Field experiences and lessons learned with photovoltaic off-grid and on-grid applications in northern Chile

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Abstract

Due to the high solar energy radiation in northern Chile photovoltaic systems for electrical energy supply in off-grid and on-grid applications present attractive energy solutions under technical and economic aspects. Field experiences made within the last more than 20 years in different projects in small scale applications up to 35 kW_p are shown with focus on project planning, design, reliability of components, capacity building and necessary support after installation. In general, a very high acceptance for renewable energy projects can be observed on all levels, from users up to regional and national decision makers, but the number of installations especially in the private sector is relatively low. Technical results and experiences are shown and main obstacles for a wider dissemination are discussed such as investment costs and access to reliable and appropriate information for users.

Keywords: Field experiences, PV on-grid, PV off-grid, small-scale applications

1. Introduction

The following paper focus on field experiences made by the authors with PV systems for off-grid and on-grid applications typically in the range of 0,5 – 35 kW_{peak}. First PV-off grid systems were installed some 25 years ago for rural electrification such as DC solar home systems and AC PV systems for schools, health centres, farms and others. PV on-grid systems present a quite new application in Chile; first pilot small-scale applications for decentralized grid connection were installed some 8 years ago, in 2014 a feed-in law with a net billing tariff system was established.

2. Technical description of typical installed PV systems

Northern Chile, especially the desert and high Altiplano regions present a very high solar energy potential throughout the whole year with relatively little seasonal changes; the mean daily global radiation in these areas is $H_{day, mean}$ = 6,9 kWh/m^{2}day (Molina, 2014).

2.1 Stand-alone off-grid applications

PV off-grid systems present technical and economic viable solutions for energy supply in remote areas, compared for example with conventional systems such as Diesel operated generators. The typical small-scale DC applications for basic electricity supply and rural electrification started some 30 years ago, focus for off-grid systems in this paper are photovoltaic systems with AC electricity supply, There is a wide range of applications with an installed peak power varying from 1 kW_p to approximately 50 kW_p, for example for rural schools, health centres, communication systems and others. As an example, Figure 1 shows the basic diagram for a 34 kW_{peak} off grid system with a storage system, charge regulators, three phase inverter and a genset backup for electricity supply of a waste water treatment plant in a remote area.

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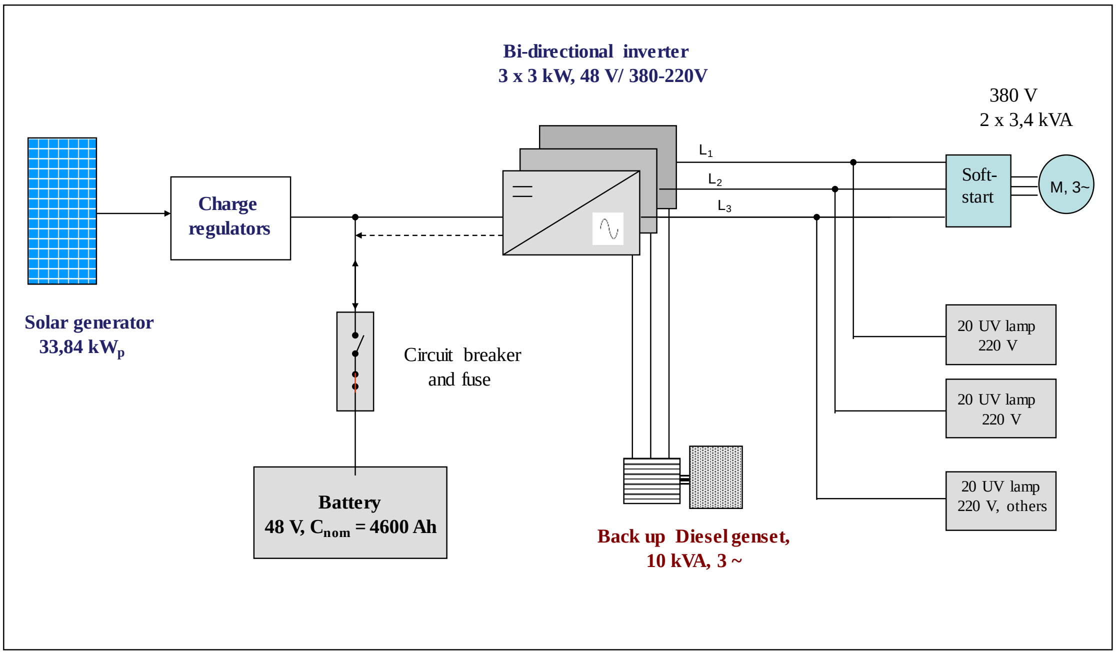

Fig.1: Basic diagram for a 34 kWp PV off-grid system with a storage system and genset backup

The system design was relatively simple due to the fact that the load was easily to determine and also relatively constant over the years of operation. In this case, a daily electrical energy consumption of $E_{el.,day}$ = 100 kWh/day was calculated in order to operate a total of 60 UV lamps in 24-hour operation and two three phase waste water pumps with an electrical power of 3 kW each, operating periodically during day and night. The solar generator consists of 144 solar modules (72 cell modules, Si poly crystalline) with a peak power of P_p = 235 W_p, organized in 12 subarrays (each subarray with 3 modules in series connection and 4 strings), each subarray was connected to a MPPT charge controller.

