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Technico-economical Optimization of Photovoltaic Pumping Systems

Pedagogic and Simulation Tool Implementation in the PVsyst Software

Final Report

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Summary

The main objective of this project is the elaboration of a general procedure for the simulation of photovoltaic pumping systems, and its implementation in the PVsyst software.

This first implies establishing a general model describing the pump electrical and hydraulic behaviour, valid over any running conditions encountered within a photovoltaic system. In order to be useful in such a general software, this model should be built using data usually available in the manufacturer's data sheets. We have developed a phenomenological model, which may be completely determined from several kinds of manufacturer specifications, including simplified to very detailed running data sets. The model precision will of course be function of the completeness of the input parameters data set.

This model will then be included in a simulation process of the whole PV and pumping system (hourly-step simulation), taking the environmental conditions into account, and involving the major technologies available on the market (direct coupling, booster, DC-input or MPPT converters or inverters, buffer batteries, use of conventional AC pumps, etc). Beyond the usual environmental variables (meteo, user's needs), many other operating characteristics should also be user-defined (variable static level over the year, dynamic drawdown level in a buried well, head corrections for pressure or level in the tank, friction losses, level limits, etc).

The simulation results include a great number of significant data, and quantify the losses at every level of the system, allowing to identify the system design weaknesses. This should lead to a deep comparison between several possible technologic solutions, by comparing the available performances in realistic conditions over a whole year.

This will be completed by a "preliminary design" tool performing a quick pre-sizing of the system.

This tool is mainly dedicated to engineers in charge of solar pumping projects in the southern countries. It contains many didactical elements which facilitate a deep understanding of the behaviour of such systems. The whole design procedure will be extensively explained in the "Help", making a practical and pedagogic tool for pumping systems study, even for not quite expert engineers.

This project extends the application field of PVsyst, a widely used software for the study and simulation of Photovoltaic Systems. PVsyst has been developed since 1993 at the CUEPE - University of Geneva, with financial help from the Swiss Federal Office for Energy. It is now considered as a reference in the field at international level (distributed in 60 countries).

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1. - Introduction

1.1. - Objectives

With the increasing acuity of water supply problems, especially in developing countries, solar pumping systems are taking a great importance, which will still increase in the next years.

However, Solar pumping system sizing and optimization is a rather complex task, involving a lot of variables, which mix together in a way that is not intuitive. Most pump manufacturers do indeed propose their own "standard" system configurations, valid for given typical conditions (usually based on one standard clear day). Their specifications or sizing tools don't allow to estimate the net water yield during a specified meteo time series.

To our knowledge, there is no general tool available on the market, able to size and simulate such systems with sufficient generality and accuracy, in order to compare the performance of different system configurations in a given situation. The only detailed available computer program in the field seems to be the DASTPVPS DOS program (University of München, V 5.3, 1997).

Therefore the engineer doesn't avail of any tool for optimizing a photovoltaic pumping system, exactly suited for a specific situation (meteo, levels, available flows, etc) and well-defined needs. The aim of this study is to offer the required computing basis, either for the sizing or for the detailed performance comparison of different technological options, as well as their economical evaluation. This tool should of courseavail of a real components database, including the newest devices available on the market.

This facility should be integrated in the software PVsyst, a widely used general software for the detailed study and simulation of other PV systems (Grid-connected, stand-alone or hybrid).

1.2. - Main steps of this work

This project includes the following elements:

- Establish a general model describing the **electrical** and **hydraulic behaviour** of a pump, valid for any running conditions encountered in a Photovoltaic system. In order to be useable in a general-purpose software, it should be possible to establish this model from usually available data in the manufacturer's datasheet. We have developed a **phenomenological** model, completely determined from different sets of parameters, ranging from very simple ones to very complete. The final accuracy of the model will be of course function of the completeness of the input parameter set.
- Implement this pump model as **component in the PVsyst software**. We can mention that PVsyst is a simulation software for Photovoltaic systems, widely used over the world (460 licensed companies and universities, more than 1'000 users in 55 countries). It is generally considered as the reference tool in the field.
- Give to the user the opportunity of defining by himself the required parameters for the model (from manufacturer's datasheet), with a check of the coherence, and detailed (graphical) display of the global behaviour of this model as function of diverse parameter. Creation of an exhaustive specification sheet, describing the parameter and behaviour of the pump device.

- Create a database of the main pump devices suited for photovoltaic systems, available on the market. This base may of course be completed by the user, and will be periodically updated as for all PVsyst components.
- In collaboration with the CIEMAT (Centro de Investigationes Energeticas, Madrid), which disposes of a specialised measuring facility, **check of the accuracy of the modelling**, using detailed measurements performed on several pumps of various technologies.
- This model is included in a **general simulation process** of the whole pumping system (hourly steps simulation), taking the environmental conditions into account (meteo, pumping depth, user's needs), and various regulation/coupling technologies (direct coupling, direct with booster, power converters, batteries, pumps connected in cascade, reconfiguration of the PV field according to available solar power).
- The coupling technology between the PV array and the pump(s) is specified in the software through the "Controller" component, which defines the detailed parameters of any possible control device (power limitation, efficiency, etc). The first simulations of a system may be conducted with a dummy, optimised device, without reference to really available devices.
- Several pumping systems are considered: deep well borehole (with dynamical drawdown characteristics according to pumped flowrate), pumping from a lake or river, pressurization system, etc. The user's needs may be specified in detail.

As a contrary to many modelling projects, the implementation of this tool in the PVsyst software guarantees its accessibility for anyone, and allows to take advantage of the general existing environment for the study and simulation of PV systems.

2. - The pump model

In this work, the key point is the pump's modelling.

Some pump modelling attempts are reported in the Solar PV literature. Valuable work has been done about centrifugal pumps (Alonso-Abella 2003, Suehrcke 1997), resulting in semi-phenomenological rules which have been used here. A thesis of Moraes [Moraes-Duzat 2000] describes detailed physical models of most motor and pump's technologies. Other authors present models often valid for reproducing accurately the results of one or two well-measured pumps. In all these projects the modelling tool is not really published, and the model parameters are usually basic physical parameters of the motor or pump components, often obtained by adjustment on the measured data, but never specified in the manufacturer's datasheets.

2.1. - Requirements for a useable model

To be implemented in a general purpose simulation software, the pump model should match the following characteristics:

2.1.1. - Input/Output variables

The model should describe the dynamic evolution of the output variable – usually the **flowrate** – as a function of the pertinent input variables, which are basically the **head** and **voltage** input, for any conditions within the admitted operating values. Indeed, when a given voltage is applied to the pump, this will run at an operating point characterised by a flowrate yield, as well as by a **current** drawn from the source. Therefore current is also a function of the Voltage and Head inputs.

The general model will give all the relationships between these 4 variables. Therefore it will include the determination of the Current/Voltage characteristic of the pump, which is necessary to the calculation of the operating point when coupling the pump directly to the PV array.

Unlike classical grid-connected pumping systems, which work at fixed voltage and power determined by the pump's (hydraulic) needs, the solar pump system should operate at variable voltage according to the available solar power at a given time.

