


BEST PRACTICES FOR PHOTOVOLTAIC IRRIGATION SYSTEMS

SolaQua

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This manual is freely available in the webpage of the project and in zenodo platform (in SolaQua community).

For more details, please visit www.sol-aqua.eu

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Acronyms

1xh	North-South horizontal axis tracker
AC	Alternate Current
DC	Direct Current
E_{AC}	AC energy
E_{aux}	Auxiliary energy
E_{PV}	PV energy
ETo	Reference Evapotranspiration
EU	European Union
EPC	Engineering, Procurement, Commissioning
FC	Frequency converter
G	In-plane global irradiance
G*	Iradiance at Standard Test Conditions
G_{IP}	Irradiance during the IP
G_{max}	Irradiance that allows the PV generator to provide the maximum power that the pump can consume at a given cell temperature
G_{start}	Minimum irradiance to reach the power threshold
G_{used}	Irradiance effectively used by the system
G_{useful}	Available useful irradiance during the IP
IP	Irrigation Period
I_{SC}	Short-circuit current
ISINPA	Irrigators, SMEs, Investors and Public Authorities
KEMT	Key Enabling Materials and Tools
l	Smallest dimension of the perimeter of the PV generator
MP	Motor-pump
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
N_s	Number of PV modules in series
P*	Nominal power of the PV generator
P_{AC}	AC power

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PID	Potential Induced Degradation
PLC	Programmable Logic Controller
PPA	Power Purchase Agreement
$P_{p=const}$	Constant PV power for a constant pressure value
PR	Performance Ratio
PR_{PV}	PR considering only losses strictly associated to the PV system itself
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
PVIS	PV Irrigation System
RE	Renewable Energy
S(25)	Static structure oriented to the South and tilted 25º
SI	Solar Irrigation
SME	Small and Medium Enterprise
STC	Standard Test Conditions
T_C	Cell temperature
T_C*	Cell temperature at STC
T_{Mm}	Maximum monthly mean ambient temperatures
T_{mm}	Minimum monthly mean ambient temperatures
UR_{EF}	Ratio of the irradiation required to keep P_{AC} stable during the irrigation scheduling to the same irradiation during the IP
UR_{IP}	Ratio of the total irradiation throughout the irrigation period to the total annual irradiation
UR_{PVIS}	Ratio of the irradiation strictly required to keep P_{AC} equal to the stable AC power requirement to the total irradiation throughout the IP
V^*_{OC}	Open-circuit voltage at STC
V_{AC}	AC voltage
V_{ACGRID}	AC voltage of the grid
$V_{ACoutputFC}$	AC voltage at the output of the FC
V_{DCGRID}	DC voltage imposed by the grid
$V_{DCoutputFC}$	DC voltage at the input of the FC
V_{MPP}	Maximum Power Point Voltage
V_{OC}	Open-circuit voltage

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$V_{p=const}$	Voltage at constant PV power for constant pressure
WP	Work Package
ΔS (60)	Delta structure
σ_{cloud}	Passing cloud resistance ratio
β_c	Coefficient of variation of voltage with cell temperature

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1. Introduction

1.1. SolaQua in a nutshell

SolaQua's overall objective is to increase the share of **renewable energy (RE)** consumption in Europe by facilitating the market uptake of **photovoltaic irrigation systems (PVIS)** in the farming sector. PVIS is based on a combination of **photovoltaic (PV)** technology, hydraulic engineering, and high-efficiency water management techniques to optimize irrigated farming.

The consortium of SolaQua, which represents more than 70% of European irrigators, is aware of the potential of PVIS to decisively improve the sustainability of farming and rural communities in Europe. Nevertheless, to fulfil this potential, it is necessary to overcome the existing barriers to the market uptake of SI. To do this, SolaQua will accelerate the clean energy transition in European agriculture by facilitating the development of a well-functioning market for SI. This will be done by producing and exploiting a set of 7 **Key Enabling Materials and Tools (KEMT)** and by creating awareness, skills, action, engagement, and commitment (ASAEC) opportunities among more than 150,000 farmers, 70 local SMEs, and 40 Public Administrations in Europe and beyond.

The execution of SolaQua will result not only in a reduction of the cost of PVIS for farmers but also in the availability of effective standards for consumers and environmental protection, more efficient policies and supporting schemes, and new business opportunities for SMEs. Furthermore, to exploit the project's results and to trigger the PVIS market, SolaQua will facilitate a joint promotion of more than 100 MW of reliable and affordable PVIS led by the end-users themselves: the farmers.

To achieve the overall objective of increasing the share of RE in the European farming sector by facilitating PVIS market uptake, SolaQua has established the following 5 specific objectives:

1. **Produce and disseminate a set of 7 KEMT**, designed to solve technical, economic, and legal issues which are acting as barriers for the market uptake of SI.
2. **Produce awareness and skills of PVIS among the target groups in six countries** (France, Italy, Spain, Romania, Portugal, and Morocco). At least 150,000 potential end-users will be reached, 70 SMEs will be trained, and 38 Public Authorities will be able to produce more informed policies and supporting schemes.
3. **Trigger the European PVIS market by facilitating a joint promotion of at least 100 MW of PVIS**, exploiting SolaQua's KEMT and led by the target audiences engaged in PVIS because of the project's dissemination and communication actions.
4. **Increase the effectiveness of public supporting schemes for on-farm investments for the promotion of PVIS**: SolaQua will produce a new European Agrarian Fund for Rural Development (EAFDR) financial instrument that will be implemented in 3 European regions and will support more than 40 MW of new PVIS capacity.
5. **Facilitate market uptake of reliable and affordable PVIS in markets outside the EU** that will result not only in increased cooperation but also in business opportunities for European SME´s and investors.

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1.2. Purpose and scope

This document is **KEMT 1**, a technical guide for **best practices in planning, installing, operating, and maintaining solar irrigation (SI) systems**. It includes all the specifications, controls and protocols that must be followed to produce reliable PVIS.

In addition to international and national regulations on both photovoltaic and irrigation systems, if the best practices presented here are followed, it is possible to guarantee a level of quality and performance sufficient as to qualify PVIS projects as collateral for long-term investments.

This document is based on the know-how and experience of the partners to compile state-of-the-art and proven solutions. It includes inputs of the Irrigators, SMES, Investors and Public Authorities (ISINPA) partners represented in the consortium.

This document will be used in the dissemination actions of SolaQua and will be freely available online.

The original version of this document was written in English. It was then translated to French, Italian, Portuguese, Romanian, and Spanish.

1.3. About this document

After this small introduction, this document starts with a chapter (chapter 2) to clarify some concepts of both irrigation and photovoltaic fields. In addition, it presents the main specificities of PVIS, including key performance indicators to technically evaluate them.

The next chapters present best practices (as well as good and bad ones) in PV irrigation systems. In more detail:

- Chapter 3 is about **Planning a PVIS**
- Chapter 4 is about **Designing a PVIS**
- Chapter 5 is about **Installing a PVIS**
- Chapter 6 is about **Operating and Maintaining a PVIS**

Some of the information presented in this document was previously collected in other works developed by some SolaQua partners, particularly in **Technical specifications and quality control procedures for contractual frameworks** (Narvarte et al., 2017) and **Good and Bad Practices – Manual to improve the quality and reduce the cost of PV systems** (Martínez-Moreno and Tyuyyundzhiev, 2013). This Best Practice Guide updates some of the contents and figures of previous documents.

The reader will find, for many of the photographs presented in this document, a quickly and clearly highlight symbol about the nature of the situation being presented. Table 1 includes these symbols and their meaning.

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Table 1 – Many of the photographs of this document include one of the symbols presented here.

Symbol	Meaning of the symbol
	Good practices
	Bad practices
	Some improvements should be made

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2. Classification

Irrigation for agricultural applications is an intensive water and electricity-consuming activity. Most of the current agricultural irrigation systems are powered from the national electric grid or diesel generators. However, both the increase in the price of this conventional electricity and the trend to phase-out fossil fuels, has boosted the look for alternatives to power these systems. Solar photovoltaic irrigation systems appear as a solution due to the decrease of the PV modules prices in international market, as well as the removal of technological barriers that limited the power of PV irrigation systems.

Along this document, and under SolaQua project, PV irrigation systems (PVIS) are large-power PV irrigation systems, without batteries, and able to work in stand-alone mode. Before entering into the details of the best practices for PVIS, some concepts need to be clarified and some classifications must be made.

2.1. Irrigation

Irrigation is the controlled application of water for agricultural purposes through manmade systems to meet water requirements when rainfall is not sufficient. Crop irrigation is vital throughout the world in order to provide the world's ever-growing population with enough food. Irrigation can be defined as replenishment of soil water storage in plant root zone through methods other than natural precipitation. Irrigation water is brought to cultivated land through artificial means, such as pipes, hoses or canals. The irrigated land usually contains crops, grass or vegetation which would not receive enough water from rainfall or other natural sources. Sometimes the reason to irrigate a portion of land is characterized by a dry season with less-than-average amounts of rainfall. The water used for irrigation might be taken from surface water (dams, reservoirs, rivers, …) or groundwater (wells or boreholes). It must be underlined the importance of a responsible and sustainable water resource management to avoid water-stress and water pollution in agriculture. Over-irrigation affects the groundwater reserves, and excessive fertilization pollutes aquifers.

2.2. Crop water requirements

High-efficiency water management techniques need a high-level knowledge about the crops water requirements. PVIS must be designed and sized in accordance with these needs, fitting the energy production to the real water requirements in every period of the year.

The crop water requirements are defined as the amount of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by the various crops to grow optimally. The crop water requirements always refers to a crop grown under optimal conditions, i.e. a uniform crop, actively growing, completely shading the ground, free of diseases, and optimal soil conditions (including fertility and water). In these conditions, the crop can reach its full production potential under the given environment. The crop water requirements mainly depend on the climate (in a sunny and hot climate crops need more water per day than in a cloudy and cool climate), the crop type (crops like maize or sugarcane need more water than crops like millet or sorghum), the growth stage of the crop (fully grown crops

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need more water than crops that have just been planted). The major climatic factors which influence the crop water requirements are sunshine, air temperature, air humidity and wind speed. The highest crop water requirements are thus found in areas which are hot, dry, windy and sunny. The lowest values are found when it is cool, humid and cloudy with little or no wind.

Evapotranspiration

The influence of the climate on crop water needs is given by the reference crop evapotranspiration (ETo) (Allen et al., 1998; Pereira et al., 1999). The ETo is usually expressed in millimetres per unit of time, e.g. mm/day, mm/month, or mm/season. Grass has been taken as the reference crop. The reference crop evapotranspiration is defined as the rate of evapotranspiration from a large area, covered by green grass (usually Festuca arundinacea), 8 to 15 cm tall, which grows actively, completely shades the ground and which is not short of water. There are several methods to determine the ETo. They include experimental methods based on the use of an evaporation pan, or theoretical ones that use measured climatic data – e.g. (Allen et al., 2011a, 2011b; J. Farahani et al., 2007; Verstraeten et al., 2008).

Crop coefficient

The relationship between the reference grass crop and the crop actually grown is given by the crop coefficient, Kc (ETo × Kc = ET crop). Both ET crop and ETo are expressed in the same unit usually in mm/day (as an average for a period of one month) or in mm/month. The crop coefficient, Kc, mainly depends on the type of crop and the growth stage of the crop. Fully developed maize, with its large leaf area will be able to transpire, and thus use more water than the reference grass crop; Kc of maize is thus higher than 1. Cucumber, also fully developed, will use less water than the reference grass crop, thus Kc of cucumber is less than 1. A certain crop will use more water once it is fully developed, compared to a crop which has just recently been planted. The climate influences the duration of the total growing period and the various growth stages. In a cool climate a certain crop will grow slower than in a warm climate. Thus, to determine the crop factor Kc, it is necessary, for each crop, to know the total length of the growing season and the lengths of the various growth stages.

Effective rainfall

Crop water requirements can be supplied to the crops in various ways by rainfall, by irrigation, and by a combination of irrigation and rainfall. In cases where all the water needed for optimal growth of the crop is provided by rainfall, irrigation is not required, and the irrigation water requirements equals zero. In cases where there is no rainfall at all during the growing season, all water has to be supplied by irrigation. Consequently, the irrigation water need equals the crop water need (ET crop) (G. Allen et al., 2007; Jensen and Allen, 2016).

In most cases, however, part of the crop water requirements is supplied by rainfall and the remaining part by irrigation. In such cases the irrigation water requirements is the difference between the crop water requirements and that part of the rainfall which is effectively used by the crops. When rainwater falls on the soil surface, a portion can infiltrate into the soil, stagnate on the surface, or flow over the surface as runoff. When the rainfall stops, some of the water

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stagnating on the surface evaporates to the atmosphere, while the rest slowly infiltrates into the soil. From all the water that infiltrates into the soil, some percolates below the root zone, while the rest remains stored in the root zone. In other words, the effective rainfall is the total rainfall minus runoff minus evaporation and minus deep percolation. Only the water retained in the root zone can be used by the crops and represents what is called the effective part of the rainwater. The term effective rainfall is used to define this fraction of the total amount of rainwater useful for meeting the water need of the crops.

Crop water requirements determination

The first step in the agricultural sector is to compute how much water is needed by crops with regard to climate conditions (agricultural water demand). Some techniques, such as, meterological data measurment soil moisture monitoring, lysimeter, Eddy Covariance (Allen et al., 2011a), the Bowen ratio (Fritschen and Fritschen, 2005) and surface renewal, are used to monitor and measure irrigation requirements. While the monitoring approach may require delicate and expensive sensors or the assistance of experts, the application of models (Evett et al., 2012, 2006) could provide a low-cost method for on-farm and regional systems for computing the crop water requirements and estimating the depth of water storage required to satisfy the agricultural demand.

Efficiency of the irrigation

Once the crop water requirements is known, improving the efficiency of the irrigation application is a key strategy for water savings in agriculture. The term “efficiency” is commonly used to indicate “the level of performance” of a system.

In the agricultural sector, to quantify the efficient use of irrigation water the term “water productivity” is often used, that is the concept of applying irrigation water efficiently to optimize production. The water productivity is expressed as the agricultural production per unit of water applied, diverted, or consumed (rainfall and/or irrigation) to foster crop production (Playán and Mateos, 2006). As pointed out by (Playán and Mateos, 2006), an increase in water productivity ameliorates gains in crop yield, while reducing the amount of irrigation water contributing to unrecoverable losses. The increase of water productivity could be the solution for food needs accompanying the projected population growth. Nowadays, many strategies are implemented to improve water productivity, starting with the optimal choice of irrigation system.

2.3. Water source and pumping system

Irrigation water can come from groundwater, through wells, or surface water, through canals. A sustainable irrigation water management is mandatory to preserve groundwater quality and availability, assuring a natural recharge of aquifers and avoiding contamination from fertilizers. In this regard, the EU Water Framework Directive 2000/60/EC establishes the necessary approach to preserve good quality, chemical and ecological status of groundwater.

The most common irrigation system pumps water to an elevated reservoir or water pool (source–pump–reservoir) – **“Pumping to a water pool”** (at variable pressure and water flow).

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This type of installation makes it possible to store water and energy, thus increasing the supply reliability.

The second type is the irrigation system that pumps water directly to the distribution network (source–pump–crop) – **“Direct pumping”** (systems working at constant pressure and flow for each irrigation sector). In this kind of system, water is withdrawn from the water source and then directly distributed to the plant emitters in a single pumping stage (Reca-Cardeña and López-Luque, 2018).

Pumping systems are usually made up of one centrifugal motor-pump, or more than one centrifugal motor-pumps arranged in parallel. To pump at variable flowrates to different heads efficiently, frequency converters (FC) are commonly used in PVIS.

2.4. Irrigation network

Most of the components of a PVIS do not differ substantially, neither in their design, nor in their management, from those used in other conventional irrigation system. The design and management of any irrigation system depends on the type of crop and cropping techniques, climatic conditions, soils, water availability and quality, and other technical and socioeconomic constraints.

An on-farm irrigation network conveys the irrigation water to the emitters. In PVIS, pressurized irrigation methods are commonly used, namely, sprinkler or drip irrigation. The selection of the proper irrigation system depends on several factors, such as water availability, crop selection, soil characteristics (deep percolation, runoff, evaporation rate and topography) and the associated installation and maintenance costs. The main systems are separated into **gravity systems**, where water moves naturally over the soil surface due to the force of gravity, and **pressurized systems**.

In terms of PVIS sizing and design, the irrigation network is characterized by a system curve that relates water flow to pressure losses. The correct definition of this curve is essential to define the pump characteristic that is best suited to determine the operating point of the pumping system for maximum efficiency.

An important measure to evaluate the performance of irrigation systems is the **application efficiency**, which is defined as the ratio of the average depth of irrigation water contributing to the target divided by the average depth of irrigation water applied. The ratio is multiplied by 100 to express the application efficiency as a percentage. The target depth is generally based on the soil water depletion before irrigation or a smaller amount to adjust for rainfall contributions. The target can also include excess water for reclamation or for salinity control. Many studies have been conducted to determine the application efficiency for different systems, and the overall conclusion is that pressurized systems are generally more efficient for transporting water to crops than traditional gravity systems (Chimonides, 1995). In recent years, several irrigation systems have significantly improved the application efficiency at the farm level, enhancing irrigation water management. Although the traditional gravity approach is still widely used, particularly in the southern part of Europe, it is gradually being replaced (European Environment Agency, 2009). Nevertheless, the application efficiency of a system depends on the amount and timing of water applied, as well as on the considered crop, soil and climate conditions. To maximize crop yield and meet the crop water requirements, irrigation to refill soil water

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depletion is typically applied. This approach is valid for most field crops and many orchard crops. aooku

Improving the crop technical efficiency may be another solution to overcome the water for food issue. The choice of the best cultivar, such as more drought-tolerant cultivars, or crop management with regards to the soil and climate conditions can provide a method to improve water productivity. For instance, shifting the planting date in response to climate change can be beneficial, especially for those crops with a spring-summer growing season. Simulations of irrigation requirements under climate change scenarios, where the planting date was shifted by a month or even earlier in the spring, showed optimal results (Döll, 2002; Lovelli et al., 2012) for some crops. In fact, planting earlier in the spring increases the length of the growing season, and it can increase the potential yield if the soil moisture is adequate and the risk of heat stress is low (Maracchi et al., 2005). Otherwise, earlier planting combined with a short-season cultivar would avoid heat and water stress (Tubiello et al., 2000).

2.5. Irrigation methods

Irrigation methods can be broadly classified as sprinkler and micro-irrigation. A consolidated description of design and management are included in various manuals such as those by (Hoffman et al., 2007; Stetson and Mecham, 2011; Tiercelin and Vidal, 2006).

Sprinkler irrigation systems may be stationary or continuous moving.

Micro-irrigation systems include high-tech methods with large capital and maintenance investment: surface and subsurface drip irrigation for row crops, field crops, and orchards, micro-sprinklers and micro-sprayers for horticulture and under-tree irrigation, and bubblers for orchards (Keller and Bliesner, 1990; Lamm et al., 2006; Venot et al., 2019).

A more detailed description of irrigation methods is available in Annex I.

2.6. Energy source and types of PVIS

Regarding the energy source, PVIS can be:

- **Stand-alone solar photovoltaic irrigation system**.
- **Hybrid solar photovoltaic irrigation system**.

In what concerns stand-alone irrigation systems, the irrigation system is only fed by the energy produced by the photovoltaic (PV) generator using frequency converters (Figure 1).

In the case of hybrid systems, the irrigation system is fed both by the energy produced by the PV generator and by other energy source. The other energy source must be diesel generator sets, gas generator sets or the conventional electricity grid.

Two types of hybridization can be found:

- **Hydraulic hybrid systems** (Figure 2): the hybridization is carried out into the hydraulic circuit – the water outflow pipes are associated in parallel, and the sources of energy are not electrically interconnected. These systems can work isolated from the

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electrical grid and therefore, may be an interesting solution in countries in which the connection of the PV to the grid is regulatory hampered.

- **Electric hybrid systems** (Figure 3): The hybridization among the PV generator and the other source is carried out in the electric part of the system. These systems are considered as self-consumption systems and are subject to applicable regulations.

As summarized in (Almeida et al., 2020), hybrid systems with PV are needed when the irrigation network requires more irrigation hours than those available with PV, usually due to the diameter of the pre-existing tubes. Hybrid systems are also an interesting solution if there is a peak of irrigation in some months of the year, and as a strategy to solve problems associated to PV power intermittences.

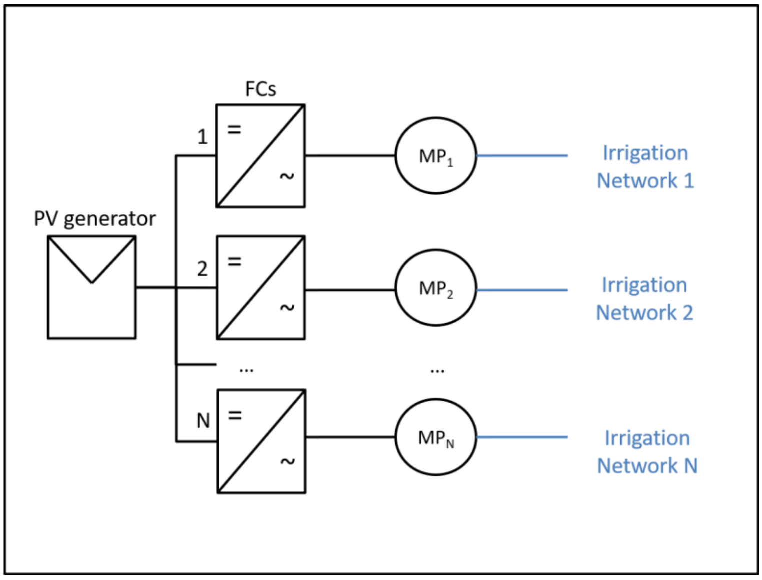

Figure 1 - Stand-alone PV systems: the irrigation system is fed by energy produced by PV generators. Figures depicted in black represent the electrical part, in blue the hydraulic part. FCs stands for frequency converters, while MP is for motor-pump.