In order to assure a long system life time, the selected battery is a OPzV lead acid gel battery with a system voltage of 48 V and a nominal capacity of $C_{nom.}$ = 4.600 Ah, see Figure 2. A Diesel generator has been installed as a backup unit, which is connected directly to the three-phase bi-directional inverter, but has not been used so far.

Fig. 2: Principal components of 34 kWp PV off-grid system (Putre, northern Chile)

A monitoring system was installed in order to observe the system performance, most important the battery performance and the real consumption data; the following Figure 3 shows the daily electrical energy consumption and the minimum daily battery voltage, in this case during a period of 4 months in the critical winter months with lower solar radiation from May to August.

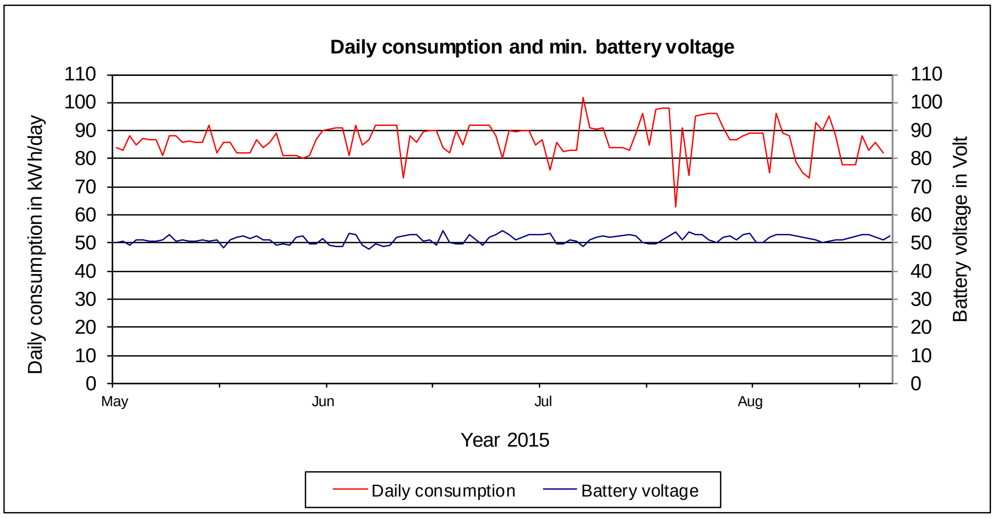

Fig. 3: Daily consumption and daily min. battery voltage of 34 kWp PV off-grid system (Putre, Arica and Parinacota Region)

2.2 PV-grid connected systems

PV-grid connected systems present a relatively new application in Chile. A feed-in law with a net billing tariff system was introduced in 2014 (SEC, 2019), but so far, this did not lead to a widespread use especially for small and medium-scale systems in northern Chile. Due to the existing tariff system, most interesting applications can be identified in agriculture and industry; the systems focus on self-use, only excess energy is injected to the grid. A standard three phase PV installation with a peak power of 25 kW_p is shown in Figures 4 and 5, in this case for a 12 hectares farm with the main electrical energy demand for irrigation. The used inverter makes installation on the DC side relatively simple: a DC power switch is integrated as well as fuses, so that the different PV strings can be connected directly to the inverter DC inputs.