Now in many cases the motor is specified for use at a nominal voltage, and detailed I/V (current/voltage) behaviour is not available. The Flowrate is then given as a function of Head and input electrical **Power**. These only 3 variables are in principle sufficient for characterizing the operating point, when the power input is fed through some power-conditioning unit, which will provide an adequate voltage.

Besides these 4 operating variables, some pump types also require special starting conditions (starting peak current due to friction forces).

2.1.2. - Applicability to any technology

The model should cover any motor-pump's technology, available on the market for use in PV systems: centrifugal pumps, positive displacement pumps (including piston, membrane or diaphragm, progressive cavity, rotating displacer, etc.). These pumps can be driven by various AC or DC motor technologies.

The model will also apply to other standard pumps (not specifically designed for solar applications), with AC induction motors, driven by frequency converters.

This justifies the choice of a **phenomenological model**, acting on the input/output variables without taking the technological details of the components (motor, pump) into consideration.

2.1.3. - Parameter Availability

Ideally, the parameters necessary for achieving the modelling should be available from the manufacturer data sheets, in order that any user of the program can input its own pump model characteristics. The model will be adjusted using the performances announced by the manufacturer over a set of operating conditions. General considerations, either established using the detailed measurements or found in the literature, should help to extend the modelling to marginal operating conditions.

In practice, each manufacturer specifies his pumps using a particular data set, more or less complete. The program should be able to make use of any of them. Of course the more complete ones will yield the better modelling results when extended to marginal operating ranges.

Details about the motor or pump technology and related fundamental parameter are usually not available. Therefore, the model should apply to the motor-pump group as a whole, without reference to intermediate values like torque or speed, which are highly technology-dependent and rely to unavailable specific technical parameters.

2.2. - Description of the model

2.2.1. - Model Structure

Let us define the following variables:

- Up, Ip = Voltage and current applied the pump.
- Pp = Up * Ip = Input power of the pump
- Uc, Ic, Pc = Voltage, Current and Power applied to the input of the power converter, if any.
- FR = Flowrate produced by the pump
- HT = Total Head, sum of the Static Head (related to the difference between input and output water levels), and Dynamic Head, due to friction losses in the pipes and system. Dynamic head is dependent on the flowrate, and will be computed by the system simulation process.

The pump characteristics may be considered as a set of operating points represented as a surface in the 4-variable space, i.e. corresponding to the equation:

$$\Phi \text{ (Up, Ip, HT, FR)} = 0.$$

This function will be defined over an operating domain, which is bounded by some limits (usually specified by the manufacturer):

- Maximum voltage applied to the motor-pump,
- Maximum electrical power,
- Maximum current
- Maximum Head (implies maximum current),

and toward the low values:

- Power threshold for starting operating (i.e. not null flowrate), which is a function of the Head.

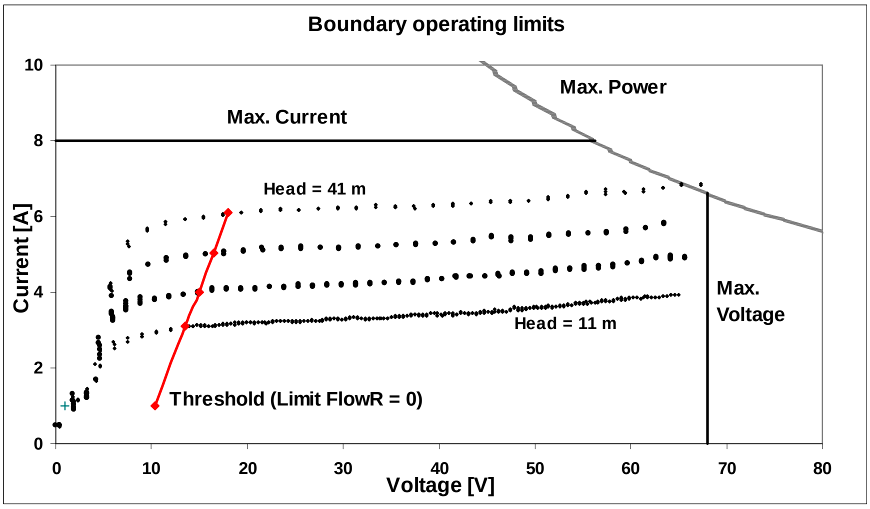

Fig 2.1. - Boundary limits of the operating domain
and I/V measurements for pump Watermax BU (CIEMAT measurements [3])

The equation Φ=0 implies that only 3 of the 4 variables are independent. Therefore, using also the relation Up*Ip=Pp, the model will provide relations allowing to calculate any one of the above variables, as functions of two others. The basic functions are:

- Ip = f (Up, HT), the fundamental relationship which will be used for determining the operating point when directly coupled to a PV array.
- FR = f (Pp, HT), completing the preceding relation for determining the corresponding flowrate.
- Pp = f (FR, HT) will be used for example for sizing the PV array power, or for determining the efficiency.

The other relations may be obtained by numerically inverting these 3 fundamental ones.

As a complement, the model should also provide functions for determining the Power, Voltage or Current threshold (i.e. the boundary where the flowrate drops to zero) as function of the Head.

2.2.2. The Phenomenological Model

The problem is now to determine this function Φ. As previously stated, we would like to avoid references to technology-specific parameters, that is to physical models describing the motor or pump. Therefore our model is mainly based on the known performances, i.e. the operating points either specified by the manufacturer, or measured by other sources.

If these points are sufficiently well distributed over the operating domain of fig 2.1, they will completely define the pump behaviour. The informatic model has to interpolate between the given points; in practice, it will perform cubic interpolations between points, and linearly extrapolate the data up to the boundaries. Therefore this model is just a phenomenological one, without any physical contents.

Physical assumptions will be necessary only if the data set is not sufficiently well distributed for allowing extrapolations within the entire operating domain. These very general assumptions will be established according to general behaviours observed when measuring a great number of pump technologies. These are not yet quite fixed in the model, and will probably be refined during our future works. Of course this lack of primary information in the basic data will result in lower accuracies of the model's predictions.

In practice the manufacturers use to specify the performances of their products by giving different kinds of data sets. We identified 4 of them, and each one has to be treated specifically; that is, the algorithms of the basic functions mentioned above will be different for each category.

2.2.3. - Given Ip and FR as f(Head) for fixed Voltage

These are the common data usually specified for **positive displacement** pumps suited for solar use. Complete characterisation of the model requires such data sets for several operating voltages. For one voltage, a set of data will specify some points (HT, Ip, FR) distributed along a vertical line on the fig 2.1.