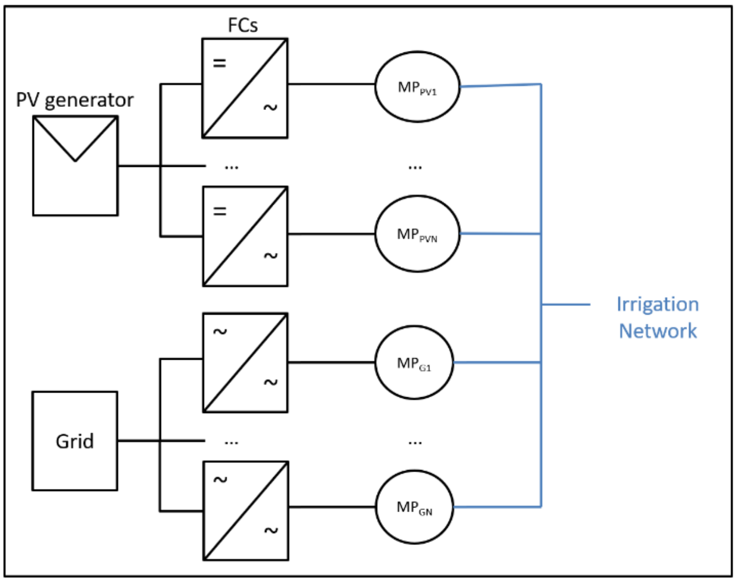

Figure 2 - Hydraulic hybrid systems: the irrigation system is fed by energy produced by PV generators but also from other sources (diesel or gas generator sets and conventional electricity grid), but hybridization is carried out into the hydraulic circuit.

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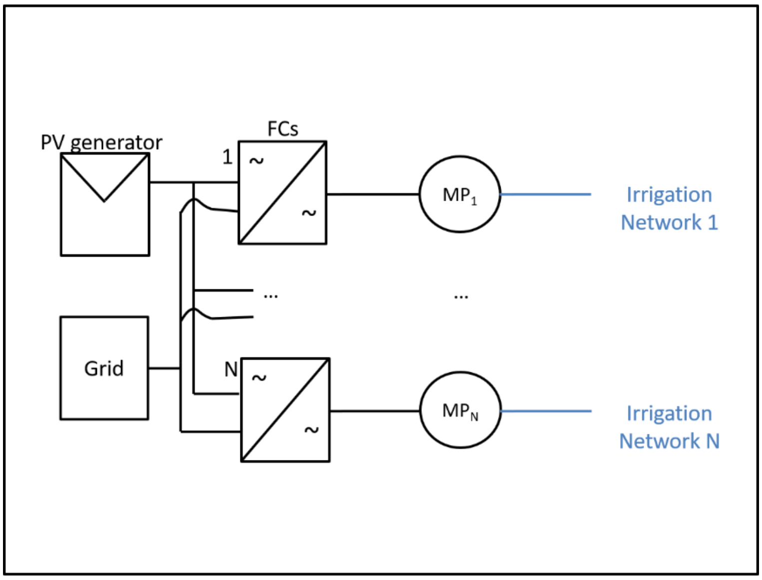

Figure 3 - Electric hybrid systems: hybridization among PV generators and the other sources is carried out in the electric part of the system.

Finally, if the irrigation period of a specific crop is only in few months of the year, some countries allow the possibility of export the PV energy to national grid in the non-irrigation period. To do this, a grid-inverter must be added to the system, as well as a single pole double throw switch. This way, the system is a PV irrigation system during the irrigation period (the PV generator is connected to the frequency converters through the switch), while it is a typical grid-connected system outside the irrigation period (the PV generator is connected to the grid-inverter through the switch). This configuration can be seen in the next figure, in which the switch is in the PV irrigation system position.

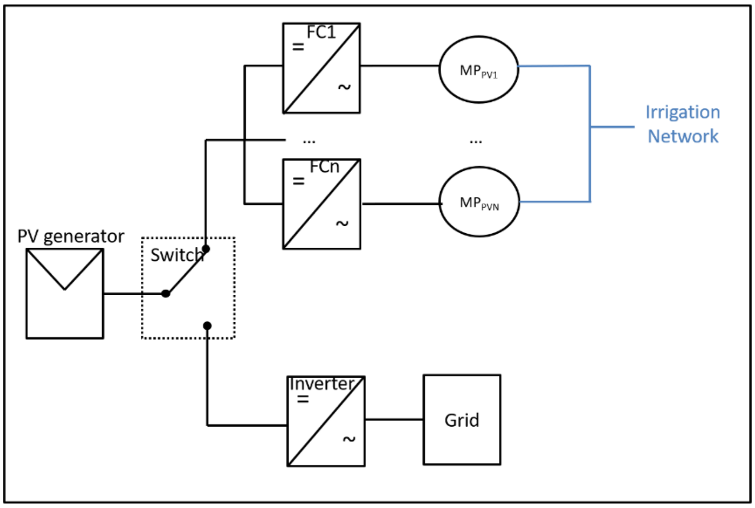

Figure 4 - Mixed systems: the system is a PV irrigation system during the irrigation period, and a grid-connected system outside the irrigation period. The switch allows the change between the two operating modes and, in the case of this figure, the switch is in the PV irrigation system position.

2.7. Stakeholders involved in PVIS

Multiple stakeholders are involved in PV irrigation systems. Accordingly, it is important to clarify them, as well as their roles and responsibilities.

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- **EPC (Engineering, Procurement, and Construction):** is the entity responsible for engineering, procurement, and construction of the PVIS.
- **O&M (Operation and Maintenance) provider:** is the entity responsible for the operation and maintenance of the PVIS (it can or cannot be the same as the EPC).
- **Data-related services provider:** is the entity responsible for the monitoring system. It can also be the O&M provider.
- **Technical advisors:** external engineers or companies that ensure that components, procedures, and practices are of high quality, i.e. external institution specialized in quality control of stand-alone large-power PVIS.
- **Authorities:** local, regional, national, or international authorities to assure that the system complies with all normative.
- **End-user**: the farmer, co-operative, water union association, irrigation community or agroindustry in which the PV system is installed.
- **Financial entity**: in the case of a Power Purchase Agreement (PPA), the owner of the PV plant is the financial entity.

2.8. Specificities of PVIS

It is crucial to keep in mind that an PV irrigation system is based on a combination of PV technology, hydraulic engineering, and high efficiency water management techniques. PVIS must:

- Be **integrated in the pre-existing irrigation system**. The PV must be adapted to the previous irrigation components and irrigation needs. This is a key aspect as most of the potential market for PVIS is already irrigated lands.
- **Match PV production and irrigation needs**. The use of North-South horizontal axis tracker is one of the best solutions to guarantee this match: it maximizes the water pumped during the irrigation period, the daily profile of irradiance is almost flat, it allows the enlargement of the irrigation hours per day when compared to the typical static structure oriented to the equator, and it requires less nominal PV power to pump the same water volume than a PV static structure.
- Be **robust against PV power fluctuations** due to passing clouds. This is another key point to assure the economic feasibility since PVIS are large power ones and do not integrate batteries.
- **Ensure reliability for**, at least, **25 years** to guarantee the compliment of the business plan. Following the best practices presented in this document will allow this reliability.

More details about these specificities can be found in (Narvarte et al., 2017).

Key performance indicators

Passing clouds

The quick intermittence of PV power due to the passing of clouds can carry out control instabilities, leading to a sudden stop of the frequency converter (FC), encompassing water hammer and AC overvoltages that seriously threaten the integrity of both the hydraulic and

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electric components of the PVIS. To avoid those instabilities, ad-hoc control algorithms have been developed and patented (Fernández-Ramos et al., 2019, 2018) to support PV power instabilities without the need of batteries. FCs in PVIS usually have routines for tracking the maximum power point (MPPT) voltage of the PV generator and control the operating voltage and the frequency of the pump in a fast and stable way with a proportional-integral-derivative controller (PID). Despite this being true, a balance is required between a fast response and stability because the faster the response, the greater the probability of having instabilities when the available PV power changes. As the PID controller may not be fast enough, specific algorithms run on PLCs to detect the power intermittence, prevent the instability and avoid the FC abrupt stop (Fernández-Ramos et al., 2018). To do this, DC voltage is monitored and, when a fluctuation that puts at risk the FC is detected, the PID controller is switched off and the frequency is reduced to allow power regeneration in the pump. This eliminates the occurrence of undervoltages and avoids abrupt stops of the FC. Once the frequency has been adjusted, the PID controller is restored for normal operation. Therefore, the system must be able to withstand sudden intermittences of PV power caused by passing clouds.

To assess whether the system resists quick PV power intermittences due to passing clouds a passing cloud resistance ratio (σ_{cloud}) is defined as:

$$\sigma_{cloud} = \#\, resisted\ clouds / \#\, clouds \qquad \text{(Eq. 1)}$$

where ”# resisted clouds” is the number of resisted clouds and ”# clouds” is the total number of clouds in a specific period of time. The total number of clouds is counted taking into account just quick PV power drops, no matter whether they produce or not a FC abrupt stop, because the quick increase of PV power does not usually produce an abrupt stop of the FC. In the same way, the number of resisted clouds is counted considering just quick PV power drops that do not lead into FC abrupt stops. The ”quick” adjective, in this context, is determined by the size of the PV generator. Abrupt stops are usually provoked by deep drops in short periods of time, and should be avoided for PV power ramps of duration greater than or equal to:

$$\Delta t(\mathrm{s}) = \frac{l(\mathrm{m})}{20(\mathrm{m/s})} \qquad \text{(Eq. 2)}$$

where *l* is the smallest dimension of the perimeter of the PV generator expressed in meters.

The PV power drop depth needs to be specified taking into account the weather conditions of the place where the PV generator is located. As the PV power drop information is not always available (for example when there is an abrupt stop), the study has to focus not only on the PV power drop but on the irradiance drop, measured by a calibrated cell or a calibrated PV module, that causes it.

(Herraiz et al., 2020) shows that around 97% of the clouds that cause an equivalent drop on the irradiance measured by the calibrated cell and on the PV power, are associated to irradiance drops of a 50% or less. There are few clouds that generate irradiance drops of a 60% and almost none that generate bigger drops. Assuming that if the system resists clouds that cause a 50% irradiance drop it will also resist clouds that cause lower drops, it is reasonable to focus the study on this type of clouds.

As a conclusion, it can be said that if the passing cloud resistance ratio is calculated for 50% irradiance decreases in a 3- or 4-seconds interval and associated to PV power decreases, it will be lower than that obtained under less restrictive conditions. In any case, time interval and

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irradiance drop depth must be reviewed according to the characteristics of the PV irrigation system and the weather conditions to avoid small number of clouds under study that would make the study not representative.

PR for photovoltaic irrigation

To analyze the global performance of PV grid-connected plants it has been described the *performance ratio* (*PR*) – IEC 61724:1998 –, which is the ratio of AC energy delivered to the grid, E_{AC}, to the energy production of an ideal loss-less PV plant with 25^{0}C cell temperature and the same solar irradiation (Luque and Hegedeus, 2002). It is an index widely used in general PV environments that provides an indication of both the technical quality of the PV system's equipment and the efficient use of the available irradiation. It gives a good idea of how much of the ideally available PV energy has been used.

Due to the specificities of PVIS, it is interesting to distinguish between irradiation losses for three different reasons: the non-irrigation period – associated to the crop –, the intrinsic characteristics of the irrigation system design (direct pumping or pumping to a water pool), and external circumstances that may affect the *PR* like the irrigation community habits or the different rainfall over time. To take them into consideration, the *PR* can be expressed as follows (R.H. Almeida et al., 2018):

$$PR = \frac{E_{\text{PV}}}{P^*/G^*} \times \frac{1}{\int Gdt} \times \frac{\int_{\text{IP}} Gdt}{\int_{\text{IP}} Gdt} \times \frac{\int G_{\text{useful}} dt}{\int G_{\text{useful}} dt} \times \frac{\int G_{\text{used}} dt}{\int G_{\text{used}} dt} \qquad \text{(Eq. 3)}$$

where E_{PV} is the PV energy; IP is the irrigation period determined either by the crop and its water needs; G_{useful} is the available useful irradiance during the IP determined by the relationship between the PV generator nominal power (P^*), the PV generator structure, and the type of irrigation system (water pool or direct pumping); and G_{used} is the irradiance effectively used by the system and depends mainly on whether the farmer activates the system during the IP and on the number and length of abrupt stops of the FC.

To clarify these concepts, an example of G during the IP (G_{IP}), G_{useful} and G_{used} is shown in Figure 5 for a direct pumping system. G_{IP} is the total irradiance during the irrigation period (Figure 5a) determined by water needs. In the example the irrigation period runs from April to October because water needs are covered by pumping along that time interval. G_{useful} is the irradiance required to deliver the power needed to pump water at the needed constant pressure (Figure 5b). It is worth noting that with irradiances below G_{useful} the system will not be able to pump because there will not be enough power to start de pump and reach the required pressure, and irradiances higher than G_{useful} will be partially wasted because the PV generator cannot supply more power than that consumed by the pump working at the required conditions. Finally, G_{used} is the part of G_{useful} that has been used due to the availability of water and the irrigation scheduling (Figure 5c). In this last figure, the irradiance from 7 am to 14 pm was wasted due to the irrigation scheduling or the lack of water during that day and not because of technical problems in the PV system or the needs of the crop.

Figure 6 shows the graphical representation of G_{useful} for a PVIS pumping to a water pool (working at a variable frequency). In this second example, the FC starts working when the available power is greater than a start threshold. That means that when the FC has not been started yet and the available irradiance (G_{IP}) is below the minimum needed to reach the power threshold (G_{start}), the FC can't be started and the irradiance is wasted and is not considered part of G_{useful}. The same

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happens once the FC is running and G_{IP} drops below G_{stop} (minimum irradiance level under which the FC cannot be running anymore and needs to be stopped). From that moment on, if the FC stops and G_{IP} is lower than G_{start}, it will not be part of G_{useful}. In the same way, if the available irradiance is greater than the one that allows the PV generator to provide the maximum power that the pump can consume at a given cell temperature (G_{max}), the difference $G_{IP} – G_{max}$ will not be part of G_{useful}.

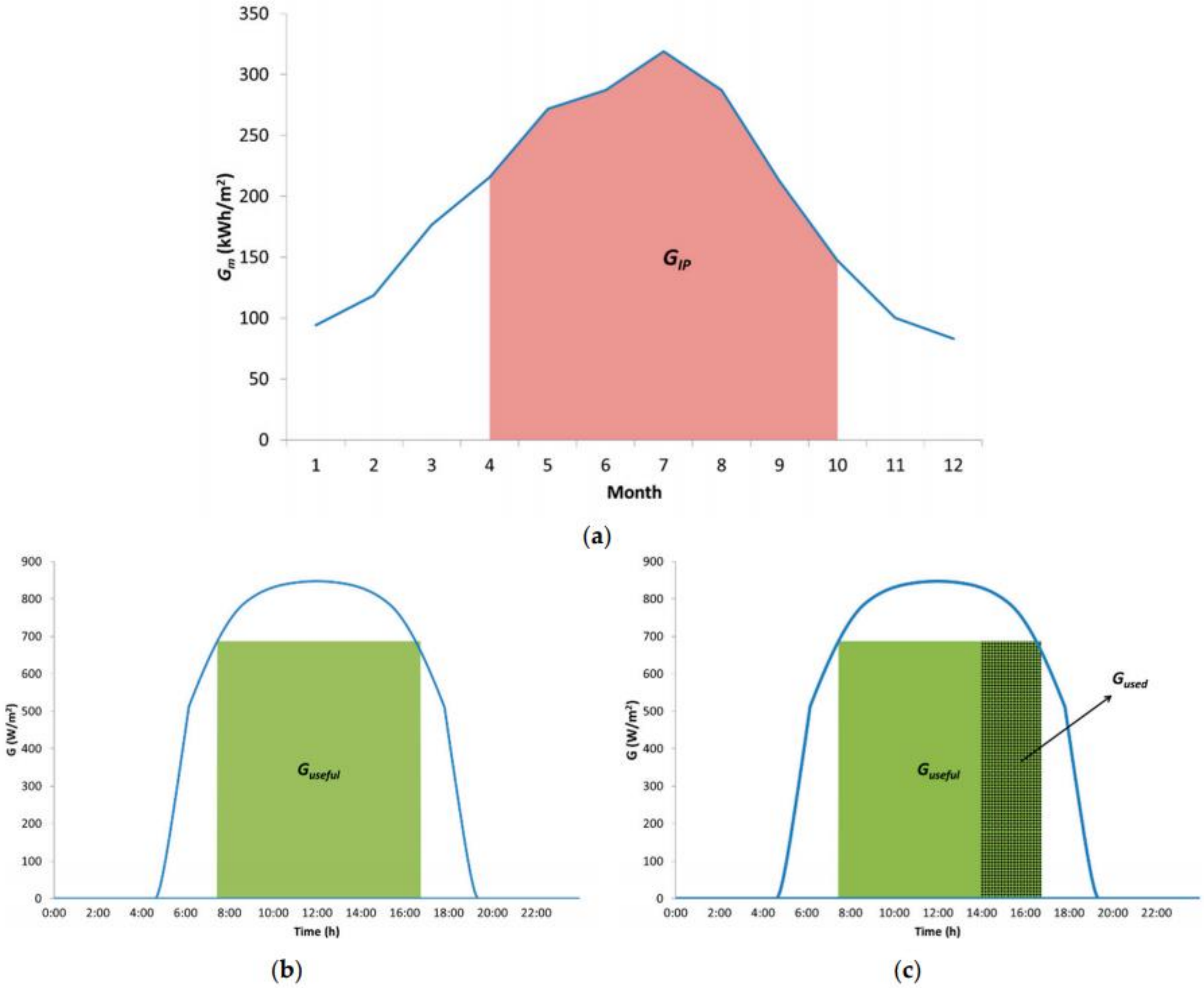

Figure 5. Graphical representation of the different irradiations considered: (a) $\int G_{IP}$ is the irradiation during the irrigation period, (b) $\int G_{useful}$ is the useful irradiation during the IP determined by the design of the PV irrigation system; and (c) $\int G_{used}$ is the irradiation effectively used by the system.

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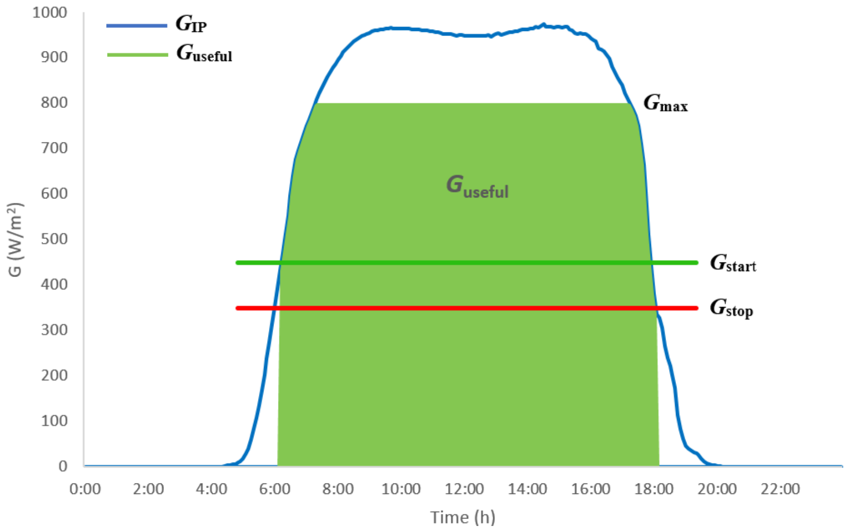

Figure 6. Graphical representation of the useful irradiance for a PV irrigation system working at a variable frequency.

Equation (3) can be rewritten as:

$$PR = PR_{\mathrm{PV}} \times UR_{\mathrm{IP}} \times UR_{\mathrm{PVIS}} \times UR_{\mathrm{EF}} \quad \text{(Eq. 4)}$$

where:

$$PR_{\mathrm{PV}} = \frac{E_{\mathrm{PV}}}{P^*/G^*} \times \frac{1}{\int G_{\mathrm{used}}dt} \quad \text{(Eq. 5)}$$

PR_{PV} is the *PR* considering only losses strictly related to the PV system itself, i.e., actual versus nominal peak power, dirtiness and thermal losses, DC/AC conversion losses and losses caused by the PLC malfunction (including those provoked by FC abrupt stops). It is intrinsic to the technical quality of the PV component, the correct operation of the PLC control and its maintenance.

$$UR_{\mathrm{IP}} = \frac{\int_{\mathrm{IP}} Gdt}{\int Gdt} \quad \text{(Eq. 6)}$$

UR_{IP} is the ratio of the total irradiation throughout the irrigation period to the total annual irradiation (Figure 5a). It is intrinsic to the irrigation period, which depends on water needs of the crop and the climatic conditions, in case of direct pumping, or on the relation between water needs, pumping capacity and pumped water storage capacity, in case of pumping to a water pool. Note that it is one if the analysis is done on a month inside the irrigation period.

$$UR_{\mathrm{PVIS}} = \int G_{\mathrm{useful}}dt \Big/ \int_{\mathrm{IP}} Gdt \quad \text{(Eq. 7)}$$

UR_{PVIS} is the ratio of the irradiation strictly required to keep the P_{AC} in between the limits of the AC power needed to keep the pump running, according to the conditions imposed by the irrigation system, to the total irradiation throughout the IP (Figure 5b and Figure 6). It is intrinsic to the PV irrigation system design: type of irrigation system (direct pumping or pumping to a water pool), the ratio between the PV peak power and the PV power required for irrigation, on the tracking geometry and on the accuracy of the PLC control algorithms setup (start and stop threshold for the FC, time the system remains stopped after a controlled stop of the FC, time the FC is kept running under the stop threshold before it is stopped in a controlled way...). This ratio is also highly dependent on weather conditions.

$$UR_{\mathrm{EF}} = \frac{\int G_{\mathrm{used}} dt}{\int G_{\mathrm{useful}} dt} \quad \text{(Eq. 8)}$$

UR_{EF} is the ratio of the irradiation required to keep the P_{AC} in between the limits of the AC power needed to keep the pump running during the irrigation scheduling to the same irradiation during the irrigation period. It considers the irrigator's decisions.

Hybrid systems

In the case of hybrid systems, it is also necessary to define the PV share of the system.

$$PVS = \frac{\mathrm{E}_{\mathrm{PV}}}{E_{\mathrm{PV}} + E_{\mathrm{aux}}} \quad \text{(Eq. 9)}$$

where E_{aux} is the energy of the auxiliar source of energy (usually diesel or grid energy).

Indices calculation

The different performance indices and the passing cloud resistance ratio need to be periodically calculated to evaluate if the PVIS is working properly. Starting from the irradiance information provided by the calibrated cell or the calibrated PV module (*G*), it is important to identify irradiation losses caused by the non-irrigation period, the intrinsic characteristics of the irrigation system and other external circumstances like the irrigation schedule, and obtain the irradiation throughout the irrigation period (G_{IP}), the irradiation strictly required to keep the P_{AC} in between the limits of the AC power needed to make the pump run during the irrigation period (G_{useful}) and the same irradiation during the irrigation scheduling (G_{used}). Both DC and AC power are also necessary. Table 2 includes all the information needed to calculate the proposed indices.

