed by local loads, delivered to the grid or both.

For grid connected applications, it is necessary to assess and consider the technical conditions of the grid at the site. In large PV plants aimed for bulk generation, step up transformers are often included so that they can be interconnected at high voltage. Regarding PV plants associated with a certain site demand, PV is typically a second source of electricity (or third when Diesel Gensets are present) to complement the utility feed. The PV source is interconnected to the grid either at utility feed connection point on the utility side (facility's main switch) or as a branch within an existing service panel inside the consumer's distribution circuit. Some design considerations include:

- PV plant maximum current rating to the grid
- Dispatch capacity into the grid (priority of dispatch)
- Distance and routing from PV plant switchgear to interconnection point
- Main service panel current, voltage, and phasing
- Main service panel age, condition, and available space for additional branch
- Local utility metering requirements

### 2.1.2.7 Load profile

The facilities' load information is relevant for PV plants that generate mainly for self-consumption, such as institutional, residential, commercial and industrial customer categories that typically have different daily and seasonal load profiles that must be compared to PV output profiles. For example, a plant sized to maximize the ability of the PV to offset the needs of a back-up genset during black-outs will be different from one that does not experience grid interruptions and whose goal is to maximize the annual PV yield.

For autonomous and backup plants, the load profile dictates storage needs, PV



generator size and backup genset power capacity, if needed. For example, an off-grid residence with permanent annual occupation will typically require enough storage capacity to satisfy the nominal energy needs, during periods of low irradiation, with an autonomy in the range of 3 to 6 days; whereas for a school with daily blackouts and a good coincidence factor between PV generation and load, the optimum battery autonomy will be in the order of 1 day of nominal load.

#### 2.1.2.8 Access for repairs and maintenance

Even if one of the main advantages of PV technology is that it requires very little up keeping, convenient access is necessary for scheduled routine inspections and to replace failed components. Access to equipment is often limited with fencing or by being located on rooftops or indoors and therefore requires scheduled procedures to service it. It is also important to consider the infrastructure means that will be available to the maintenance crew when planning the design of the PV plants, in particular the size and maximum weight of the components. Some relevant maintenance access items are:

- Security clearances to allow for access to the plant components
- Maximum volumes and weights of components
- Storage space for spare parts and tools
- Water for washing of the PV generator
- Service safety areas for access to rooftop equipment

#### 2.1.3 Pre sizing of components

Preliminary sizing can be done with simplified methods based on state of the art best practices but a more detailed method requires modeling and iteration. For PV, as with most other renewable energy technologies, one tries to convert a capacity-based commodity (kW<sub>p</sub>) into an energy-based commodity (kWh). The economic optimum size is not critical for

grid-tied bulk generation plant, but more critical for autonomous, back up and net-metered plants. The reason is that the utility automatically delivers alternative power not supplied by a grid-tied PV plant, but the autonomous PV plant developer must assure sufficient supply available at all times and the net-metered plant owner does not profit for any surplus generation that is not balanced by consumption.

##### 2.1.3.1 Grid-tied

For grid-tied plants, the optimal design should provide the best economic payback once a comprehensive evaluation of all costs and benefits during all the life-cycle of the plant is done. However, since the sensitivity of cost to size is relatively flat, other criteria that may dominantly affect the size of a plant are:

- Sized to fit electrical infrastructure (substation capacity, transformer, feeders)
- Sized to fit available surface (ground, roof, building)
- Sized to meet or offset a target of annual energy (kWh) load
- Sized to offset a target fraction of peak power (kW) demand
- Sized to obtain maximum incentive (premium tariffs, rebates)

##### 2.1.3.2 Autonomous and back up

Autonomous plant sizing is usually done so that the PV yield covers all or a pre-established fraction of the load. However, these requirements have more variables than grid tied arrangements and the following aspects need to be addressed:

- The inverter capacity rating must meet surge AC power needs (5" and 30' rating)
- For DC loads directly connected at the DC bus bar, the breaker and battery charge controller rating must meet the surge power needs. If there are DC loads at a different voltage than the battery, a DC-DC converter is needed and its rating must meet the surge needs
- The PV generator is sized to meet energy needs under the seasonal

daily average worst combination of weather and load

- The PV generator is sized to meet the minimum allowable solar fraction of the nominal load
- The storage capacity is sized to meet a minimum autonomy supplying the nominal load without generation

### 2.1.4 Plant design

When designing a PV power plant, the results of the site analysis and resource data are considered and then the components are selected and integrated in such a way that will meet the performance objectives. Iteration is often done to optimize the solution considering also market and component availability conditions. The first decision parameter is to determine whether the plant will be grid-tied or autonomous or both (dual type back up). Most autonomous and back up plants use, on the DC side, extra low voltage (ELV) (up to  $\approx 75$  V). For small grid tied plants, up to approximately 10 kW, designers can choose between using extra low voltage DC ( $\approx 75$  V) or low voltage (LV) (up to 1 000 V) to the inverter. For larger plants, low voltage on the DC side is the most common practice. The main considerations between these two voltage classes are the relative intrinsic electrical safety and shade tolerance of ELV PV generator layouts versus the higher efficiency, lower wire losses, and reduced cost for LV PV generator layouts.

#### 2.1.4.1 Component selection

##### 2.1.4.1.1 PV modules

When considering investment costs, PV modules are the most significant single element of a PV plant, however various PV modules are often similarly priced and therefore other considerations end up influencing the module selection.

Some of the relevant considerations are:

- Efficiency: Efficiency becomes relevant if there are space considerations that constrain or exclude lower efficiency modules (4-8% at STC). Higher efficiency modules

(> 13% at STC) have the additional advantage where costs for items like land, structure and wiring are smaller. Nevertheless, it is important to keep in mind that some thin film technologies, although they may have lower efficiencies, may exhibit a higher yield per installed capacity, particularly in hot weather.

- Installation and handling: Modules with frames are used more commonly than frameless modules. For large installations, plug connectors have displaced traditional junction boxes with terminals. Grounding methods and physical size are also relevant. Smaller modules are cheaper to ship, easier to handle and present less structural demands but may be more labor intensive regarding wiring because more units are needed for the same total capacity.
- Market availability: Demand for PV modules has, sometimes, been higher than supply, causing delays or product substitutions.
- Electrical ratings: The current, voltage and capacity parameters of each module add up and combine according to the electrical layout of the PV generator and the resulting overall parameters must be compatible with the DC input characteristics of the inverter in grid-tied applications or with the battery charge controller if there is storage. The AC output to the grid must not exceed the current limitations of the AC interconnection.
- Aesthetics: Some modules are specifically designed to visually blend in well with the architecture and unique designs.
- Recognized certifications; there are International and National Standards that increase developer confidence and testing organizations can provide certifications to the manufacturers.
- Warranty: Most manufacturer's warranties include terms of 1 to 3 years workmanship and, for PV modules, a warranty on the power

- produced for up to 25 years<sup>8</sup>. In addition, most modules have about a 10-year warranty on material and workmanship.
- Manufacturer history, reputation and after sales service.

#### 2.1.4.1.1.1 Module nameplate binning practices

Dispersion in electrical parameters between identical modules is inevitable and manufacturers usually list their products with ranges of  $\pm 5\%$ . The emphasis on final yield, as with European style feed-in tariffs, has encouraged manufacturers to state their power ratings and, if requested, they can provide individual reports on the performance test results of each module. The predicted performance of a plant will be influenced by manufacturers' module binning procedures because, when connected in series, the lowest performing module curtails the output of the whole string. These module mismatch losses can be minimized by grouping balanced modules in each string with tolerances as narrow as  $\pm 2\%$ .

#### 2.1.4.1.1.2 Short and long term degradation

Most PV generators lose power over time due to the combination of the following factors:

- Staebler-Wronski (S-W) degradation
- Light-induced degradation (LID)
- Early degradation
- Long-term degradation

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<sup>8</sup> Warranties from several manufacturers such as Atersa ([www.atersa.com](http://www.atersa.com)), Heliene ([www.heliosenergy.es/eng/index.php](http://www.heliosenergy.es/eng/index.php)), aleo Solar ([www.aleo-solar.com](http://www.aleo-solar.com)), Zytech ([www.zytech.es/index.asp](http://www.zytech.es/index.asp)), Sharp Solar (<http://www.sharppusa.com/SolarElectricity/SolarProducts/LiteratureDownloads.aspx>), Canadian Solar ([www.canadiansolar.com](http://www.canadiansolar.com)), First Solar ([www.firstsolar.com](http://www.firstsolar.com)), Trina Solar ([www.trinasolar.com](http://www.trinasolar.com)), Suntech ([www.suntech-power.com](http://www.suntech-power.com)) [Websites accessed on June 2013].

S-W degradation occurs in hydrogenated amorphous silicon modules and causes an initial reduction of 15-25% in power over the first 1,000 hours of exposure. Typically the manufacturer's ratings correspond to the stable degraded condition but when considering the electrical parameters of the PV modules to establish the operating range of the conversion equipment one must account for the additional initial output.

LID (light induced degradation) occurs due to oxygen impurities that get trapped during the ingot formation process. The initial efficiency degrades under illumination until it reaches a stable performance and that accounts for a loss of 1% to 3% in power in wafer type silicon modules.

Early degradation defects are early defects that may appear during operation and are listed below [19]:

- The degradation of the EVA: changing the color from transparent to yellow and sometimes to brown. This defect can be induced by UV radiation combined with temperatures above 50 °C that cause a change in the chemical structure of the polymer. The yellowing/browning decreases the light penetration and thus the output power.
- Delamination: adherence loss between different layers of a PV module with light decoupling and water penetration inside the module that causes electrical risks and chemical degradation of parts of the module.
- Bubbles: mainly appear due to a chemical reaction where some gasses are released. Bubbles reduce the cell lifetime because the heat dissipation is more difficult.
- Cracks in cells: the market tendency is to manufacture thinner wafers that have a higher risk of breakage during module manufacturing. The appearances of micro-cracks are usually not visible but can cause isolation of parts of the cell thus curtailing current generation.
- Hot spots: A hot spot is a region in a PV module which is working at

higher temperature in comparison to its surroundings due to maintained partial shading of the module, cell damage, mismatch or interconnection failure. The hot spot may cause damage to the cell or to the encapsulate.

The described defects can appear after a period of operation due to poor manufacturing quality control, faulty PV plant design, faulty plant and/or module operation. The causes of other module component degradation are not well understood and can include corrosion to the wire terminals.

Long-term degradation is common to most PV technologies. According to different studies the values may range between 0.5% and 1.0% [20]. It is recommended to take a linear annual degradation value of 0.8%.

#### 2.1.4.1.2 Grid tied inverters

The modular concept of PV technology provides a lot of flexibility when selecting an inverter. In grid-tied plants the capacity of the inverter may be similar to that of the PV generator or, more commonly, much smaller since a PV generator can consist of multiple strings each connected to one inverter connected in parallel on the AC side. The following considerations apply to plants with either central or string inverters in which several PV modules are connected to a single inverter.

An initial consideration in the selection of the grid tied inverter is that it is compatible with the DC output voltage characteristics of its PV generator and that it has the required electrical interface capabilities for the grid to which it is connected. The maximum allowed inverter input voltage must be higher than the maximum open circuit voltage ( $V_{OC}$ ) in the worst case conditions (cold weather and high irradiance). The PV generator's Maximum Power Point voltage ( $V_{MP}$ ) range should also be within the inverter's operating range. For grid dependent inverters typical ranges of operating DC voltages are 150 V<sub>DC</sub> to 600 V<sub>DC</sub>. In Europe and other countries,

PV generators typically operate in an ungrounded configuration. For parallel operation with the grid, the PV inverter output is at the same voltage and frequency as the utility grid - in Lebanon typically 230 V<sub>AC</sub> at 50 Hz as it is in Europe and many parts of the world for residential single-phase applications. The voltages are higher for three-phase commercial and utility scale plants. In some large utility scale plants, the inverters' output is stepped up to high voltages (HV) through the use of a transformer.

The second aspect in the selection of the inverter is its continuous operation power rating and temperature. Inverters for residential plants are available in several power ratings, such as 1, 3, 4 and 6 kW. If the DC power available coming from the PV generator is higher, the inverter curtails the PV power to its rated output. As the power available from the PV generator is, most of the time, less than the STC rating, the inverter's AC power rating is smaller than the PV generator DC power rating. An inverter factor of 0.8 or more is used in plant design in sunny climates like Lebanon to optimize costs. For example, a PV generator with a combination of modules that could produce an aggregate capacity of 20 kW<sub>DC</sub> at STC may be connected to one or more inverters with an aggregate power rating of 16 kW<sub>AC</sub>. In some designs, even if occasionally the inverter limits part of the PV generator's maximum power, only a very small fraction of potential generation will be lost [22]. Nevertheless the quality of the inverter is a very important parameter because it affects efficiency and cost if it fails earlier than expected and sometimes designers give priority to a brand and are flexible with regards to the inverter factor.

#### 2.1.4.2 Electrical accessories and switchgear

Electrical components such as wire, conduit, switches, connection boxes and breakers have to be sized to support the required current and voltage, meet the specifications for the intended service environment and need to comply with local electric codes and common practice.



According to the state-of-the-art standards, voltage differences of potential between conductors and between conductors and earth are rated as follows:

- a) extra-low voltage (ELV): not exceeding 50 V a.c. or 120 V ripple-free d.c.
- b) low voltage (LV): exceeding extra-low voltage, but not exceeding 1 000 V a.c. or 1 500 V d.c.
- c) high voltage (HV): exceeding low voltage

**Overprotection devices:** PV string overcurrent protection is not required in Extra-Low Voltage (ELV) PV generators where the PV modules are mounted in such a way and location that fire cannot be caused by an arc or melted metal coming out of the back of the PV module. In all other cases, where there are more than one parallel-connected strings, each PV string shall be protected with a fault current protection device. The rated tripping current ( $I_{TRIP}$ ) of the overcurrent protection device installed is related to the maximum reverse current allowable as specified by the PV module manufacturer.

The wiring of a PV plant is sized considering the maximum voltage drop values between components. Table 9 indicates the recommended values for the maximum voltage drop.

Wiring	Max. Voltage drop (%)	Reference Power
PV modules to inverter (grid dependent)	3	STC capacity
PV modules to charge controller (autonomous and dual)	2	STC capacity
Battery charge controller to battery (autonomous and dual)	2	STC capacity
Battery to inverter (autonomous and dual)	1	Inverter 30' rating

From inverter to loads (AC) (autonomous and dual)	5	Inverter 30' rating
From inverter to the grid (grid dependent and dual)	1	Inverter rating

Table 9. Recommended maximum voltage drop values in wiring

In addition to the consideration of the voltage drop, the wire should be capable of carrying the maximum expected current (i.e., in the worst conditions). The following safety factors are considered when sizing:

- When no overcurrent protection device is provided, the PV generator cable must be capable of carrying 130% of the  $I_{sc}$ ; and
- When overcurrent protection device is provided, the PV generator cable must be capable of carrying 125% of the  $I_{sc}$ .

### 2.1.4.3 Energy storage

Lead acid batteries are the more common technology used but many different qualities of batteries are available. To choose the most adapted option for a particular application, the relevant characteristics to analyze are the purchase price and, from the technical data sheet, the practical capacity related to the maximum recommended depth of discharge (DoD), the predicted service lifetime and cycling life. Service lifetime refers to the operational calendar time of a battery under normal operating conditions and temperature and cycling life refers to the total number of discharge and recharge cycles that a battery can withstand (see Figure 35).