It is unfortunately a common practice to specify such a data set for only one "nominal" voltage (for example little pumps: battery 12V or 24V). This is of course not suitable for computing direct-coupled configurations. The extension to other voltages requires a strong hypothesis, which is (in this first status of the model) that the Pump Efficiency is constant when varying the voltage. Fig 2.2 shows an example of measured efficiency profile. We can observe that within the reasonable operating range 30-64V, the variations are of the order of 15%

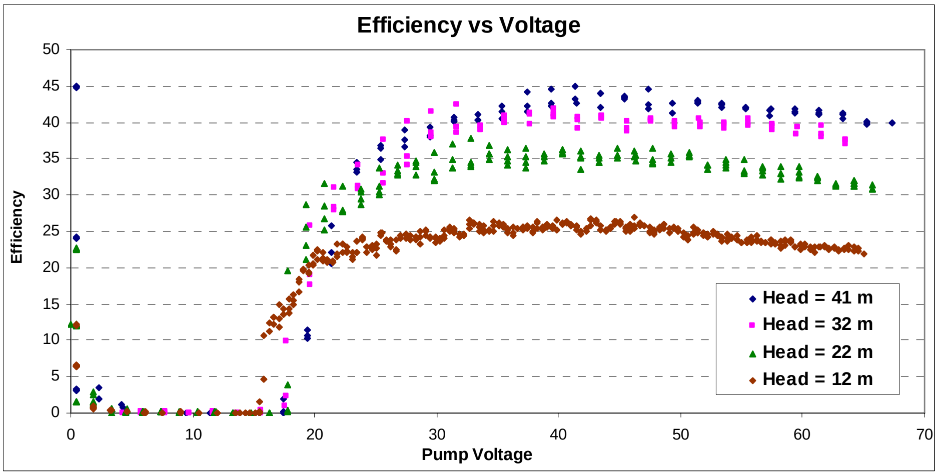

Fig 2.2. - Efficiency vs voltage for Watermax BU (Alonso-Abella [3])

If we avail of 2 voltage curves the efficiency figure is a linear interpolation, which already improves the model's accuracy.

2.2.4. - Given Pp and FR as f(Head) for fixed Voltage

This is equivalent to the preceding scheme, as for each data point the current may be easily determined from power, using the fixed voltage parameter of the curve.

2.2.5. - Given FR as f(Pp) for fixed Heads

Grids of FR (Pp) curves for different Heads is the usual way of specifying the **solar centrifugal** pumps. These allow to get a very good determination of the Hydraulic/Power behaviour, but don't hold any information about the Voltage/Current characteristics. Therefore such data are suited only when the pump is coupled to the PV system through a power converter (see below).

If needed, the basic function Ip (Up, HT) requires additional informations. These could be provided either by a set of Ip/Vp points for at least two head values (on which we can adjust curves), or by several parameters at a time: Nominal voltage and Current at a given reference Head, $\Delta V/\Delta I$ at fixed Head (i.e. dynamic resistance) and $\Delta I/\Delta H$ at fixed voltage.

When specifying parameters instead of curves, we assume linear behaviours, which will of course penalise the accuracy. But in the reality, these parameters are never available in the data sheets and this option is quasi-usefulness.

2.2.6. - Given HT and Pp as f(FR), fixed voltage or speed

Standard **centrifugal** pumps designed for **grid applications** are usually specified by one only Head vs Flowrate curve, for nominal grid conditions (i.e. fixed voltage, 50 Hz). To be fully determined, the model will also need a **power or efficiency curve as function of the Head**. This is not always provided by the manufacturers, as the power consumption is not a key parameter when using grid-powered pumps.

Using this only information at nominal speed, centrifugal pump behaviour at other speeds may be very well described by the so-called "affinity laws" ([Alonso-Abella 2003], [Suehrcke 1997]). These relations state that for two operating points at different speeds, one has:

$$FL_1/FL_0 = \omega_1/\omega_0, \quad P_1/P_0 = (\omega_1/\omega_0)^2, \quad H_1/H_0 = (\omega_1/\omega_0)^3$$

Solving these equations allows to determine any operating point from two given variables. Buts this calculation doesn’t take the motor efficiency change with speed into account, leading to some deviations especially at low speed.

Such pumps are most of the time driven by AC synchronous motors, and may be powered using a cheap standard Frequency Converter (FC) [Alonso-Abella 2003,1998]. In this case the inverter is part of the pump model, and the I/V characteristics of the pump itself is not relevant (included in the inverter characteristics). Our model is based on the input power to the inverter (pump's power modified by inverter efficiency), and the voltage input characteristics is either a MPPT or a DC-fixed voltage behaviour.

With centrifugal pumps specified in this way, when using a DC motor, the Ip/Vp characteristics is strongly dependent on the motor technology, and seldom known. Therefore the implementation of a power converter in the pump model is also required.

2.2.7. - Power Converters

Most of systems are equipped with some electronic device for matching the PV-array power to the pump power requirements. DC-DC converters are used for providing the high current at low voltage required by the pump at low power levels. DC-AC inverters produce the suitable voltage for AC motors; with synchronous motors, they may also modulate the frequency for matching the pump speed to the best operating conditions. These converters may also provide the Maximum Power Point Tracking (MPPT) functionality to get the best from the PV array.

Usually the Power Converter is treated independently in the system simulation process. But when the pump model input specifies power input only, without information about the I/V characteristics, then the Converter Model should be coupled to the pump model. In this case the Pump should be supposed to run at its nominal voltage (or optimal frequency), for which the given Power/Flow characteristics is valid. That is, the converter is supposed to provide the suitable electrical characteristics to the pump at any time. And no information about the real intermediate Voltage or Frequency will be available in the model.

Most of the time the power converter is proposed by the pump manufacturer, and one can admit that his pump characteristics are given in relation with the use of this converter/pump association.

In this case the simulation process has to consider this converter/pump set as a whole. The input electrical characteristics will be that of the Converter (DC fixed or MPPT input), and the output hydraulic variables will be the flowrate and head. This "black box" model should of course take the Converter efficiency (as function of the power) into account.

2.3. - Pump Model Accuracy

The performances of the model were checked using the very good laboratory data of CIEMAT [Alonso, 2004], for several pumps. The measurement sets are recorded under several fixed heads, with or without power converter, by slowly varying the input current. Each measurement point includes input voltage and current (therefore power), flowrate and head. Data with converter include of course both input and output Voltage and Current, and eventually frequency.

2.3.1. Check of the basic model

We first used data of a diaphragm positive displacement pump, driven with a DC motor (Model Watermax BU from All Power), for which we avail of very good data sets at Heads = 12, 22, 32 and 41m (fig 2.3).