Table 2 – Information needed to calculate the different indices, provider, and time resolution. If the information required at system start-up changes, the new values and the day of change must be recorded.

Data	Provider	Time resolution
PV generator nominal peak power	EPC, and O&M provider	System start-up
FC P_{DC} start threshold (each FC), i.e., the minimum DC power required to start pumping	EPC, and O&M provider	System start-up
FC P_{DC} stop threshold (each FC), i.e., the minimum DC	EPC, and O&M provider	System start-up

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power required to stop pumping		
FC frequency min. threshold (each FC), i.e., the minimum frequency required to start pumping	EPC, and O&M provider	System start-up
FC controlled stop min. interval, i.e., the time between a controlled stop and the next start of the FC	EPC, and O&M provider	System start-up
FC abrupt stop min. interval, i.e., the time between an abrupt stop and the next start of the FC	EPC, and O&M provider	System start-up
FC controlled stop alarm interval, i.e., the time between a controlled stop due to an alarm and the next start of the FC	EPC, and O&M provider	System start-up
FC abrupt stop alarm interval, i.e., the time between an abrupt stop due to an alarm and the next start of the FC	EPC, and O&M provider	System start-up
Irrigation period change date (yyyy/mm/dd)	EPC, and O&M provider	Whenever the IP is changed
Irrigation period start date (mm/dd)	EPC, and O&M provider	Whenever it changes
Irrigation period end date (mm/dd)	EPC, and O&M provider	Whenever it changes
FC status (on/controlled stop/abrupt stop/irrigator stop/PV maintenance stop/IS maintenance stop/others)	Data-related services provider	1 sec.
Solar irradiation (*G*)	Data-related services provider	1 sec.
Cell temperature (T_M)	Data-related services provider	1 sec.
Theoretical DC power (calculated from solar irradiation and cell temperature)	Data-related services provider	1 sec.

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DC current (I_{DC})	Data-related services provider	1 sec.
DC voltage (V_{DC})	Data-related services provider	1 sec.
DC power (P_{DC})	Data-related services provider	1 sec.
Output frequency	Data-related services provider	1 sec.
AC power (P_{AC})	Data-related services provider	1 sec.
FC alarms (optional if FC status is provided)	Data-related services provider	1 sec.
FC start order (if more than 1 FC)	Data-related services provider	1 sec.

Examples of the application of these indices are available in the Training Manual for PVIS Installers also developed under SolaQua Project.

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3. Best practices in Planning a PVIS

3.1. Site identification

Land availability to install the PV generator

1) The land on which the PV generator is located must be shadow-free and large enough to install the structure designed to support a PV generator of the required power.

2) PV generators must be located as close as possible to the frequency converters and motor-pumps.

3) PV generators for solar irrigation should preferably be installed on the ground.

Roofs are not recommended for PVIS except if the surface and orientation of the roof allows the installation of the required PV generator power and with the adequate tilted angle.

Floating PV systems refer to installations mounted on structures that float on a body of water, like a basin or a lake. This option has not been sufficiently tested so far, so its use cannot be recommended for long term applications as its quality cannot be assured.

Supporting structure

1) The use of North-South horizontal axis trackers is highly recommended for solar irrigation systems (see Figure 7).

Crops have different water requirements along the year. While the water requirements is high during the spring-summer season, it could be negligible or even nil in autumn-winter. Therefore, it is important to design the systems in such a way that the water being pumped is adapted to the crop requirements. The use of North-South horizontal axis tracker supporting structures is a particularly convenient way to achieve this, mainly due to the following reasons:

- It is the supporting structure showing the greatest difference between the water volumes pumped in summer and winter seasons.
- It allows the flow of pumped water to be almost constant throughout the day. This same profile could be achieved using a static generator installed on different surfaces with different orientations, at the expense of increasing the installed PV power.
- It allows to reach the power threshold to start pumping earlier in the morning, and the power threshold to stop later in the afternoon, which means that the number of daily working hours of the system increases.
- It requires less nominal PV power to pump the same volume of water than a static structure.

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Figure 7

The use of two axis trackers (Figure 8) is dismissed in PVIS due to three main reasons: they are more expensive than one axis trackers; they need much more maintenance; their energy production during the irrigation period (summertime) is very similar to one-axis tracker's production. This recommendation is supported by the fact that the use of two axis trackers in grid-connected PV power plants has been abandoned worldwide during the last years and replaced by one-axis trackers.

Figure 8

2) Static supporting structures should be used when the correct operation and maintenance of a PV tracker cannot be guaranteed.

When the correct operation and maintenance of a PV tracker cannot be guaranteed, a static supporting structure for PV modules should be used as this kind of structures need much less maintenance.

- **South-oriented[1] structure**

The tilted angle must be adapted to the needs of pumping water period. In general, these needs are higher in summertime, thus PV generator tilted angle must be the one that optimizes the

[1] This structure must be South-oriented when the system is the North hemisphere. If the system is in the South hemisphere, the structure must be North-oriented.

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pumping of water in that period. In this case the latitude – 10° is usually a good approximation to establish that tilted angle. For example, a solar irrigation system located in Seville (Spain), whose latitude is 37°, would install the south-oriented PV modules at 37°-10°=27° tilted angle. It is important to highlight that the minimum tilted angle must be 20° to avoid dust accumulation.

- **Delta structure**

This so-called supporting structure consists on a generator made up of two halves, one oriented to the East and the other to the West, both halves with an inclination of 60^0. The benefit of this kind of structure is that it behaves like a North-South horizontal axis tracker in terms of water pumping profile in both daily and annual water production.

Figure 9 shows the PV peak power needed for south-oriented and delta structures (represented as S(25) and ΔS (60) respectively), normalized by the PV peak power of a North-South horizontal axis tracker (1xh). It is possible to see that:

- For the S(25), it is necessary to install twice the PV peak power of the 1xh if the irrigation period is considered.
- For the ΔS(60), it is necessary to install 1.75 times the PV peak power of 1xh (for both yearly and irrigation period values).

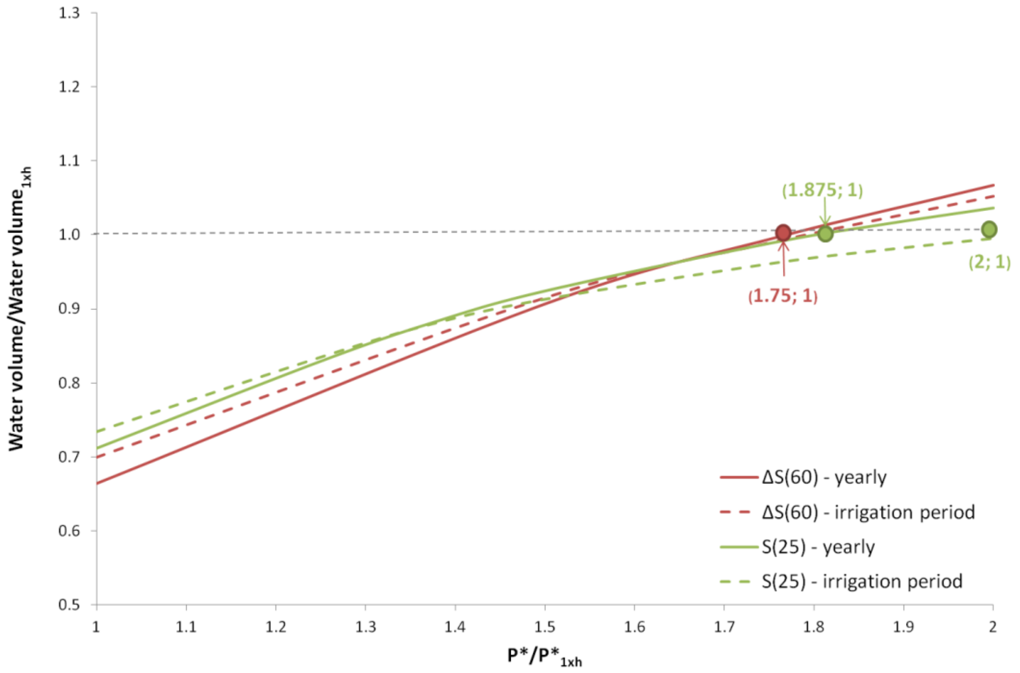

Figure 9 – Water volume pumped by a PVIS with ΔS (60) and S(25) normalized by the water volume pumped by a 1xh (Water volume/Water volume1xh) as a function of its PV peak power normalized by the PV peak power of 1xh (P*/P*1xh). The continuous lines represent yearly values and dashed lines show the water volume pumped during the irrigation period. The points with Water volume/Water volume1xh=1 represent the required oversizing of ΔS(60) and S(25) PV peak power to equal the performance of the 1xh (R.H. Almeida et al., 2018).

If the reader wants to know more about the performance of the different structures in PV irrigation systems, more detailed information can be found in:

- Solutions for adapting photovoltaics to large power irrigation systems for agriculture (Narvarte et al., 2018).
- PV arrays with delta structure for constant irradiance daily profiles (R. H. Almeida et al., 2018).

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Land covering

1) The following table details the need of land for each PV structure considered for PVIS.

Table 3 - Need of land per kWp of PV generator.

Need of land per kWp of PV generator (m^2)		
1 Axis	**Static (S(25))**	**Static (ΔS(60))**
15	8	12

The following examples of real large-power PVIS demonstrate that the land occupation of the PV generator does not represent a problem:

- In Alter do Chão, Portugal, a 200 ha super intensive olive tree farm is irrigated using a 140 kWp PV generator that covers 3000 m^2, which means 0.15% of the total area of the farm.
- In Uri, Italy, a 5.4 ha plantation of artichokes is irrigated using a 40 kWp PV generator that takes 0.15% of the total farm area.

Water source and availability

1) It is essential to know the water source to be used. When the water source is a well or borehole, an aquifer testing is mandatory to characterize the flow boundaries and water levels. The quality of the water source must be confirmed by a hydrogeologist to assure the water availability and its exploitation in a sustainable way.

2) In surface water sources, such as ponds, rivers, canals and others, it is very important to know their water extraction capacity during the irrigation months, which usually coincide with the driest and hottest period.

Crop water requirements

1) If an irrigation system is working before the installation of the PV part, in principle the crop water requirements will not change. In this sense, the PVIS must be adapted to the existing hydraulic infrastructure, so that must be configured in such a way that the PVIS is able to pump water the number of hours per day that the crop needs in each growing stage.

2) The monthly crop water needs are a fundamental input in the design of the PV part of a PV irrigation system. The crop water requirements varies throughout all its cycle, thus in designing a PVIS, it is necessary to know when that value would be the highest one. If the PVIS can supply water during the most demanding period, it will be also feasible to do it along the rest of the irrigation period.[2]

3) It is important to avoid the water resources overexplotation – the monthly crop water needs will not change with the inclusion of the PV in the irrigation system.

[2] Detailed information of this point can be found in Annex III, section Crop water needs

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Restrictions, permits and regulation

1) The following aspects may affect the PV generator location: electrical lines, watercourses, drover's road, roads, pipelines, special areas of conservation.

2) An initial study of the relative locations of trackers, buildings, fences, walls, etc. must be carried out to avoid later modifications to these elements that will increase the final cost of the civil works. The pictures below (from Figure 10 to Figure 13) show the consequences of bad initial planning: shadows of monitoring systems, walls and trees are cast over the PV modules.

Figure 10 to Figure 13 include some bad examples of relative locations.

Figure 10

Figure 11

Figure 12

Figure 13

3) All the components of the PVIS should fulfil national and international standards, guaranteeing quality, integrity, and an optimal performance after their installation.

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4) Some particularly interesting standards related to PV specific devices such as modules, arrays, and frequency converters are listed in Annex II.

5) All locally applicable standards and needed permits shall be taken into account.

6) PVIS installed in rural environments need permits and licenses from local authorities. Execution projects have to meet the local legal framework.

7) PVIS must meet the regional and national regulatory framework in force regarding the development, implementation and energy production from renewable energies power plants.

8) PVIS must meet the protected areas legislation and directives when projects are planned in geographical areas with special habitat protection, such us, for example, the Natura 2000 ecological network in the EU.

9) PVIS must comply with current national and regional legislation regarding land use.

3.2. Participation of end-users

1) Farmers are the ones who know their land, their crops and their irrigation needs best. Any planning exercise for a PV irrigation system must be a participatory process that involves the end-users.

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4. Best practices in Designing a PVIS

4.1. System sizing and design

1) There are multiple tools to design and simulate PV systems but there are few that allow the simulation of stand-alone and battery-free PV irrigation systems. UPM recommends the use of SISIFO – a software tool developed at UPM to simulate the energy yield of both PV grid-connected systems and PV irrigation systems. It is freely available at www.sisifo.info

No matter the used software, the designer must know the characteristics of the simulation tool, including the different assumptions that are made.

Input data

General characteristics of the farm

1) The following data may be available to design a PVIS:
   - Location of the farm (latitude and longitude).

2) The following data should be collected to have a general overview of the system:
   - Crop.
   - Area of the farm.

3) A block diagram detailing the power source, the type and number of motor-pumps and FCs must be available.

4) The collection and validation of these data is the responsibility of the farm owner – individual farmer, agroindustry, irrigation community, etc.

Water needs

1) If the PVIS is going to be installed in an already existing irrigation facility, the following monthly data are needed:
   - Water volume.
   - Electric energy or combustible consumption.
   - Daily irrigation hours.

2) If the PVIS is going to be installed in a new irrigation facility, the monthly water volume for the specific crop that will be irrigated is needed.

3) The collection and validation of these data is the responsibility of the farm owner – individual farmer, agroindustry, irrigation community, etc.

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4) The duration of the irrigation period in the worst month[3] will determine the choice of the type of PVIS – stand-alone or hybrid. If the number of irrigation hours per day is higher than the number of sun hours, a hybrid system is needed.

5) In the case of hybrid systems, both with the national grid or diesel generators, the auxiliary energy source can be used:
   - According to the available PV power.
   - According to the end-user desire.
   - According to the time of the day – for example, in systems with the national grid, it is possible to use the energy from the grid only in some periods (according to the electricity price at different moments).

6) If the irrigation period is only a few months of the year, some countries allow the possibility of export to national grid in the non-irrigation period.

In this case, a grid-inverter must be added to the system. This way, the system is a PV irrigation system during the irrigation period (the PV generator is connected to the frequency converters), while it is a typical grid-connected system outside the irrigation period (the PV generator is connected to the grid-inverter) – see Figure 4.

Water source and irrigation network

1) The following information is needed to design a PVIS:
   - Geometric head.
   - Friction losses.
   - Total depth of the well.
   - Operating pressure (if direct pumping).
   - Maximum water flow.

2) If the friction losses are not known, a good approximation is 10% of the geometric head.

3) If an irrigation automatism is installed, detailed information on its working is needed.

4) The information requested in the next tables is needed to design a PVIS system.

IRRIGATION NETWORK									
Number of irrigation sectors									
Sector	1	2	3	4	5	6	7	8	…*
Working pressure of each sector [bar]									
Water flow of each sector [m3/h]									
Area of each sector [ha]									

5) The collection and veracity of these data is the responsibility of the end-user.

6) If pivots are installed in the system, they must be fed by the PV generator.

[3] The worst month is the one with the biggest difference between water needs and incident irradiation.

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Pumping system

1) The information requested in the next tables is needed to design a PVIS.
For motor-pumps and frequency converters, a table must be provided for each individual model.

PUMPING SYSTEM – ENERGY SOURCE			
Energy source			
If diesel group:	Power [kVA] Voltage [V] Maximum current [A] Specific consumption []		
If grid:	Contracted power [kW] Contracted tariff		

PUMPING SYSTEM – MOTORPUMP								
Pump type Number of pumps								
Pump 8 points of the head-flow curve 8 points of the power-flow curve Minimum working frequency [Hz]								
Motor 8 points of the efficiency curve Maximum current [A]								

PUMPING SYSTEM – FREQUENCY CONVERTER	
Frequency converter type Number of frequency converters Input voltage range [V] Maximum current [A] Maximum power [kW]	

PUMPING SYSTEM - FREQUENCY CONVERTER								
Type Number of FC								
Efficiency curve 8 points of the P2-efficiency								

2) The collection of these data is the responsibility of the EPC provider.

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Solar resource

1) The typical meteorological year (TMY) or synthetic series shall be used as data input for a PVIS simulation.

2) At least global horizontal and diffuse horizontal irradiations, as well as ambient temperature need to be available.

Output data

1) A simulation of the PVIS is mandatory, as well as the following outputs:
    a. Final configuration of the PV generator – including the type of PV modules, series and parallel connections and type of structure.
    b. Type of system – stand-alone or hybrid.
    c. Final configuration of the irrigation network.
    d. List of components of the complete PV irrigation system.
    e. Monthly values of incident irradiation.
    f. Monthly values of AC power delivered by the frequency converters.
    g. If inverters are used, monthly values of AC power delivered by the inverters into the grid.
    h. Monthly values of water volume.
    i. Performance ratio (*PR*), including the utilization ratios as defined in section Key Performance Indicators.
    j. PV share (*PVS*).

4.2. Photovoltaic generator

1) Single PV generator for all FCs (see Figure 14).

The use of a single PV generator to feed all FCs increases the use of PV energy (Gasque et al., 2020) – for example, at low solar irradiance levels, the full power of the PV generator can be assigned to one FC making it works (on the other hand, if each FC has its own PV generator, the pumping system will be stopped).

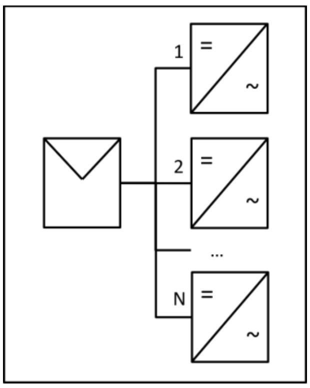

Figure 14

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PV modules

1) Only crystalline silicon PV modules are accepted due to their proven quality and reliability, in addition to their wide availability in all worldwide markets and their competitive market prices.

Other technologies such as thin-film, concentrators, etc. have not been sufficiently proved or suffer high power degradation over time, avoiding the long term quality that is necessary along the 25 years of the PVIS lifetime.

2) Bifacial crystalline silicon PV modules are accepted.

3) Each PV array must be formed by PV modules of the same manufacturer, type, and model.

4) PV modules must be resistant to Potential Induced Degradation (PID) and the Manufacturer Warranty should include damages caused by PID on PV modules.

5) All plugs (module plugs, cable plugs and connection boxes plugs) must be of the same model and manufacturer (or declaration of compatibility) to ensure good connections. They must be placed in such a way that they are free of accumulation of dust, sand or water to avoid short-circuits and/or premature degradation.

6) DC cables must be attached to the supporting structure using UV resistant cable ties or placed in trays to avoid loose cables that could rub against sharp objects that could damage their insulation or even cause trip hazard.

7) PV modules must not exhibit "hot spots" or "hot cells" when there is not shade cast over them and the variable frequency drive is feeding the pump normally.

8) Preferably, as a protection measure against indirect contact, the PV arrays (active poles) should not be grounded.

9) The expected operational ranges of PV array voltages and currents (V_{OC}, I_{SC}, V_M and I_M), due to expected module temperature and electrical behavior, must agree with the technical specifications of the FC.

10) In case the PV array is composed by more than three strings in parallel, all the strings must be protected with fuses in both poles. String fuses must be rated (at 50^0C) between 2 and 4 times the PV modules STC short-circuit current, and below the rated DC current of module cables.

Strictly, electric security at no-grounded PV arrays requires only one fuse. However, the second fuse allows for easy string electrical separation from the rest of the PV array, which can be useful for inspection and maintenance purposes. An intermediate solution consists on protecting one pole with a fuse and providing some easy isolation mean to the other pole.

Extreme desert temperatures reach 50^0C in the shade and anything inside a box can be hotter than that. Hence, fuses must be rated at 70^0C for this extreme environment.

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Number of PV modules in series

1) The minimum and maximum voltages that are allowed at the input of the frequency converters (FC) limit the number of PV modules that can be connected in series.

The open circuit voltage of a PV module under standard test conditions (STC), V_{OC}^{*}, is typically 36 V or 43 V for 60 solar cells or 72 solar cells PV modules respectively. This V_{OC}^{*} depends on the temperature of the solar cell, T_C, according to the following equation:

$$V_{OC} = V_{OC}^{*}[1 + \beta_c(T_C - T_C^{*})] \quad \text{(Eq. 10)}$$

where T_C^{*} is the temperature of the solar cell at STC (25^{0}C), β_c is the coefficient of variation of the voltage with the temperature of the solar cell and V_{OC} is the open circuit voltage under certain ambient conditions.

It is significant to observe that, considering that a minimum T_C in a certain location can reach minus 10^{0}C at sunrise and a value of β=-0.31%/^{0}C, the corresponding open circuit voltage is V_{OC} (60 cells)= 39.9 V and V_{OC} (72 cells)= 47.7 V, which leads to a maximum number of PV modules in series of N_S(60 cells)= 20 and N_S (72 cells)= 16. To surpass this number of PV modules means that the maximum open circuit voltage can be higher than the maximum input voltage of the FC at certain moments of the year.

2) The motor-pump and the national grid (if present) also influence the number of PV modules in series.

The most common motor-pumps in PVIS are three-phase ones with AC input voltages (V_{AC}) of 400 V or 690 V. The following equation relates the output AC voltage of the FC ($V_{AC_{outputFC}}$) and its input DC voltage ($V_{DC_{inputFC}}$).

$$V_{DC_{inputFC}} = \sqrt{1 + \frac{3 \cdot \sqrt{3}}{2\pi}} \cdot V_{AC_{outputFC}} \quad \text{(Eq. 11)}$$

In addition to the pump voltage, if there is an extensive length of wires between the FC and the pump and/or there are filters between them, the voltage drop must be compensated to ensure 400 V or 690 V at the motor-pump input, which means that higher voltages at the FC output are needed. Table 4 details the required values of $V_{DC_{inputFC}}$ depending on the $V_{AC_{outputFC}}$.

Table 4 – The required values of $V_{DC_{inputFC}}$ depending on $V_{AC_{outputFC}}$.

V_{AC} [V]	$V_{AC_{outputFC}}$ [V]	$V_{DC_{inputFC}}$ [V]
	400	541
400	415	561
	430	581

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	690	933
690	705	953
	720	973

So, in the case of a stand-alone PVIS pumping to a water pool at a variable frequency, the FC will be able to track the MPP whenever the corresponding MPP voltage (V_{MPP}) is higher than the $V_{DC_{inputFC}}$ values set out in Table 4. But if $V_{DC_{inputFC}} > V_{\mathrm{MPP}}$, the DC bus voltage will remain at $V_{DC_{inputFC}}$ and will not be that corresponding to the MPP and some potential PV energy will be wasted.