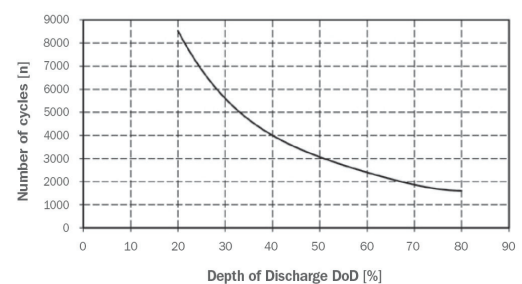


Figure 35. Cycling life and Depth of Discharge for OPzS batteries at 20°C (Source: Hoppecke)

For a long term application, it makes economic sense to purchase high quality batteries with long lifetimes and cycling life (>8-12 years and >1 500 cycles at 80% DoD). It may even be advisable to oversize the PV generator to achieve frequent full charge status of the battery. On the other hand, in a region where batteries are readily available and easily replaced or if the project horizon is short term, it may be preferable to buy a cheaper option that will need more frequent replacement (3-5 years). Battery disposal or recycling should be considered as an upfront design issue, especially when lower grade batteries are selected.



Figure 36. Back up grid tied PV plant with storage. The cabinet for storage and power conversion is easily accessible, well ventilated and the PV generator roof mounted in two rows. Kfarshouba Intermediate public school, South (Lebanon) – Pilot project implemented by the CEDRO project

Excessive discharge can damage the battery and should be avoided by limiting the cyclic discharge to a minimum SoC that, depending on the quality of the battery, ranges between 20% and 70%. When this set point is reached, the loads have to be disconnected or the battery recharged. The *practical* capacity is the fraction of the rated capacity that can be extracted from a full charge condition as recommended by the manufacturer. For the same required *practical* capacity, a battery with a lower allowed SoC will require a smaller rated capacity. All batteries experience a slow self discharge that needs to be accounted for. Accelerated ageing can be caused by prolonged periods of neglect without periodic full recharge. Temperature also strains battery life. Temperatures higher than 20°C increase the rate of self-discharge and may deteriorate battery performance and the operational life [21]. It is essential that batteries be shielded from temperature

extremes and that they be kept in a dry, well-ventilated location to avoid build-up of explosive gases (see Figure 36).

The battery of an autonomous PV plant is sized so that its *practical* capacity endures 3 to 10 days of autonomy to supply the average daily energy requirements. For backup applications, the battery usually only supplies the so called secured loads and lower autonomy is used (0.5 to 2 days). For a winter daily average load of 2 kWh, and a 3-day autonomy target, a practical capacity of 6 kWh is needed. For a depth of discharge of 80% a 7.5 kWh battery is required. For a typical nominal battery voltage of 48 V, 156 Ah of battery capacity would be required.

In the case of the back-up PV plants as installed for the CEDRO project; the battery is sized in order to provide electrical supply to the essential secured loads during the power cuts until the grid is available again. When there is grid supply, the PV generation helps to reduce the consumption from the utility grid by supplying the load of the facility and charging the battery as well as back-feeding to the grid any surplus power. The batteries used in these installations are rated from 10 kWh for the smaller installations of 1,125 Wp to 18 kWh for the installations of 2,700 Wp.

#### 2.1.4.4 Mounting systems

The requirement in the design for structures is that they secure the modules to the underlying surface, ground-mounted or rooftop, over the predicted lifetime of the plant under harsh out-door conditions. The modules are fastened to the structure directly or using rails, but the structure itself can either be anchored, or merely weighted down (ballasted). Structures are calculated to withstand the weight of the PV generator components, the local extreme wind loads, seismic and snow loads if it is the case, in accordance with local practice during installation.

#### 2.1.4.5 Grounding

An earth connection for all relevant components of the installation is needed

in order to protect devices and for safety issues.

#### 2.1.4.6 Economics and design

Several indicators are commonly used to assess economic value but it is always advisable to consider the cost over the full life cycle horizon of the plant. A very good indicator is the cost of energy, expressed as a long-term discounted measure called the “levelized” cost of energy (LCOE) [23] or Levelized Energy Cost (LEC). This term factors in the capital cost of the plant plus operating and component replacement costs, and internalizes a selected discount rate. Given the fact that PV plants have high capital costs and low operating costs, the LCOE is sensitive not only to costs and performance but also to the discount rate available and the rate of inflation. The formula for the LCOE calculation is the following:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

Where,

- LCOE = Average lifetime “levelized” electricity generation cost
- $I_t$  = Investment expenditures in the year  $t$
- $M_t$  = Operation and maintenance expenditures in the year  $t$
- $E_t$  = Electricity generation in the year  $t$
- $r$  = Discount rate
- $n$  = Life of the system

The *discount rate* is an important factor because it sets a minimum threshold for the return on equity (ROE)<sup>9</sup> of the investment. Usually projects will be financed using a mix of equity and loans. For the investment to be profitable, the discount rate would need to be higher than the interest rate paid on loans.

As a reference under current economic conditions in Lebanon, an internal rate of return (IRR) of 14% to 20% offers investors

an attractive *return on equity* (ROE). The exact ROE will vary in each case, as it will depend on the *debt to equity* ratio of the investment (*financial leverage*) and the *cost of loans*.

For grid tied plants that deliver to the grid all their bulk production at a fixed tariff for a certain period of time and the revenue forecast is well established, other indicators such as payback period, internal rate of return (IRR), net present value (NPV), are used.

#### 2.1.4.7 Design and component selection

After the high level definition of the plant has been established, design consists in matching the characteristics of the components to the operating conditions identified for the site.

The temperature range needs to be analyzed keeping in mind that the lowest

PV generator voltage takes place on the hottest day and the highest voltage on the coldest day. For that full range, the combination of PV module type, electrical layout of series and parallels and the converter match efficiently. For design it is common to choose a low and a high temperature that have little chance of being exceeded in the winter and summer months.

Consequently, a solar temperature gain needs to be added to the ambient reference high temperature that will be between 30°C to 50°C depending on how well ventilated the PV module is.

The total number of modules in series per string establishes the generator’s DC voltage because voltage adds up while the current is the same. The module’s output parameters -  $V_{OC}$ ,  $I_{SC}$ ,  $I_{mp}$ , and  $P_{maxSTC}$  have temperature coefficients and one must keep in mind that the temperature coefficients are negative and during the summer there will be a significant decrease of the output with respect to the rated STC capacity.

After the inverter and module have been chosen, the number of modules in each

<sup>i</sup> ROE measures the rate of return on the ownership interest. ROE shows how well a company uses investment funds to generate earnings growth.

string are iterated considering that it must be long enough to reach within the inverter's voltage range with the warmest reference temperature condition and short enough that the maximum voltage rating is not exceeded with the coldest temperature.

Table 10 summarizes the temperature conditions in Lebanon [24].

The total number of modules in series per string establishes the generator's DC voltage because voltage adds up while the current is the same. The module's output parameters - VOC, ISC, Imp, and PmaxSTC have temperature coefficients and one must keep in mind that the temperature coefficients are negative and during the summer there will be a significant decrease of the output with respect to the rated STC capacity.

After the inverter and module have been chosen, the number of modules in each string are iterated considering that it must be long enough to reach within the inverter's voltage range with the warmest reference temperature condition and short enough that the maximum voltage rating is not exceeded with the coldest temperature.

#### 2.1.4.9 Modeling and yield estimates

As a first preliminary estimate, a simplified method of monthly and annual yield can be done without specific software by multiplying daily average values of just three previously defined terms:

$$\text{Annual final yield (kWh}_{AC}) = (\text{PV generator STC capacity (kW}_P)) \times (\text{Reference yield, } Y_r, (h)) \times (\text{Performance Ratio, PR (\%)})$$

But to achieve accurate results, these terms must each be well characterized. The PV generator capacity at STC in kW<sub>p</sub> is simply the sum of the modules' nameplate STC rating. The reference yield (in units of hours of irradiation at 1 000 W/m<sup>2</sup>) should correspond to the in-plane orientation of the PV generator and varies for each location. For Lebanon, the data available at the European PVGIS website is a good reference (see section 2.1.2.1 *Resource at the selected Location*). The performance ratio (PR) is a dimensionless quantity that has a dependence on ambient temperature, component quality, well matched design, and the capacity to evacuate or consume

Zone	Zone 1: Coastal		Zone 2: Western Mid-mountain	Zone 3: Ilnad Plateau	Zone 4: High Mountain
City	Beirut	Bayssour	Qartaba	Zahle	Cedars
Max. Temperature (°C)	32.8 (Aug)	33.9 (May)	31.7 (Jun)	39.4 (Jul)	34.4 (Jul)
Min. Temperature (°C)	4.4 (Jan)	1.1 (Jan)	0.0 (Jan-Feb)	-6.7 (Jan)	-11.1 (Feb)
Average daily max (°C)	23.6	20.6	19.8	22.5	15.4
Average daily min (°C)	9.7	13.7	13.2	9.8	5.6
Average daily (°C)	23.1	20.2	19.5	20.3	14.6
Average night (°C)	20.4	13.7	14.1	11.9	7.1

Table 10. Temperature conditions in Lebanon (Source: UNDP/GEF [24])

#### 2.1.4.8 Intermittency and coincidence factor

The solar radiation profile may not correspond well with the demand profile. The intermittency of resource on a surface occurs on at least three time scales:

- 1) Seasonal - as the average daily radiation varies throughout the year
- 2) Daily – influenced by weather

all the electricity generated. For grid-tied plants that are connected to stable grids, the performance ratio tends to be in the range of 0.65-0.80. For autonomous and back up applications, the performance ratio is in the range of 0.40 to 0.65. For example, and typically in Lebanon, we would have a solar radiation on South facing plane at a slope of 30° with a reference yield of 6.84 peak sun hours /day (2,132 h/year) with a PR of 0.70. The expected final yield in this instance should be around **1,500 kWh<sub>AC</sub>** for each installed kW<sub>p</sub>.



Advanced commercial software is available to perform detailed hourly simulations of energy and many other parameters. Some of the relevant modeling principles are:

**Solar radiation and weather** - a site's climate requires at least 10 years of accurate data, ideally in hourly format. The core measured parameters are global horizontal irradiation and air temperature. Several other parameters are often derived in simulation programs like diffuse horizontal irradiation and direct beam irradiation.

**PV plant characteristics** - The basic types characterize the module yield increasing linearly with radiation and decreasing with temperature, however more sophisticated ones characterize the plant and its components considering horizon shade profile; each module type with several electrical parameters like current, voltage, shape factor and temperature correlations and thermal dissipation properties; inverter efficiency curve and voltage operating range; wiring electrical resistance; orientation and ground cover ratio; and expected lifetime and replacement of components to calculate the LCOE.

**Load profile** – For grid tied plants that sell all their production the only limitation is grid availability. But for grid-tied net-metered, back up or autonomous plants, sizing and economics are very sensitive to load magnitude and profile and, unfortunately, hourly data is seldom available and engineers often make estimates based on customer categories and monthly readings. For more accurate design it is recommended to record hourly, or even better 30' the energy consumed to establish the reference load profile.

**Economic factors**- Economic parameters vary as a function of the required economic indicators but, in general, they will try to characterize the lifecycle costs and income (or avoided costs) of the PV plant. Such terms may typically include; Plant supply and installation cost; scheduled component replacement cost (i.e., battery every 6 years, inverter every 12 years, etc.); maintenance and operation cost including insurance; financing terms like loan, down payment, discount rate; electricity sale price and

foreseen price evolution; taxes and income tax structure for the owner; incentives like rebates, tax credits and soft loans.

#### 2.1.4.9.1 Example commercial simulation programs

Table 11 shows a sample of software programs that are in common use as of 2012 with a basic list of characteristics. The list is not intended to be comprehensive, partly because of the impracticality of assembling such a list and partly because many are only used for specialty purposes, not for full energy simulation<sup>1</sup>. With respect to weather data input, some programs are simulation-based and others are estimation-based. Simulation programs rely on individual time-step records, typically hourly, to calculate accurate profiles for each day but hourly weather data may not be available. Estimation programs typically begin with generally available monthly-average data and synthesize daily profiles using correlations. Another difference is how losses are calculated. Some programs treat factors such as inverter efficiency, shading, dust, and wire losses as constants while others treat them more accurately as varying magnitudes.

Name	Type: Simulation, Estimation, or both Execution: Web or Local	Licensing	Treatment of loss mechanisms	Applicability in Lebanon
PVSYST(Univ. of Geneva, Switzerland)	Type: Both Execution: Local	800 CHF single- user	Highly detailed, time-varying	Yes. Climate data can be added
PV*SOL (Valentin Software, Germany)	Type: Both Execution: Local	Single-user: 395€ (Basic) 468€ (Pro) 998 – 1228 (Expert)	Less detailed, but time-varying	Climate data Beirut
RetScreen (Canada Dept of Nat. Resources)	Type: Estimation Execution: Local	Free	All as constants	Yes. Climate data Beirut and Tripoli
PV f-Chart	Type: Estimation Execution: Local	\$400 US single- user	Most as constants, some as time- varying	Climate data can be added
PV Planner	Type: Both Execution: Web	pvPlanner full coverage: 850€ single-user	Some losses numerically modeled and other assessed by a user.	Yes

Table 11. Sample PV modeling software

### 2.1.4.10 Examples

#### 2.1.4.10.1 Example school with back up PV plant

We will look at a primary school located in Akkar in Lebanon that receives a yearly average of 4.84 peak sun hours [kWh/m<sup>2</sup>] per day at a horizontal plane. The school opens 5 days a week from the month of October to the month of March and for this period the optimum tilt angle is 45° corresponding to an average 5.27 peak sun hours [kWh/m<sup>2</sup>] per day. Akkar is located in climatic zone 1 in Table 8 (reference city Bayssour) [24]. The average minimum temperature in the coldest month is 13.7°C and the record low is 1.1°C, suggesting a design low temperature between these two extremes would be appropriate, or 7.4°C. The average high temperature in the warmest month is 20.2°C and the record high is 33.9°C, suggesting a design high temperature between these two extremes of 27.5°C. We assume there are no significant losses due to shading and that the PV modules will be periodically cleaned by the school's facility manager so there are no soiling losses. The school suffers daily blackouts on average of 5 hours daily that coincide every second week with lecture hours that are from 8:00 to 14:00. The purpose of the PV back up plant is to secure supply during the power cuts to previously selected priority loads. During blackouts, power is taken from the DC bus

bar (PV generator and the battery) to feed the priority loads whilst the non-essential loads in the school remain disconnected until the grid is available again. Since the school hours of consumption are during the daytime the solar generation balances part of the consumption and the battery only discharges significantly on cloudy days.

When there is grid supply, the grid feeds part of the loads and charges the battery (the inverter should be a dual-mode inverter) and the PV generation helps to reduce the consumption from the utility grid, as well as back-feeding to the grid any excess power on a net-metered arrangement with the utility.

The demand of the priority loads was calculated to be 11,895 Wh/day. The quality requirements are that the service is to be provided at standard 230 V-50 Hz AC electricity to the secured priority loads with an average energy daily availability of 11,895 Wh from the PV plant during the working days. For this school, the electricity provided from the PV will cover at least 45% of the priority loads' electricity demand (at least the 45% of the priority loads' consumption will be supplied from renewable resources).

The rated maximum power to the loads is 3,780 W. The battery capacity must be sufficient to cover at least the blackouts of one day of storage at the average daily energy use of the priority loads. The loads

are served via a maximum 15 A circuit. For intrinsic electrical safety, a DC plant rated voltage of 48 V is used. Sufficient space on the roof of the building is assumed to be available.