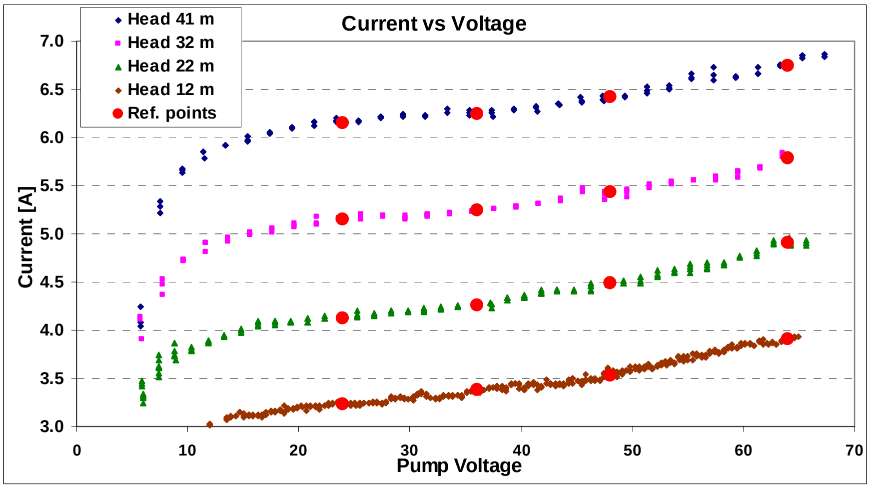

Fig 2.3. - Measured I/V data of the pump Watermax BU (Alonso-Abella 2004)

Just for a good understanding of the pump's behaviour, we may show the same measured data on a FlowRate/Power diagram:

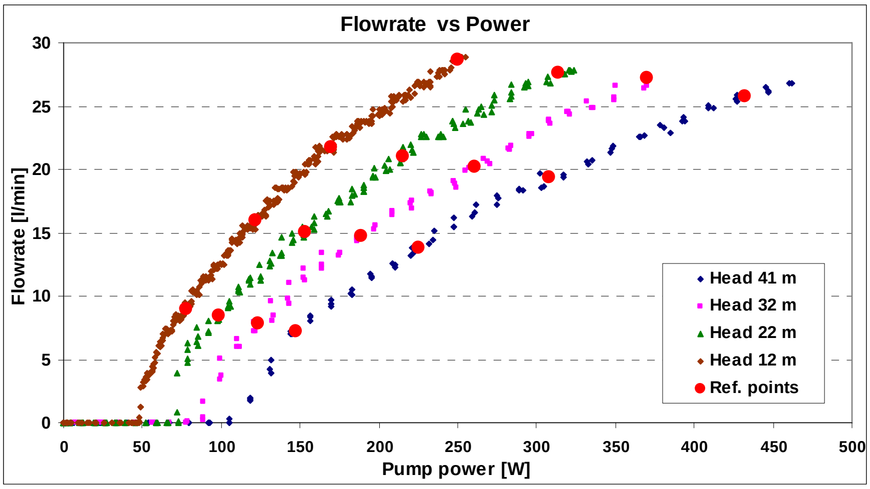

Fig 2.4. - Measured Flow/Power data of the pump Watermax BU
(Alonso-Abella 2004)

As a complete set of parameters for defining the model, we can choose 4 operating points at each Head among these data, for respectively 24V, 36V, 48V and 63V. This sample of 16 points may be the basis for constructing and testing any of the "phenomenological" models described above. As the model represents a surface that passes through these fixed points, the errors at these points are null.

The errors introduced by the model are the uncertainties of the interpolation function between the given points, and the extrapolations until the operating boundaries (which are often worse determined, because of the linear approximation, and the lack of "extremity" fixing point).

As an example, fig 2.5 shows the errors on calculated Current and Flowrate (using the model *Ip and FR vs Heads*, for fixed Voltages) by respect to measured values. The scattering also reflects unavoidable measurements uncertainties. Nevertheless we can observe that most of the points lie within a +/- 5% range in Flowrate, and +/- 3% in Current.

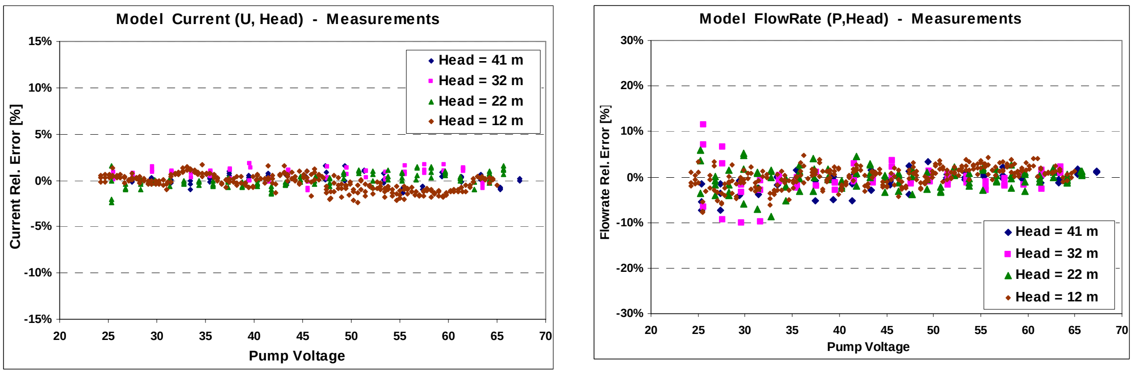

Fig 2.5. - Errors Model – Measurements, for Current and Flowrate.

With this set of data, or some subsets of it, each model described above, and each basic function of each model, may be analysed in this way, and gives similar results.

2.3.2. Check of the model based on 4 points at one only voltage

The next figure shows the result degradation when the model is only based on the **4 points** for 4 heads at one given voltage (i.e. 48V). This corresponds to a data set (i.e. at "nominal" voltage) usually available from most manufacturers.

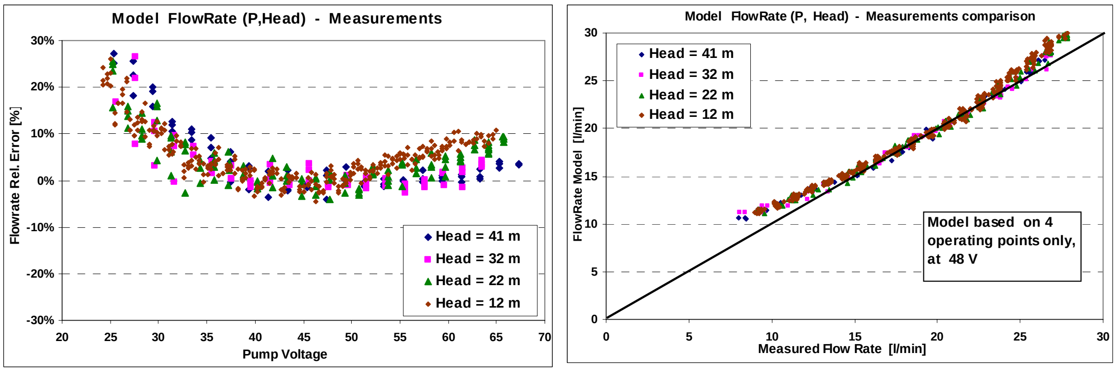

Fig 2.6. - Error with model based on only 4 points at 48V.

Here we draw the results as function of the voltage, in order to illustrate the deviations by respect to the basic given data at 48V. We remind that the main additional hypothesis is here that the pump efficiency is constant according to the voltage. It can be seen that the results remain quite acceptable over the medium operating voltages, and would deviate significantly only for marginal situations in a real system designed for this voltage.

2.3.3. - Check of the centrifugal model based on "Similarity Laws"

Finally, we used data - also provided by CIEMAT - from a centrifugal pump (Solarjack SCS 14-160) for the analysis of the model based on the Similarity Laws.