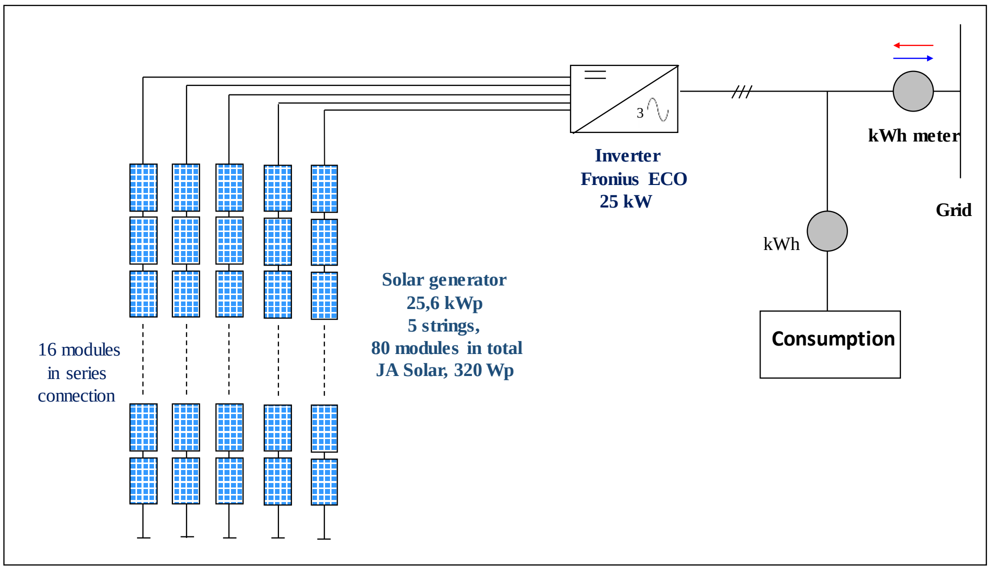

Fig. 4: Basic diagram for a 25 kWp PV on-grid system

Fig. 5: Principal components of 25 kWp PV on-grid system (Arica, northern Chile)

Since installation, the system is working well, but main disadvantage of this classical PV grid connected system is the fact that the solar grid inverter switches off in case of a grid failure without electrical energy supply for the user. Therefore, the integration of a storage system with a hybrid inverter presents a very interesting alternative in two aspects: self-consumption increases and mainly, the solar system continues operating in off-grid mode in case of grid disconnection. A first pilot project was carried out in Arica with a 5 kW_p installation for a 4 hectares farm. (Antúnez et al., 2016).

In a first step, an energy audit has been done before installation in order to obtain precise data about the electrical energy demand. Electrical energy demand is given by two water pumps for irrigation (2 HP each with a total daily operating of 7 hours), refrigeration, illumination and typical household appliances. The consumption was measured and registered as 10-minute values during a total period of 3 months. The daily electrical energy consumption varies between 15 – 20 kWh/day. Figure 6 shows a typical daily load profile with a total electrical energy consumption of $E_{el.}$ = 19 kWh/day. The operation of the two irrigation pumps can clearly be identified, as well as the on-off cycles of the refrigerator during the whole day. Another interesting aspect to mention is the stand-by consumption of all electronic devices connected; a constant stand-by consumption of $P_{el,standby}$ = 60 W can be observed.

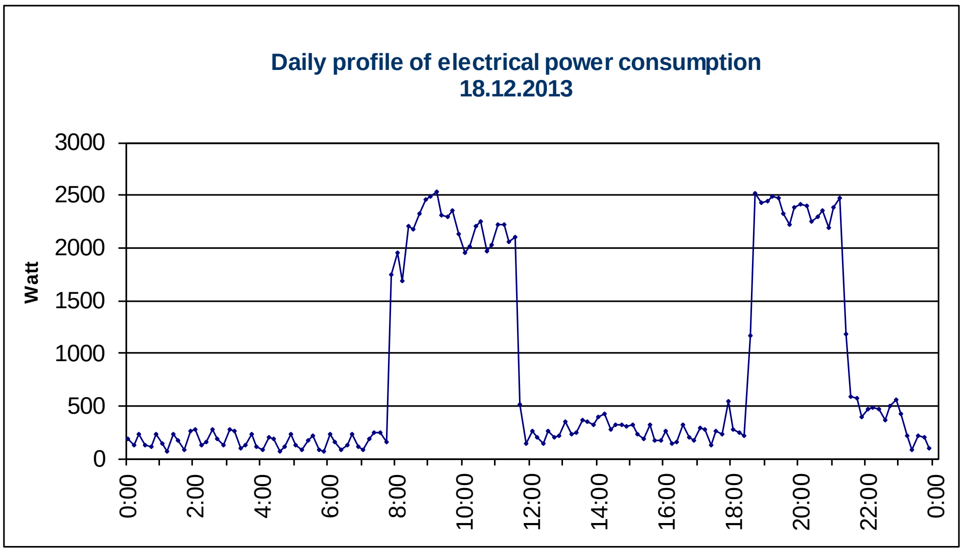

Fig. 6: Typical daily load profile of 4-hectare farm (Arica, Arica and Parinacota Region)

These measurements on site not only give precise information about the electrical energy consumption and daily load profiles, but also help to improve the load management. In order to increase self-consumption, the adaption between solar electricity generation and consumption can be improved significantly by changing the irrigation schedule during the day, that means, concentrate major consumption during sunshine hours, in this case. starting irrigation later in the morning and earlier in the afternoon. Considering the measured load data, the system design gave results, presented in Table 1:

Table 1: Main system parameter, grid connected PV system with storage

Parameter	Value
Typical daily electrical energy consumption	15 – 20 kWh/day
Solar generator peak power	5 kW_p
Hybrid inverter with integrated system manager and charge unit	5 kW
Battery	Lead acid, gel, OPzV, C_{100} = 1.100 Ah
System voltage DC	24 V

As mentioned before, the hybrid inverter operates in two different modes. In normal operation, the electric grid is connected, priority lies on self-consumption, only the solar surplus energy is injected to the grid. The battery use in on-grid mode can be programmed and limited by defining the battery's depth of discharge. In back-up mode, the grid is disconnected and the system works in off-grid mode; the batteries can be recharged by the solar generator and the battery's depth of discharge also can be programmed and limited. The basic functional diagram and the installed system are shown in Figures 7 and 8.