In the case of large hybrid PV-grid systems, both the PV generator and the three-phase 400 V grid are connected to the FC input. The grid imposes the DC bus voltage, $V_{DC_{BUS\_GRID}}$, in accordance with the following equation (Fitzgerald, Kingsley, & Umans, 2003):

$$V_{DC_{BUS\_GRID}} = \sqrt{2} \cdot V_{AC_{GRID}} \quad \text{(Eq. 12)}$$

where $V_{AC_{GRID}}$ is usually 400 V or 690 V, but it can vary depending on the tuning of the transformer. In particular, hybrid PV-grid irrigation systems located at the beginning of the grid line can have higher $V_{AC_{GRID}}$ values. Table 5 sets out the $V_{DC_{BUS\_GRID}}$ values corresponding to different $V_{AC_{GRID}}$.

Table 5 – $V_{DC_{BUS\_GRID}}$ values corresponding to different $V_{AC_{GRID}}$.

$V_{AC_{GRID}}$ [V]	$V_{DC_{BUS\_GRID}}$ [V]
400	566
415	587
690	976
705	997

If the PV generator is able to supply enough power to feed the pump at a certain frequency without the support of the grid and with a V_{MPP} higher than that imposed by the grid, $V_{MPP} > V_{DC_{BUS\_GRID}}$, all the energy will be provided by the PV generator and the voltage of the DC bus will be V_{MPP}, absorbing the maximum PV energy available. If $V_{MPP} < V_{DC_{BUS\_GRID}}$, the PV generator will not work at V_{MPP}, wasting some PV energy.

Finally, in the case of direct pumping at constant pressure and water flow (and therefore, constant power, $P_{p=cte}$) for both stand-alone or hybrid PV-grid irrigation systems, the previous analysis is valid just by substituting V_{MPP} by $V_{p=cte}$ where $V_{p=cte}$ is the PV generator voltage needed to deliver $P_{p=cte}$.

3) Electronic devices to connect/disconnect a module per string according to the cell temperature are not recommended. Alternative solutions can be found in (Narvarte et al., 2019).

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PV peak power

1) The PV peak power at the input of each variable frequency drive must be equal to or above 93% of the nominal power. In other words, the sum of the losses of the PV generator due to initial degradation, mismatching and wiring cannot be above 7%.

This value of the losses is proposed as an absolute maximum and must be understood in the absence of anomalous effects (shades, frequency converter saturation, etc.). Lower losses can be specified, in particular with PV modules offering positive tolerance in rated power. Whichever the case, this value must be consistent with the Yield Assessment baseline loss scenario used for the simulation.

Integration of the PV generator in the farm

1) Special efforts should be made to properly integrate PV plants in their surrounding environment and ecosystem.

Figure 15

Figure 16

4.3. Supporting structure

North-South horizontal axis tracker

1) The only trackers that can be used in a PVIS are North-South horizontal axis trackers.

2) If a tracker is used, the manufacturer must prove its reliability by providing a certificate of absence of failures in the previous 5 years (for example, with wind events). If any failures had occurred, full documented proof of analyzing, documenting, and solving the problem, provided by independent third parties, shall be required. This requirement can be substituted by equivalent warranties for a minimum period of 5 years.

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3) The tracker must be resistant to weather conditions (especially wind), including the extraordinary ones.

4) The tracker must have one-up portrait configuration.

5) The tracker needs to include a safety position in presence of high winds speeds.

6) Only trackers already tested in identical conditions and showing good performances may be used.

7) Single, dual or multi-row trackers can be considered.

8) Trackers must include a back-tracking algorithm.

9) The rotation angle of the tracker should be up to ±55°.

10) The tracker must include, in addition to the tracker control system, a shadow management system, a wind management system, and a communication protocol.

11) The tracker must be able to do an automatic reset if there is an interruption in the electricity supply.

12) The tracker status information must be included in the monitoring system of the PVIS. Remote monitoring must be available.

13) The tracker must have an emergency button to stop it.

4.4. Connection boxes

1) All active electrical components must be identified with appropriate fixed labels.

The boxes in Figure 17, Figure 18, and Figure 19 have fixed labels warning of the risk of electric shock. This is important information, alerting people to the existence of live connectors, bus-bars, fuses and other electrical components in the boxes. This enables technical and maintenance staff to be warned and take appropriate actions before opening the boxes.

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Figure 17

Figure 18

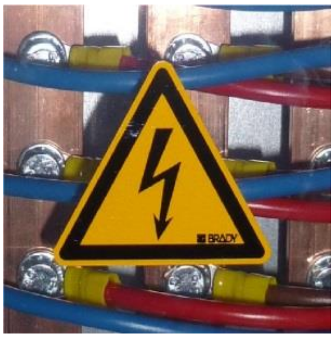

Figure 19

2) Connection boxes should have and respect the proper Ingress Protection rating (IP) selected according to the environment.

The connection boxes must have (and respect) at least IP54, in accordance with the standard IEC 60529, and must be resistant to UV radiation.[4]

3) Cable entering connection boxes must be correctly installed and sealed.[4]

4) All connectors must be correctly crimped and fastened to avoid overheating.[4]

5) Boxes must be cooled and/or heated when they contain electronic components sensitive to temperature.

When a box contains electronic devices and thermal switches, it is important to consider if cooling or heating the box is required. Some of the devices will not operate properly at very low or high temperatures or will simply be switched off when a threshold temperature is reached.

[4] Detailed information of this point can be found in Annex III, section Connection boxes.

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To avoid such occurrences, temperature sensors, heaters and fans can be installed, as it is shown in Figure 20.

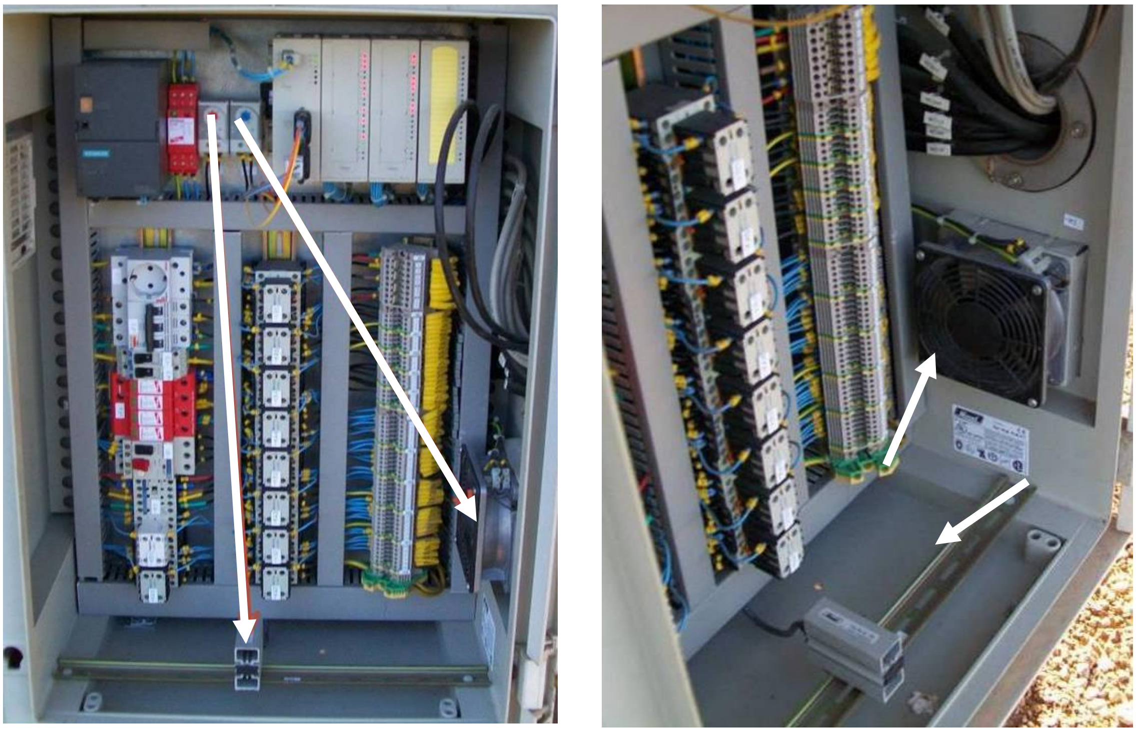

Figure 20

6) The parallel association of strings must be done inside connection boxes (see CN1 in Figure 21).

This box must include at least the following protections:

- Protection DC fuses for each string, for positive and negative poles. Fuses can be installed just in the positive pole while the negative pole holder can contain just a cylindrical conductor ("dummy" fuse).
- Protection against direct lightning strikes and transient overvoltage.
- DC switch-disconnector.
- String monitoring system.

If the PV array is composed by only two strings, they can be directly paralleled by means of “Y” connectors.

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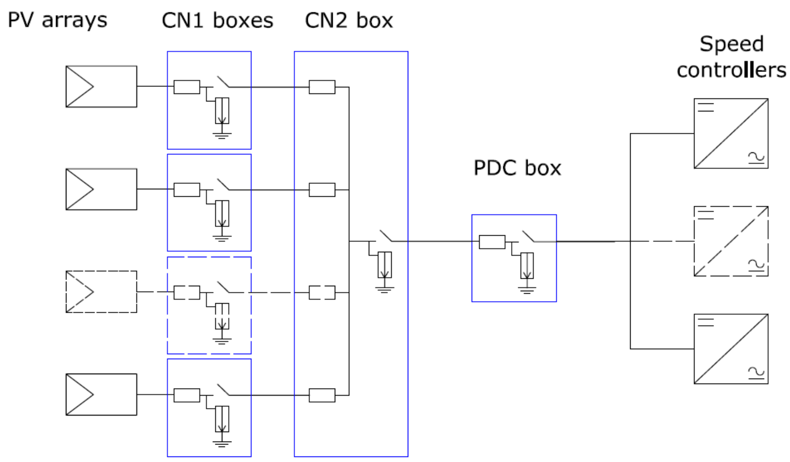

Figure 21

7) Electrical lines from the parallel boxes must be protected by a line protection box (see CN2 in Figure 21).

This box must include at least the following protections:

- Protection DC fuses for each line. Fuses can be included just in the positive pole while the negative pole holder can contain just a cylindrical conductor ("dummy" fuse).
- Protection against direct lightning strikes and transient overvoltage.
- DC switch-disconnector.

8) Every individual string must be protected, at least, by a fuse.

The connection box in Figure 22 has fuse holders for each individual conductor. This is the correct way for electrical lines protection as it allows the connections from the bus-bars to the parallel arrays to be totally isolated from connecting cables and to operate them safely. Fuses are included just in the positive terminal fuse holder; the negative terminal holder contains just a cylindrical conductor ("dummy" fuse). In this way every string is protected in the event of high currents and the number of fuses required is reduced by half. Consequently, locating blown fuses is quicker and the cost of the connection boxes is reduced.

If the fuse holders with the “dummy” (or real) fuses are not included and they are replaced by bridging wires, the associated bus-bar cannot be isolated from that pole of the PV array.

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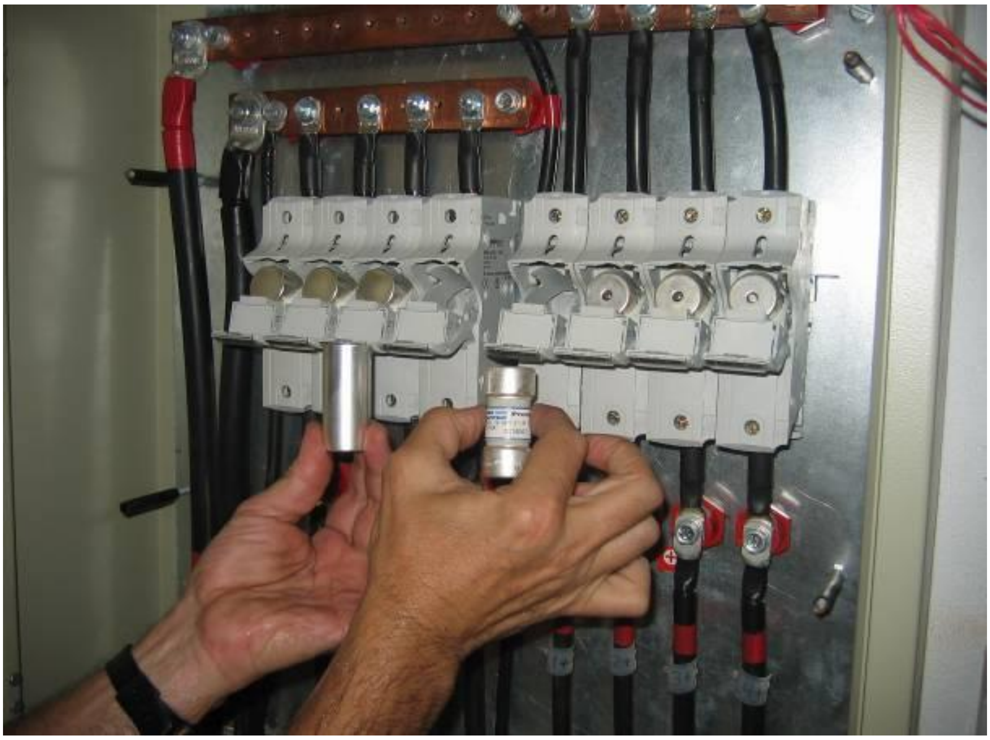

Figure 22

9) Fuses must be properly oversized to avoid overheating and premature degradation.[5]

10) DC components like fuse holders must NOT be manipulated when DC circuits are switched ON.[5]

11) Overvoltage protection devices (operative surge arrestors) between both positive and negative poles and earth (another one between poles is optional) must be included.

This is not strictly necessary if the cable that connects these boxes and the variable frequency drive has a length lower than 20 m and the FC input has an equivalent protection. Moreover, in the case of ground-connected PV generators, this protection is only necessary in the pole that is not connected to ground.

12) A load breaking switch must be installed (to safely open the DC part in case of emergency).

This is not necessary if the FC has it.

13) The FC lines must be protected by a general DC box (see PDC in Figure 21).

This box must include at least the following protections:

- A leakage current measurement device connected between the DC lines and earth.

[5] Detailed information of this point can be found in Annex III, section Connection boxes.

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- A R class protection DC fuses (ultra-rapid fuses) for each pole.
- DC switch-disconnector.
- Protection against direct lightning strikes and transient overvoltage.
- Shunt resistance for DC current monitoring, mounted in the positive pole.
- For PV-grid/genset hybrid systems, a flyback diode to protect the PV generator against polarization when there is not solar irradiance and the grid or genset is connected.
- For PV-grid/genset hybrid systems, a DC reactance must be installed in the frequency converter DC input line to protect the DC circuit against harmonic distortion effects.

14) Cables in connection boxes should be correctly arranged and not too long.[6]

15) The elements inside the connection boxes should be correctly ordered and disposed so that positive and negative poles are as separated as possible.

This is done to minimize the risk of direct contact and to facilitate string testing.

Cables and busbars of different poles should be properly separated from each other.

Poly-Methyl–Methacrylate (PMM or equivalent) sheets for preventing direct contact with live wires, fuses, busbars, etc., must be used.

Figure 23 shows that the active cables from the positive and negative terminals of the strings enter the connection box through both the right and left sides. This results in cables passing behind the positive and negative busbars. Over time, due to vibration and thermal cycling, continuous contact between cable conductors and copper busbars can damage the cable insulation/sheaths and cause short-circuits. A better solution would have been to connect all the cables from the positive terminals through one side of the connection box and the negative ones through the opposite side as shown Figure 24. This is a more secure design because it results in positive and negative cables and busbars being adequately separated.

[6] Detailed information of this point can be found in Annex III, section Connection boxes.

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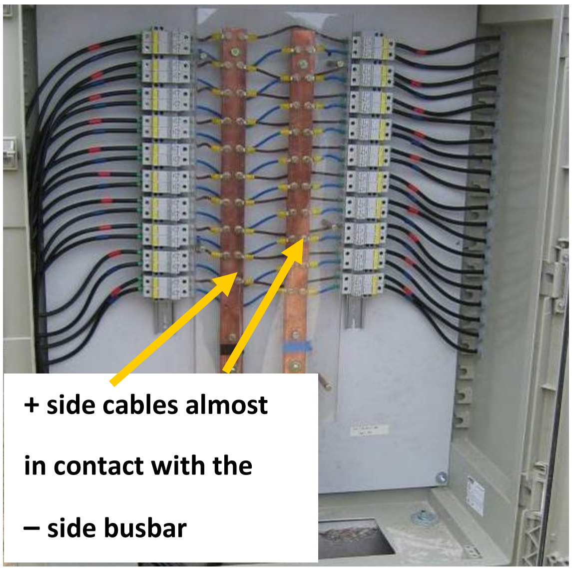

Figure 23

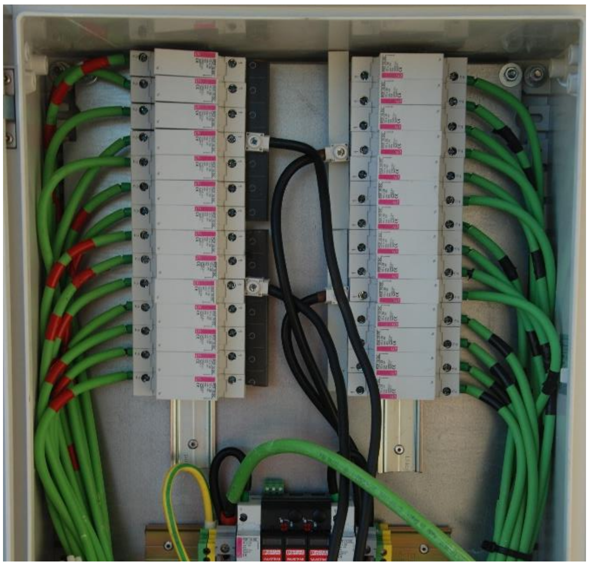

Figure 24

16) Individual labels for each cable, reporting about its polarity and its origin are mandatory.

17) Doors and covers must resist chemicals (grease and other).[7]

18) Doors and covers must contain a blocking system to avoid damage due to wind gusts when they are open.[7]

19) DC cables from connection boxes to FC input must preferably run-in underground tubes (one tube per pole, except when using wiring with double isolation). The extremes of the tubes must be sealed once the tubes and cables are totally laid to avoid the entrance of rodents.

4.5. Frequency Converters and control units

1) The control unit can be integrated or not in the frequency converters.

2) If more than one FC is used, an external control unit must be used.

This external control unit must control, at least, the start and stop of each motor-pump.

3) The efficiency of the FC must be at least 95% for output frequencies higher than 35 Hz.

4) FCs should properly operate at their nominal power and with an ambient temperature T_a = 50°C.

[7] Detailed information of this point can be found in Annex III, section Connection boxes.

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5) In order to preserve the quality of the general electricity service, the variable frequency drive should comply with IEC 61000-6-2 and IEC 61000-6-4 (EMI), with EN 50178 (Grid quality requirements) and also with particular national codes. The use of ferrites at the output of the frequency converter to avoid electromagnetic noise is strongly recommended.

6) When the distance between the FC and the motor-pump is long, it is necessary to protect the motor-pump against harmonics. The protection that must be added at the output of the variable frequency drive will be different according to this distance:
    a. Up to 50 m: AC reactance.
    b. Between 50 m and 150 m: dV/dt filter.
    c. Higher than 150 m: a sinusoidal filter.

7) The FC should include protection against inverse polarization in its DC input, short-circuits in its AC output, over-voltages (operative surge arrestors) in both DC input and AC output, and insulation failure with output to relay. It is frequent that the frequency converters do not include the protection against inverse polarization if the connection is directly done in the DC bus. In this case, there are two alternatives:
    a. To add an external protection against inverse polarization. In any case, if there is a direct connection to the DC bus, it must be protected by fast fuses or any other mean to limit the charge/discharge current of the internal capacitor of the frequency converter.
    b. To connect the DC wires to the standard input of the frequency converter, avoiding the direct connection to the DC bus. In order to this, the positive pole will be connected to the R-S-T inputs of the frequency converter. This way, the diode bridge rectifier will act as protection.

8) The FC should include detection and protection in case of lack of insulation in accordance with the requirements of standard IEC 60364-7-712.

9) In order to facilitate the acceptance tests, the electric box of the variable frequency drive must include means (shunt, toroid, etc.) for measuring DC input current with accuracy of, at least, 0.5%. Such means must be duly certified and fully accessible during reception test.

This specification applies only if acceptance tests consider not only a PR or a PR_{STC} measurement, but also additional equipment characterization.

10) Own consumption of FCs can be powered by the line of auxiliary services.

11) The FC should be located inside a specific building (electrical room) with adequate fans or air circulation systems to avoid overheating. The building door should have a blocking system (or alternative option) to avoid damage due to wind gusts when it is open.

12) The FC must be able to support a sudden fall of PV power due to passing clouds.

13) The passing cloud resistance ratio (σ_{cloud}) – Equation 7 – cannot be lower than 95%.

14) In the case of an external control unit, it must:
    a. comply with IEC 61131.
    b. be installed in an IP54 waterproof protection box.
    c. be connected to an uninterruptible power supply.
    d. have shielded signal cables.

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Specificities of the FC and PLC

1) The DC bus of the FC needs to be accessible (because the PV generator may be connected to this part of the FC).

2) If hybridization is done in the electric part of the system, the PV generator must be connected directly to the DC bus of the FC through a diode connected in direct bias (this diode is to allow the flow of the electric current just from the PV generators to the FC).

3) If the only energy source feeding a FC is PV, the positive pole of the PV generator must be connected to the AC input of the FC, while the negative one must be connected directly to the negative part of the DC bus.

It is recommended to short-circuit the R, S and T inputs of the FC. With this connection, an external diode is not needed since the FC is fed before the diode bridge, which will protect the system.

If the FC does not include an integrated PLC, an external one must be connected.

4) FC parameters need to be accessible (it is needed to change some parameters to allow the correct work of the FC according to the irrigation network).

5) The FC and/or the PLC need to have, at least, analog inputs for:
    a. DC voltage of the PV generator.
    b. Incidence irradiance in the PV generator.
    c. Cell temperature.
    d. Pressure (if direct pumping)
    e. Water level in the borehole (when pumping from a borehole).
    f. Water level in the water pool (when pumping to/from a water pool) – this can be a digital signal, for example if water buoys are installed for empty and/or full water pool.

6) The FC and/or the PLC need to have, at least, analog outputs for:
    a. Set-point voltage.
    b. Set-point pressure (if direct pumping).

7) The FC and/or the PLC need to be selected according to the needed digital inputs and outputs.