Estimate of the load. The priority loads inventory (Table 12.) is based on the reported needs and assumes the mandatory requirement that the appliances are all high efficiency. All loads have a daily average on working days. The other general loads, which can also be fed from the PV, but only when there is surplus PV generation, are not considered for the daily energy calculation. From the table we have that the rounded off average demand is 11,895 Wh/day. The inverter has to be able to supply the total installed power (3,760 W) and foresee future increases. The required inverter specifications are: rated power (30 min)  $\geq 4,000$  VA; rated surge power (5 sec)  $\geq 8,000$  VA, and a desired efficiency at an operating power of 2,000 W  $> 85\%$ .

For this type of load profile with a very high average coincidence factor and climate, prior experience suggests that approximately 30% of the energy will flow through the battery. It should be noted that the loads will mainly be fed by the grid and the PV generation, only during grid power cuts while the battery undergoes a duty cycle. Over a 15-year period the estimated battery throughput is (considering that the battery works 13 weeks a year – blackouts that coincide every 2<sup>nd</sup> week with lecture hours and the school is open 26 weeks a year (from October to March)-):

$$11,895 \text{ Wh/day} \times 0.3 \times (5 \text{ days/week} \times 13 \text{ weeks}) \times 15 = 3,479 \text{ kWh}$$

The useful energy per discharge cycle is  $12,391 \text{ Wh} \times 0.8 = 9,912.8 \text{ Wh}$

Therefore, the number of cycles over a ten-year period is approximately

$$3,479,000 \text{ Wh} / 9,912.8 \text{ Wh/cycle} \approx 350 \text{ capacity cycles.}$$

Main Loads	Unit Power (W)	Qty	Power (W)	Average use(hr/day)	Daily Energy (Wh/day)	Maximum simultaneous power
TC-Lamps	38	36	1,368	6	8,208	1,368
Compact fluorescent	18	9	162	6	972	162
Computers	200	2	400	3	1,200	400
Printers	30	1	30	0.5	15	30
Photocopier (standby)	10	2	20	5	100	
Photocopier (operation)	800	2	1,600	0.5	800	1,600
Television	200	1	200	3	600	200
<b>TOTAL</b>					<b>11,895</b>	<b>3,760</b>

Table 12. Priority loads of the example school

The battery useful capacity has to supply at least the demand of the priority loads during the blackouts (5 hours out of 6 hours each working day). We chose a battery type that can handle a maximum depth of discharge of 80% at typical discharge rates of 10 hours and a voltage of 48 V<sub>DC</sub>. This means that the nominal storage capacity has to be higher than 12,391 Wh since:

$$C_{10} = (11,895 \text{ Wh/day} \times (5\text{h}/6\text{h})) / 0.8 \geq 12,391 \text{ Wh}$$

At a rated voltage of 48 V this means that the rated capacity is  $C_{10} \geq 12,391 \text{ kWh} / 48 \text{ V} = 258.1 \text{ Ah}$

Consider a battery whose specifications meet at least the following characteristics:

- Product: lead-acid deep discharge
- Voltage: 48 V
- $C_{10}$  at 20°C = 300 Ah
- Cycle duty:  $> 500$  cycles at 20°C at 80% Depth of Discharge (DoD)

The PV generator should produce on average at least the 45% of the energy required by the priority loads (approx. 5,352/day). When the energy produced by the PV plant is low, the battery will be charged with the grid (when no blackouts occur); we will assume a Performance Ratio

(PR) of 60%. The minimum nameplate PV STC capacity must be:

$$P_{pv} = (5,352 \text{ Wh/day}) / (0.60 \times 5.27 \text{ h/day}) \geq 1.69 \text{ kW}_p$$

A  $75 \text{ W}_p$  crystalline module with 36 cells and a  $V_{oc}$  of 21 V and an  $I_{sc}$  of 4.8 A is selected. The PV generator will require strings of 4 modules each, or  $225 \text{ W}_p$  per string and 6 parallel strings will be needed to satisfy the minimum power requirement of  $1.8 \text{ kW}_p$ . The charge controller must be rated for a maximum voltage of:

$$V_{oc} \times \text{"\# of modules in series"} \times \text{"Cold Weather Temperature Factor"} = 21 \text{ V} \times 4 \times 1.2 = 100.8 \text{ V}$$

Battery charge controllers (BCC) can be oversized to account for future increases in load and PV capacity. We will assume a 30% future expansion factor when sizing the charge controller. The minimum rated current for the BCC in the warm weather conditions is:

$$I_{BCC} > I_{sc} \times \text{"\# of strings in parallel"} \times \text{"future expansion factor"} \times \text{"Warm Weather Temperature Factor"} = 4.8 \times 6 \times 1.3 \times 1.25 = 46.8 \text{ A}$$

The charge controller's voltage set points for equalization and floating will be adjusted to a customary 2.50 and 2.25V per cell, respectively, and will be temperature compensated. These values are typical thresholds for lead-acid cells. With 24 cells forming a 48 V battery, the set points will be  $2.50 \times 24 = 60 \text{ V}$  for equalization and  $2.25 \times 24 = 54 \text{ V}$  at  $25^\circ\text{C}$ . The BCC will be set to disconnect the battery when its SoC reaches 20%, which corresponds to the maximum DoD allowed.



Figure 37. Back up PV plant installed on the roof of Meniara Public School in Akkar (Lebanon) implemented by the CEDRO project

#### 2.1.4.10.2 On-grid plants

Not all grid-tied plants are designed to maximize the financial results. In some countries, PV plants in public facilities have been installed as showcases to demonstrate environmentally sustainable energy generation. If the purpose of the plant is to sell bulk electricity to the grid, meeting the electric load of a grid-tied customer that has a high quality service from the utility is not the critical design parameter. Generally the limiting factors for utility connected systems will either be the available area or budget.

#### 2.1.4.10.3 On-grid house

Consider a plant located near Beirut, Lebanon, that receives 5.84 peak sun hours [ $\text{kWh}/\text{m}^2/\text{day}$ ] of radiation (as a yearly average) at the plane of PV generation, south facing, and with  $30^\circ$  slope. Beirut is located in climatic zone 1 and taking the data from Table 8 (Beirut)[24]; the average minimum temperature in the coldest month is  $9.7^\circ\text{C}$  and the record low is  $4.4^\circ\text{C}$ , suggesting a design low temperature between these two extremes would be appropriate, or  $7^\circ\text{C}$ . The average high temperature in the warmest month is  $23.6^\circ\text{C}$  and the record high is  $32.8^\circ\text{C}$ , thus a design high temperature in between these two values of  $28.2^\circ\text{C}$ . The PV generator can be mounted on the south-facing roof slope at a  $30^\circ$  using aluminum solar racking with top-down clamps.

The annual consumption for the household is equal to the Lebanese average of 6,907 kWh [25]. In this climate, a well-designed PV plant will have an estimated performance ratio (PR) of about 0.70 and therefore be able to produce about  $1,500 \text{ kWh}/\text{kW}_p$  per year; a  $5 \text{ kW}_p$  PV generator would be needed to fully offset this home's energy use. The designers found that a visually appealing layout of 11 Sharp 240  $\text{Wp}^{10}$  polycrystalline modules totaling  $2.64 \text{ kW}_p$  would fill 75% of the available rooftop area, leaving satisfactory room for service and emergency access, and integrate well



with an SMA Sunny Boy 2100TL (2,100 W) inverter using 1 string of 11 modules in series. The proposed plant configuration can be expected to offset about one-half of the household's electricity needs in a net-metering scheme.

The chosen inverter has a power rating of 2,100 W<sub>AC</sub> with a DC MPPT voltage range of 200–480 V<sub>DC</sub> and a maximum input voltage of 600V. The inverter to PV generator factor is 0.8, consistent with the inverter factor recommended for sunny climates like Lebanon (as described in section 2.1.4.1.2 *Grid tied Inverters*)

The maximum DC voltage for a generator is calculated as the voltage under worst case conditions. According to the state-of-the-art standards this value corresponds to the product of the number of modules in series, the module open-circuit voltage and the safety factor (i.e. “cold weather temperature factor”) of 1.2.

$$\#series \cdot V_{oc} \cdot 1.2 = 11 \cdot 36.9V \cdot 1.2 = 487.08V$$

If a more detailed analysis will be done, the maximum DC voltage can be obtained by the product of the number of modules in series, the module open-circuit voltage and a cold weather voltage adjustment factor, which itself is equal to the temperature coefficient of open-circuit voltage (−0.329 %/°C) multiplied by the temperature difference between the design minimum and the STC temperature of 25°C.

$$\begin{aligned} \#series \cdot V_{oc} \cdot (1 + \beta_{V_{oc}} \cdot (T_{min} - T_{STC})) = \\ = 11 \cdot 36.9V \cdot (1 - 0.00329 \cdot (7 - 25)) = 429.94V \end{aligned}$$

Both values (487.08V and 429.94V) are well below the maximum input voltage of the inverter (600V).

The MPPT voltage conditions in cold and warm weather should be within the MPPT conditions of the inverter which are 200–480V. We assume a module temperature 15° C above ambient temperature.

$$\begin{aligned} \#series \cdot V_{mpp} \cdot (1 + \beta_{V_{mpp}} \cdot (T_{min} - T_{STC})) = 11 \cdot 30V \cdot \\ (1 - 0.00329 \cdot (7 - 25)) = 349.54V \end{aligned}$$

$$\begin{aligned} \#series \cdot V_{mpp} \cdot (1 + \beta_{V_{mpp}} \cdot (T_{max} - T_{STC})) = 11 \cdot 30V \cdot \\ (1 - 0.00329 \cdot ((33.1 + 15) - 25)) = 304.92V \end{aligned}$$

We have a low voltage (LV) PV generator and therefore a fault current protection device should be included. The rated tripping current ( $I_{TRIP}$ ) of the overcurrent protection device installed shall be as specified by the PV module manufacturer. If the manufacturer does not give any recommendation,  $I_{TRIP}$  shall be determined with the following formula:

$$I_{sc} \cdot 1.25 \leq I_{TRIP} \leq 2 \cdot I_{sc}$$

For our case, the  $I_{TRIP}$  shall be in-between 10.65A and 17.4A.

$$8.52A \cdot 1.25 \leq I_{TRIP} \leq 2 \cdot 8.52A$$

$$10.65A \leq I_{TRIP} \leq 17.04A$$

The DC connection to the inverter can be done with a UV outdoor resistant double insulation wire or by connecting the module wires in a junction box to wire inside conduit. The required cross section for copper wiring is calculated considering the maximum voltage drop between the inverter and the PV modules that should be below 1%. For the PV installation designed and, in this case, considering a distance of 20 m from the PV modules to the inverter, the minimum required cabling cross section is the following

$$s \geq \frac{2 \cdot L \cdot I_{mpp}}{\gamma_{20} \cdot \Delta U_d} = \frac{2 \cdot 20m \cdot 8A}{56 \cdot 11 \cdot 30V \cdot \frac{1}{100}} = 1.73mm^2$$

The inverter's output voltage is 230V<sub>AC</sub> and its maximum output current is 11 A<sub>AC</sub>. This requires AC switchgear, wiring, and over-current protection at 125% of 11 A, or 14 A. The next largest standard sizes are a 16 A circuit breaker mounted within the existing electrical supply panel as the point of common coupling.

As before, the required cross section for copper wiring is calculated by considering the maximum voltage drop between the inverter and the supply panel. The maximum drop considered for the calculation is 0.5%.

$$s \geq \frac{2 \cdot L \cdot I_n \cdot \cos \varphi}{\gamma_{20} \cdot \Delta U_d} = \frac{2 \cdot 10m \cdot 8A \cdot 1}{56 \cdot 230 \cdot 0.5 \cdot \frac{1}{100}} = 2.48mm^2$$

The AC run from the inverter to the supply panel is typically shorter than 10 meters, with a minor to negligible wire loss.

#### 2.1.4.10.4 Commercial building

Commercial buildings often have flat roof tops and optimally tilted PV generators tend to be fastened to the building structure. If they have low dead load limits and we want to use ballasted structures they can be placed at shallower tilts to reduce the wind load and thus the amount of ballast weight. Also to consider in commercial rooftops is that PV ground cover ratios will most likely be smaller than for ground-mounted because of the obstructions by skylights, elevator shafts, HVAC equipment, etc. The following reference example is not applicable as described in today's daily blackout conditions in Lebanon but it is adequate should a reliable grid be available 24/7.

A dairy company in the Mediterranean region aims to reduce their electricity bill by consuming electricity from PV installed on the roof of the factory. The company has a yearly consumption of 1,500,000 kWh and a building with flat roof.

Using Beirut as an example site and a tilt angle of 23° to optimize roof space, the reference yield is 2,124 sun peak hours per year. The estimated performance ratio (PR) is about 0.75 being able to produce about 1,593 kWh/kW<sub>p</sub> per year. In order to generate all the energy demand (based on a net-metering scheme) we would need a 940 kWp installation.

In this case we have property limitation and the only available space is the roof of the factory; therefore the generation will be limited to the space available. High performance PV modules such as monocrystalline should be selected in order to cover the energy demand as much as possible.

For this PV installation the designers considered to use 748 mono-crystalline

PV modules of Atersa 250 Wp<sup>11</sup> divided into four 40 kW<sub>AC</sub> central inverters<sup>12</sup> (since it is a very homogenous installation) with a DC operating range of 210 – 420V and maximum DC input voltage of 530V. 187 PV modules are connected to each inverter corresponding to an inverter factor of 0.86 (40 kW/46.7 kWp). For this climate, module type and inverter, an optimal layout of 17 strings in length of 11 modules is proposed.

The final PV capacity is 187 kWp which correspond to an annual yield of around 298,000 kWh. The PV generation corresponds to a 20% of the total energy generation of the company.

As in the previous example, the DC voltage of the PV generator should not exceed the maximum input voltage of the inverter (520V).

$$\#series: V_{oc} \cdot 1.2 = 11.37.62 V \cdot 1.2 = 496.58 V$$

The strings are collected in three 6-pole

DC junction boxes with 15 A string fuses. The 66 A ( $I_{sc} \cdot 1.25 \cdot 6$  poles) PV output circuits from the junction boxes terminate at two 100 A 2-pole unfused 1000 V DC disconnect switches at the inverter's input.

The wiring cross section is selected for a voltage drop of 1% and a distance of 25 m. The required cross section for copper wiring is at least 2.21 mm<sup>2</sup>.

On the AC side the plant is connected to a line on the customer side of the facility's main panel and has a utility-owned energy meter that meets net metering requirements. The plant also contains a remote data-logging measurement system with weather instrumentation, inverter and meter communication, and a wireless communication data transmission in order to monitor the performance of the plant.

<sup>1</sup> Atersa model A-250M

<sup>m</sup> Fronius IG 500

### 2.1.5 Installation

Plants should be designed for ease of installation and good accessibility. The contractor's staff must be selected so that each team member has the skills for their required tasks. Structures, foundations and fastening should be done following sound civil engineering criteria and electrical cabling should be installed so that they are not subject to scuffing or cutting. On site safety must be maintained to prevent injuries to crew members and damage to the equipment. The approved engineering documentation should always be available on site and updated to reflect clear traceability of any authorized changes. Once the plant is operational, commissioning must be done to fully test the components and installation before commercial operation and hand over.