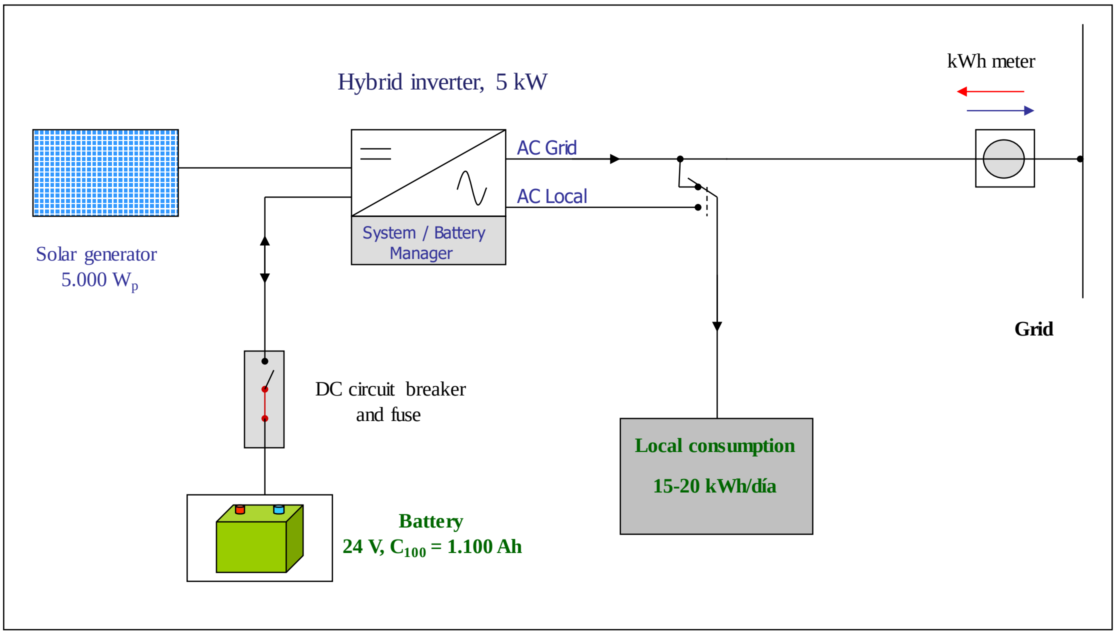

Fig. 7: Basic diagram for a 5 kWp PV on-grid system with battery storage

A monitoring system, including a calibrated solar cell for irradiance measurement was installed in order to obtain reliable data about the system`s performance. The inverter in these applications assumes additional functions such as a battery and system management. In this pilot installation, the installed OPzV battery has a relatively high capacity and can be reduced in future installations for a lower investment cost. The battery has demonstrated an excellent performance, the measured battery efficiency (E_{out}/E_{in}) was calculated to η_{Bat} = 87 % (Antúnez et al., 2016).

Fig. 8: Principal components of 5 kWp PV on-grid system with storage (Azapa, Arica and Parinacota Region)

The installed solar generator has a peak power of P_{peak} = 5 kW_p and is composed of a total of 20 solar modules with a peak power of 250 W_p each, organized in two strings with 10 solar modules in series connection. The monitoring systems measures, among other parameters, the solar irradiance and generated DC power. Figure 9 presents the relation between solar irradiance and generated solar electrical power, measured over several months from June to October 2015. The measured curve can be approximately described as a linear relation between solar generator power and solar irradiance using a correction factor FC_p which considers the power degradation in relation to the solar cell temperature. Due to the increasing solar cell temperature at higher irradiances the measured electrical power with a solar irradiance of 1.000 W/m^2 is $P_{el.}$ = 4.200 W. The correction factor is FC_p = 0,84.

$$P_{sg,cc} \approx FC_p \cdot \frac{P_p}{1.000\ W/m^2} \cdot S \qquad \text{(eq. 1)}$$