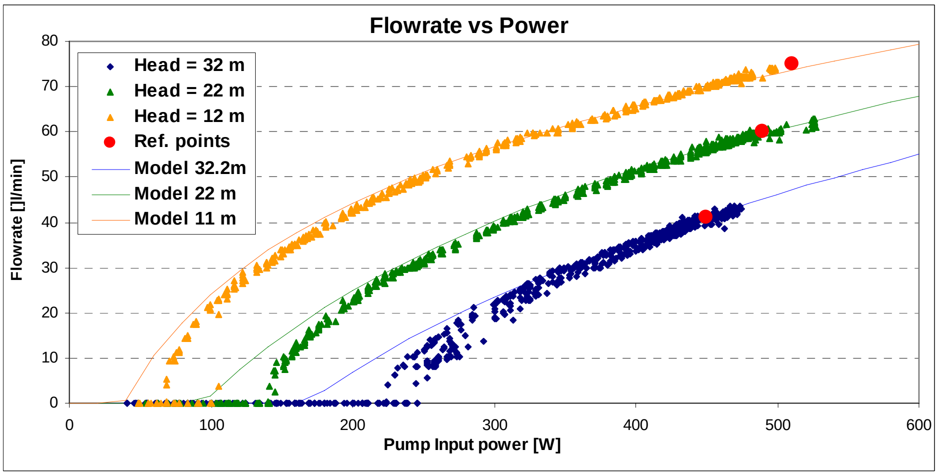

Fig 2.7. - Measurements of a Centrifugal Pump (Solarjack SCS14_160)

Such a pump has a different behaviour as positive displacement pumps. The Flowrate / Power curves seem somewhat similar at first sight. Nevertheless they show a semi-quadratic shape, and stay much more parallel to each other. The production threshold is more sensitive to the head, and flowrate doesn't increase as quickly with power at lower heads.

As we have seen in paragraph 2.2.6, we may apply here the semi-physical model called "Similarity Laws", related to the pump's speed: for 2 operating points such as the flows are proportional to speed, then the powers ratio behaves as the square and the Heads ration as the cube of the speed ratio.

Fig 2.8 shows the results of this model by respect to measured data, using only **3 reference operating points** (Pp, HT, FR) measured at Heads = 11, 22 and 32 meterW. The model reproduces quite well the high flowrates for any head, but shows a systematic error below about 20 l/h, perhaps due to the motor efficiency at lower speeds.

The model behaviour may also be visualised on the fig 2.7, superimposed on the measured data. Here again, one can see that the model is not able to well evaluate the pumping threshold, and gives still significant values when the measurements show a null FlowRate.

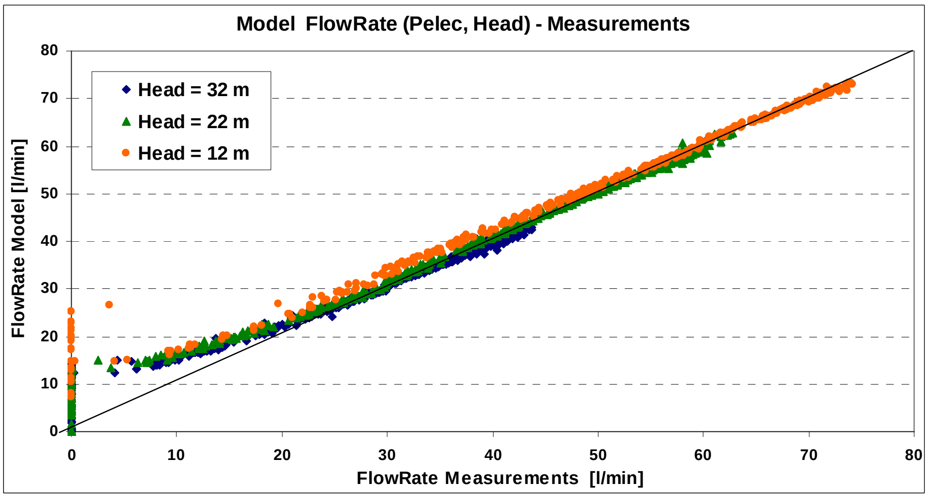

Fig 2.8. - Flowrate Model - Measurements comparison (Similarity Laws)

The electrical Current/Voltage characteristics is quite different from the Positive displacement pump. It shows a remarkable property: below the flow threshold, the pump behaves quasi perfectly as an ohmic load (current proportional to voltage). In this regime the pump is running, but at an insufficient speed for attaining the external required head. When this head is attained the pump starts to produce a water flow, and the current suddenly increases.

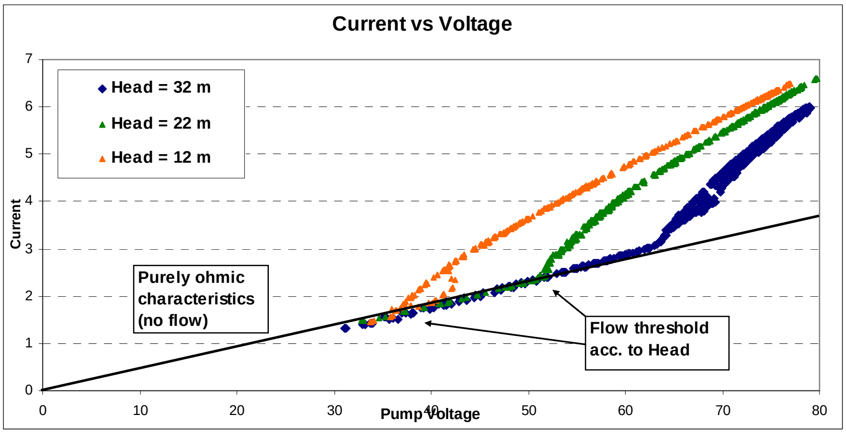

Fig 2.9. - Measurements of a Centrifugal Pump - I/V behaviour

2.3.4. - Model based on Manufacturer data

Do not confuse **Model accuracy** with **Parameter accuracy** !

The model is accurate when, using adequate parameters, it is able to reproduce the device behaviour within the whole operating range. It is said "robust" when parameter errors don't result in too big errors over this range. We have seen that this model, based on real measured operating points, is accurate if we avail of a good set of points, and stay rather robust – at least around nominal conditions - in the lack of information at marginal conditions.

But adequate parameters are not always available. Either pumps may be slightly different from one unit to another one, and the parameter are given for a generic series. Or the operating points are not measured with sufficient precision, or are given with optimistic values (by manufacturers).

When applying the basic model to the Watermax BU pump, with the 16 basic points analogous to the mentioned ones, but specified by the manufacturer, the results errors are split between 0 and +20% (according to voltage). This does not reflect the model accuracy, but is only related to the effective value of the parameters. This indicates that the performances – especially at low heads - given by the manufacturer overestimate the real performance of this particular pump (by about 10% on an average).