8) The FC and/or the PLC must be able to communicate with the irrigation automatism (if an irrigation automatism is part of the PVIS).

9) The FC and/or the PLC do not substitute the irrigation automatism.

Programming of the FC/PLC

1) The FC/PLC needs to include, at least, the following routines:

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- Start and stop – the start and stop of the different FCs must be done according to the PV power available at each moment (hysteresis must be included in the system to avoid consecutive starts and stops). Additionally, to assure the lifetime of the system, the number of starts of each pump per hour must be limited.
- MPPT (if pumping to a water pool) or constant pressure (if direct pumping) – when the system is pumping to a water pool, the routine must guarantee that the PV generator is working at its maximum power point. On the other hand, in case of direct pumping, the routine must guarantee the correct pressure in the system.
- Cloud-passing – when the PV generator detects a huge drop in irradiance due to a passing cloud, the FC must activate its cloud-passing routine, which will guarantee that the system will not stop abruptly due to the cloud.
- Empty and/or full water pool – a motor-pump that pumps from a water pool to an irrigation network must stop when the water pool is empty. On the other hand, a motor-pump that pumps water from a borehole or a canal to a water pool must stop when the water pool is full of water.
- No-load motor protection – if the motor is working with no-load, the motor must stop.
- Error routine – if an abrupt stop or other internal error is detected by the FC, the error routine is activated. It must include the steps to be followed after each error (e.g.: minimum interval of time until the next start of the FC).

2) The following protections should be considered:
   - High and low-level pressures.
   - Motor temperature.
   - Frequency converter temperature.
   - Leakage current.

3) If more than one FC/motor-pump is connected to the same PV generator, different power thresholds must be considered to start and stop each FC.

4) If more than one FC/motor-pump is connected to the same PV generator, only one FC can have the MPPT routine at a time.

5) If a system includes a set of pumps to do direct pumping and a set of pumps to feed a water pool, in case of low level of irradiance and in the presence of irrigation needs, priority will be given to direct pumping pumps unless the water pool is empty – in this case, if there is enough PV power available, the pumps that will work are the ones to fill the water pool.

Emergency/stop button

1) Each FC needs to include an individual emergency button to allow an immediate stop if needed. It must be easily accessible. If this button is pressed, the stop of the FC must be a controlled one.

4.6. Motor-Pumps

1) The traditional way of selecting a pump is just to look for the pump that shows the highest efficiency at the duty point (usually at 50 or 60 Hz). This methodology is unsatisfactory for PVIS, particularly for the water pool ones since they work at different frequencies and working points. Accordingly, (R. H. Almeida et al., 2018) proposes a pump selection method

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for PVIS pumping to a water pool that should be considered as a best practice. This method has the following four steps:

- "To select the pumps with an H-Q curve at 50 Hz with the greatest slopes from those that can work at a certain duty point.
- To select the pumps (from the previous ones) in which the duty point is in the "right-hand third" of the H-Q curve. The duty point at the right-hand part of the H-Q curve, together with its great slope, will allow a wide range of operating frequencies.
- To identify the lowest operating frequency at which the pump is able to elevate water into the pool. It will be defined by the H-Q curve with the lowest frequency that intersects with the system curve. The pumps with the lowest frequencies will be preferable, as they will allow a wider range of operating frequencies.
- To select the pump with the best efficiency between those fulfilling the previous steps."

2) In principle, all three-phase motors can work at variable frequency. Although, it is always better to confirm this information with the motor manufacturer.

3) The motor must include a thermal protection.

The motor must stop if its temperature is higher than a defined threshold.

4) It is important to consider the acceleration time allowed by the motor (usually presented in the motor datasheet).

5) It is important to know the allowed maximum number of start-ups of the motor-pump per hour.

This should be included in the start and stop routine of the motor-pumps in order to avoid excessive starts and stops that could damage the pump.

6) When the distance between the FC and the motor-pump is long, it is necessary to protect the motor-pump against harmonics. The protection that must be added at the output of the FC depends on this distance:
    a. Up to 50 m: AC reactance.
    b. Between 50 m and 150 m: dV/dt filter
    c. Higher than 150 m: a sinusoidal filter.

4.7. Switching elements between the pump and the frequency converter

1) A connection box may be included between the frequency converter and the motor-pump. This box will include a contactor to isolate the motor-pump and will allow the connection of an external source of power to easily perform an evaluation of the motor-pump without the use of the FC (see Figure 25). It is extremely important that, if switching elements are installed, they must be operated without load.

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Figure 25

4.8. Batteries

1) The use of batteries is not allowed.

A system with batteries will present a higher cost and complexity, which will decrease its reliability and economic feasibility.

4.9. Monitoring system

1) The installation of a monitoring system is mandatory in a PVIS.

2) The monitoring is a responsibility of the Data-related services provider.

3) Access to energy meter(s) is mandatory.

4) Access to water volume meter(s) is mandatory.

5) The monitoring system must be able to communicate with and receive relevant information from:
   - All FCs
   - All PLCs
   - All irrigation automatisms
   - All the tracker control units
   - All the reference PV modules
   - All the energy meters
   - Pulse flow meter
   - Dynamic water level meter (when pumping from a borehole)
   - Level of the sensors in the water tank (when pumping to/from a water tank)
   - Pressure transducer (in the case of direct pumping)

6) Table 6 includes all the variables that shall be measured and recorded in the monitoring system – they are categorized as mandatory, highly recommended, recommended, and optional –, as well as its ideal time resolution for monitoring purposes.

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Table 6 - Variables that shall be included in the monitoring system, as well as its time resolution.

Variable		Time resolution
Date (day and time)	Mandatory	1 sec.
Solar irradiation (one record per sensor)	Mandatory	1 sec.
Cell temperature (one record per sensor)	Mandatory	1 sec.
Theoretical DC power (calculated from solar irradiation and cell temperature)	Mandatory	1 sec.
DC current (one measure per FC)	Mandatory	1 sec.
DC voltage (one measure per FC)	Mandatory	1 sec.
DC power (one measure per FC)	Highly recommended	1 sec.
AC current (one measure per FC)	Optional	1 sec.
AC voltage (one measure per FC)	Optional	1 sec.
AC power (one measure per FC)	Mandatory	1 sec.
Output frequency (one measure per FC)	Mandatory	1 sec.
Power Factor (one measure per FC)	Highly recommended	1 sec.
FC Temperature (one measure per FC)	Optional	1 sec.
FC Status (one measure per FC)	Mandatory	1 sec.
FC Alarms/Alarm status (one measure per FC)	Recommended	1 sec.
FC start order	Mandatory (if more than 1 FC)	1 sec.
Water flow (one record per irrigation network)	Mandatory	10 sec.

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Working pressure (in the case of direct pumping)	Mandatory	1 sec.
Dynamic water level	Recommended	5 min.
AC energy	Mandatory	5 min.
Water volume	Mandatory	1 day
Position of the tracker	Mandatory	5 min.
Reference position of the tracker	Optional	5 min.

7) A centralized monitoring system should be used.

8) The monitoring system must include communication facilities through GSM or via internet and must store locally the data.

9) The monitoring system must instantaneously alert the operator to any defects. This way, they can be repaired immediately, energy and water losses will be minimized, and crop production will not be affected.

10) The monitoring system can include remote control of the PV installation.

4.10. Irradiance and cell temperature sensors

1) The sensors to measure the effective incident irradiance over the PV arrays, G_{ef}, and their cell temperature in operation, T_C, shall be reference PV modules of the same manufacturer, type and model than the ones installed in the PV arrays.

Even if it is usual the use of a single calibrated solar cell of the same technology as the PV modules (which includes a thermocouple to measure T_C), the use of PV modules of the same technology will improve accuracy in the measurements. The PV reference module has a thermal, spectral, and angular response closer to one of the PV modules of the array than a calibrated solar cell. In addition, a PV module acting as an irradiance sensor is less sensitive to localised shadows than a PV cell.

Both a calibrated solar cell and a PV reference module can be seen in Figure 26.

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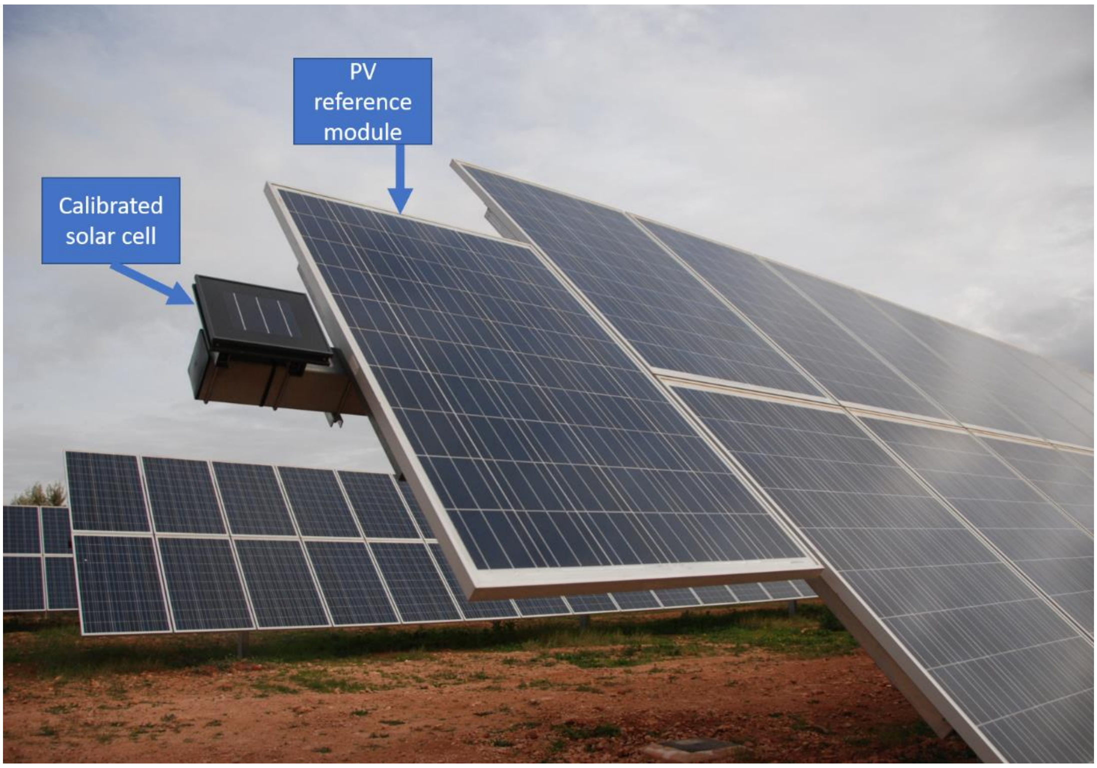

Figure 26

2) Reference PV modules must be installed in the same plane as the PV arrays (and must be fixed the same way than the PV array). Shadows must be avoided.

3) A good practice is to install the sensor on the top of the structure (for static structures), or on the center (for North-South horizontal axis trackers).

4) The PV reference modules for measuring G_{ef} has to be short-circuited and the resulting current has to be monitored. It will be equipped with class 0.5 shunt resistors in such a way that the corresponding voltage for the STC irradiance G* = 1000 W/m^2 ranges from 100 mV to 200 mV.

5) The PV reference modules for measuring T_c has to be open-circuited to measure cell temperature

6) Electronic devices needed to use PV modules as irradiance and temperature sensors must be protected inside boxes with proper IP rating (see Figure 27).

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Figure 27

7) A single PV module can be used both as irradiance and cell temperature sensor (see Figure 27).
Taking advantage of the by-pass diodes, a part of the PV module is short-circuited with a shunt resistor (to measure irradiance), and the other part remains in open-circuit (to measure cell temperature).

8) PV reference modules will be distributed along the PV plant, in order to get G_{ef} and T_C average representative values, to estimate the dust energy impact (by cleaning just a group) and to provide redundancy for increasing monitoring reliability. The following rules apply:
    a. At least, one PV reference module per 1 MWp of PV generator.
    b. If only one PV reference module is installed, it must be installed in a central point of the PV generator.
    c. The distance between any point of a PV array and a reference module must be less than 300 m.

9) A PV reference module will be supplied and kept on dark conditions, to allow future recalibrations of the installed one(s). Recalibrations should be done every two years.

10) Measurement procedures will be in accordance with IEC 60891, IEC 60904-2 and IEC 60904-5. Stabilization and calibration of reference PV modules must be done by a well-recognized independent laboratory.

11) Irradiance sensors should be free of localized soiling.

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4.11. Wind speed sensors

1) Wind speed sensors should be installed on a separate tower (and not at the top of a tracker). This sensor is mandatory in tracking PVIS.

2) The wind protection threshold must be carefully determined to prevent production losses (threshold too low) and material destruction (threshold too high).

When the speed monitored is above a safety threshold, an alarm is generated. Consequently, the trackers move to the wind-protection position in order to guarantee their physical safety against high wind gusts.

It is very important to establish an appropriate threshold to avoid false alarms which will reduce the final energy production.

3) The tower must be securely anchored to the ground.

To prevent the tower from collapsing, 3 anchor points separated 120 degrees apart from each other are required. If they are separated by 90 degrees, one more anchor point is needed.

4) It must be prevented that the tower casts shadows over the PV generator.

4.12. Other sensors

1) AC energy meter(s) are mandatory.

2) A shunt to measure DC current of the PV generator must be installed.

3) Water volume meter(s) are mandatory.

4) A sensor to measure the water level in the borehole must be installed.

This way, the motor will not work with no-load.

5) A sensor to measure the water level in the water pool must be installed.

Although some applications may require the exact level of water in the water pool, most of the times it is enough to have four water buoys at different levels – two for empty water pool and two for full water pool. Two buoys are considered for each situation in order to add hysteresis to the system.

6) A sensor to measure the water flow must be installed.

7) A sensor to measure the motor temperate must be installed.

8) A sensor to measure the pressure is mandatory.

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4.13. Security of the plant

1) The PV generator and all buildings must be protected against theft, for example, by installing alarm security systems (Figure 28).

Figure 28

2) Technical buildings must be protected against thefts and vandalism.

Adequate lock systems must be installed in doors of technical buildings in PVIS applications to avoid attempted vandalism and robberies as shown in Figure 29 and Figure 30.

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Figure 29

Figure 30

3) The PV generator location should not be close to main roads or public paths to avoid vandalism.

4.14. Feeding of the auxiliary charges

1) If the PVIS is a stand-alone one and grid connection is not available, a small stand-alone PV system must be installed to guarantee the feeding of all the auxiliary charges (such as the monitoring system, the control system or the alarm security system).

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5. Best Practices in Installing a PVIS

5.1. Quality control before installation

1) The quality control before installation must be done by the Technical Advisors (the external institution specialized in quality control of stand-alone large-power PVIS).

Testing of PV modules prior to project execution

1) It is necessary to check that the PV modules meet the required technical specifications. In order to do that, 12 PV modules must randomly be selected among the ones that will be installed in the PV generator. The following measurements will be performed:
   - Peak power: the measured PV peak power must be within the tolerance limits specified by the manufacturer. This measurement needs to be done before and after LID degradation (after the modules exposure to the sun – at least 20 kWh/m^2).
   - Electrical characterization: the temperature coefficients with power, open-circuit voltage and short-circuit current will be measured. These values will be used to a better estimation of the PV generator productivity.
   - Detection of hidden faults and micro-cracks of the PV cells: current will be injected into the modules and electroluminescence will be performed.
   - Detection of visible faults: visual inspection to detect failures in welds, delamination, bubbles, broken, cracked or torn external surfaces, voids in or visible corrosion of any of the layers of the active circuitry of the module, module markings (label) not present or unreadable, etc.
   - Propensity to PID: a test is performed to check the tendency of the PV module to PID. Since this test can be destructive, a smaller sample of modules will be checked.

Preparation of irradiance and cell temperature sensores

1) Two PV modules must be prepared as irradiance and cell temperature sensors.

2) A PV modules will be installed in the PVIS (in the same plane of the PV generator).

3) A PV module will be kept to perform technical control procedures.

Preparation of reference PV modules

1) Three reference PV modules must be prepared.
   These modules will be used in the quality control at provisional and final reception of the installation.

2) A reference PV module will be installed in the PVIS.

3) Two reference PV modules will be supplied and kept on dark conditions, to allow future recalibrations of the installed one(s). That should be made every two years.

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Motor-pump testing

1) When a new motor-pump is going to be installed, it is worth recommended that the manufacturer carry out a bench testing to characterize the head-flow curve, as well as the motor and pump efficiencies at different speed ranges. This information will be useful for subsequent quality controls of the system and monitoring of the motor-pump performance.

2) In the case that the motor-pump is already working in the irrigation farm, an on-site characterization of the motor-pump should be made to also obtain the head-flow curve, as well as the motor and pump efficiency at different speed ranges.

5.2. Installation

PV generator

Supporting structure

1) Tests must be carried out to adjust the foundations design to soil properties.

A geological study of the land on which the PV generator is going to be installed must be carried out. The objective of such a study is to assess the properties of the ground before selecting the foundations to use (as this selection is determined by the mechanical constraints and the soil quality). Foundations must accommodate the effects of weight and wind (as defined by the appropriate Eurocode or/and other norms). This study would also eliminate the possibility of unnecessary works.

Each type of foundation (concrete footing, pile, mini-pile, etc.) is suited to specific land-types. Shallow foundations, such as concrete footings, could be suitable in compacted and stable land (rocks, aggregates), while deep foundations, such as piles or mini-piles, could be required in un-compacted lands which might be prone to seasonal climactic variations (e.g. expansive clays, areas close to water table).

2) Soil improvement and consolidation will be done, if necessary.

3) The land in which the PV generator is going to be installed must be flat (ensuring a good level base).

Sloping lands must be object of earthworks ensuring a level base or minimal slope as previous step before the foundation works. This is imperative when installing North-South horizontal axis trackers, which need to be placed on a flat and stable surface with limited slopes.

4) Supporting structures must be rigid and resistant to wind gusts in accordance with EN 1991 and to corrosion environments equal to or higher than C4, in accordance with the standard ISO 9223.

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5) Supporting structures must be made of aluminum or hot dipped galvanized steel. The installation procedures must ensure anti-corrosion protection. This is also applicable to doors, trays, bolts, nuts, washers and fixation elements in general.

6) All the parts of the supporting structure must be correctly assembled, fit with each other and be compatible to avoid galvanic corrosion.

7) Supporting structures must allow every single module to be accessible for periodic inspections.

8) All metallic parts of the structures must be grounded.

A good earth connection protects people and electronic devices against leakage currents. All metallic parts of the supporting structure, including those where direct contact cannot be made as they are separated by non-conductive material, must be interconnected or bonded and grounded. This is in order to protect people against electric shock in the event of faults or electrical storms (Figure 31 and Figure 32). Otherwise, the ungrounded components could reach dangerous voltage levels relative to ground. This could happen with the post in Figure 33 due to the black insulating layer.

Figure 31

Figure 32

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Figure 33

9) Grounding wires must be clearly identified.

It is advisable to use conductors which are clearly distinguishable from the power cables for earthing structures. The ground conductor can be bare wire or with a covering of a different colour, usually yellow/green.

10) PV modules are usually fixed with clamps on the long edges (Figure 34). Fixing the PV modules on the short edges (Figure 35) may be permitted for certain models and under certain conditions.

Fixing the PV modules on the short edges reduces the ability to deal with climatic loads such as wind and snow. The maximum load due to extreme meteorological conditions depends on the location of the system and should be compared to the permitted loading on the modules. These would typically be in the range of 2400 Pa to 5400 Pa.

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Figure 34

Figure 35

Clamps must be symmetrically placed to avoid excessive distance between the PV module attachment point and the edge to achieve better attachment of modules to the structure, as shown in Figure 34, rather than Figure 36.

Figure 36

It is important to refer to the PV module installation manual for additional information concerning the installation procedure and appropriate fixing points.

11) Clamps must be used according to their specifications and must match the size and shape of the modules.[8]

12) Anti-theft screws and nuts are recommended when mounting PV modules.[8]

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[8] Detailed information on this point can be found in Annex III, section Civil works – supporting structure.

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13) Supporting structures must fit to the module frames, and all parts of the structure must fit with each other.

Figure 37 shows a PV module that has not been mounted in an appropriate manner since the supporting structure does not fit to the PV module frame. It is bent and incorrectly held by a threaded steel rod. The PV module may become detached during heavy winds or even be irreversibly damaged. In addition, the screw is too long and can pose a risk to staff.

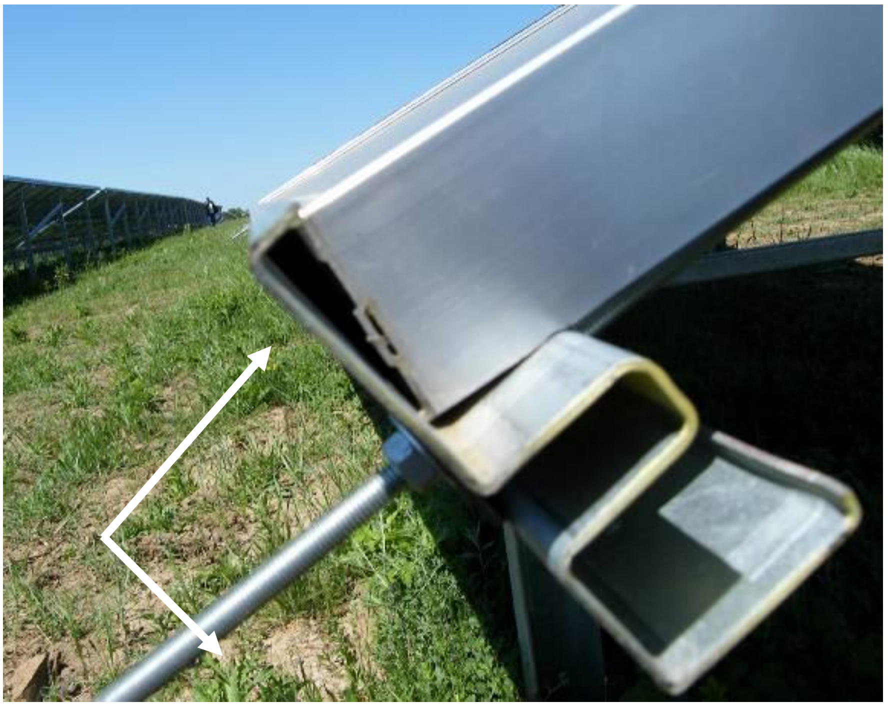

Figure 37

14) Supporting structures and junctions must be rigid.