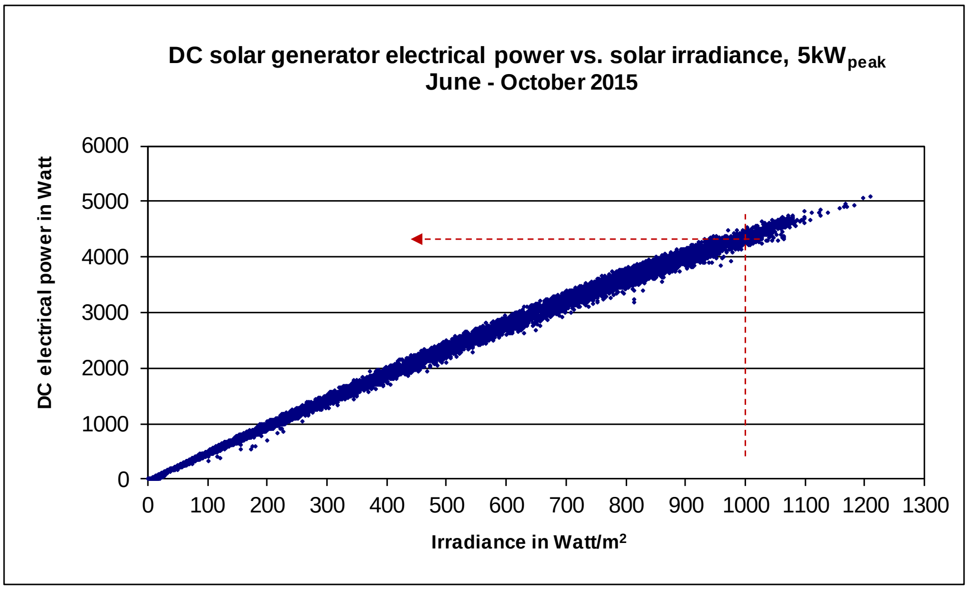

Fig. 9: Relation between solar irradiance and generated solar electrical power (5 kW_p PV grid connected system)

Figure 10 shows an example of daily profiles of solar generation, consumption on site and export of electricity to the grid. The solar generated electricity (red curve) first recharges the battery in the morning. In this example, there is a relatively low electrical energy consumption during the whole day (blue curve) with battery support in the evening and during night. Due to the low demand on this day, electricity is injected to the grid during the day (green curve).

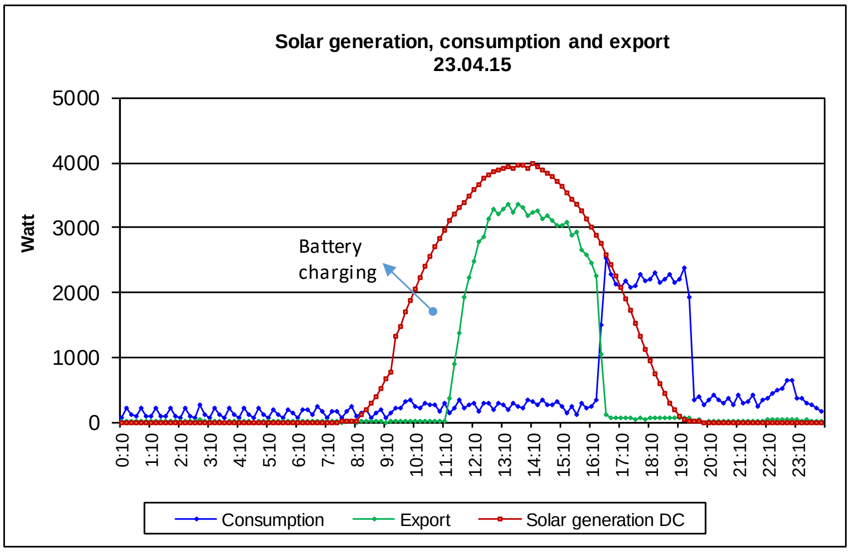

Fig. 10: Solar generation and electric power of the inverter (5 kW_p PV connected system)

Due to the fact that the battery is operating also in normal grid operation and due to the battery's capacity of C_{100} = 1.100 Ah the self-consumption rate is quite high in this pilot installation. The energy balance over the whole year 2015 is shown in Figure 11. The blue curve represents the solar generation in AC at the inverter output, the two columns (green and red) show the total electrical energy consumption on site. The self-consumption rate is 89% (average value over the year), that means only 11 % of total yearly energy demands is covered by the grid.