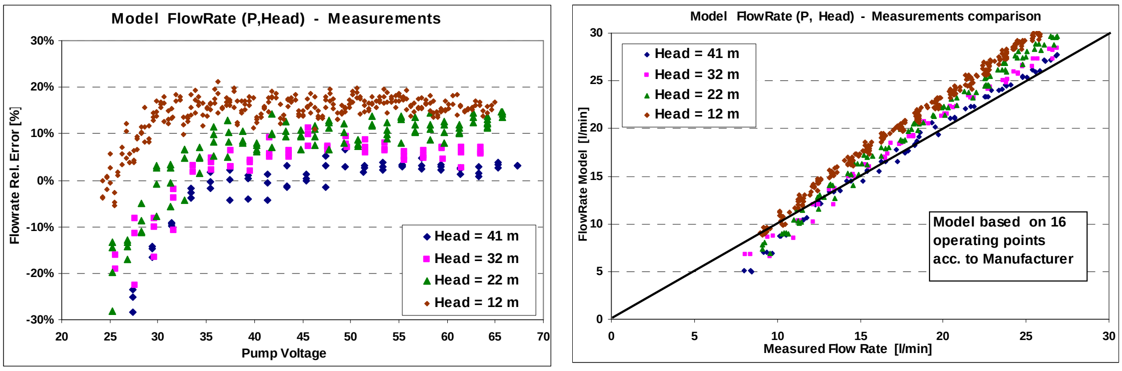

Fig 2.10. – Model – Measurement comparisons with Manufacturer's data

In practice any model will never be able to give better results than the input parameter accuracy !

2.3.5. – Power threshold

The pump's threshold is the operating point at which the pump is beginning to produce a flow. The threshold conditions are different for centrifugal and positive displacement pumps.

With **positive displacement** pumps, the flow begins as soon as the pump is running. The power applied under the threshold is dissipated in the motor without any movement. In most pumps the friction of the moving pieces is stronger at stop, requiring a starting peak current which ensures an initial torque. After starting the current is strongly reduced. This starting over-current is very important in the solar applications, on one hand because the sun's available power is slowly increasing in the morning, and on the other hand because the high currents provided by photovoltaic array are far from the maximum power point. This question will be discussed later in the system part.

A second "running" threshold is defined as the power at which the running pump will stop. These threshold data have to be specified in the pump model; in PVsyst we define a starting over-current (at low voltage), and the stopping threshold in terms of voltage or power.

With **centrifugal pumps**, the pump begins running at very low power, and flow only begins when the speed reaches the power threshold depending on the external head. As we saw on fig 2.9, the pump behaves as a pure resistance (this assertion is based on this measurement, it should be confirmed by measurements on other pumps).

In the PVsyst "Similarity" model, specifying this resistance should allow in principle to determine the voltage threshold for any given head. But we saw that the power behaviour is not quite good at low flowrates, so that this is not quite reliable. Conversely, if we can specify (as parameters) the power threshold for 2 or 3 heads, this provides a mean for implementing a correcting function to the model in the low flows regions.

2.4. – Implementation of the model in the PVsyst software

For being effectively useable in a general-purpose PV software, this should offer a comfortable interface, which allows to easily define the model parameters from manufacturer datasheet. In PVsyst, the user can choose the working units, and avails of graphical representations when entering the data.

As the pump behaviour is highly non-linear and not intuitive, the program will perform coherence and plausibility checks, and shows an extensive set of checking and "pedagogic" graphs.

Such graphs – for example efficiencies as function of various parameters – are rarely (never) shown in data sheets, nor even in engineer/scientific publications. They are yet very useful for intuitively comparing pumps performances in a given system.

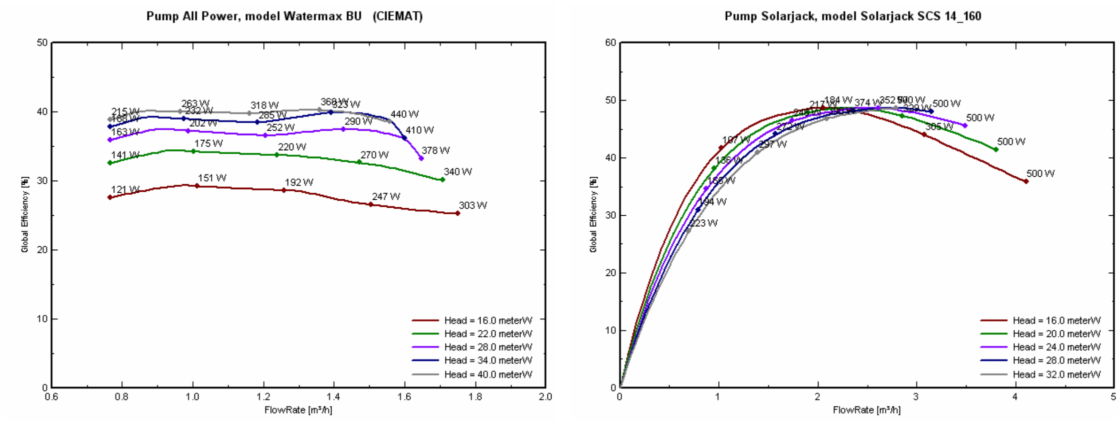

Fig 2.11. – Exemple of graphs available in PVsyst.
Compared efficiencies for Pos. displacement and Centrifugal pumps

The example of fig 2.11 shows the very different figure of the efficiency. When with this positive displacement pump the efficiency is very constant according to the flowrate (but increases with head), the centrifugal technology's efficiency shows a maximum for a "nominal" flowrate, relatively independently of the head.

3. – Modelling the complete pumping system

The program offers two complementary approach: a pre-sizing part and a detailed simulation part.

3.1. - Pre-sizing tool: early quick sizing and evaluation

While a pumping system is a rather complex system, involving many variables and operating at very different conditions over the day and the year, component sizing is a rather difficult task. The customer usually specifies its water needs in volume, as well as the head (level difference) at which it should be pumped. He may also define a required autonomy duration and a time fraction during which he accepts that the water needs are not met by the system (empty tank).

Starting from these requirements, and using rough, but quick yearly simulations, the program is able to determine the PV array, pump size and tank volume that are necessary to meet these water demand requirements. It also gives a very rough estimation of the costs.

This very simplified simulation runs over one year in daily values. It uses monthly meteo data as input, generates a random 365-days time series, and uses a well established meteo model to determine the irradiance on the PV plane. Then the pumping system's behaviour is calculated, on the basis of very general performance parameter (such as PV array efficiency, pump efficiency, coupling performances, etc), pre-defined for several pump, PV module technologies and regulation/coupling strategies. This simulation is repeated with different array and pump size arrangements, until matching the user's requirements.

The results show the monthly yield of water (with respect to the specified needs), the missing water, and the excess PV energy (when the tank is full).

Of course, this early layout proposition should be asserted by a detailed simulation, using real commercially available components, and taking all system features into account.

An example of output report of this early stage - an internal document which should of course not be used for presentation of a pumping system to a customer - is shown at Annex 2.

3.2. - Project Design: the detailed system simulation

3.2.1. - General considerations

Any pumping system shows highly non-linear characteristics. We can mention the pump starting threshold, PVarray – pump electrical mismatch, converter efficiencies, well characteristics, operating limits, etc. This is why using "thumb rules", extensions of manufacturer partial data, or even the "Presizing Tool" described above, are not suitable for accurate performance evaluations or fine optimizations.

Therefore a detailed study should involve a step-by-step hourly simulation over a realistic meteo period. PVsyst offers the framework of such a simulation in hourly values, according to various meteo data and detailed modelling of components.