### 2.1.6 Operation and maintenance/monitoring

The business model for PV plants is based on long term operation at very low operation costs and for this reason they are designed with the objective that they be performing adequately at least for 25 years. Because they are built with static components, maintenance tasks are simple and relatively inexpensive but they should not be neglected because (also due to its static behavior) undetected faults could dramatically affect performance. Common scheduled up-keeping tasks include module cleaning to remove soiling, inspection of mechanical fastenings and structure, inspection of electrical connections and cabling, testing of inverter operation, replacement of damaged PV modules, vegetation control and surveillance against theft and vandalism.

Large commercial and utility plants should generate enough revenue to afford O&M contracted to professional staff. Some O&M contractors offer integrated services that also include monitoring, insurance and performance assurance. For domestic or institutional plants, up keeping and monitoring is usually done by the owner, as part of the building's general maintenance, following the designers' guidelines.

The cost of O&M can widely vary not only as a function of technology, plant size and site conditions but also as a function of market development in the country. In mature PV markets, spare parts and specialized suppliers of goods and services are readily available and more competitive than in less developed markets. Reference rule of thumb O&M costs for plants can be differentiated according to plant size:

- Plants in the order of 1 to 5 MW are in the range of 1.5 to 2.5 USD cents per kWh of energy generated
- Plants in the order of 5 to 20 MW are in the range of 1 and 2 USD cents per kWh.
- In less developed markets such as Lebanon, one could expect initial costs of 4 – 5 USD cents per kWh. This cost may increase as the plant ages and increased maintenance is required to ensure good performance.

Autonomous and backup plants are more complex and expensive, maintenance-wise, than pure grid-dependent plants due to the additional components such as batteries and load control devices, and also due to their relative smaller size.

PV generation is not visible as with other electricity generation technologies that have moving parts or produce noise and it is important to have an effective interface with the operator to monitor the performance of the plant through displays, indicators and data recording. The overall assessment is done by calculating the performance ratio (PR) that requires at least the measurement of the plant output and the solar radiation at the plane of the modules. A low performance ratio indicates a component malfunction but more measurements are then needed to establish in which part of the plant is there a problem; and, in very large plants it is cost-effective to have a person on-site to monitor operation, up keep and be able to repair incidents quickly to minimize yield losses. There are remote monitoring tools that get the data from the inverter or with external meters and sensor and provide calculated key performance indicators. An example of a monitoring display is given in Figure 38.

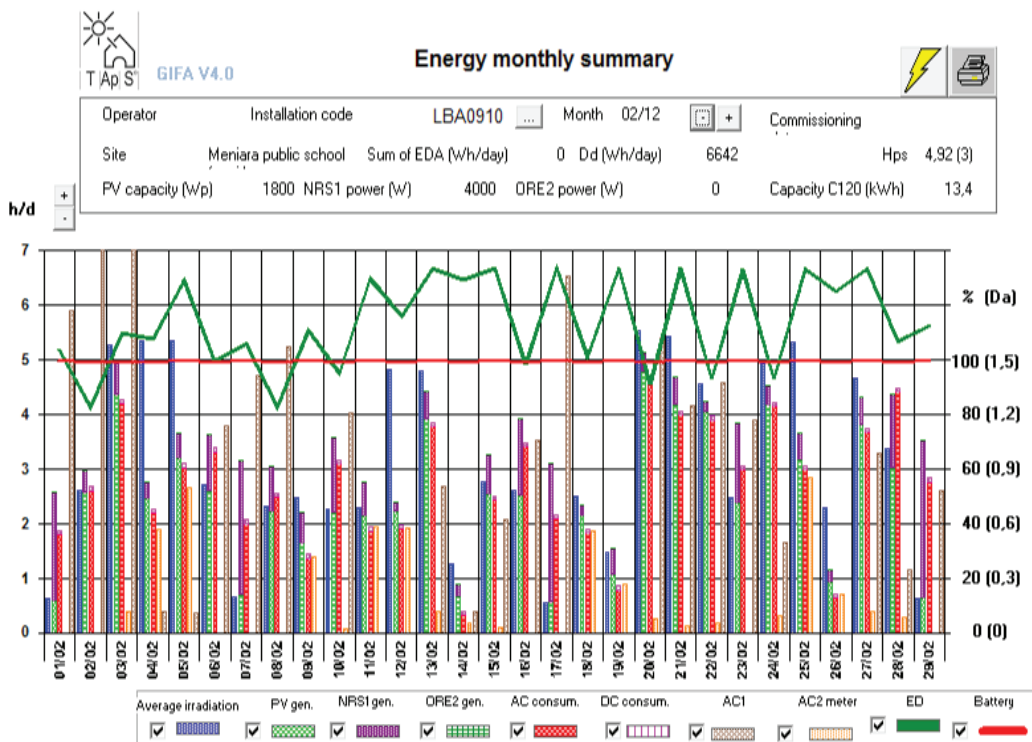


Figure 38. Monitoring display for a 1.8 kWp back-up PV system installed in Meniara Public School in Akkar, Lebanon within the CEDRO project (source TTA)

### 2.1.7 End of life

One of the main advantages of PV technology is the production of electricity with relatively very low environmental impact. With an estimated 25+ years as operating lifetimes, the plan to responsibly remove a plant without any environmental impact should be taken into consideration, both financially and environmentally. There is an increasing awareness of the economic benefits of recycling and reusing the most valuable materials in the module (i.e., Al, Si and glass) and the rest of the system's components. Some manufacturers guarantee to collect their modules and much of the material can be salvaged or recycled and some of the initial cost could be recovered, although discount rates limit these financial benefits when viewed in current terms or value.

An additional environmental benefit of PV plants is that they do not require water for operation, which is important considering that large plants can be installed in arid regions with minimal infrastructure.

## 2.2 Environmental impacts and potential hazards

During normal operation, photovoltaic generators do not emit substances that may threaten human health or the environment. In fact, through the emissions savings from the reduced use of conventional electricity production, they can lead to significant emission reductions [26]. The component manufacturing phase is the most relevant concerning environmental aspects for PV technology and the end of life phase has a minor influence compared to it.



### 2.2.1 Manufacturing phase

Within the manufacturing of PV technology, the cell process is the dominant process for primary energy demand.

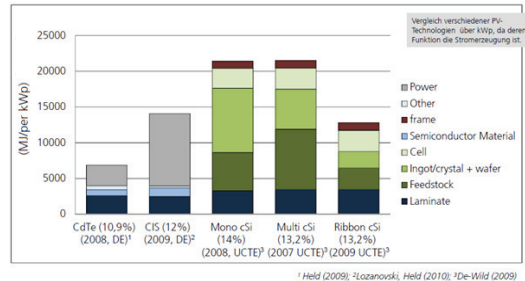


Figure 39. Primary Energy Demand per kWh  
(Source: Schischke, 2011 [28])

The primary energy demand per kW capacity is different for the different technologies. The primary energy demand required for a kWp of CdTe cell is almost one third of the primary energy demand required for the production of mono and multi-crystalline silicon cells [28]. With regards to the manufacturing waste, accumulated amounts of waste during PV cell production can be considered rather small [30].

Due to the improvements in the manufacturing chain of PV modules, the mounting systems and inverter gain more relative importance with regards to the environmental impact. The components consisting of power converters, charge controllers, structure and wiring have a share of 30% to 50% of the total impact [29].

#### 2.2.1.1 Transport and installation

Transportation of PV components could be a relevant impact factor, given size and weight of PV plants, but this largely depends on the distance between manufacturing and installation. The installation itself has a lower impact [28].

#### 2.2.1.2 Operation phase: Energy payback time (EPBT)

Energy Payback Time (EPBT) can be used as an indicator for the energy “efficiency” of a PV plant. It is sensitive to the site of the plant (resource) and also to the particular country energy mix that it displaces. It indicates how many years the plant has to operate before it reaches the energy break-even point. That means that after the EPBT is reached, the amount of energy used to manufacture, transport, install and operate and dispose of the plant has been offset by the clean electricity production which has replaced primary energy (that, otherwise, would have been consumed from electricity production in other facilities). The International Energy Agency (IEA) compared the EPBT of several small PV installations reporting a range between 1.6 and 3.3 years for rooftop-mounted PV plants and between 2.4 and 4.7 for PV façades (depending on the country situation and technology used) [31].

For larger PV plants (several megawatt range), the EPBT is from 1.4 to 3.8 years depending on the PV technology used [32].

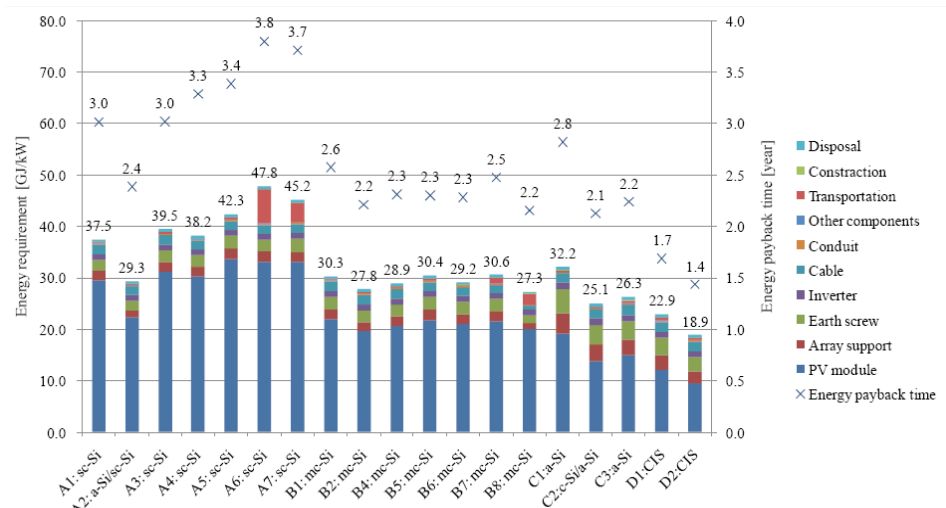


Figure 40. The energy requirement and the EPBT of the Mega-solar system (Source: Ito et al., 2010)[32]

Although tiny amounts of semiconductor materials are imbedded in the module, toxic compounds cannot cause any adverse health effects unless they enter the human body in harmful doses. The only pathways by which people might be exposed to PV compounds from a finished module are by accidentally ingesting flakes or dust particles, or inhaling dust and fumes. The photovoltaic material layers are stable and solid, and are encapsulated between thick layers of glass or plastic. Unless the module is grinded to a fine dust, dust particles cannot be generated. All the photovoltaic materials have a zero vapor pressure at ambient conditions; therefore, it is impossible for any vapors or dust to be generated during normal use of PV modules.

### 2.2.1.3 Recycling at end-of-life

Recycling of PV modules is still at an early stage. The various designs and manufacturing procedures determine the means of module disassembly and layer separation.

For crystalline Si based modules, which consist of approximately 80% of glass, the first step is to manually dismantle the aluminum frames and the junction boxes. Afterwards, the modules are crushed in a mill and glass, plastics and metals are separated. Currently, the major part of the extracted mixed glass which is used by the flat glass is recovered. The recovery is performed by flat glass recyclers morphology and composition of a PV module is similar to those flat glasses used in the building and automotive industry<sup>13</sup>.

Two processes are followed for the recycling of non-silicon based PV module: one of the recycling processes starts by crushing the module and separating the different fractions. The second process employs a chemical bath to delaminate and separate the different module components. These processes are designed to recover up to 90 % of the glass and 95 % of the semiconductor material contained<sup>14</sup>.

### 2.2.1.4 Potential hazards of PV modules

There are certain environmental hazards associated with the **manufacturing** and **end-of-life disposal** phases of PV modules life cycles. The main concern is associated with the presence of Cd in CdTe and CdS solar films and the presence of Pb in crystalline Si modules (if they contain Pb-based solder) and its potential leach out in the soil (e.g. in a landfill) [40],[41] as shown in Table 13.

Module type	Types of potential hazards
x-Si	HF acid burns SiH <sub>4</sub> fires/explosions Pb solder/module disposal
a-Si	SiH <sub>4</sub> fires/explosions
CdTe	Cd toxicity, carcinogenicity, module disposal
CIS, CGS	H <sub>2</sub> Se toxicity, module disposal
GaAs	AsH <sub>3</sub> toxicity, As carcinogenicity, H <sub>2</sub> flammability, module disposal

Table 13. Major hazards in PV manufacturing  
(Source: see reference [40],[41])

However, it should be noted that the hazardous leach would require the breaking of the whole module to very small pieces, whereas the photovoltaic layer will often be sandwiched between two layers of glass and reasonably isolated from the environment.

### 2.2.1.5 Environmental legislation and norms – status and trend

PV modules must not be disposed of in municipal landfills. In Europe, the Waste Electrical and Electronic Equipment Directive 2002/96/EC (WEEE Directive), together with the RoHS Directive 2002/95/EC, became European Law in February 2003, setting collection, recycling and recovery targets for all types of electrical goods. The

about/recycling/recycling-of-non-silicon-based-pv-modules/ [last accessed on May 2013]

13 PV CYCLE website: <http://www.pvcycle.org/about/recycling/recycling-of-silicon-based-pv-modules/> [last accessed on May 2013]

14 PV CYCLE website: <http://www.pvcycle.org/>

directive has undergone a number of minor revisions since its inception in 2002. These include updates in 2006 and 2009.

On July 24<sup>th</sup>, 2012 the new WEEE Directive 2012/13/EU was published in the Official Journal [33]. Therein, it is announced that each Member State (of EU) should ensure the implementation of the “producer responsibility” principle and, on that basis, a minimum collection rate should be achieved annually (from 2019, the minimum collection rate to be achieved annually shall be 65% of the average weight of Electrical and Electronic Equipment (EEE) placed on the market in the three preceding years in the Member State concerned, or alternatively 85% of WEEE generated on the territory of that Member State). Under the amendments, used photovoltaic modules must now be collected and recycled and for its collection and recycling in the EU, there are different initiatives already in place such as PV CYCLE<sup>15</sup>, CERES<sup>16</sup> or the thin film PV modules manufacturer, and First Solar which has its own take-back and recycling<sup>17</sup>.

### 2.2.2 Key Environmental Indicators (KEPIs) to compare PV with other power plants

#### 2.2.2.1 PV KEPIs

The KEPIs are Key Environmental Performance Indicators, representing potential environmental impacts of high relevance for a given sector. Consequently, KEPIs are the environmental results of an assessment.

The *LCA to go* project [36] has analyzed the relevant KEPIs of the PV sector. The identified KEPIs by the project are as follows:

- (1) Energy (PE consumption for manufacturing phase and maintenance)
  - **Energy consumption per life** (MJ or MJ/m<sup>2</sup>)
- (2) Electricity production (lifetime power output)
  - **Lifetime power output** (kWh or kWh/m<sup>2</sup>)
    - **Energy yield ratio** ( $PE_{out}/PE_{in}$ )
    - **Energy payback time** (years)
- (3) Product Carbon Footprint (emissions related to manufacturing and maintenance of PV plants)
  - **Carbon footprint of the plant** (kg CO<sub>2-eq.</sub> or kg CO<sub>2-eq.</sub>/m<sup>2</sup>)
    - **Carbon footprint per product unit** (kg CO<sub>2-eq.</sub>/kWh)
    - **CO<sub>2</sub> emission savings** due to replaced power (kg CO<sub>2-eq.</sub>)
    - **Carbon footprint share per component** (% or visual)

Different energy generation technologies can be compared by calculating their associated environmental impacts.

#### 2.2.2.2 PV vs. other large power plants

In Figure 41 the GHG emissions of nine different types of power generation systems are compared. The total GHG emissions were calculated considering direct emissions (caused by the combustion of fossil fuels in power plants) and indirect emissions (associated to construction, O&M and decommission of the power plants).