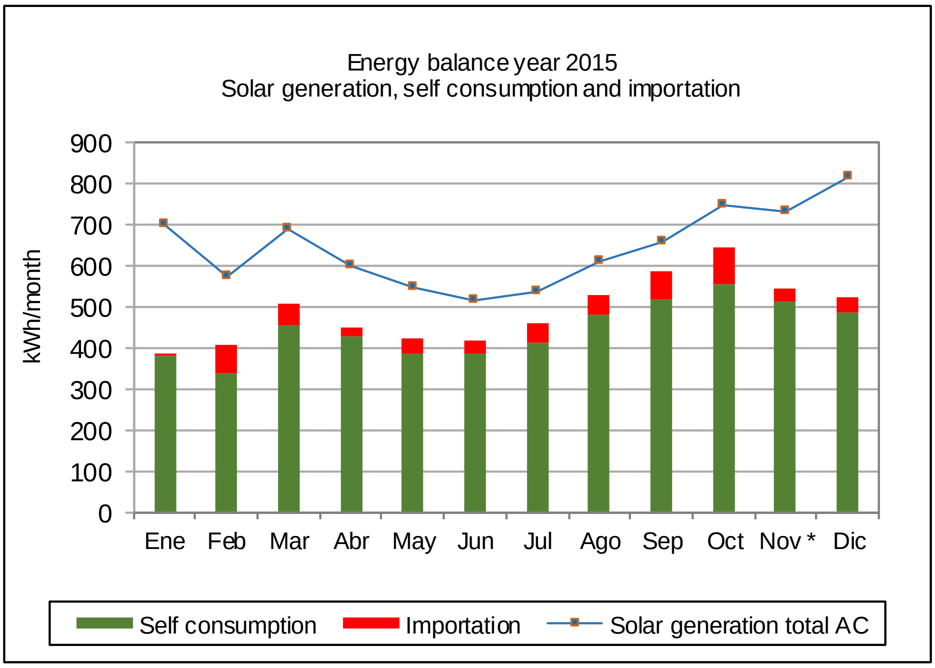

Fig. 11: Solar generation inverter AC, self-use and grid importation

3. Field experiences and lessons learned

Within the last 20 years a total of approximately 100 small scale systems with a total peak power of about 150 kW_p, DC and AC off-grid and on-grid systems, have been installed by the authors in different kind of projects. The projects and installations were carried out with international counterparts, such as UNDP, national counterparts mainly the Agricultural Research Institute INIA, public institutions such as CORFO, the local electric utility EMELARI in Arica and private users. Lessons learned and the main field experiences are pointed out in the following chapters.

3.1 Project planning and design

Generally spoken, the design of a small- or medium scale PV system is not complicated, but the following aspects should be considered carefully during planning and design:

- Determination of the electrical energy demand, especially in off-grid systems
- User participation
- Product quality

Most critical parameter in designing a PV off-grid system is the determination of the electrical energy demand, especially in systems with AC electricity supply. This aspect is not so critical in PV on-grid systems due to the fact that in grid connected systems the user normally is already connected to the grid and data about the electrical energy consumption are available for example in the electricity bill; the on-grid user normally gets information about his electrical energy consumption over the last 12 months, which is a quite good planning guide.

In the case of off-grid systems the data base is quite poor in many cases, therefore it is recommended to carry out an energy audit on site and calculate or, in many cases, estimate the actual and the future electrical energy demand. In all observed cases of PV off-grid systems with AC electricity supply the demand increased significantly within the first years of operation, which should be considered in the system design. Oversizing the PV system compared to the actual electrical energy demand is helpful, but also an effective user´s training about system operation and use of energy efficient appliances is absolutely necessary.

Another aspect, worth to be mentioned, is the importance of a strong user's participation in project planning. The users normally have some basic information about photovoltaic applications but matching the user´s expectations and the possible technical solutions often result a difficult task and needs a lot of conversation and time. During planning, the user should receive at least clear information about the following aspects:

- System's capacity and performance
- Benefits, but also limitations and possible restrictions
- Details about the initial investment cost and estimated pay-back period
- Necessary user's activities for adequate operation and maintenance
- Guideline in case of system failures

Best approach are several visits on site, discussions and information with the potential user. And finally, choosing high quality products are essential and should be selected carefully during the design phase.

3.2 Reliability of components

3.2.1 PV modules

All installed PV projects were equipped with mono- and poly-crystalline Si modules. Electrical failures on these modules cannot be reported, only failures of one of the internal bypass diodes have been seen on two 12 Volt modules which were installed in 2005 for rural electrification projects, see Table 2. First modules which have been installed in 1998 are still operating. As an example, Figure 13 shows the IV curve of one of these modules, a 50 W_p Siemens SM 50 mono crystalline Si module, which is shown in Figure 12. This module was measured in 2019 after more than almost 20 years of operation.

The history of this module is well known; the first six years of operation it was installed in a solar pumping system, in the following years it was used operating 12 Volt ventilators in a solar dryer equipment. The 12 Volt ventilators were connected directly to the solar module, that means, the module was operating the whole day.

Figure 13 shows the measured IV curve and calculated power curve under real test conditions and the calculated STC IV curve and STC power curve. The module is still operating within the specifications with an actual peak power of 44,8 W, equivalent to 89 % of its initial peak power in 1998.