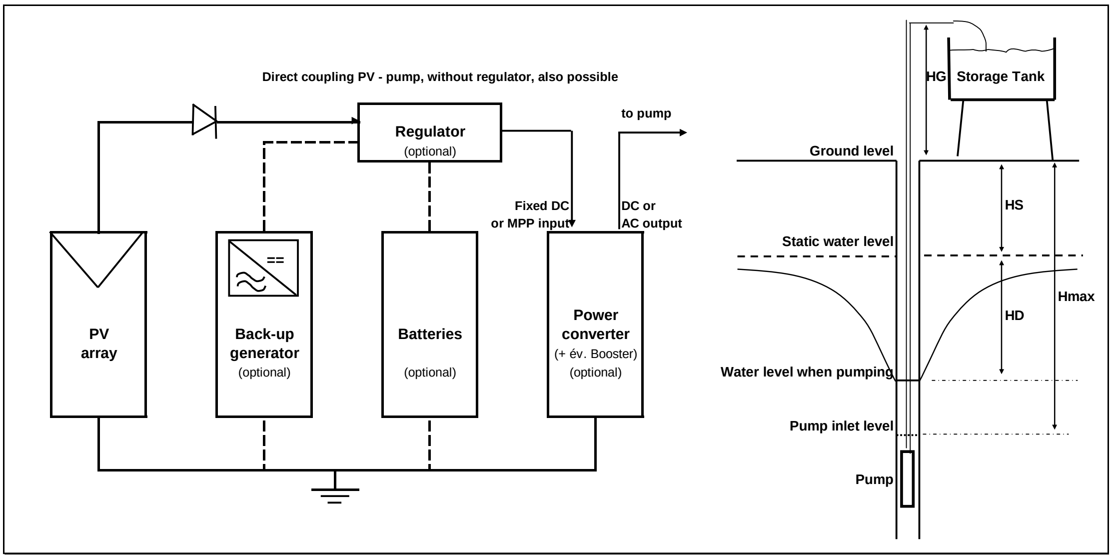

Fig 3.1. - Global schematics of a pumping system with different power conditioning / coupling options

As an example, fig 3.1 shows a typical layout of pumping system, with several regulating and coupling options. The parameter definition and the simulation process have to take the following aspects of the system into account:

- Definition of the user's water needs, which may be constant, in seasonal or monthly values,
- Characterization of the storage tank, if any,
- Dynamic behaviour of the well, with eventual drawdown limits,
- Photovoltaic energy yield (including meteo data, plane orientation, PV array characteristics, shadings, etc),
- Motor-pump device,
- Regulation and power converter strategy,
- Eventual battery storage or auxiliary back-up generator.

In the present state, PVsyst treats 3 pumping system types, all with storage tank: deep well, pumping from a lake of river, and pressurization for water distribution. Moreover, there is a wide choice for the technology of these systems (power conditioning and transfer, regulation strategy). A main advantage of PVsyst is the ability of simulating several technological solutions for comparisons and optimisation.

3.2.2. - Deep well modelling

Deep well in isolated sites is the main application of PV pumping systems. Such a system requires a modelling of the borehole behaviour, with the definition of several specific parameters.

Head definition

Head is usually expressed in units of level difference [meterW]. Physically, passing to pressure units involves multiplying the height by the water density (= 1000 kg/m3) and gravitation constant ($g = 9.81$ m/sec²). For getting [bar], we have to divide by 100'000 [Pa/Bar].

The pump has to provide a total head resulting of several contributions. In case of a pump immersed in a well, if we take reference to the ground level, we have (fig 3.1):

HTot = HOut + HStatic + HDyna + HFriction

where:

HOut =	height of the outlet pipe above the ground (assuming that outlet pressure is negligible).
HStatic =	static head due to the depth of the water level in the well, in absence of any pumping.
HDyna =	dynamic head: in a borehole well, the effective water level is dynamically lowered by the water flow extraction.
HFriction =	friction losses in the piping circuit, which depend on the flowrate.

Borehole modelling

If we consider the borehole as an impervious tube, when pumping the water level will drop as the flowrate Q [m3/h] divided by the hole area Aw [m²].

On the other hand, the re-filling of the well from the surrounding porous medium is a diffusive process. One can admit as a reasonable hypothesis that the refilling flowrate is proportional to the stress, i.e. the drawdown dynamic head.

Under these hypotheses the real level in the well (or HDyna evolution) will obey the following equation:

$$dHDyna / dt = - 1/\tau * HDyna + Q(t) / Aw$$

One can easily see that for steady-state conditions (dHDyna / dt = 0), this equation leads to a drawdown height HDyna proportional to the flowrate. Indeed, compared to a reference case, we have for any flowrate:

$$HDyna = Q * HDref / Qref$$

Under this hypothesis, the ratio HDref/Qref is a characteristics of the well, which we will call the "**specific drawdown**" (expressed in [meterW / m3/h]).

This parameter is mainly related to the geologic properties of the surrounding ground (permeability, storage capacity), and the construction technique of the borehole. It may be measured rather easily, using a portable engine-pump and measuring the water depth and flowrate in stabilized conditions.

Borehole parameter

As a matter of fact, a pumping test is often performed in situ for measuring the borehole performance, which yields essentially 3 parameters: the static level (HStat), a reference flowrate available from the well Q_{ref}, and the corresponding dynamic level (HD_{ref}). [Navarte, 2000] reports several results of such tests in Africa, of which we give some examples.

	HStat [m]	HDref [m]	Qref [m3/h]	HDref/Qref [m/m3/h]
Angola				
Rotunda	20	25	7.2	3.5
Chamaco	12	20	6.9	2.9
Lupale	20	24	5	4.8
Morocco				
Abdi	13	22	21.6	1
Ourika	17	2	10.8	0.2
Iferd	10	50	36	1.4

Table 1. Characteristics of some borehole in Africa [Navarte, 2000].

We can observe from these examples that the Dynamic contribution is not to be neglected !

The recovery time τ (corresponding to a 1/e re-filling) is easily calculated from the steady state conditions:

$$\tau = Aw * HDref / Qref$$

For example, in the case of a borehole of diameter 0.15 m in Rotunda, this is about 4 minutes. Therefore this dynamic model describes the short term behaviour of the well.

Long term variations are likely due to modifications of the phreatic water level along the seasons. They may be introduced in PVsyst by specifying a monthly profile of the static head HStat. Long-term exhausting effects caused by an excessive water drain (or climate change) involve complex (and not sustainable) phenomena which are not modelled here in PVsyst.

Finally, the simulation (as well as the real system regulation) should take the maximum head Hmax, i.e. the inlet level of the pump, into account for stopping the pump, avoiding dry-running.

3.2.3. - Pumping system parameter

Deep well main parameter include the definition of all the levels mentioned above, including the pump depth for stopping it when the dynamic level reaches this dangerous level (dry-running safety level sensor).

Pumping systems from a lake or river are similar to deep well systems, but with some technical simplifications:

- The pump may be placed near the source (no more than 4-5 m above the water surface, less at high altitudes, for avoiding cavitation problems).
- The pump is not necessarily of "Submersible" type, therefore much cheaper. On the other hand, it's maintenance is more easy as more accessible.