<sup>15</sup> <http://www.pvcycle.org/> [last accessed on May 2013]

<sup>16</sup> <http://www.ceres-recycle.org/> [last accessed on May 2013]

<sup>17</sup> <http://www.firstsolar.com/en/Sustainability/Environmental/Product-life-cycle-management/Product-Collection> [last accessed on May 2013]

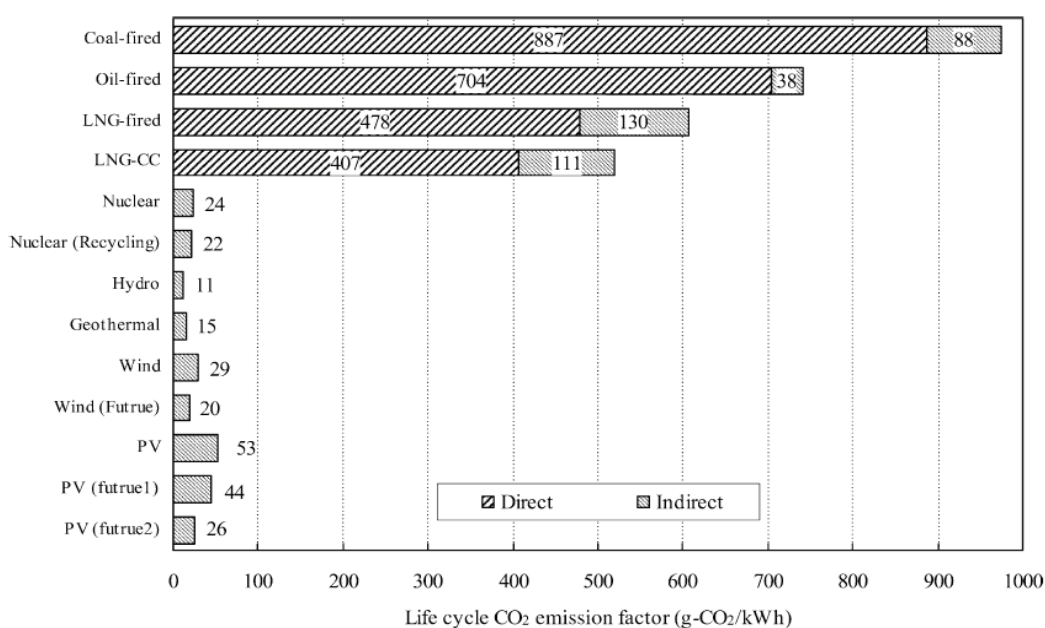


Figure 41. Life cycle CO<sub>2</sub> emission factors for different types of power generation technologies (Source: Hondo, 2004 [37]).

Small PV roof type grid-tied plants (3 kW) for self-consumption were studied in all the cases (base and future). In the base case it was assumed that the PV cells were solar-grade (SOG) polycrystalline silicon; in the Future case 1 it was assumed that the cells used were the same type of cells with higher efficiency, and in Future case 2 the

cells used were SOG amorphous silicon (a-Si) with higher production. A 30-year lifetime was assumed for the nine types. Although nuclear energy rated the best regarding the GHG emissions, this technology requires high amount of energy per unit of electricity produced (see Figure 42).

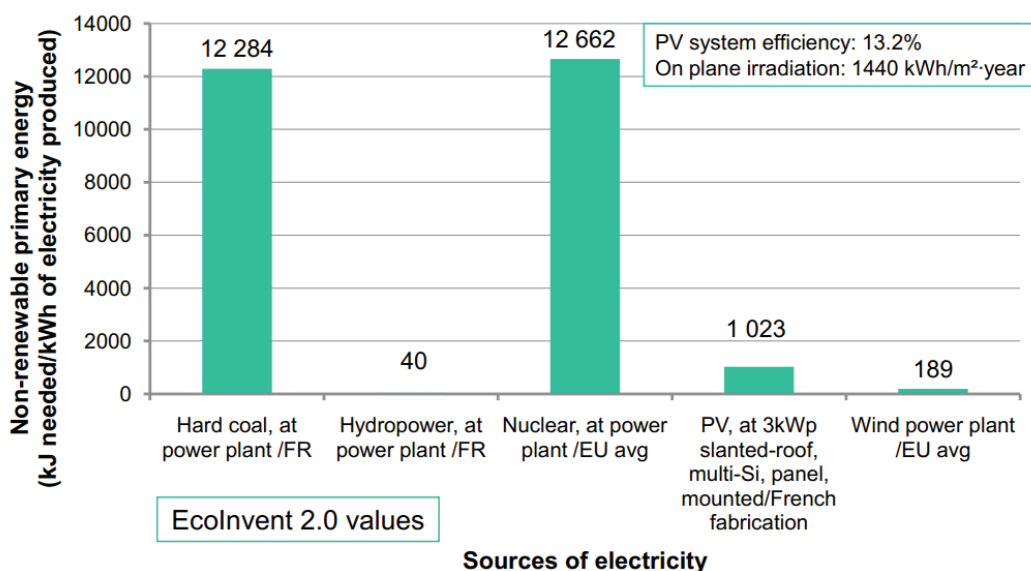


Figure 42. Comparison sources of the required energy per unit of electricity produced for different electricity generation sources (Source: ESPACE project [38])



Specifically, each kWh generated by a PV plant will save the following CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions **Error! Reference source not found.**, in relation to a coal thermal power plant:

$$- \quad 0.6 \text{ kgCO}_2 / \text{kWh}$$

$$- \quad 0.506 \text{ gNO}_x / \text{kWh}$$

$$- \quad 0.701 \text{ gSO}_2 / \text{kWh}$$

PV plants have a dramatic environmental benefit when compared to a coal thermal power plant and therefore this kind of technology should be promoted as part of a new sustainable energy paradigm. For example, a 1.3 MW PV plant which produces 1,885,650<sup>18</sup> kWh annually saves the following emissions;

$$1,885,650 \frac{\text{kWh}}{\text{year}} \cdot 0.6 \frac{\text{kgCO}_2}{\text{kWh}} = 1,225,672 \frac{\text{kgCO}_2}{\text{year}} = 1,226 \frac{\text{tCO}_2}{\text{year}}$$

$$1,885,650 \frac{\text{kWh}}{\text{year}} \cdot 0.506 \frac{\text{gNO}_x}{\text{kWh}} = 954,139 \frac{\text{gNO}_x}{\text{year}} = 0.9 \frac{\text{tNO}_x}{\text{year}}$$

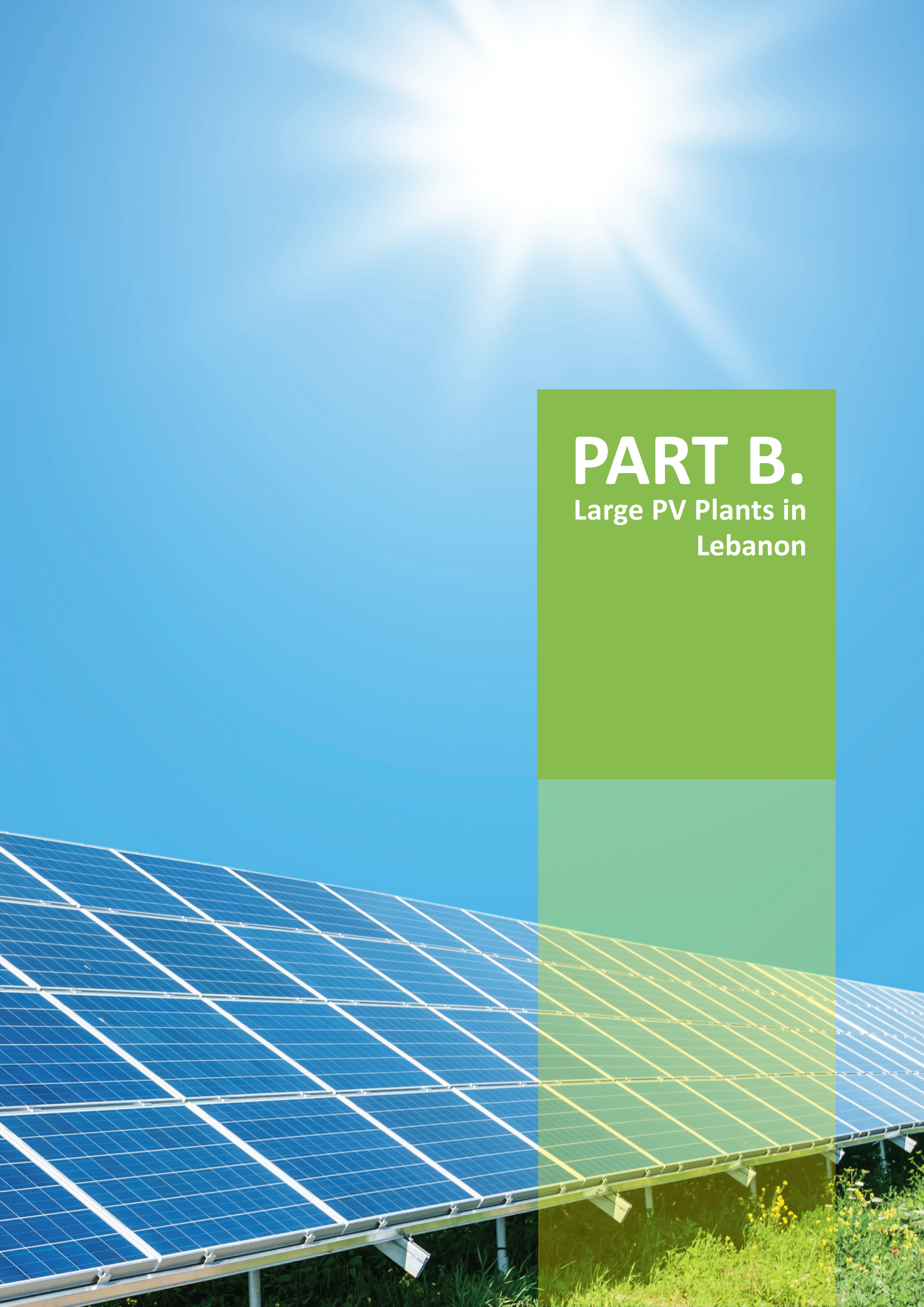
$$1,885,650 \frac{\text{kWh}}{\text{year}} \cdot 0.701 \frac{\text{gSO}_2}{\text{kWh}} = 1,321,841 \frac{\text{gSO}_2}{\text{year}} = 1.3 \frac{\text{tSO}_2}{\text{year}}$$

Supposing that the PV plant will have an operational lifetime of 30 years, the saved emissions will be 36.1 kton of CO<sub>2</sub>, 27 tons of NO<sub>x</sub> and 39 tons of SO<sub>2</sub>.

<sup>18</sup> Considering the 1,934kWh/(m<sup>2</sup>\*year) in Lebanon and a PR of 0.75.







# PART B.

Large PV Plants in  
Lebanon

## 3 Design of a PV plant concept

### 3.1 Key factors in PV plant development

#### 3.1.1 Regulatory and planning requirements

Lebanon is suffering from severe power shortages. According to the Policy Paper for the Electricity Sector published by the Ministry of Energy and Water in 2010, the combined power generation capacity and imports in Lebanon in 2009 was 1,500 MW, while the average demand was 2,100 MW, with a peak in the summer of 2,450 MW. The estimated total energy demand in 2009 was 15,000 GWh (a 7% increase from 2008), whereas total electricity production and purchases amounted to only 11,522 GWh (a 6% increase from 2008). Due to this deficit, the greater Beirut area suffers from power cuts for 3 hours per day on average, the South for 8.2 hours per day and the whole country for about 6 hours per day.

According to the Policy paper, the average power generation costs of Lebanon's electric power utility, EDL (Electricité Du Liban) in 2010 were estimated to be 17.14 US cents per kWh, while the frequent power cuts have forced the population to rely on even more expensive back-up arrangements, typically consisting of diesel generators.

Other estimates by the World Bank quantify that about one-third of the Lebanon's total electricity demand is met by these privately-owned and operated diesel generators, with recent estimates putting the cost over 30 US cents per kWh.

Figure 43 shows the gap between EDL supply and demand in 2009 [42]. If no additional supply sources are secured, this situation is expected to worsen as electricity demand is projected to increase 7% annually between 2009 and 2015.

In order to overcome the acute power shortages, the Ministry of Energy and Water (MEW) Policy Paper has set a target to increase the total available power generation capacity in Lebanon to 4,000 MW by 2014 and to 5,000 MW thereafter. This is mostly to be achieved by new and rehabilitated gas-fired power plants. For the installation of new renewable energy power generation capacity, the target by 2020 has been set at 115-165 MW, including new hydro (40 MW), wind (60-100 MW) and waste to energy (15-25 MW).

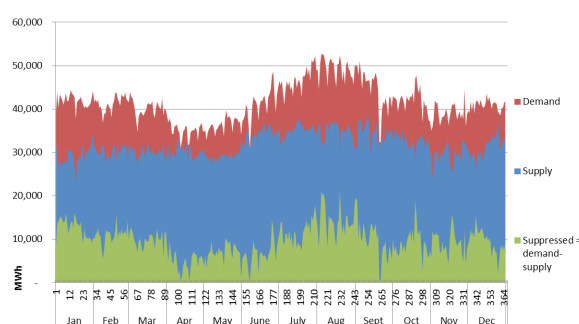


Figure 43. Daily demand, supply, and suppressed electricity in 2009 (Harajli et al. 2010 [42])

After several demonstration projects, most of them PV plants developed within the CEDRO<sup>19</sup> project, the potential for smaller, distributed renewable electricity generation has been recognized also as an important complementary source to offset current shortages.

As a result of this demonstration phase, a first regulatory scheme for grid connection of RE based generation was adopted in national legislation in November 2011 under a "net-metering" basis, aimed at enabling self-consumption<sup>20</sup>. Although net-metering is not feasible to PV plants developed solely to sell to the grid

their entire respective production, the introduction of net-metering in Lebanon is important in order to develop the market, to promote private investment

<sup>19</sup> The complete list and details of the pilot projects are available from <http://www.cedro-undp.org/en/projects/>

<sup>20</sup> The application procedure is available from <http://www.edl.gov.lb/news/NetMetering.pdf>



in self-consumption plants, to reduce the operation of private diesel gensets and to incentivize the electricity sector to consider alternatives to the current monopolistic generation.

Large grid tied PV plants can be implemented for self-consumption to offset back up diesel generation and also, if required, can use the net metering scheme with the distribution utility. For plants that only sell bulk electricity to the grid to be implemented, they can be operated by the generation utilities or

specific permitting or licensing procedures for independent power production will need to be defined in Lebanon, with the subsequent technical, administrative, legal and financial arrangements. There are reference examples of licensing that have been adopted worldwide, commonly referred to as Power Purchase agreements (PPAs). Table 14 shows a reference list of key aspects to be included in a PPA model<sup>21</sup> for PV plants. The most common feature all PPA and FiT arrangements for RE generation are that they are always granted priority of dispatch to the grid.