Supporting structures have to be attached in a rigid way to avoid loss of shape as in Figure 38. Small rods have been used to attach two structures, but they are not strong enough to keep them straight. Figure 39 shows the proper way to attach them as it uses a rigid piece that fits perfectly, keeping the two structures straight, adding strength to the whole structure and preventing deformation in the future. This type of attachment could be used as a thermal expansion joint if it is fixed on one side only. However, care should be taken to ensure that there is no loss of strength to the structure.

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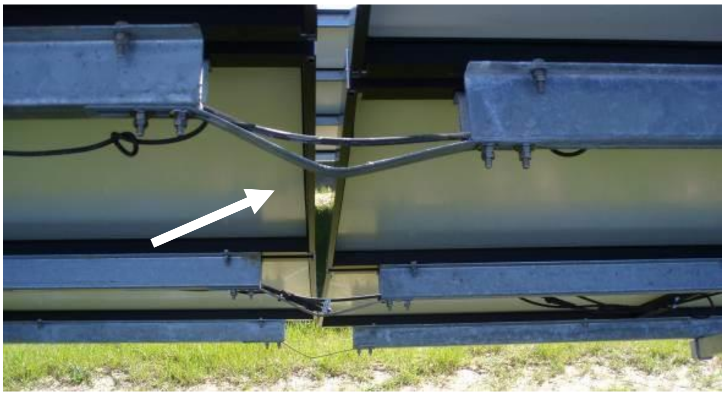

Figure 38

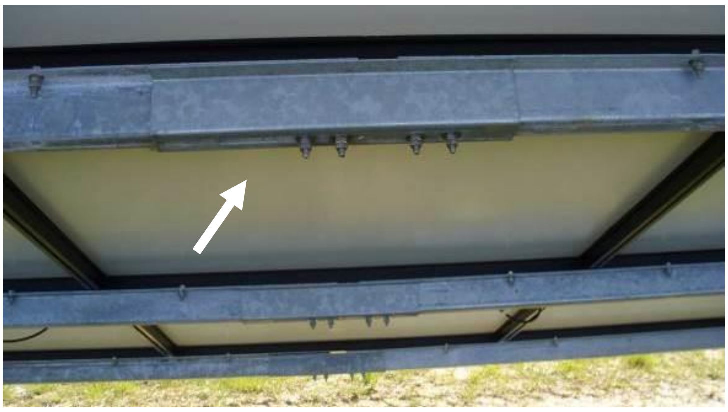

Figure 39

15) All material used in the structures must be compatible.

The metallic materials of the PV module frames, the supporting structures as well as screws, washers, nuts, etc. must be compatible. Some materials are not compatible and should not be used in combination without the proper separation. Otherwise, galvanic corrosion may appear if incompatible materials are in contact, such as aluminum and stainless steel as shown in Figure 40.

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Figure 40

16) Structures must resist outdoor climate conditions (rain, salt, low temperature, sunlight).

The structures have to be constructed from stainless steel or be protected against degradation (mainly oxidation) with a treatment such as galvanizing or special painting. The strength of the structures could be reduced with time if this protection is not correct. Figure 41 to Figure 47 show examples of good and bad practice. In Figure 41 to Figure 45, galvanized or painted protection has not been applied or has been carried out incorrectly. Figure 46 and Figure 47 show where the correct protection has been applied. Nevertheless, as they are painted or cold galvanized, they have to be monitored and repaired when required before the degradation becomes evident.

Supporting structures are not necessarily made of metallic materials. Other materials such as wood can be used. Wood has to be varnished to protect it against the environment agents.

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Figure 41

Figure 42

Figure 43

Figure 44

Figure 45

Figure 46

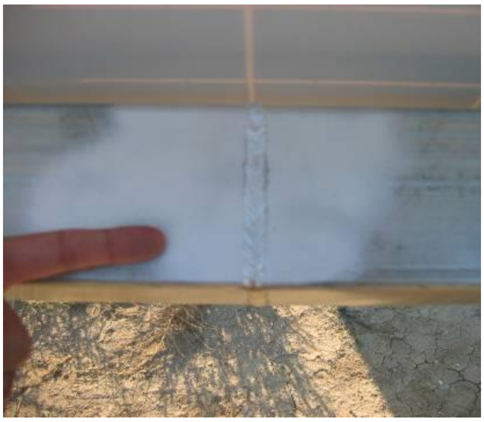

Figure 47

17) Mounting systems must allow for thermal expansion of all the system components.[9]

18) Anti-bird devices should be installed on the top of the PV modules (see Figure 48 and Figure 49).

[9] Detailed information on this point can be found in Annex III, section Civil works – supporting structure.

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Figure 48

Figure 49

PV modules

1) PV modules must be protected from shocks and vibrations to avoid micro-cracks.

2) PV modules must be transported and installed in good conditions to prevent micro and macro-cracks, as well as other damages in the modules.

3) PV modules must be protected from vegetation.

The structures of Figure 50, Figure 51, and Figure 52 are of such a height that low vegetation can reach the lowest PV modules. As a result of this, vegetation casts shadows over the panels that decrease the production of the installation and, at worst, can accelerate the degradation of PV

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modules causing hot spots. Arranging the structure at a greater height would have avoided this situation. With appropriate monitoring of the installation, the vegetation could be cut before it reaches modules (Figure 53). Care needs to be taken to ensure that during ground maintenance, equipment with rotating blades or string cannot cause small stones to be projected which might damage the PV modules.

Figure 50

Figure 51

Figure 52

Figure 53

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Enclosure of the PV generator

1) PV plants must be enclosed with a fence or a wall.[10]

2) The enclosure must be provided with a metallic gate large enough to allow the entry of maintenance vehicles.[10]

3) The space between the fence and the PV generator must be large enough to allow the passage of maintenance vehicles.[10]

Shadows

1) Solar tracker drivers must be conceived in such a way they do not project shadows over the PV modules

Some North-South horizontal-axis trackers models have a single motor to move multiple rows. This is an advantage that optimizes the operation, the energy consumption and the cost of the solar tracker. However, it must be designed in a correct way in order to avoid shadows projected over the PV modules. Figure 54 shows how the tracker transmission beam projects a shadow over the bottom of the PV module, which can be the origin of future hot spot effects.

Figure 54

[10] Detailed information on this point can be found in Annex III, section Enclosure of the PV generator.

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2) The back-tracking function of the tracker must be well calibrated to avoid shadows.

Back-tracking function must be calibrated when setting the operation parameters of the tracker functioning. This calibration mainly depends on latitude, distance between rows and land slope.

A good calibration leads to a good performance along the year as shown in Figure 55 (in which it can be observed a narrow line of sun projected on the ground, that indicates a good back-tracking functioning). However, bad calibration can lead good results for some year periods but shadow problems in other periods, as shown in Figure 56, in which it can be appreciated how the rows project shadows over the bottom of the PV modules of the rear row.

Figure 55

Figure 56

Drainage and water protection

1) Based on the climatic data and specially the rainfall data, and the site's configuration and topography, the Contractor will be responsible for designing and building a drainage system to protect the installation infrastructures against erosion and flash floods. This drainage system must be properly maintained.[11]

2) Service buildings must be waterproof, including cable entry points.[11]

Frequency converter(s) and PLC

1) The FC(s) and PLC must be placed in a dedicated building – the engine room.

2) The FC(s) and PLC must be inside a specific electric board.

[11] Detailed information on this point can be found in Annex III, section Drainage and water protection.

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3) The FC(s) and PLC supporting structures must be built with adequate load-bearing capabilities.

4) The FC(s) and PLC supporting structures must be made of non-flammable materials.

5) Frequency converters cooled down by natural convection must be placed vertically in well ventilated areas and comply with clearances to walls and obstacles.

The temperature of the FC increases significantly when operating. Where FCs are cooled by natural convection, they must be placed vertically, in well ventilated areas with at least minimal clearance to walls, other objects and other inverters as specified by the manufacturers. Failure to observe these guidelines may result in overheating, reduced efficiency and reduced life expectancy.

6) The FC must be properly cooled – fans and air ducts should be installed if necessary.

Buildings which house FCs generally operate at an elevated temperature and for this reason such buildings must have their own air circulation system.

However, the air flow may not reach the internal sections of the FC. Therefore, the temperature inside it can be higher than the recommended value resulting in a reduction in its efficiency. Moreover, these high temperatures can cause an over-temperature alarm to be activated and the FC turned off. A good practice is to add fans or air circulation systems which also cool the internal sections of the FC.

7) FC cooling fans must remain clean and free of dust.

Some FCs have in-built fans to improve their cooling and therefore attain higher efficiencies. However, these measures are useless if they are not properly maintained. If the room is full of dust and the filters of the FC fans are clogged, its cooling and efficiency are reduced.

Wiring

1) Cables trays must be protected during the construction phase.[12]

2) Cables must be placed in cable trays.[12]

3) Buried cables should be protected by rigid tubing or ducts.[12]

4) Buried cables should be buried below freezing depth.[12]

5) Electrical conduits must be sealed in both conduit ends to avoid access to small rodents and others.[12]

[12] Detailed information on this point can be found in Annex III, section Wiring.

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6) Buried electrical conduits in trenches must be marked with appropriate warning type for underground cables and pipelines.[13]

7) Electrical cables installed in the trackers between PV modules and connection boxes must avoid the contact with moving elements of the structure.

Electrical wires connecting PV modules and connection boxes must be fixed to the metallic structure in a way that they are not affected by the turn movement of the tracker.

Wiring should not come into contact with mobile elements. Cables must be separated from mobile elements (Figure 57) or/and protected under adequate and resistant conduits (Figure 58). Figure 59 shows a couple of wires coming into contact with a mobile metallic element of the tracker, which in the short or medium term can damage the wire protection with the risk of an electrical contact between the ground and the PV generator's poles.

[13] Detailed information of this point can be found in Annex III, section Wiring.

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Figure 57

Figure 58

Figure 59

8) Manholes and chambers must be properly installed.[14]

9) Manholes should be raised above the ground for additional protection.[14]

10) Signal cables must be shielded cables.

[14] Detailed information of this point can be found in Annex III, section Wiring.

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11) The underground cable ducts and trenches must be constructed below the depth established in the National low voltage regulation.

12) The LV cable will be laid in a minimum depth of 0.8 m on a sand bed of 0.1 m thick and protected with flexible corrugated tube of an adequate section to leave 50% of its space for future needs. Refilling will be done in layers of 15 cm thickness, each properly compacted. About 15 cm above crest level of the cables a signal band for each of the cables will be laid.

13) The crossings of roads will be made through appropriate cement cable ducts or polyethylene heavy duty (PEH) pipes, with a wall thickness of not less than 5 mm.

14) Chests or manholes must be installed every 90 m and in any change of direction.

5.3. Start-up of the system

1) All components and materials must be in accordance with the project documentation.

2) The correct labeling of all equipment must be verified.

PV generator structure

1) The following should be verified:
   - Grounded of the structure.
   - PV modules mechanical integrity.
   - PV modules clamps, screws and nuts.
   - PV modules cables and connections.

2) If the structure is a tracker, the following must be verified:
   - Tracking algorithm.
   - Back-tracking algorithms.
   - Tracker operation under wind alarm.
   - Tracker night position.

Control of the system – frequency converter and PLC

1) An auto-tunning must be performed in each FC.

2) After the auto-tuning, motor parameters must be confirmed.

3) The start and stop thresholds of each motor-pump must be defined and adjusted to maximize PV energy use.

4) The acceleration and deceleration times of the motor-pumps must be defined.

5) The tuning of the proportional-integral (PI) control parameters must be done.

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This tunning must guarantee the stability of the system in the start-up phase of each motor-pump, in normal operating conditions and under cloud-pass occurrences.

Since the dynamic behavior of the hydraulic system is different in each PVIS, the definition of both the proportional gain and integral time must be done in-situ. The derivative control is usually not applied due to the electromagnetic noise presented in these systems.

UPM is currently looking for a way to auto-tune the PI control parameters. UPM is also trying to develop a method to test the performance of the system under passing-clouds occurrences without the need for real clouds (trying to simulate the interference of the clouds in the system).

6) If the irrigation network includes filters, the stability of the system while cleaning the filters needs to be confirmed. The adjustment of the PI control can be needed.

7) FC(s) and PLC programs must be tested, including the different working routines (to verify its good performance and to test important protections).

8) The following system protections must be verified:
   - No-load motor.
   - Empty well (if the system includes a well).
   - Empty water pool (if the system includes a water pool).
   - Full water pool (if the system includes a water pool).
   - High pressure level.
   - Low pressure level.

Monitoring system

1) The monitoring system must be in operation since the start-up of the PVIS system (all input signals must be available at that time).

5.4. Commissioning of the system

1) The commissioning of the system must be done after an initial period of Sun exposure long enough for the total irradiation on the PV arrays reaches at least 20 kWh/m^2 and, in any case, not less than one month.

2) The commissioning of the system must be done by the Technical Advisors.

PV generator characterization

1) I-V curves should be measured to at least 3% of the PV modules installed, as well as to all strings of the PV generator.

2) Visual and thermographic inspections must be performed in all PV modules.

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Any PV module showing the "major visual faults" specified at the norm IEC 61215 will be rejected.

Thermal (IR) images must be obtained in accordance with IEC 60904-14, with the PV system in normal operation and must respect the following conditions:

- On-plane irradiance higher than 700 W/m^2.
- Irradiance variations during the previous 10 minutes less than 20%

Hot-spots acceptance/rejection criteria are (Moretón et al., 2015):

- ΔT_{HS}^{*} ≥ 100ºC leads to automatic rejection, even when the hot-spot is caused by any shadow affecting the PV array.
- ΔT_{HS}^{*} > 20ºC in absence of shades leads to automatic rejected.
- $10^{o}\text{C} \leq \Delta T_{HS}^{*} \leq 20^{o}\text{C}$ in absence of shades will lead to measure the effective power loss, understood as the decrease of the PV module operation voltage in relation to a non-defective module of the same string. The PV module will be rejected if such effective power loss exceeds 20%.

PV generator structure

1) The following should be verified:
   - Grounded of the structure.
   - PV modules clamps, screws and nuts.
   - PV modules cables.

2) If the structure is a tracker, the following must be verified:
   - Tracking algorithm.
   - Back-tracking algorithms.
   - Tracker operation under wind alarm.
   - Tracker night position.

Frequency converter and control of the system

1) The efficiency of the frequency converter must be measured according to the characteristics of the irrigation system:
   - For water pool systemsdifferent working frequencies must be tested (from minimum to maximum frequencies).
   - For direct pumping systems, efficiency must be measured for the different working points of the irrigation network.

2) The frequency converter and/or an external PLC is used to control of the system. The following routines should be verified:
   - Start and stop – accordingly to the available PV power and end-user needs.
   - Cloud-passing – the system needs to be reliable against PV power fluctuations.
   - MPPT (in the case of water pool systems) – the system must follow the maximum power point of the PV generator.

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- Pressure control (for direct pumping systems) –pressure stability must be guaranteed.

Motor-pump characterization

1) The efficiency of the motor-pump must be measured according to the characteristics of the irrigation system:
   - For water pool systems, different working frequencies must be tested (from minimum to maximum frequencies).
   - For direct systems, efficiency must be measured for the different working points of the irrigation network.

System productivity

1) The full operation of the system will be measured and monitored during a full week.

The following indices will be calculated:

- PR
- PR_{PV}
- UR_{IP}
- UR_{PVIS}
- UR_{EF}
- *PVS* (in the case of hybrid systems).
- Passing cloud resistance ratio.

2) A comparison with the expected results must be done.

Monitoring system

1) The following must be verified:
   - The monitoring system.
   - The recorded variables.
   - The frequency and validity of the recorded values.
   - The communication and data storage procedures.

Other aspects

1) The following system protections must be verified:
   - No-load motor.
   - Empty well (if the system includes a well).
   - Empty water pool (if the system includes a water pool).
   - Full water pool (if the system includes a water pool).
   - High pressure level.
   - Low pressure level.

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6. Best Practices in Operating and Maintaining a PVIS

1) The O&M contractor must carry out the main activities of Operation and Maintaining a PVIS.

2) The following maintenance activities must be considered: preventive, corrective, predictive and extraordinary.

3) An O&M manual for preventive maintenance must be available.

4) A record of the O&M activities performed must be done and integrated in the monitoring system.

6.1. Preventive maintenance

1) PV modules must be kept cleaned, especially localized dirt must be avoided.

2) PV modules must be protected from vegetation.

3) PV parallel string boxes must be periodically checked and verify that all fuses are correctly working. The use of fuse-disconnect switches with light signaling may be useful for this task. In the same way, the overvoltage protection devices must be checked.

4) Tracking algorithm must be periodically confirmed.

5) The PV tracker must be periodically checked, particularly the hydraulic actuators, the mechanical drive mechanisms, and the proper functioning of the anemometer, in accordance with the manufacturer O&M manual.

6) Regular energy meters readings must be done.

7) Motor pump performance must be monitored to detect the loss of efficiency to schedule the motor-pump maintenance works.

8) Motor temperature must be monitored to prevent motor damages or even burning.

9) Maintenance of buildings, fence and security equipment must be done.

10) An Annual Maintenance Plan must be available.

6.2. Corrective maintenance

1) The corrective maintenance takes place after a failure detection through the remote monitoring, by the plant operator or by the annual maintenance plan.

2) Three main activities can be performed under corrective maintenance – fault diagnosis, temporary repair, and repair.

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Fault diagnosis is the process of identification of the fault, temporary repair is the repair to restore the function or item for a limited period of time (until repair is carried out), and repair is the restoration of the function or item permanently.

3) The corrective maintenance must be done, if possible, during night-hours (to avoid influencing the PV generation).

4) The corrective maintenance is usually contractually obliged to comply with maximum response times.

6.3. Predictive maintenance

1) By analyzing historic yield assessment and key performance indicators, predictive maintenance activities can be developed.

2) When there is the need to change the FC or the motor-pumps, several factors must be considered regarding both mechanical and electrical installation.

6.4. Extraordinary maintenance

1) An extraordinary maintenance is needed in case of:
    a. theft, fire, or endemic failures.
    b. regulatory changes.
    c. equipment deterioration.

2) The unavailability of spare parts may lead to repowering and/or revamping of the system.

3) If there is the need to repower the PV modules, special attention is needed in what concerns PV modules support and electric installation.

6.5. Overall performance

1) The system must be monitored 24 hours a day, 365 days a year.

2) A report of the overall performance of the system should be automatically done each month. This is a responsibility of the Data-related services provider or O&M contractor.

3) The weekly report must contain the following information:
    - AC energy delivered by the FC
    - Hydraulic energy
    - Water volume
    - PR
    - PR_{PV}
    - UR_{PVIS}
    - UR_{EF}

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- *PVS* (in the case of hybrid systems)
- Passing cloud resistance ratio
- Alarm log.

6.6. Availability of spare parts

1) The most critical spare parts must be available close to the PVIS (according to the contracts).

6.7. Final evaluation (after two years of operation)

1) The final evaluation of the PVIS must be done after two years of operation.

2) The final evaluation must be done by the Technical Advisors.

3) The procedure to follow in the final evaluation is like the one presented in Chapter 5.4 – Commissioning of the system. In addition, the annual performance of the system along years 1 and 2 must be included – the annual values of PR_{PV} must be equal to or higher than 0.8.

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Annex I

In PVIS, irrigation methods can be broadly classified as sprinkler and micro-irrigation.

Sprinkler irrigation systems may be stationary or continuous moving. They include portable (non-fixed) set systems, solid set or permanent systems. The latter, automated, consist of center-pivots, linear-move systems, travelling gun sprinklers and side-move systems. These systems are well described and analyzed by (Keller and Bliesner, 1990) and, in Spanish, by (Tarjuelo Martin-Benito, 2005), who provided an excellent basis for system design. Nevertheless, the guides and information provided on the internet sites of the manufacturers of sprinklers and equipment are also relevant for design and for efficient use of farm sprinkler systems. The water distribution uniformity throughout the irrigated field is the main objective of system performance (Mantovani et al., 1995). Thus, the considered water-saving practices aim at achieving high distribution uniformity and controlling wind effects, which also leads to high distribution uniformity. In addition, practices and design also aim at improving water infiltration and reducing runoff, which can be achieved through appropriate sprinkle selection. Irrigation system design, mainly referring to the selection of sprinklers sizes and their spacing, flow rates, water application depths and diameters of piping, is fundamental to ensure uniform distribution of pressure and water with reduced evaporative losses (Keller and Bliesner, 1990). As water is applied to wet the entire land, non-beneficial consumption of water can be substantial under high wind and evaporative demand of the atmosphere. Wind impacts may be higher when drops are small and when the canopy cover is low and risers are high. Sprinkler systems perform better when the soil infiltration is high and wind is low. Modern sprinkler systems that are designed to frequently apply small irrigation depths, such as center-pivot and linear moving laterals, reduce the risk of crop stress (Rodrigues and Pereira, 2009) at the expense of increased soil evaporation. Water losses occur through evaporation from soil and canopy surface. Evaporation losses are difficult to estimate; they mainly depend on wind speed and drift, the evaporative power of the atmosphere estimated by ETo, canopy cover, and the size or the coarseness of irrigation drops.

There are different types of sprinkler heads in use, depending on the actual irrigation purpose and plot sizes: rotor-type sprinklers operate by rotating streams of water over the surface. They include impact and gear-drive sprinklers producing moving streams of water and spray nozzles that discharge water on the whole wetted pattern at all times. Impact or gear-drive sprinklers can accommodate only full or part circle application patterns. Since each sprinkler covers a large area (typically 12 m head-to-head spacing), they are used on larger plot sizes.

An impact sprinkler is mounted on a bearing that allows the entire sprinkler body to spin in circles. It is rotated by the impact of a swinging arm repeatedly striking the body of the sprinkler, causing it to rotate slightly each time. Cam drive or ball drive sprinklers[15] also impact sprinklers, however the impact is caused by either a cam or a ball bearing inside the body of the sprinkler. Ball and cam drive rotors allow only the nozzle movement.

As impact sprinklers tend not to rotate in a uniform manner, they are replaced by gear-driven rotors on the market. As with cam and ball drives, only the nozzle on a gear-driven sprinkler head moves. The water moving through the sprinkler spins a turbine, which turns a set of gears, which again turn the nozzle. These gear-drive rotors have one or more streams of water rotating.

[15] These sprinklers are no longer present on the market, but may be still in use.

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In agricultural irrigation, these sprinklers are usually in operation on very large plot sizes. They require a higher input pressure.

Centre pivot irrigation is a form of overhead sprinkler irrigation consisting of several segments of pipe mounted on wheeled towers with sprinklers positioned along its length. The usually self-propelled structure moves in a circular pattern and is fed with water from the pivot point at the centre of the circle. The amount of water applied is controlled by the speed of rotation. Centre pivots can be adjusted to any crop height and are particularly suited for lighter soils. With a computerized control system, the operator is able to program many features for the irrigation process. Furthermore, it is possible to install a corner attachment system (also called "end-gun") which allows irrigation of corner areas missed out by conventional centre pivot systems.