Fig. 12: SM 50 module from 1998 on the left, compared with an actual 250 W_p module from 2018

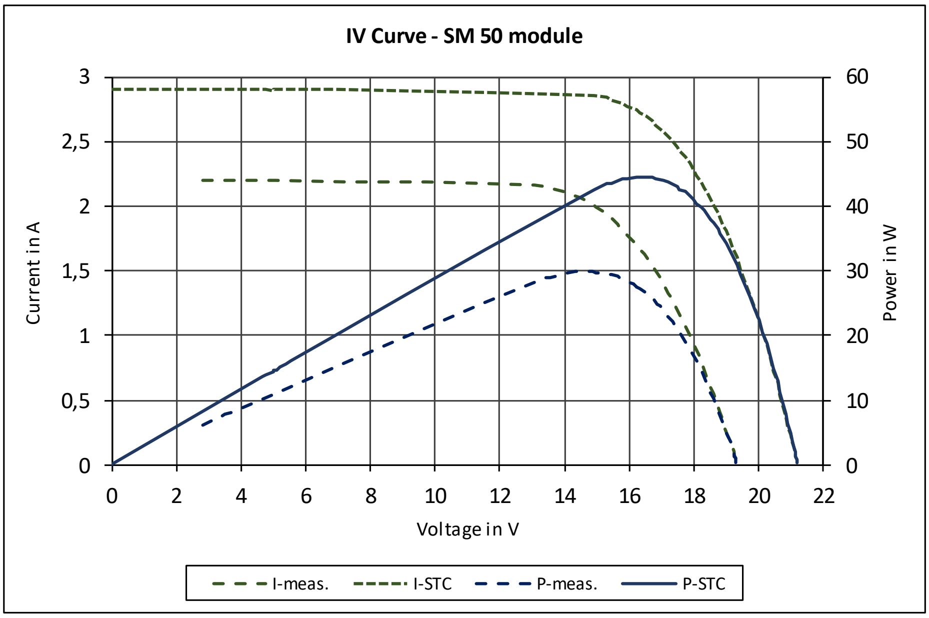

Fig. 13: Measured IV curve under real test conditions and STC curve

3.2.2 Charge regulators and inverters

In general, PV systems and components can be characterized for their very high reliability and lifetime. Regarding product quality, the situation with PV off-grid systems is more complicated than on-grid systems. The feed-in law for on-grid systems only allow the installation of certified solar modules and inverters (SEC, 2019).

For PV off-grid system there is a widespread market of solar modules, charge regulators, inverters, batteries and information about product quality often is quite poor.

The following Table 2 shows registered failures of electronic components such as charge regulators and inverters. Form a total of 90 solar charge regulators two failures have been observed; in the case of off-grid inverters a total of 24 inverters have been installed with one registered failure and finally, one on-grid inverter failed from a total of 13 installed devices. In all cases, hardware failures have been observed, normally after installation or within the first days of operation; these devices were sent back to the supplier for repair; in the case of the on-grid inverter, this device was repaired on site in cooperation with the supplier by replacing the main AC electronic board. The failure rate of electronic components is low, nevertheless, it must be considered that failures might happen.

Table 2: Number of installed components and registered failures

	PV Modules	Charge regulators	Inverters off-grid	Inverters on-grid
	Installation > year 2002			Installation > year 2012
Installed	150 kW_{peak}	90	24	13
Failure	2 modules (bypass diode)	2	1	1

As a main conclusion, as mentioned also in other publications (Feron, 2016) eventual electronic device failures can occur and should be taken into account, that means, the supplier's back up is absolutely necessary and spare parts or equipment should be available within 1-2 days.

3.2.3 Batteries

So far, all reported installed PV systems with storage use lead acid solar Gel or AGM batteries, maintenance-free solar 12 Volt grid plate batteries or 2 Volt OPzV Gel cell batteries for larger systems. The battery's quality is a decisive factor for a long-run system operation. Problems with the battery performance are not seen immediately but often occur after several months of operation. It is highly recommended select a suitable battery according to the life cycle curves and the provider or manufacturer should provide this information. Unfortunately, many suppliers, especially for grid plate solar batteries, do not publish this information. These curves are measured on a laboratory level and real conditions in the field are different, but so far, these life cycle curves are the best quality indicator in order to choose a good battery.

The following Table 3 recommends how to select a good battery, define adequate levels for depth of discharge, DOD and expected lifetimes.