<p><u>Administrative</u></p> <ul style="list-style-type: none"> <li>• Definition of the parties involved: identification, roles</li> <li>• Term or Period of agreement (typically between 5 and 20 years)</li> <li>• Sale and purchase of electricity: Obligations, billing procedures, statements, invoices, late payments</li> <li>• Exceptions</li> <li>• Defaults and Remedies</li> <li>• Settlement of disputes</li> <li>• Termination</li> <li>• Procedures for communication between the parties</li> <li>• Force Majeure</li> <li>• Representation and Warranties</li> <li>• Insurance and Indemnity</li> <li>• Governmental jurisdiction and Authorizations</li> <li>• Applicable revenue terms after term or period of agreement</li> </ul>
<p><u>Technical</u></p> <ul style="list-style-type: none"> <li>• Facility Description</li> <li>• General design and Construction</li> <li>• Interconnection, Point of Delivery</li> <li>• Metering</li> <li>• Operations and Maintenance, Testing protocols</li> <li>• Monitoring and Evaluation</li> <li>• Health and Safety</li> </ul>
<p><u>Financial</u></p> <ul style="list-style-type: none"> <li>• Payment for Energy Output</li> <li>• Price revision clauses</li> <li>• Taxes, costs and charges</li> <li>• Financing and re-financing options</li> </ul>

Table 14. Reference list of key aspects in PV plants permitting

<sup>21</sup> Based on references from the Spanish PV sector and other international experiences from <http://ppp.worldbank.org/public-private-partnership/sector/energy/energy-power-agreements/power-purchase-agreements>

### 3.1.2 Grid capacity-Voltage and frequency instabilities

The layout of the grid to which the plant is going to be connected must be assessed to ensure it can absorb the power from the PV plant. PV plants are connected to the distribution grid and its transport capacity will set dispatch thresholds (maximum power that can be fed from PV plants into the grid) and in some cases may require upgrading of the lines or the transformer.

In order to maximize the potential power that can be fed from PV plants into the grid, the Lebanese grid reinforcement should be planned where needed, not only to permit power injection from the

PV plants, but also to guarantee minimum requirements of power quality. From the grid planners' point of view, the line distribution and utilization (saturation level) must be reviewed in detail, and the connection points for future distributed PV plants can be anticipated. Then, the needs for extension or reinforcement of lines and substations can be defined based on the results from those reviews and predictions. Also, the adequacy of road accesses to the proposed site must be assessed; eventual civil works will increase the cost of the PV plant development.

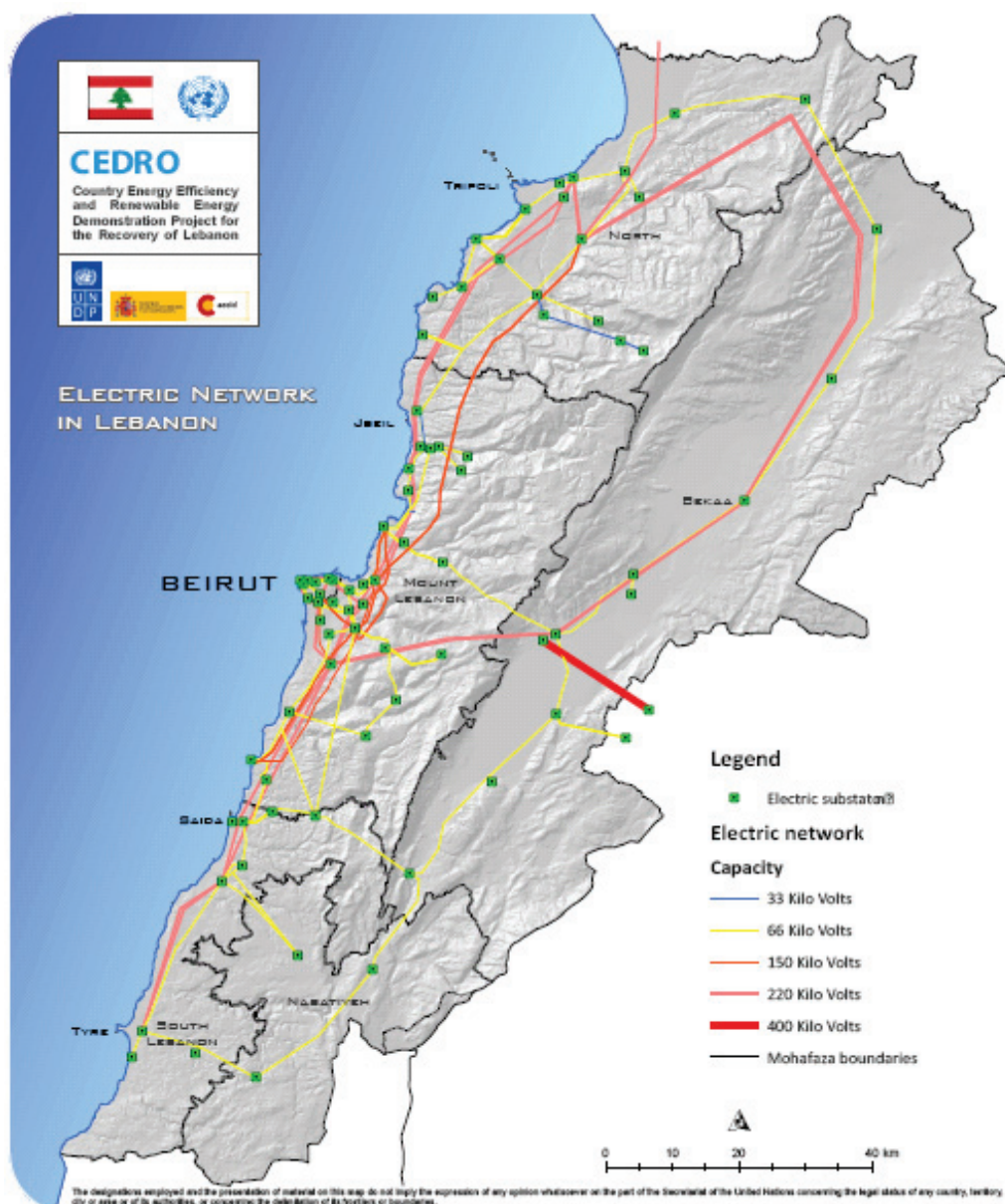


Figure 44. Electricity transport grid in Lebanon in 2009 (Source: CEDRO)

### 3.1.3 Land availability

Land ownership and cost can be especially relevant in the case of Lebanon. Some plant designs allow that other parallel uses of the land coexist with electricity production (grazing, urban environment, etc.). Besides the plot of land to install the PV generator and power conditioning equipment, those properties concerning the evacuation lines (from the PV plant to the connection point) must be taken into account too.

## 3.2 Technical design

### 3.2.1 Technological limitations of the existing electricity system in Lebanon

PV power is generated intermittently, proportionally to solar radiation and to the plant's STC capacity. To achieve the performance for which the plant was designed for, all the produced electricity should be either consumed locally or absorbed by the grid so that the plant does not have to curtail power output. Plants designed for bulk generation cannot afford grid power cuts during the daytime in the area where the PV plant will be installed.

Nevertheless if blackouts occur, PV plants must have an anti-islanding feature to avoid feeding a non-energized grid. This is achieved either by a functionality embedded into the inverters or an external automatic switch. If the grid condition is such that it has a temporary limited capacity like what happens in the Lebanese grid, it is an advantage to design the plant in such a way where it can be operational at partial capacity to match the grid condition.

### 3.2.2 Modular concept

Herein, the following terms are used:

- **Solar PV basic assembly (SBA):** an electrically connected assembly of 3 PV arrays and three inverters that can be connected to an AC low voltage (LV) grid in a three-phase arrangement.
- **Solar PV Generation Sub-plant (SGSp):** one or more solar basic assemblies physically together and connected to the grid at the same connection point.
- **PV generator:** direct current power supply unit using the photovoltaic effect to convert sunlight into electrical energy.
- **Solar PV Plant:** one or more SGSp interconnected to feed the grid (and including the transformer/s if required)

In general, large PV plants on the ground have layouts that allow for optimum and homogeneous orientation of all the modules. If it is a clear and flat plot of land and the exact location of the components are well defined, the electrical configuration can be based on relatively large inverters in the range of 60 kW to 900 kW and all the wiring is DC to the central inverter. A more flexible approach is to base the design on small inverters that are installed close to the modules and then most of the wiring is done in AC voltage. Both strategies are valid and designers select them based on the different site conditions and requirements (see also section 3.2.5 – *Option with central inverter*).

For this reference design we make a worst-case scenario and choose a concept with small inverters that is very modular and could easily be adapted to different types of projects in a range of capacities from a few hundred kW up to 2 MW. This flexibility also has relevance for site conditions where it is difficult to arrange the full PV generator with a homogeneous layout or urban settings that may have partial near shadings. For large plants on the ground in flat open spaces easy to access, the option with large inverters would be more adequate.

- **String:** a set of PV modules electrically connected in series
- **Inverter array:** assembly of photovoltaic modules electrically connected feeding one single inverter

The PV plant is composed by 4 subplants (SGSp) of 324 kW<sub>AC</sub> each. The proposed SGSp capacity is in the range of a third of a MW. Different plant capacities are possible for one PV plant, smaller or larger, by combining as many SGSp as needed.

Each SGSp will be composed by several SBAs as generation units. Each SBA has 3 inverters enabling the connection to the grid in three phases or one phase depending on the requirements.

The electricity generated by the SGSp will be three phase in LV. In order to deliver the electricity into the main distribution grid it may be necessary to transform from LV to HV to meet the requirements of the EDL lines.

The choice of a modular solution gives the flexibility to operate at partial capacity to match the grid condition in every moment; the adaptability to the space available in each case (i.e. limited ground areas, on roofs or integrated into façades; the possibility to divide the ownership and the investment if needed to make it more affordable; and easier to service).

### 3.2.3 Specific requirements for components

#### 3.2.3.1 Inverters

Bearing in mind the principles described in Section 2.1.4.1.2 - *Component Selection*, selected requirements for inverters in an sample PV plant are as follows;

- To use a larger number of small single-phase inverters in parallel in multiples of three: high flexibility of connection either single-phase or three-phase, modularity of the design, lightweight and easy to handle by local staff
- Protection class IP55 or better. This means protected against water and dust
- Proven credible track record in the past years within Lebanese conditions or equivalent and service center availability in the region in terms of technical advice, warranty issues and stocking of spare parts
- MPP tracking weighted energy efficiency higher than 92% and very low internal consumption (night)

Diagram for 1,3 MW PV farm

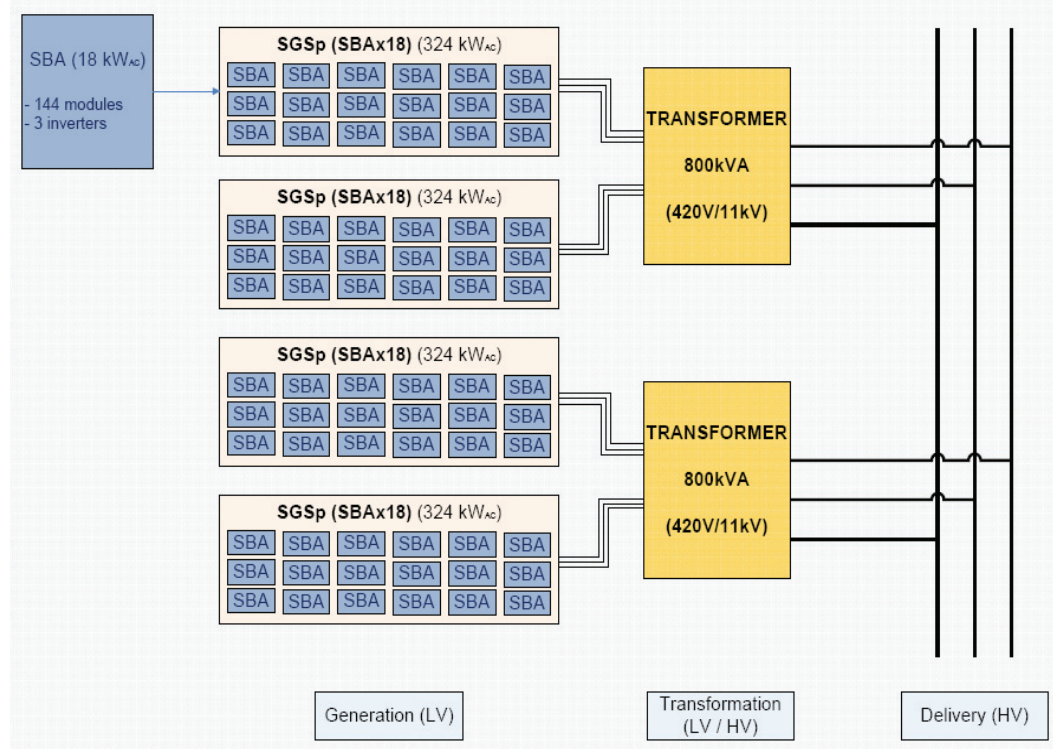


Figure 45. Modular solution of an example 1.3 MW PV plant



- Operating temperature up to +50°C and humidity range between 0 and 95%
- Upstream disconnection device
- Insulation testing feature on DC
- Compliance with standards IEC 61000-3-2 or IEC 61000-3-3 or IEC 61000-3-4 depending on the rated inverter output
- Inverter factor between 80% and 100%
- Device for regulation of Power Factor (optional)

### 3.2.3.2 Solar PV modules

To optimize the match between the PV generator layout and the inverter sets to the local solar resource and temperature, several modules and inverter configurations have been evaluated using simulation programs. Also different combinations of modules in series and in parallel have been studied from the electrical and physical perspective.

The program used for this simulation was PVsyst<sup>22</sup> and tandem structure thin film silicon, amorphous silicon and crystalline silicon modules were evaluated. The energy generated, area occupied and performance ratio (PR) have been assessed and the final selection is done according to these results.

The PV modules shall be fully operational in humidity conditions up to 95% and an ambient temperature from 10°C to 45°C. PV modules shall additionally withstand high ultraviolet radiation, wind speeds up to 120km/h and marine corrosion. They must also comply with internationally recognized standards IEC 61646 (thin film) or IEC 61215 (crystalline) and IEC 61730.

Each solar module will be independent and will have a connection box and bypass diode; the cable will have a plug connector. They shall have an aluminum frame in order to be fixed mechanically to the metallic structure.

<sup>22</sup> The software PVsyst is a market oriented tool that allows to analyze accurately different configurations of PV installations and to evaluate its results in order to identify the best solution (<http://www.pvsyst.com/en/>)

### 3.2.4 Configuration of the Solar Basic Assembly (SBA)

The objective of this section is to establish the PV solar configurations in order to maximize the electricity output injected into the grid and then to optimize the available surface usage.

The starting point of this preliminary design is the irradiation data collected from PVGIS or Med-Solar-Atlas database.

Beirut has been chosen as a reference.

Depending on the location of the PV plant, space availability and the optimum angle, the final PV generation will vary:

- When the PV modules are installed in a single-row or multiple rows without space limitations the optimal tilt for the PV modules is 30° due South
- When the SBA are integrated on different buildings, or plots of land with varying topography, the tilt and orientation will depend on the tilt and orientation of the available surface
- When the PV modules are installed in multiple rows and surface available is limited or has a high cost, the recommended tilt is 23° (see section 2.1.2.3 *Impact of partial shading*)

Several PV solar generators configurations have been tested in order to assess them in terms of power generation and surface area required. The configurations are tested with the assumption that we would have a multiple row PV generator to be mounted on flat ground, so the tilt selected for the simulations is 23°. The software PVSYST 5.1 has been used to simulate the different options and to calculate the power generation. Although many configurations with different modules and inverters have been tested, only few are shown to explain the decision process.