A linear move (also called lateral move) irrigation system is built the same way as a centre pivot; the main difference is that all the towers move at the same speed and in the same direction. Water is pumped into one of the ends or into the centre.

A travelling big gun system uses a large-capacity nozzle and high pressure to throw water out over the crop as it is pulled through an alley in the field. Travelling big guns come in two main configurations: hard-hose or flexible-hose feed. With the hard-hose system, a hard polyethylene hose is wrapped on a reel mounted on a trailer. The trailer is anchored at the end or centre of the field. The gun is connected to the end of the hose and is pulled towards the trailer. The gun is pulled across the field by the hose winding up on the reel. With the flexible hose system, the gun is mounted on a four-wheel cart. Water is supplied to the gun by a flexible hose from the main line. A cable winch pulls the cart through the field towards the cart.

Due to the high capital investment, centre pivots, linear moves, travelling big guns and side roll systems are used on high-value crops such as potatoes and vegetables. A higher level of expert knowledge is necessary to carry out irrigation with these systems, even though the labor requirement is relatively low due to the automation. Motors, water supply pipes/hoses and all mechanical components have to be maintained systematically to avoid damage and high repair costs. Sprinklers provide efficient coverage for small to large areas. Sprinkler irrigation is suited for most row, field and tree crops and water can be sprayed over or under the crop canopy.

One of the most relevant advantage of sprinkler irrigation systems include the possibility of irrigating for other purposes such as frost protection or cooling during hot periods (Deligios et al., 2019).

Micro-irrigation systems include high-tech methods with large capital and maintenance investment: surface and subsurface drip irrigation for row crops, field crops, and orchards, micro-sprinklers and micro-sprayers for horticulture and under-tree irrigation, and bubblers for orchards (Keller and Bliesner, 1990; Lamm et al., 2006; Venot et al., 2019). These low-pressure irrigation systems consist in wetting a limited portion of the ground targeting the crop root zone, which may improve the timeliness of irrigation scheduling and reduce non-beneficial water consumption by reducing soil evaporation. Achieving good performances implies adequate design, which complexity may be overcome using decision support models (Pedras and Pereira, 2009). The benefits of drip irrigation compared to the more traditional methods (e.g. surface and sprinkler irrigation) include reduced water use, controlled operational water losses, less labour and, comparatively to sprinklers, reduced energy consumption and pumping costs per unit area, as well as improved management of water, fertilization and pesticides for a range of high-profit crops (Perry et al., 2017). Microsprinklers and micro-sprayers have similar benefits, but the wetting pattern is wider and may be affected by wind. However, wind drift and soil

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evaporation in the case of under-tree irrigation are much less than for field crops. Despite advantages, managing drip or micro-spray irrigation systems is very demanding, including when automation is adopted. This type of high-tech irrigation methods may not be economically feasible under all conditions since, for field crops, economic returns tend to decrease when stricter water-saving techniques are applied (Darouich et al., 2014; Jacques et al., 2018; Rodrigues et al., 2013). Darouich et al. (2014) assessed the use of drip and improved surface irrigation systems for cotton irrigation in Syria and reported that drip irrigation should be selected when water resources are limited, whilst they recommended surface irrigation to secure the highest economic returns. Benefits are generally greater for irrigating tree and vine crops having a better developed root system compared to annual crops, in particular when proper irrigation management is adopted. Water can be easily applied near the root zone of these crops and it makes it easier to apply deficit irrigation, in particular partial root-zone drying. Soil evaporation is therefore controlled because the soil is only partially wetted near the crops, often under shadow or, when subsurface drip is applied, wetting occurs only by capillarity from the buried emitters. Advantages of drip irrigation for saline environments were recently reviewed by (Minhas et al., 2020) such as the reduced accumulation of salts in the root zone and suitability for salt sensitive crops, as well as reduced toxicity and leaf damage due to avoidance of direct contact of water with leaves.

Emitters or drippers are devices used to control the discharge of water from the lateral to the plants. They are usually spaced more than 1 meter apart with one or more emitters used for a single plant such as a tree. The basis of design is to produce an emitter which will provide a specified constant discharge that does not vary much with pressure changes, and does not block easily.

Commercial emitters are either in-line (spliced into the lateral supply tubes), or on-line (plugged on to the tubes through a hole punched into the tubing wall). Commercial emitters are usually precalibrated to discharge at a constant rate of 2, 4, 8 or 16 litres per hour. Regarding the type of the emitters in drip irrigation systems, two different groups of emitters can be distinguished. Noncompensating emitters vary their discharge according to the operating pressure. The inconvenience of noncompensating emitters is that they may produce low irrigation uniformity when pressure variability in the irrigation sector is high. To avoid this drawback, compensating emitters are used that keep the discharge constant regardless of their working pressure. In these cases, the total flow in the irrigation sector is constant as well and can be calculated by multiplying the emitter discharge by the number of emitters per sector. In the case of compensating emitters, the system curve is Q = constant, and the discharge does not vary even though the pump speed is changed. To overcome these limitations, different procedures to regulate flow as a function of the incoming power have been suggested. The first procedure is based on using variable speed pumps and noncompensating emitters that vary their discharge depending on the pressure. The second procedure is based on subdividing the farm into smaller-sized irrigation sectors and irrigating a variable number of sectors depending on the power supplied by the photovoltaic system. On the basis of these two configurations, the discharge of the irrigation system can be varied to adjust the power consumed by the irrigation system to the power produced by the photovoltaic array. Both procedures can also be applied at the same time (Reca-Cardeña and López-Luque, 2018).

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Annex II

Important standards that affect specific devices of a PV installation:

IEC 61215	Crystalline Silicon Terrestrial Photovoltaic Modules: Design Qualification and Type approval
IEC 61730	Photovoltaic Module Safety Qualification
IEC 60364-7-712	Electrical Installations of Buildings – Part 7-712: Requirements for Special Installations or Locations Solar Photovoltaic (PV) Power Supply Systems

More general devices (electric lines, cables, energy meters, buildings and protection systems) should fulfil the national regulations in force. Particularly relevant are:

IEC 601000-3-2,-3	Electromagnetic compatibility (EMC) – Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16 A per phase).
IEC 61727	Photovoltaic (PV) systems - Characteristics of the utility interface
IEC 62305-1	Protection against lightning. Part 1: General principles
IEC 62305-4	Protection against lightning. Part 4: Electrical and electronic systems within structures.
IEC 60309-1	Plugs, socket-outlets and couplers for industrial purposes – Part 1: General requirements.
EN 1991	Eurocode 1: Actions on structures.

Other standards that must be taken into account, especially in the quality control procedures, are:

IEC 62446-1	Photovoltaic (PV) systems – Requirements for testing, documentation and maintenance – Part 1: Grid connected systems – Documentation, commissioning tests and inspection.
IEC 61829	Photovoltaic (PV) array: On-site measurement of I-V characteristics.
IEC 60891	Photovoltaic devices – Procedures for temperatures and irradiance corrections to measured I-V characteristics
IEC 61853-1	Photovoltaic (PV) module performance testing and energy rating: Part1: Irradiance and temperature performance measurement and power rating.
IEC 60904-1	Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics
IEC 60904-2	Photovoltaic devices - Part 2: Requirements for photovoltaic reference devices

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IEC 60904-4	Photovoltaic devices - Part 4: Reference solar devices - Procedures for establishing calibration traceability
IEC 60904-5	Photovoltaic devices - Part 5: Determination of the equivalent cell temperature (ECT) of photovoltaic (PV) devices by the open-circuit voltage method
IEC 60904-14	Photovoltaic devices – Part 14. Outdoor infrared thermography of photovoltaic modules and plants (proposed IEC 60904-14 or alternatively IEC 60904-12-2).

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Annex III

Crop water requirements

The monthly crop water requirements are a fundamental input in the design of the photovoltaic part of a PVIS

The month during which the crop water requirement is the highest depends on the selected crop and plantation location. As consequence, it is required to combine both crop growing patterns (Kc) with the local weather (ETo) along all the life cycle. Then, the maximum number can be easily identified. The ETo values keep constant within a selected plot or site, but the Kc values vary according to the selected crop, and its variety/cultivar and phenological stage. The most important thing here is to determine the crop cycle according to the selected plant variety. From the sowing/transplanting time to final harvest, this period and duration will depend on the crop itself and the local conditions: is not the same to calculate it for short cycle maize than a long cycle one, as well as those growing stages, will differ, depending on the local climate conditions where those crops will be planted. Also, for some field crops bearing several harvesting cycles per season, as alfalfa does, the gross irrigation water needs to be calculated according to that growing period of higher water stress for the plants.

Considering globe artichoke as an example of high-per-hectare-value vegetable, being Italy, Egypt, Spain, and Tunisia the world leader in fresh heads production (more than half of the total cropped area concentrated in just three Mediterranean countries). Artichoke is a high water requirement plant, in part due to its large foliage biomass and long production cycle (up to 7 months). Drought stress during transplanting and vegetative growth can negatively affect stand establishment, delay growth and consequently reduce marketable yield. Current Kc values published for globe artichoke are given on monthly basis: December - July Kc=0.3; August Kc=0.36; September Kc=0.89; October Kc=0.77; November Kc=0.62 (Soddu et al., 2004; ISHS Acta Hort. 660). The maximum Kc=0.89 occurs when the canopy cover for the annual system reaches over 90% between August and September, thus September is considered the month during which the highest water need is expected (about 900 m^3 ha^{-1} in a typical Mediterranean site, see the figure below to compare).

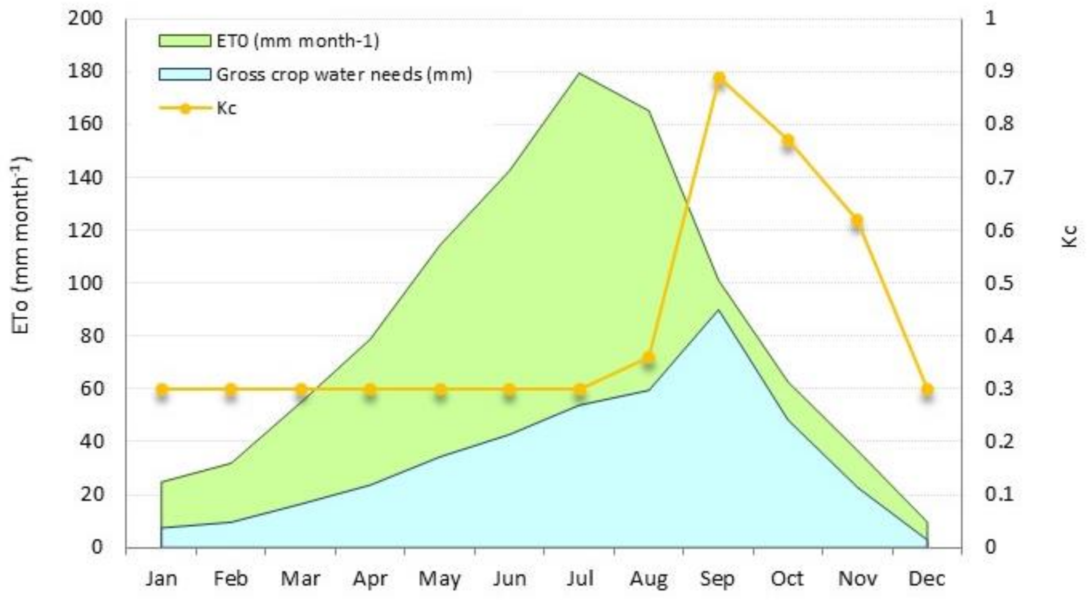

Figure 60 - Seasonal globe artichoke water requirements (mm).

When tree orchards are considered (e.g. olive tree or citrus), the gross crop water needs differ from the early growing stages, reaching the maximum demand of nutrients and water at the mature stage, when all the vegetative organs have finally developed. For example, citrus orchard (see figure below), has total gross water need varying depending on the locations between 5000 and 8000 m^3 ha^{-1}, the citrus productive cycle lasts the whole year, and (depending on the pedoclimatic conditions of the site) during summer and spring the full water requirement is supplied by irrigation being July the month with the highest needs (between 1170 and 1850 m^3 ha^{-1}).

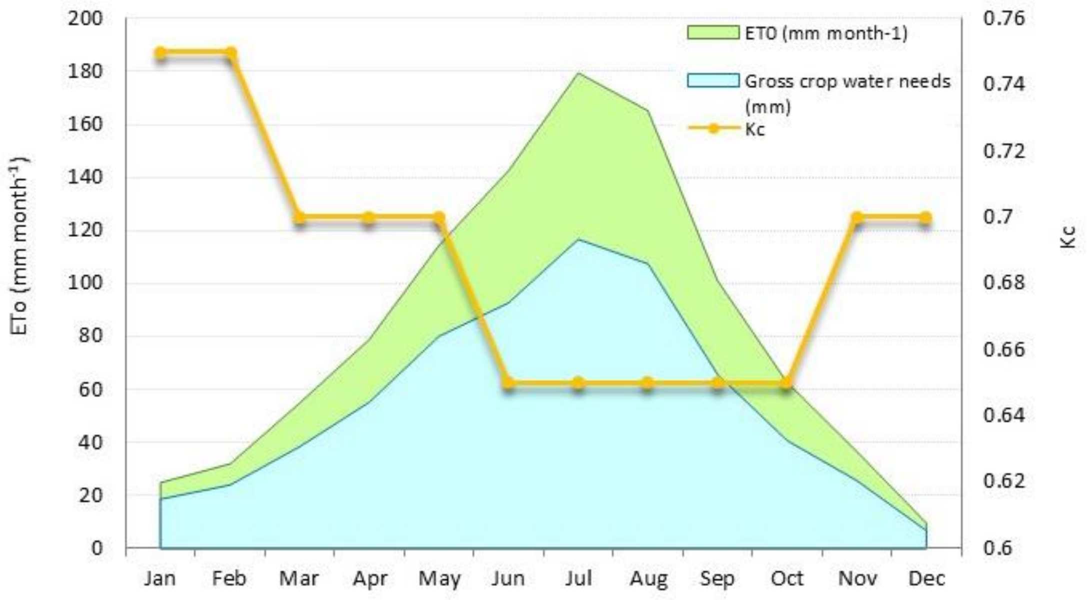

Figure 61 - Seasonal citrus orchard water requirements (mm).

In general, from the above figures and table below, it can be concluded that irrigation needs are very low from November to April, due to higher rainfall intensity in these months, and from May to October, a considerable amount of water is required for irrigation. Indeed, especially in

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Southern Europe Mediterranean area, the lowest values of effective rainfall are in July and August.

Table 7- The month of the maximum irrigation water need for some typical Mediterranean crops for an average year (total annual rainfall, 489 mm) (Alobid and Szűcs, 2019)

Species	Total irrigation water requirements (including rainfall) (m^3 ha^{-1})	Month of maximum water requirements (including rainfall)/minimum water need (m^3 ha^{-1})
Globe artichoke	4300	August/1160
Tomato	5800	July/2000
Winter wheat	3100	March/400
Sunflower	5600	June/1700
Sugar beet	8100	July-August/2000
Potato	3400	July/1300
Citrus	4800	July/1170
Olive tree	4800	June/1300

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Connection boxes

Connection boxes should have and respect the proper Ingress Protection rating (IP) selected according to the environment.

Figure 62 and Figure 63 show examples of connection boxes that have original Ingress Protection rating (IP degree) above IP43 (IPXY: the "X" figure is related to the protection against the infiltration of solid foreign objects; "Y" figure is related to the protection against the entry of water). Although the original boxes meet these specifications, incorrect installation can drastically reduce the degree of protection.

As shown in Figure 62, the connection box has been drilled to provide an entry point for the cable. However, the excess space has not been properly sealed to prevent dirt or water entering the box. This leads to loss of the original IP degree.

Figure 63 shows that the box cover has been deformed and the box cannot be closed. Therefore, its IP degree is lost because of this fault and solid objects or water can enter the box.

Figure 62

Figure 63

NO NO

Figure 64 shows that the tube which carries the cable is not fixed to the sealing gland and water or other material could enter the tube and prematurely damage the cable and the connections into the box. Figure 65 shows the correct way to fit tubes and sealing glands.

Figure 66 shows a box with a label fixed to the outside which states that the IP degree protection is IP65. That is, total protection against dust and protection against water projected with a nozzle from any direction. However, sealing glands have not installed, allowing dust or water coming from underneath to enter the box (see Figure 67 and Figure 68).

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Figure 64

Figure 65

Figure 66

Figure 67

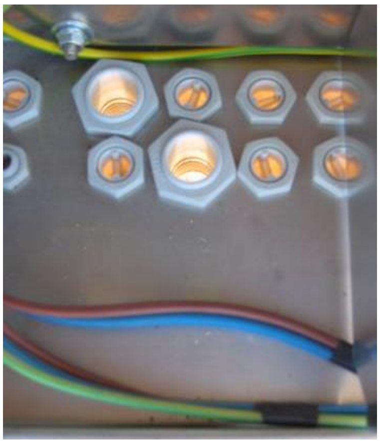

Figure 68

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Cable entering connection boxes must be correctly installed and sealed.

Cables entering a connection or junction box must pass through a sealing gland of the correct cross-sectional area which prevents the ingress of moisture or water into the box. When sealing glands are installed in such a way that cables enter the box through the top of the box, the box is not protected against water or moisture ingress. Therefore, the rubber seal must be in perfect condition and the nut seals have to be adequately tightened. Otherwise, water or moisture could enter the box, as in Figure 69. In this figure, the rusted metallic tracks and the white cover are evidence that water has entered the box.

It is recommended to install the sealing gland in the bottom side of the box to reduce the risk of water entry (Figure 70).

Top of the module

Figure 69

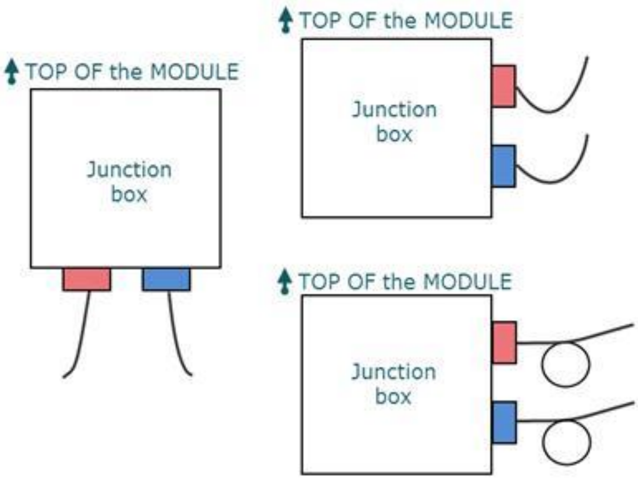

Figure 70

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All connectors must be correctly crimped and fastened to avoid overheating.

Conductors not correctly fixed to the connector by the fixing screw and conductors poorly crimped at the terminals can cause switches or cables to overheat or burn. The thermographic pictures show two different situations. Figure 71 shows the consequences of a cable not properly fixed with the fixing screw and with a poor electrical contact that could cause an internal electric arc. The cable temperature is higher than would be expected (in this particular case, more than 30°C higher than neighboring cables). This increases wiring losses and the risk of fire. When proper contact is made, all conductors (with the same cross-sectional area and current) have the same temperature, as in Figure 72. A good practice to ensure that the bolts/screws are properly fastened is to seal them as shown in Figure 73 (yellow seal). This seal allows to identify loose fastenings just with a visual inspection. This verification must be carried out every year during regular maintenance as temperature variations can cause loosening of bolts or screws.

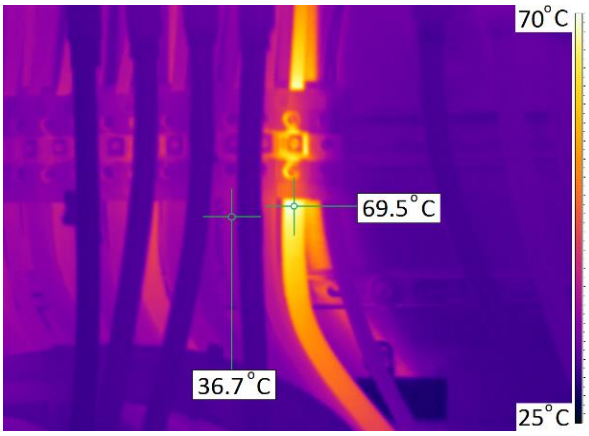

Figure 71

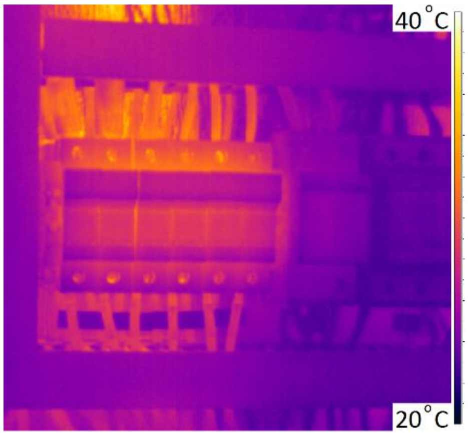

Figure 72

Figure 73

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Fuses must be properly oversized to avoid overheating and premature degradation.

Fuses for PV applications must be selected to support the maximum DC voltage and current of the corresponding PV array at any temperature condition. A bad selection can lead to premature degradation and even to short-circuit events with the risk of burning as shown in Figure 74. A recommended practice is using fuses rated close to twice the current they must conduct under STC to avoid undesired effects.

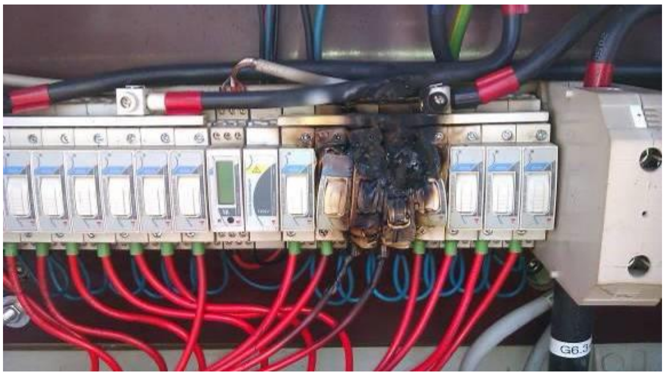

Figure 74

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DC components like fuse holders must NOT be manipulated when DC circuits are switched ON.