Table 3: Recommended battery parameters

Parameter	Grid plate solar batteries	OPzV batteries
Max. depth of discharge, DOD	20 – 30 %	30 – 40 %
Min. life cycles	2.200 cycles	4.500 cycles
Lifetime	> 6 years	> 12 years

3.3 Deep discharge control of the battery

A good working deep discharge control of the battery is another important parameter in PV off-grid systems, especially using inverters and AC electricity supply. As in most installations the inverter is connected to the battery (not connected to the charge regulator) the inverter has to assume the function of deep discharge control. All inverters control the DC input voltage level but the cut-off voltage level is very low; typical inverter fabric settings of this value are for example 10,5 V in a 12 Volt system, 21 V in a 24 Volt system and 42 V in a 48 Volt system, that means, at this voltage cut-off level the battery is completely discharged, there is no protection against the battery's deep discharge. An inverter should be selected which permits to change and adapt this value during installation and setup. Recommendable values for deep discharge control and cut-off are 11,4 V in a 12 Volt system, 22,8 V in a 24 Volt system and 45,6 V in a 48 Volt system. Another possibility for the deep discharge control uses the load output of the charge regulator in combination with a remote control input of the inverter.

3.4 Monitoring

PV on-grid systems normally have an integrated monitoring system which allows precise data analysis on-line. On the other hand, the situation with PV off-grid systems, installed in remote areas, is different. The user, in many cases, does not have information about the system's performance and normally is not so familiar with technical parameters such as electrical power, energy, charging state of the battery, etc. Therefore, it is very useful to implement a basic monitoring system in off-grid applications, at least, install a kWh meter at the inverter's output in order to control the electrical energy consumption and second, use a battery voltage meter or a simple battery monitor to inform the user about the actual battery's charging state.
A simple but very useful is a simple three LED indicator with green, yellow and red LED's, such as a traffic light, which helps the user to get a rough but sufficient information about the actual system´s performance and, if necessary, reduce the electrical energy consumption in order to avoid a shortage in electricity supply.

3.5 Training and support after installation

More and more people, users, installers, technicians, engineers, project planner, product suppliers, professionals in the public sector etc. are involved in solar energy activities. An adequate training on all levels is absolutely necessary, but experiences indicate clearly a widespread gap on this, not only in Chile but also in many other countries (Feron, 2016). Capacity building activities on all levels are essential for successful projects (IEA, 2003). Training workshops exist but, in many cases, do not accomplish the planned goals. Efficient training, in general, needs qualified personal, needs time and cannot be done successfully in a 4-hour workshop.

Regarding the user level, solar energy is something new for most of the users; a short introduction and user training by the installer is not enough to assure a good and sustainable system operation and maintenance. Experiences in the field clearly show that user support and training after installation is very helpful, for example regular site visits, several short training activities after installation at least during the first year of operation.

3.6 Main obstacles in dissemination

Compared with other countries worldwide, Chile is an emerging country regarding solar energy use. Though a very high acceptance of renewable energy can be observed in society in general, there is so far a very small private market for decentralized PV on-grid and off-grid systems. As main obstacles for a wider dissemination two aspects can be mentioned: lack of information and still high investment costs.

Regarding information, it is so far quite difficult for a potential user to get adequate information about solar energy applications, performance of typical systems, involved costs and obtain technical advisory. In the case of product suppliers many new solar companies and suppliers have been established within the last few years. Only a very small number of companies so far present a necessary technical skill to orientate potential users.

Second, the economic evaluation of PV solar energy projects is positive and the specific electricity costs for both, on-grid and off-grid PV solutions can easily compete with conventional energy supply, but the initial investment cost present the main obstacle. The costs for solar modules have decreased significantly worldwide and also on a national level, but for farmers, residential users, small or medium size companies or others it is still a quite high barrier to invest in solar energy. Investment and installation costs vary significantly due to number of installations and region. Mean values for investment and installation cost (without tax) for on grid systems without storage are approximately 2.100 US$/kW$_p$ for a system size between 1 – 5 kW$_p$, 1.900 US$/kW$_p$ for a system size between 5 – 10 kW$_p$ and 1.600 US$/kW$_p$ for a system size between 10 – 30 kW$_p$ (Fuchs and Almonacid, 2018).

Another aspect regarding investment in solar energy for a small or medium scale application refers to priorities which the different potential users might have; a farmer, for example, has to decide among different priorities on his farm (water pumping, irrigation and others) in which area to invest, energy supply often does not get the highest priority.

3.7 Conclusions

A detailed planning phase is helpful including a strong user participation in order to select the best system configuration and match the user`s expectations with technical and economic viable solutions. PV modules present in general a very high quality level and long lifetime, electronic device failures are low but might happen; the supplier's back up is therefore absolutely necessary. Batteries are the most critical components in PV systems; the use of high quality batteries is essential with long life cycles and an adequate deep discharge control of the battery must be implemented. Training measures on all levels should be strengthened and user support after installation is highly recommended in order to achieve sustainable system operation. Small and medium scale PV systems for on-grid and off-grid applications present a very high potential in northern Chile, but lack of information and high investment costs are still the main obstacles in dissemination.

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