In particular, Table 15 summarizes the final configurations assessed (considering 6 PV module types and 2 inverter types):

PV Modules Characteristics	Specifications		
Capacity STC (Wp)	100	128	140
Technology	Amorphous silicon	Tandem thin-film	Monocrystalline silicon
$I_{mpp}$ (maximum power point current) (A)	2.66	2.82	5.01
$V_{mpp}$ (maximum power point voltage) (V)	37.50	45.40	27.92
$I_{sc}$ (Short Circuit Current) (I)	3.30	3.45	5.61
$V_{oc}$ (Open Circuit Voltage) (V)	50.50	59.80	33.64
Physical Dimensions (mm)	1414x1114x35.3	1409x1009x46	1203x808x35
Module Efficiency	6.33 %	9.00 %	14.40 %
Modules Characteristics	Specifications		
Capacity STC (Wp)	140	200	250
Technology	Polycrystalline-silicon	Monocrystalline-silicon	Polycrystalline-silicon
$I_{mpp}$ (maximum power point current) (A)	7.58	5.45	8.15
$V_{mpp}$ (maximum power point voltage) (V)	18.47	36.70	30.70
$I_{sc}$ (Short Circuit Current) (I)	8.25	5.81	8.63
$V_{oc}$ (Open Circuit Voltage) (V)	22.18	45.50	37.40
Physical Dimensions (mm)	1482x671x40	1580x808x35	1640x992x35
Module Efficiency	14.08 %	15.69 %	15.43 %
Inverter Characteristics	Specifications		
Model	6000 TL	7000 HV	
Rated Power (W)	6 000	6 650	
Maximum DC Power (Wp)	6 200	7 500	
Input PV Voltage range (V)	333 – 500	335 – 560	
Maximum DC Voltage (V)	700	800	
Maximum DC Current (A)	19	23	
AC Voltage	230	230	
Maximum Efficiency /EU efficiency	98% / 97.4%	96.2 / 95.5	

Table 15. Summary of PV solar generator component considered for simulation

All the possible combinations have been tested by simulation.

In the selected design strategy, the inverter size is critical to ensure the flexibility of the PV plant and the recommended values are between 18 and 25 kW.

Table 16 reports the conclusion of the PVSYST configuration simulations. All the configurations are composed by 3 inverter arrays, as mentioned in section 3.2.2. -*Modular concept*.

Option	Configuration		PVSYST tests conclusions	Outputs		
	Inverter	Module Type		Generation(MWh/year)	Ground area (SBA) (m <sup>2</sup> )	Performance ratio (PR) (%)
1	6000 TL	a-Si 100 Wp	a. 18.00 kWp. 180 modules, 15 strings, 12 modules each.	a. 32.1	a. 480	83.1
			b. 18.70 kWp. 187 modules, 17 strings, 11 modules each	b. 33.4	b. 500	
			c. 19.70 kWp. 192 modules, 16 strings, 12 modules each	c. 34.3	c. 512	
2	6000 TL	tan-Si 128 Wp	18.43 kWp. 144 modules, 18 strings, 8 modules each.	33.1	325	83.4
3	6000 TL	m-Si 140 Wp	a. 18.90 kWp. 135 modules, 9 strings, 15 modules each.	a. 32.6	a. 222	80.2
			b. 20.20 kWp. 144 modules, 9 strings, 16 modules each.	b. 34.8	b. 232	
4	6000 TL	p-Si 140 Wp	a. 18.50 kWp. 132 modules, 6 strings, 22 modules each.	a. 31.6	a. 222	79.5
			b. 19.30 kWp. 138 modules, 6 strings, 23 modules each.	b. 33.0	b. 237	
			c. 22.20 kWp. 144 modules, 6 strings, 24 modules each.	c. 34.4	c. 242	
5	6000 TL	m-Si 200 Wp	19.80 kWp. 99 modules, 9 strings, 11 modules each.	33.3	214	78.3
6	6000 TL	p-Si 250 Wp	a. 18.00 kWp. 72 modules, 6 strings, 12 modules each.	a. 31.6	a. 237	81.7
			b. 19.50 kWp. 78 modules, 6 strings, 13 modules each.	b. 34.2	b. 256	
7	7000 HV	a-Si 100 Wp	a. 21.00 kWp. 210 modules, 15 strings, 14 modules each	a. 36.7	a. 571	81.2
			b. 21.60 kWp. 216 modules, 18 strings, 12 modules each	b. 37.7	b. 576	
			c. 22.00 kWp. 220 modules, 20 strings, 11 modules each	c. 38.4	c. 588	
			d. 22.10 kWp. 221 modules, 17 strings, 13 modules each	d. 38.6	d. 590	
			e. 22.40 kWp. 224 modules, 16 strings, 14 modules each	e. 39.1	e. 598	
			f. 22.80 kWp. 228 modules, 19 strings, 12 modules each	f. 39.8	f. 608	

<b>8</b>	7000 HV	tan-Si 128 Wp	a. 21.10 kWp. 165 modules, 15 strings, 11 modules each	a. 37.0	a. 398	81.6
			b. 21.80 kWp. 170 modules, 17 strings, 10 modules each	b. 38.2	b. 410	
			c. 21.90 kWp. 171 modules, 19 strings, 9 modules each	c. 38.4	c. 412	
<b>9</b>	7000 HV	m-Si 140 Wp	a. 21.40 kWp. 153 modules, 9 strings, 17 modules each.	a. 36.1	a. 253	78.4
			b. 22.40 kWp. 160 modules, 10 strings, 16 modules each	b. 37.7	b. 264	
			c. 22.70 kWp. 162 modules, 9 strings, 18 modules each	c. 38.2	c. 267	
			d. 23.10 kWp. 165 modules, 11 strings, 15 modules each	d. 38.9	d. 271	
<b>10</b>	7000 HV	m-Si 200 Wp	a. 21.60 kWp. 108 modules, 12 strings, 9 modules each.	a. 36.3	a. 234	78.3
			b. 22.00 kWp. 110 modules, 10 strings, 11 modules each.	b. 37.0	b. 237	
<b>11</b>	7000 HV	p-Si 250 Wp	a. 21.00 kWp. 108 modules, 6 strings, 14 modules each.	a. 36.0	a. 276	79.9
			b. 22.50 kWp. 110 modules, 6 strings, 15 modules each.	b. 38.0	b. 297	

Table 16. Performance assessment by simulation of several configurations

Table 16 with the software simulation results shows the results for 11 possible small inverter configurations. The configuration with the highest performance is #2: 18.00 kWp SBA, with 144 tandem thin-film Si modules distributed in 18 strings with 8 modules each. Figure 46 shows the expected losses under this configuration. We select this module in this example but in a real case one would have to compare performance data together with costs and service and iterate to select the combination with the best value.

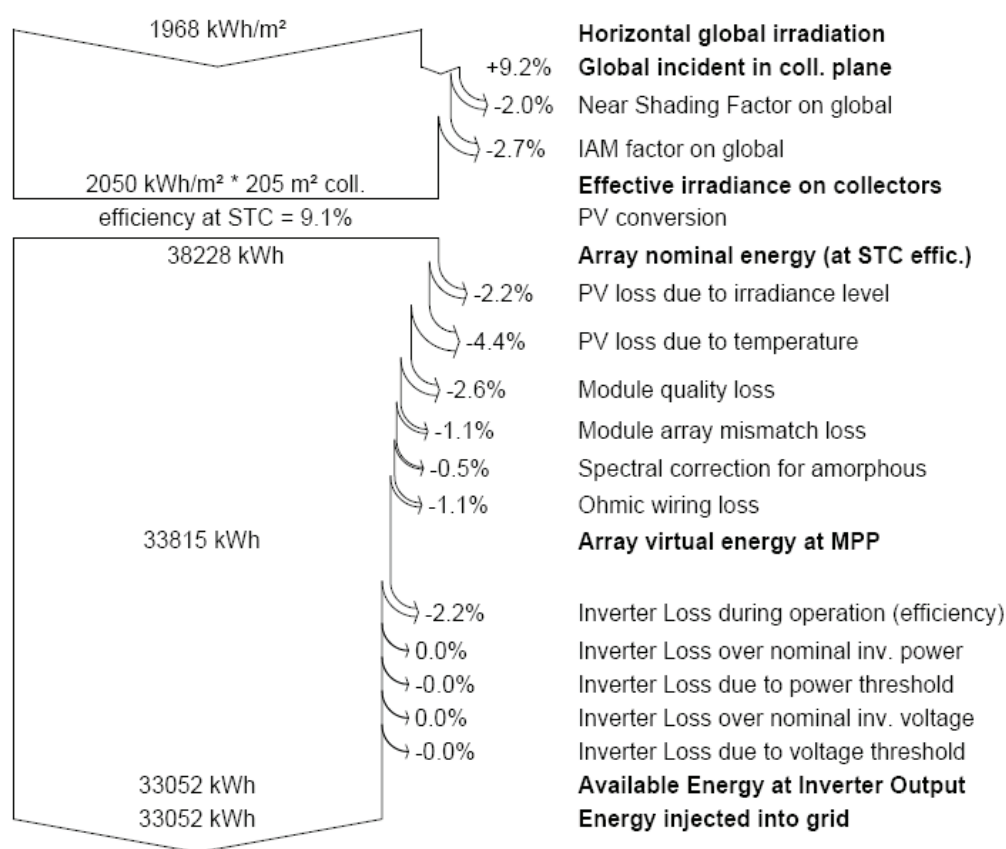


Figure 46. Loss diagram for the configuration proposal 2 (Source: PVsyst).

### 3.2.5 Option with central inverter

This design constitutes a central inverter and a modular concept based on a Solar PV Generation Sub-plant (SGSp) of approximately 300 – 350 kW. To achieve larger capacities for one PV farm is possible by adding as many SGSp as needed.

Moreover, different inverter configuration strategies are possible for each SGSp like

the one based on large central inverters or configurations like the one selected for this example, based on string inverters and several small PV solar basic assemblies (SBA). The performance of two inverter strategies has been assessed by simulation and the results are shown in Table 17 and 18.

Inverter Characteristics	Specifications	
Model	Sunny Mini Central 6000 TL	SolarMax 300TS
Rated Power (kW)	6	300
Input PV Voltage range (V)	333 – 500	430 – 800
Maximum DC Voltage (V)	700	900
Maximum DC Current (A)	19	720
AC Voltage/ frequency	230	3 x 400V / 50Hz
CEC Maximum Efficiency	98%	96.3

Table 17. Tested inverters specifications



Proposed configuration for one SGSp		Outputs		
		Generation (MWh/year)	Ground area (m <sup>2</sup> )	PR (%)
18 SBA (324 kW <sub>AC</sub> )	2592 Tandem thin-film PV modules with 128 Wp each 54 inverters with 6kW <sub>AC</sub> each	605	5,850	84.9
1 SBA (300 kW <sub>AC</sub> )	2535 Tandem thin-film PV modules with 128 Wp each (13 modules in 192 strings) 1 inverter with 300 kW <sub>AC</sub>	572	5,721	83.3

Table 18. Simulation results for two different SGSpS

From a performance point of view, the results obtained are very similar and the choice depends, for each project, on the particular site constraints and operation scenario.

Using small inverters has a more complicated electrical design that requires more connections and materials but it is safer because most of the wiring is AC. The maintenance activities require more complexity, however, but all the components are easy to replace and handle without heavy machinery, and stocking replacement parts is not a big investment. With larger inverters the investment cost is lower and lower maintenance is needed for fewer units. However, the components are more complex and need machinery to replace them; all the wiring to a central point of connection to the inverter is in DC and holds a greater electrical risk.

On the other hand, PV plants with smaller SBA are more adaptable to space available if it is not a flat homogeneous plot of land. The installation could be distributed into canopies, on ground, on roofs, on buildings, with different tilts and orientations for each SBA depending on the space available.

The SGSp and consequently the PV plants composed by small SBA are more flexible as it enables the connection and disconnection of the units achieving the desired capacity in every moment. Also the use of single-phase inverters enables the connection in single-phase and three-phase according to the needs.

Table 19 shows an example for ranking of different inverter size strategies according to different attributes (3=best, 1=worst). Depending on project conditions each attribute is going to have a higher or lower weight on the decision.

Attributes	Small Inverter	Medium-Inverter	Large inverter
Location adaptability to achieve performance	3	2	1
Three-phase or single-phase adaptability	3	3	1
Output flexibility (partial connection/disconnection according to grid requirements)	3	2	1
Wiring (number of lines)	1	2	3
Monitoring and control system	2	2	3
Maintenance	2	2	3
Costing	2	2	3
Safety	3	2	1

Table 19. Ranking of small inverter vs large inverter configuration according to different criteria

### 3.2.6 Proposed solution

In this section the selected solution is described: A PV plant with a rated power of  $1.3 \text{ MW}_{AC}$  and a PV generator STC capacity of  $1,327,104 \text{ kW}_{DC}$ . The plant has 4 sub-plants of  $324 \text{ kW}_{AC}$  connected in parallel on the AC side.

#### 3.2.6.1 General requirements

##### 3.2.6.1.1 Environmental and climatic conditions

All equipment shall be fully operational in the following conditions:

- Relative humidity up to 95%
- Ambient temperature from  $10^{\circ}\text{C}$  to  $45^{\circ}\text{C}$
- Marine environment with high presence of dust, salty air, humidity, insects, rats, etc.
- External equipment shall additionally withstand the following conditions:
  - High ultraviolet radiation
  - Wind speeds up to  $120 \text{ km/h}$

##### 3.2.6.1.2 Solar PV generation sub-plants (SGSp)

The PV plant will be composed by Solar PV Generation Sub-plants (SGSp) of  $324 \text{ kW}$ . Each SGSp will be composed by 18 Solar Basic Units (SBA) as an AC generation unit.

#### 3.2.6.2 Plant description

Each SGSp has the following components according to the layouts and configuration described in the Plant Specifications:

- **PV generator:** the set of PV modules electrically connected to provide the requested optimization of electricity generation. Module specifications, electrical connections and layout configuration characterize this component.
- **Inverter:** this is the component for electricity conversion from a direct current (DC) into an alternate current (AC) that converts the current produced

by the modules into AC compatible with the grid Low Voltage (LV) connection point characteristics.

- **DC wiring:** cables, fuses, protections, switches, connection boxes in the electric line between the modules and the inverter.
- **AC wiring:** cables, fuses, protections, switches, connection boxes in the electric line between the inverter and the grid connection point.
- **Transformer:** responsible for the transformation from LV to High Voltage (HV) for final electricity delivery into the main grid (if required).
- **Data logging:** responsible for the storage of performance indicators, generation calculations, specific events.
- **Monitoring and control sub-system:** this component is required for operational lifetime performance indicators measurement and visualization as well as to control and manage the PV facilities operation.

##### 3.2.6.2.1 Technical requirements

#### Functional Configuration

The PV plant has been designed in order to inject into the grid as much as possible. For this reason the equipment chosen will be in conformity to this strategy and in particular the inverters that convert the DC electricity from the PV generator to grid quality AC. The inverters are “grid dependent” and therefore are not able to operate in autonomous mode and disconnect from the grid if the voltage or frequency are outside defined limits. Therefore these SGSp do not act like a large Uninterruptible Power Supply (UPS) (unless they are connected in parallel with a standby generator temporarily isolated from the main grid). The inverters must have adjustable voltage and frequency tolerances to adjust the grid dependency with the voltage and frequency characteristics of the site.

The PV plant will offset part of the power consumed in the distribution grid. The solar PV facilities shall include “curtail” capability to manage grid stability or capacity issues at times of special conditions. Future scenarios could consider dual mode PV facilities associated to large consumer sites that could either feed the grid or operate autonomously in case of a blackout.

### Orientation, Inclination and Shadowing

The mounting structure of the PV modules will be due South and have a tilt of  $23^\circ$  if the installation has multi-row layout in order to save space (see section 2.1.2.3 *Impact of partial shading*).