A very poor practice involves opening a fuse holder under load as this creates a serious risk of electrical shock and destruction of equipment. DC circuits must de-energised before any intervention is made. Figure 75 shows the consequence of opening a fuse carrying a DC current of approximately 40 amps. An electric arc developed between the fuse sides and caused a fire inside the box, leading to the destruction of the connection box. Fuses are a form of protection which cannot be opened under load and therefore special load breaking switches that are designed to open the circuit under load are used.

Figure 75

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Cables in connection boxes should be correctly arranged and not too long.

The cables should be arranged neatly in the connection box and the length of cables should be slightly longer than the required length to facilitate repairs which might be required. Operators should be able to quickly identify each cable in the event of a fault. Figure 76 shows a connection box in which insufficient care has been taken in its wiring and where the cables are disordered and are of excessive length. Therefore, it is difficult to find a specific cable. This arrangement also increases the wiring losses and the final cost of the installation.

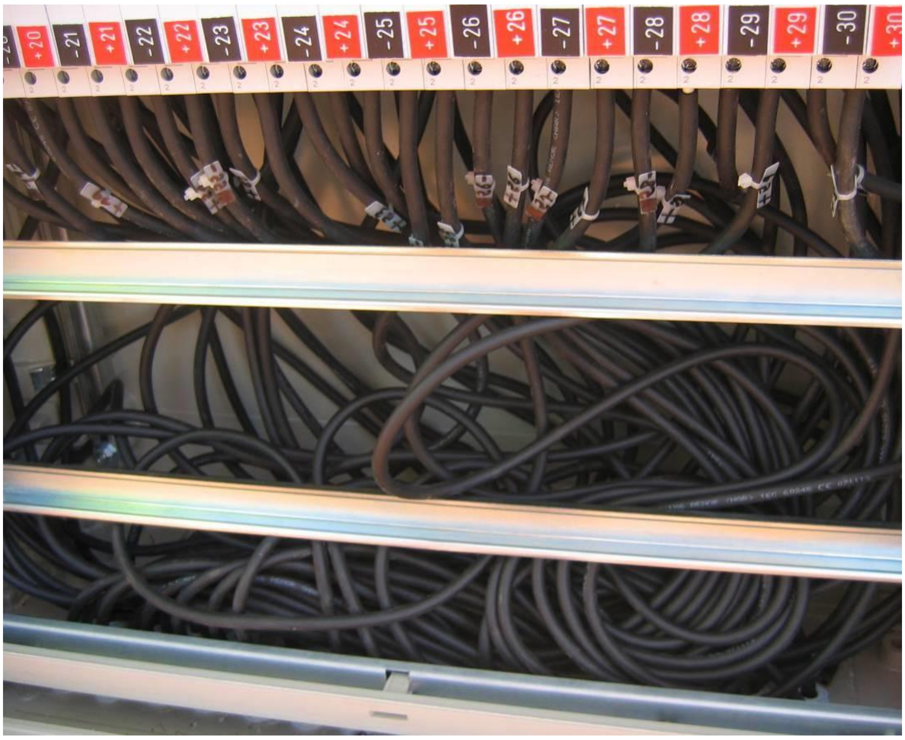

Figure 76

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Doors and covers must resist chemicals (grease and other) and must be blocked when open to avoid damage due to wind gusts.

The doors and covers of the connection boxes have to serve to prevent the ingress of water or soil (as described by the IP rating) and protect cables and electronic devices. They must resist or be protected from degradation due to water or grease. Figure 77 shows boxes which have been damaged because of reaction between grease and the box material. The doors or covers must be blocked when open to avoid damage due to wind gusts (Figure 78). Otherwise, the boxes can degrade prematurely, deteriorate and leave their content unprotected (Figure 79).

Figure 77

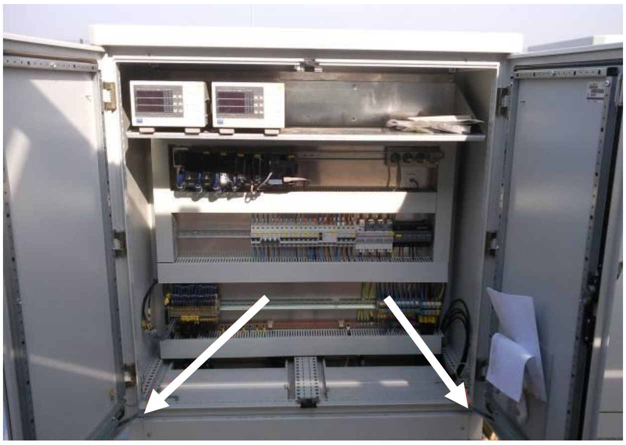

Figure 78

Figure 79

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Connection boxes must contain all required components.

Figure 80 and Figure 81 show the primary and secondary connection boxes respectively of a PV installation. They are properly labeled to warn of the risk of electrical shock. The cables are arranged properly inside the boxes and each single cable is also identified with an individual label. If all electrical components are properly identified with labels, the possibility of incorrect connections is considerably reduced. Fuse holders are installed in both active poles for each cable as well as surge arrestors which are required to protect electronic devices. Positive and negative bus-bars are identified with labels and are adequately separated with a methacrylate sheet to avoid direct contact. There are also labels warning of the risk of electric shock.

Nevertheless, three improvements can be made. Firstly, there is no information sheet to provide detail of the location of modules and strings that are connected in this box. Second, in the primary box, the positive and negative cables from modules are too close with inadequate separation to avoid short-circuit and there is a risk of direct contact in the event of a fuse holder failure or cable movement. Third, in the secondary box there is no load-breaking switch which is required for disconnection under load. Despite these possible improvements, these boxes are very close to the optimal arrangement.

Figure 80

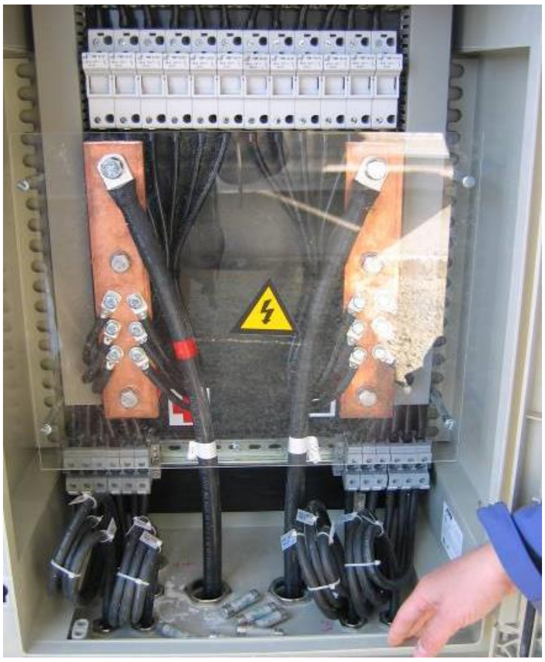

Figure 81

The box shown in Figure 82 incorporates the improvements described above. There is a map in the inside cover that presents clearly the locations of the PV modules connected to the box. Positive and negative cables are easily identified by colour and are adequately separated to

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avoid short-circuits or faults and to allow for safe adjustment. Finally, there is a load-breaking switch (the grey/white device on the right of the box) which allows the circuit to be opened under load. The only improvement, which could be made to this box, is to include fuse holders in the negative cables also, to allow for the isolation of each individual string at both poles.

Figure 82

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Civil works – supporting structure

Clamps must be used according to their specifications and must size and shape of the modules.

In Figure 83 to Figure 86, the PV modules are fixed to the supporting structure by clamps designed to support PV modules. These clamps avoid shading as well as electrical corrosion, but they must fit perfectly to the PV module frame (i.e. the dimensions of the clamps must match the PV module) and they have to be properly tensioned to achieve good attachment, as shown in Figure 83 and Figure 84. Otherwise, modules can become detached as a result of high wind loading, as has happened in the installations shown in Figure 85 and Figure 86.

Figure 83

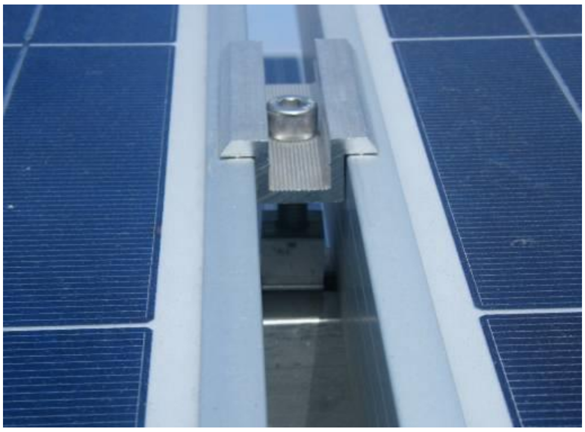

Figure 84

Figure 85

Figure 86

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In contrast to the previous pictures, Figure 87 and Figure 88 show how the modules are ineffectively fixed to the supporting structure. The clamps used are not aligned and do not match the shape of the PV modules (Figure 87) or they are not correctly installed in the gaps between the PV modules because the washers do not fix the module properly (Figure 88). This could easily detach as a result of wind loads or thermal expansion.

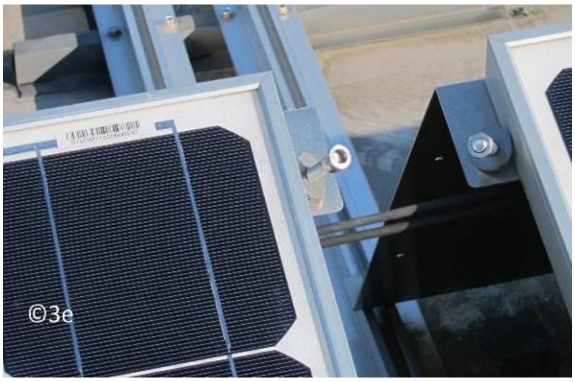

Figure 87

Figure 88

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Anti-theft screws and nuts are recommended when mounting PV modules.

This is one of the security measures more frequently used in PV plants since their emplacement in the isolated countryside, far from urban centers, turns these facilities sensible to theft and vandalism. The use of anti-theft fixing elements is a cheap and effective deterrent measure whose only defect is that it is an obstacle when the modules have to be disassembled, if they need some kind of maintenance intervention. Figure 89 shows a kind of anti-theft nut installed between the PV module frame and the supporting structure.

Figure 89

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Mounting systems must allow for thermal expansion of all the system components.

The mounting systems must allow for thermal expansion of all the system components (both longitudinal and transversal expansion). PV modules or fasteners such as bolts and nuts, for example, may fail if the mounting system does not allow for this expansion.

In the case of longitudinal thermal expansion, it is typical to use expansion joints with a maximum distance of 6 to 10 meters between two consecutives joints (Figure 90). They should be placed so that the structure could expand without creating additional mechanical stress (for example, joints should not be placed inside a rigid triangle, as in Figure 91).

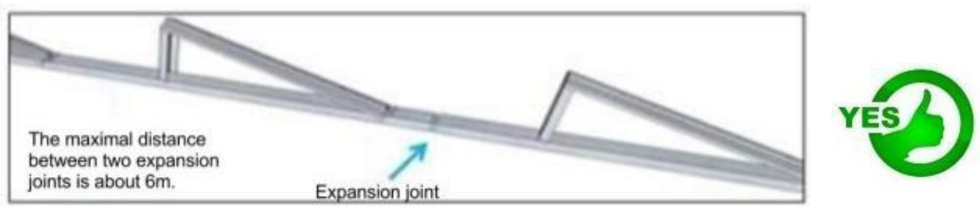

Figure 90

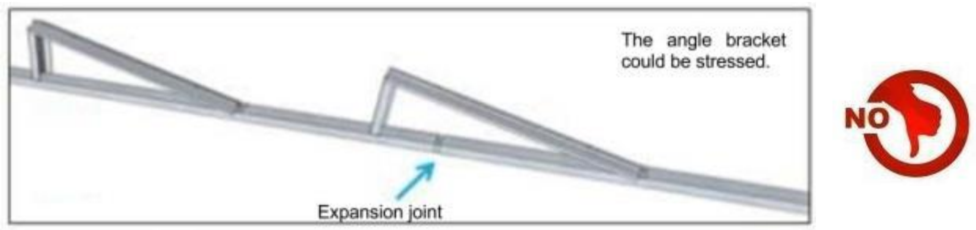

Figure 91

In the case of transversal expansion, a typical solution involves inserting gaps every 10 to 15 meters, as shown in Figure 92.

Figure 92

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Enclosure of the PV generator

PV plant must be enclosed with a fence or a wall.

This element of the installation has two objectives: to protect the installation against larceny and, more importantly, as a barrier to protect against electric shock by ensuring adequate distance between personnel outside the installation and the live electrical equipment inside. Poor installation of the fence or any breach in the fence will render it useless.

Figure 93 shows a good fence installation which allows some small wild animals to enter the PV plant but not people. On the other hand, the remaining pictures show different faults in the fence. In Figure 94 and Figure 95, the fences have a gap large enough to allow a person to enter the enclosed area. Figure 96 shows a hole in a fence that means that it does not achieve its function.

Figure 93

YES

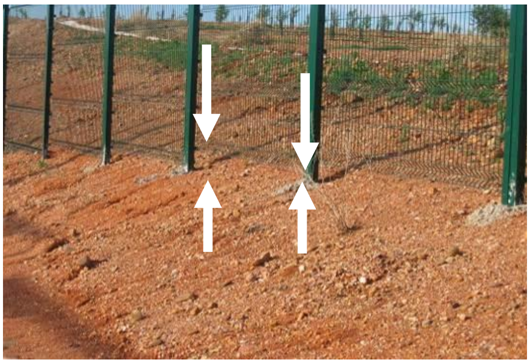

Figure 94

NO

Figure 95

NO

Figure 96

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The enclosure must be provided with a metallic gate large enough to allow the entry of maintenance vehicles.

The PV enclosed area needs to be planned for maintenance operations in which vehicles have to drive around. Some of these O&M activities are cleaning of PV modules and tracker repairs.

Figure 97 shows a fence provided with a vehicles entrance while in Figure 98 a pedestrian access can be appreciated.

Figure 97

Figure 98

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The space between the fence and the PV generator must be large enough to allow the passage of maintenance vehicles.

PV generators mounted on solar trackers allow a separation between trackers large enough for vehicles circulation. However, the distance between the perimeter trackers and the fence must also be large enough for maintenance vehicles and free of obstacles.

Figure 99 shows a good gap between the PV generator and the fence. Figure 100 illustrates an anemometer installed in the corridor between the PV generator and the fence, which makes it difficult for vehicles to pass through. Figure 101 shows on the left side of the PV generator that the distance between the fence and solar panels is too narrow to allow vehicles to pass through.

Figure 99

Figure 100

Figure 101

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Drainage and water protection

Based on the climatic data and specially the rainfall data, and the Site's configuration and topography, the Contractor will be responsible for designing and building a drainage system to protect the installation infrastructures against erosion and flash floods. This drainage system must be properly maintained.

Water can cause erosion and landslides which can leave concrete footings without earth support, as is shown in Figure 102 and Figure 103, or cause fractures, as shown in Figure 104. The fracture of concrete footings can also cause separation of structures, as shown in Figure 105, and the possibility of PV module breakage.

Figure 102

Figure 103

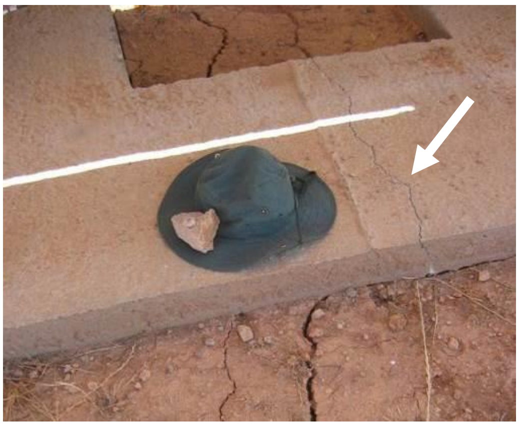

Figure 104

Figure 105

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The absence of a proper drainage system can transform foundations, paths and buildings into dams and lead to flooding as shown in Figure 106 and Figure 107.

Figure 106

Figure 107

NO

Drainage system channels must be clean to allow water to flow easily (Figure 108). Otherwise, the accumulation of vegetation, stones, sand, etc. could block drainage channels and cause flooding (Figure 109).

Figure 108

YES

Figure 109

NO

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Service buildings must be waterproof, including cable entry points.

Service buildings housing frequency converters, filters, control and monitoring systems, transformers, and other equipment must be waterproof to avoid electrical faults and damage to the devices. The buildings have to be watertight to maintain integrity so that all possibilities for water ingress are sealed. Figure 110, Figure 111, and Figure 112 show how water has entered the building through the roof because of a leak and through the floor or foundation. Figure 113 shows evidence of flooding as the cables are dirty with mud once the water has evaporated.

Figure 110

Figure 111

Figure 112

Figure 113

Cable entry points in buildings must be waterproof; otherwise, water can enter the building. Pipe or tubing entry points have to be sealed, unlike the arrangement in Figure 114. Apart from the sealing of pipes or tubes, other techniques can be used. Advantage can be taken of the "drop

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of water" principle for entry points on a vertical wall, with cables curving below the entrance (Figure 115) or curved sleeves for entry points on a horizontal roof.

Figure 114

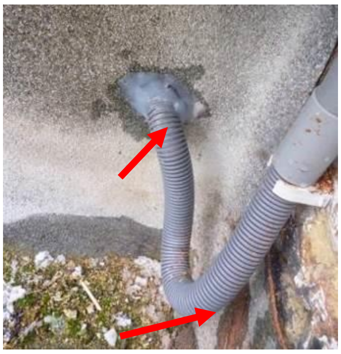

Figure 115

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Wiring

Cables trays must be protected during the construction phase.

The next pictures show the case of a PV generator in which the cables are located in trays on the ground. Unfortunately, those trays are close to drainage channels and during the construction of the channels, concrete has been allowed to flow into the cable trays (Figure 116 and Figure 117). The concrete has also reached the wires situated in these trays. This could degrade the properties of the cable insulation and sheaths or other cable covering as a result of chemical reactions with the cement, decreasing its insulation properties or even its external resistance to environmental conditions (low or high temperatures, rain, frost, etc.) even though these cables were designed for external use.

Figure 116

Figure 117

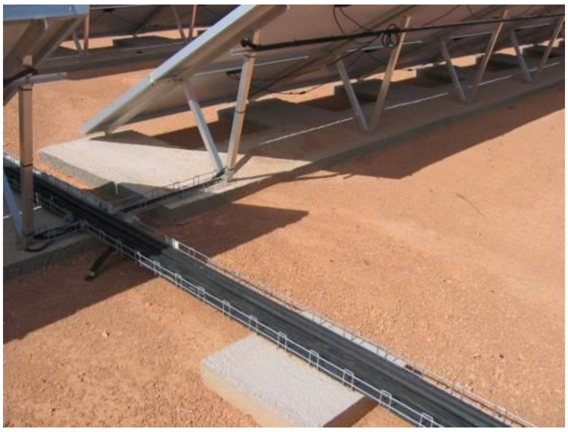

Figure 118

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Cables must be placed in cable trays.

Figure 119 shows current-carrying cables running from the connection boxes to the inverter in a particular installation. The way the cables have been installed is a hazard as personnel could trip on them. In order to be able to locate and trace specific conductors and to avoid a trip hazard, cable trays should be used as shown in Figure 118.

Figure 119

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Buried cables should be protected by rigid tubing or ducts.

Buried cables benefit from additional protection against mechanical damage if they are properly installed. However, cables should not be placed directly in trenches as they can be damaged by backfill. Also, some cable sheaths are made of organic materials (for example, vegetable oil) and could be eaten or damaged by rodents or moles. Additionally, ducts and tubes allow easy replacement of cables if needed.

In the case shown in Figure 120, cables between connection boxes and inverters are directly buried in the trench. A better solution would have been to place the cables in tubes or pipes to protect them from moisture and from land animals, which can damage or prematurely degrade the cables and cause excessive leakage currents or failure.

It is also advisable to use different pipes to protect power and signal cables. This way, any interference from the power to the signal cables will be avoided.

Figure 120

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Buried cables should be buried below freezing depth.

Trenches to accommodate buried cables should be deep enough, as the cables must be below the freezing depth. High temperature differences cause variation in cable length and this can lead to damage of cables if stretching is excessive. It is necessary to refer to local regulations and construction norms for more information on the minimum depth of cables.

Figure 121 and Figure 122 show two trenches in the same installation. In the region in which the installation is located the freezing depth is 60 centimetres (as the freezing depth is location-specific). Cables in Figure 121 are not protected against freezing because the trench is not deep enough. On the other hand, the correct trench depth in Figure 122 allows cables to be protected against freezing effects.

Figure 121

Figure 122

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Electrical conduits must be sealed in both conduit ends to avoid access to small rodents and others.

Buried electrical cables installed into rigid or elastic conduits must be protected from rodents and other small animals that can enter the conduit through the ends of the pipelines and damage the wires. To avoid this trouble, cables must be protected by sealing both conduit ends by means of polyurethane foam or similar, as shown in Figure 123 and Figure 124.

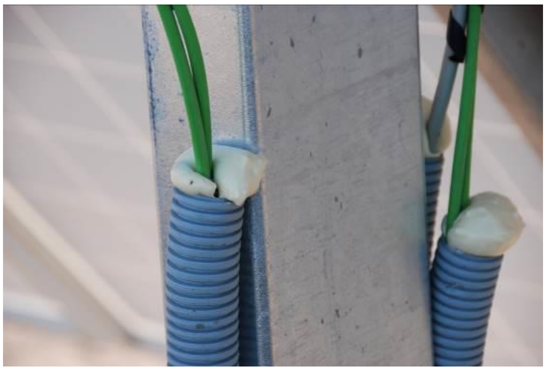

Figure 123

Figure 124

YES

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Buried electrical conduits in trenches must be marked with appropriate warning type for underground cables and pipelines

Warning devices with visual characteristics have to be placed to indicate the presence of cables and piping systems buried in ground when opening trenches and more generally during digging work. Figure 125 shows the placement of a plastic protective mesh.

Figure 125

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Manholes and chambers must be properly installed and maintained.

Figure 126 and Figure 127 show damaged manholes or chambers for which the protection that should be provided is lost. This allows water, soil, dust or rodents to enter the manhole and access the pipes connected to the manhole if they are not properly sealed (Figure 126).

Figure 126

Figure 127

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Manholes should be raised above the ground for additional protection.

Sometimes manholes or chambers are broken because heavy machinery is driven across. A good option to avoid this is to raise the manholes or chambers some centimeters from the ground level, as shown in Figure 128 Figure 129. Another option is to avoid installing manholes on paths or any other routes used by heavy machinery.

Figure 128

Figure 129

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