### General Layout

Each PV plant will be composed by SGSp, and each SGSp will be organized in Solar Basic Unit (SBA). This SBA allows the design to achieve standardization and modularity. It is the “building block” of a SGSp. It has a surface area small enough that can be easily placed in any of the spaces available at the sites. It can produce three phase LV

and it can be connected in parallel with the grid by itself or together as with as many others as required by each facility’s desired design capacity.

The total ground surface area of each SBA is  $205 \text{ m}^2$  if the modules are placed on a  $23^\circ$  slope. It is a PV-STC capacity of  $18.43 \text{ kWp}$  and a rated AC power of  $18 \text{ kW}_{AC}$ . The number of modules are allowed to be mounted either in “Horizontal” or “Vertical” position while maintaining the same wiring layout and keeping it very simple. It has 144 modules organized in 3 inverter arrays of 48 modules each arranged in 6 strings of 8 series-connected modules each. Details are shown in Figure 47 and Figure 48.

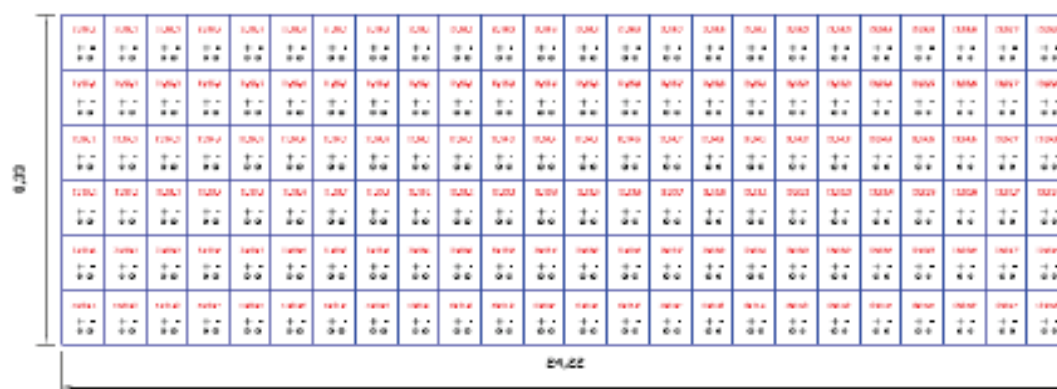


Figure 47. Example layout of SBA modules in vertical position

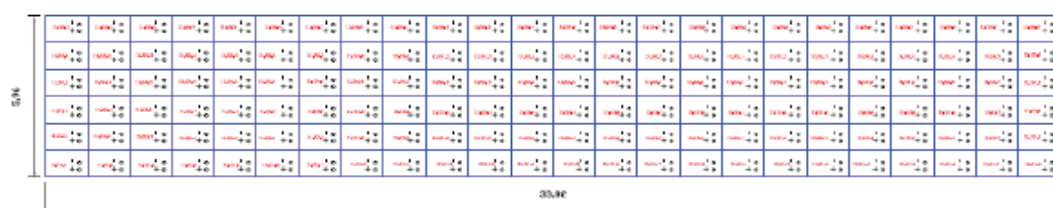


Figure 48. Example layout of SBA modules in horizontal position

Also the total number of modules in each unit has been assessed for performance by iteration using simulation. This design shows a good balance between the inverter's rated power and the STC rated capacity for the selected modules operating in the local conditions. The inverter sizing factor is 0.98.

Solar PV Basic Unit - SBA						
Number of modules	Capacity STC per module (Wp)	STC Capacity of inverter array		Number of inverters	AC power	
144	128	18.43 kWp		3	18 kW	
Inverter Array (DC)						
Num. of strings	Modules in series	V <sub>mp</sub>	V <sub>oc</sub>	I <sub>mp</sub>	I <sub>sc</sub>	Capacity STC
6	8	363.2 V	478.4 V	16.9 A	20.7 A	6 144 Wp

Table 20. Main characteristics of the SBA and each Inverter Array

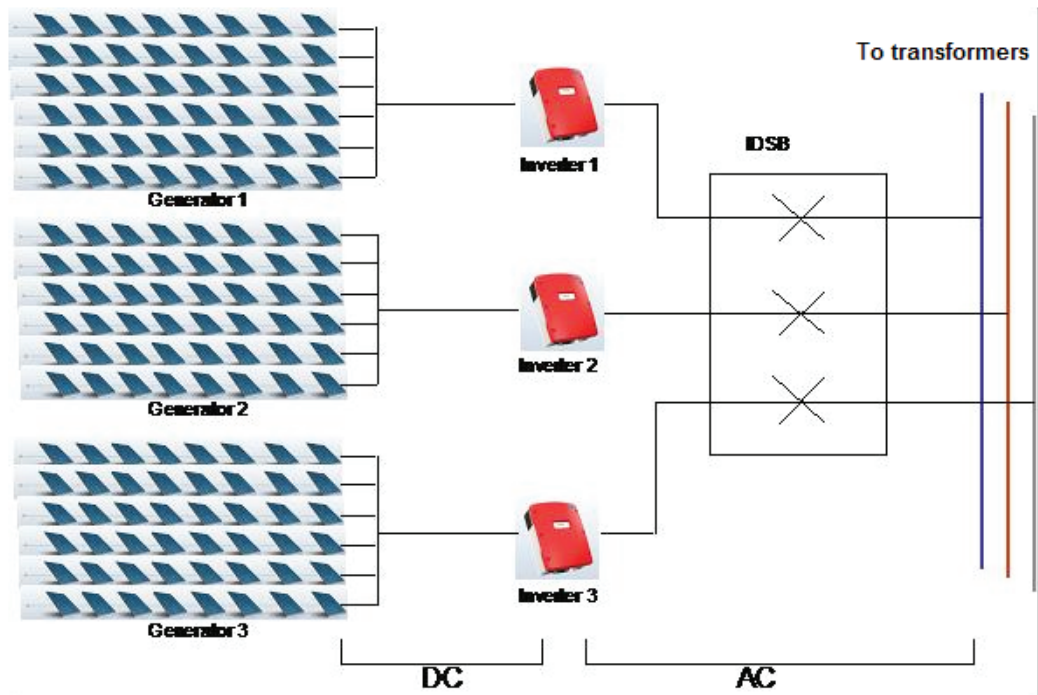


Figure 49. 18 kW SBA diagram

In the SGSp there are 18 SBA. The SBA has been thought to fit in different spaces depending on where the plant will be installed. One or more SBA electrically connected in parallel at a single point and sharing a structure is an SGSp and in a PV plant there are as many as required by the physical and/or electrical layout.

#### Inverter

Each single phase inverter (of  $6\text{kW}_{AC}$  rated power) will convert the DC electricity from

one inverter array and there are three equal inverters for each "SBA" which will usually be connected to each phase of a three phase system. Nevertheless, in some cases if it is necessary, they could be connected to one of the phases.

#### DC wiring

The chosen criteria to choose the DC voltage is listed below, with some contradictions which should be mitigate as much as possible according to the particular project context:

- More safety: obtained when working with extra low voltages (ELV) for reduced risk of electrical shock and arcing.
- More performance: obtained when the voltage in DC is low voltage (LV) and close to the AC voltage of the LV grid.
- Less loss from Joule effect: obtained reducing the modules in strings connected in parallel. This means longer strings and higher voltages.
- Less wiring cost: obtained working with higher voltages, because the wiring section can be smaller, especially when the distance between the inverter and the PV generator is long.

As said, the inverter array will be formed by strings of 8 modules connected in parallel forming a generator. Each generator of 6 strings will be connected to the input of the junction box. This junction or combiner box will also hold the elements for the protection of each of the 6 strings separately. Because in this case DC low voltage (< 1,000 V) has been selected for performance, special attention has to be placed on the insulation class and risk of electric shock related to the wiring.

The junction box of the arrays has 12 input wires (6 +ve and 6 -ve) and an output of 2 wires, one for positive and one for negative polarity that will go to the DC protection box of the inverter in a floating connection.

The features that should be considered for the cables are:

- Unipolar
- Double insulated (Class II)
- Fire proof
- Halogen-free

The section of the DC cables between modules and inverters has to be sized to limit the total voltage drop in DC circuit to a value of less than 3% of its STC rated capacity.

## AC Wiring

The electrical AC wiring design of the PV plant deals with everything between the inverter's AC terminals and the connection point to the main grid (through the transformer if needed) as well as any issues surrounding that connection point. The connections and switchboards should be standardized as much as possible.

- Multipolar cables double insulation (Class II) should be used for AC cables between inverters and transformer.
- Connection between transformer and the protection cells will be done in single core cables.
- Medium voltage (HV) distribution cables connected to the transformer will be made of twisted 3-core cables.

## Transformer

The outcomes of the inverters are connected to the transformer through protectors, switches and connection boxes. The transformers could vary their size from 50 kVA to 2,500kVA or more. The selection of the final transformer will depend on the number of SGSp in the PV plant.

For example, in the case of the 1.3 MW PV plant, two transformers are selected with 800 kVA each; which transforms from 400 V to 11 kV.

Medium voltage protection cells equipped with fixed breaking equipment should be provided to the transformer. The cells should comply with standard: IEC 298-265-129-694-420-56

## Metering and monitoring system

Metering for invoicing is done at LV at the connection point to the grid. The inclusion of a data monitoring setup is recommended to read and record performance data from each inverter, aggregate it for the entire local PV plant and make the information available via the Internet or mobile network (like GSM), but also with simple pilot lights,



with different access levels for different user groups to:

- Collect data to assist the grid operator to build up experience on grids with distributed generation.
- Assess the performance of the PV plant and identify and warn the plant operator or owner if it supplies less than the expected output. Warn the maintenance staff.
- Provide data for general awareness about PV generation to decision makers, investors, professionals, educational institutions and the general public.

### Safety issues

The PV plant will be equipped with protection means that ensures disconnection in case of grid failure or internal fault in the plant itself, so as not to disturb the proper functioning of the grid to which they are connected, both during normal operation and during the incident.

Other forms of protection should be included:

- Protection against electric shock
- Protection against fire
- Protection against over current
- Protection against effects of lightning and surge over-voltage
- Earthing system
- PV plant component electrical isolation

### 3.3 Financial analysis

A spreadsheet model tool has been prepared in order to assess the key financial performance parameters of the PV farm concept presented in the previous sections. Please find this tool in the attached CD to this report.

The model is developed from a private developer point of view, and allows for the projection of 20 year cash flow analysis under several input variables:

- Type of funding source (rebate, private (or own) funding

and bank loan, or a combination)

- General macroeconomic hypotheses (inflation rates, discount rates)
- Plant operational period (a minimum of 25 years is recommended)
- Initial capital costs (including all equipment purchase, EPC, evacuation lines to HV EDL network)
- Replacement costs (under equipment specific operational lives assumptions)
- Operational costs (Management, Operation & Maintenance (M&O&M), permitting, insurance)
- Revenues (under different PPA tariff options)

The first main output from the tool is the “levelized” cost of energy (LCOE), which can be taken as a reference for PPA tariff to ensure a minimum balance of costs (with little or no profit). Sensitivity analysis can be carried out in order to assess the financial performance of a PV farm considering several PPA tariffs.

The second main output from the tool are the internal rates of return of the private or own funds at 3 temporal periods (10, 15 and 20 years), which are a quick reference for return on equity to be considered for the considered PPA tariffs. Reference IRR levels for profitability are considered at 20%; the tool can be used to assess which PPA tariff would enable a certain IRR.

Moreover, the tool can be used to assess the level of rebate needed to achieve a certain IRR under a given PPA tariff.

Finally, the third main output of the tool is the set of financial performance graphs for each PPA tariff assessed, which show the evolution of the cash flow in each year.

Table 21 shows the financial analyses of a 1.3MW PV plant in the Beirut area carried out under three different scenarios.

Financial parameters (20 year analysis)	Scenarios		
	PV market not mature	PV market not mature 30% rebate	PV market mature
Initial investment funding mix	100% equity (or own)	30% rebate 70% equity	100% equity (or own)
Overall initial investment costs to cover with private funds	3,935,646 USD	2,754,952 USD	3,034,746 USD
M&O&M costs (Year 1 ref.)	94,808 USD/year	94.808 USD/year	46,365 USD/year
PR; PV plant yield	0.75; 2,070 MWh/year	0.75; 2,070 MWh/year	0.83; 2,291 MWh/year
Output 1: LCOE	0.23 USD/kWh	0.18 USD/kWh	0.12 USD/kWh
Output 2a: <i>if PPA tariff = 0.25 USD/kWh</i> payback period IRR @ 10 years IRR @ 15 years IRR @ 20 years	10 years 1.8 % 6.0 % 7.8 %	7 years 8.8 % 12.0 % 13.2 %	6 years 11.8 % 14.7 % 15.7 %
Output 2b: <i>for IRR@20 years = 20% PPA tariff needed</i>	0.45 USD/kWh	0.33 USD/kWh	0.30 USD/kWh
Output 2b: <i>for IRR@20 years = 20% and if PPA tariff = 0.25 USD/kWh rebate needed</i>	50 %	50 %	19 %

Table 21. Financial analysis of a 1.3MW PV plant development in the Beirut area under different scenarios

Figure 50 shows the Cash Flow evolution for Scenario “PV market mature” with 100% equity funds and considering a PPA tariff of 0.25 USD/kWh, which would allow an IRR after 20 years of 15.7% (Table 21), and a payback period of 6 years.

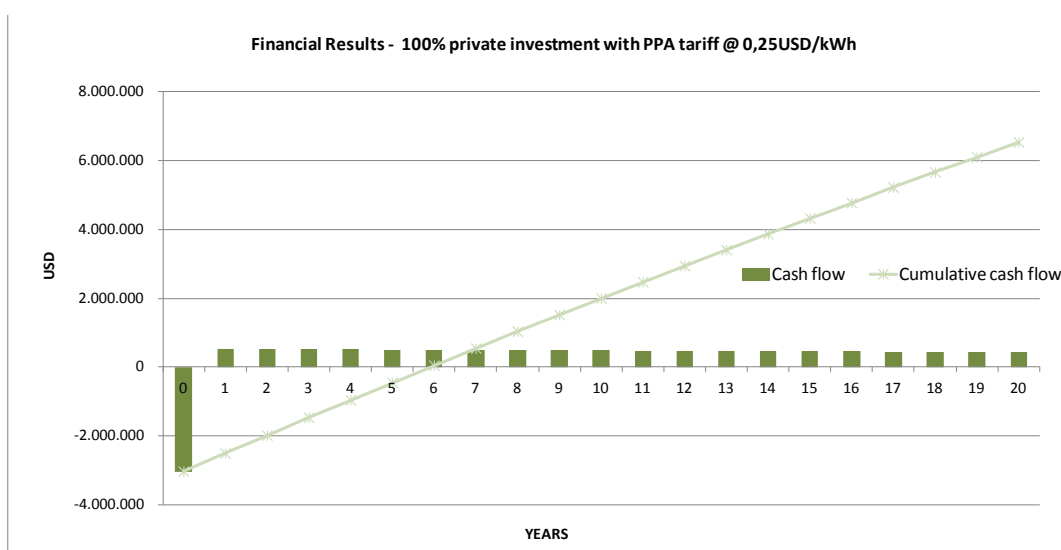


Figure 50. Projected cash flow evolution for a 1.3 MW PV plant in Beirut developed with private funds under a PPA selling tariff of 0.25USD per kWh; the IRR after 20 years would be 15.7%.

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