Again, the lake or river level may be specified in seasonal or monthly values.

Pressurization system assumes pumping from a generic water source (other storage, lake or river), into a tank which ensures a water static pressure allowing for distribution to customers. This is an alternative of "high" tanks like water towers. The pressurization is obtained by the compression of the air in the closed impervious tank volume when water level increases.

The pump's problematics is the same as for lake/river, except that it's maximum head capabilities are usually higher.

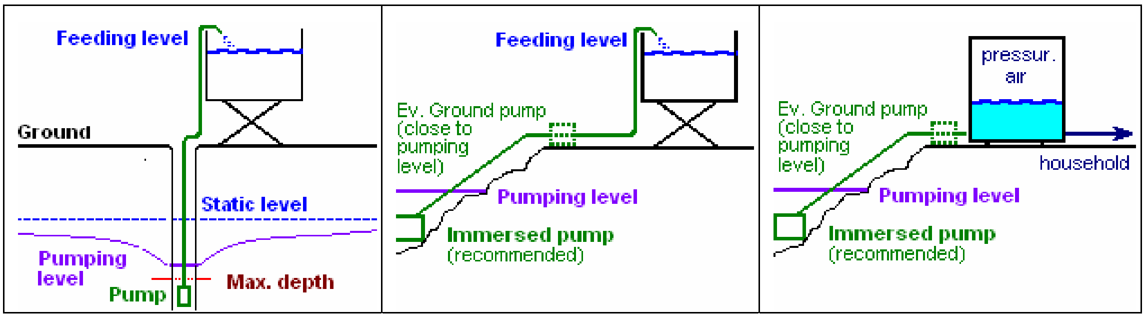

Fig 3.2. - System types and pictograms in the PVsyst dialog

For all systems, PVsyst also asks for the pipes length and diameter, in order to calculate the friction loss at each simulation step. When defining the parameter a Head diagram shows the different Head contributions (fig 3.3).

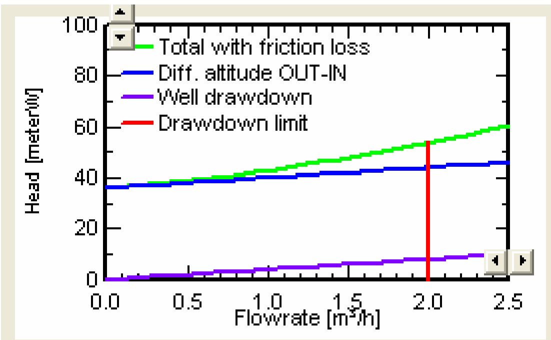

Fig 3.3. - Heads summary indication in the parameter definition

3.2.4. - Storage

In most installations, the storage tank is placed rather high, in order to allow water utilization by free outflow. Storage tank should be sized according to the desired autonomy (number of days without sufficient sun, under the specified consumption).

Usually the pipe outlet pours water at the top of the storage tank. The residual pressure (giving rise to kinetic energy in the jet), is neglected.

A slight efficiency improvement could be expected by filling the tank through the bottom, which would avoid loosing the height between the outlet and the water level in the tank; this of course requires the use of a non-return valve in the pipe. PVsyst will also treat this case for evaluating the benefits.

In pressurization systems, the storage and air volume ratio will be closely related to the minimum and maximum tank and pumping pressure.

3.2.5. - Photovoltaic Energy Yield

The simulation will take advantage of the existing complete treatment of the available PV-power in PVsyst: wide meteo input choice (including extensive database, and import from several external sources), plane orientation (with tracking or shed arrangement possibilities), shadings, PV-array characterization (one-diode model, special features for thin film modules, wide PV-module database), evaluation of all losses (IAM, module quality, mismatch, temperature, wiring resistance, etc).

3.2.6. - Power and Regulation Strategies

Power coupling between the photovoltaic array and the pump(s) is the main technological feature of the pumping solar systems. PVsyst treats about eight different configurations.

The specificities of these configurations are defined in the Control Device ("Regulator") parameter. They may involve additional devices like power switches, power converter, batteries and their charging control, etc.

Direct coupling between PV array and pump is not efficient, but can be improved using mainly two strategies of low technology: either connecting two or several pumps in cascade, or reconfiguring the PV array in series or parallel according to the irradiance level.

Better efficiencies involve power converter devices. In PVsyst, the definition of the power converter takes place either in the Regulator device, or in the Pump definition. This is especially the case with DC to AC inverter, as the AC feeding electrical characteristics (often 3-phased) is not undertaken in the program, and is considered as internal in the pump's "black-box" model.

3.2.7. - Direct coupling

Direct coupling of DC-pumps with the PV array is still widely used, especially in small pumping systems, owing to its simplicity. Many studies already reported the Array-Pump coupling and its unavoidable mismatch in the Current/Voltage characteristics [Roger, 1979].

Direct coupling is only possible with DC motor pumps. The simplified electrical layout is the following:

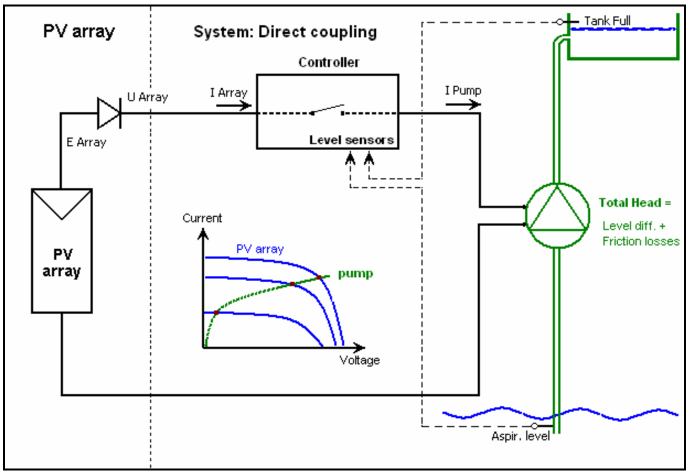

Fig 3.4. - Direct coupling layout

Such a configuration implies in a **very careful optimization.** At any time, the operating point is the intersection of the two I/V characteristics: PV production and pump consumption. If the pump curve is too high (array current undersized), the pumping threshold will be high, penalizing the low irradiances (low season, bad days and morning/evening). If it is too low, the full potential power of the array is not used during bright hours. The optimal sizing is therefore depending either on the **irradiance distribution** (i.e. location, orientation, meteo), and on the periods at which the **water needs** are the more important.

Due to high current (at low voltage) starting requirements, this type of systems is very inefficient by lower irradiances, using only a low fraction of the potential PV power. Use of PV tracking systems may slightly improves the situation.

Moreover, the pump characteristic is strongly dependent on the **head**, displacing the I/V characteristics parallel to itself. Therefore, the sizing will also be dependent on the conditions of use, impeding using simple "thumb rules" valid for any system at any place, and often proposed by manufacturers.

Absolute maximum ratings have to be respected: the pump should not be fed with dangerous voltages or over-powers whatever the irradiance conditions. This prevents over-sized PV-array, unless overload protections are implemented in the control device.

At the system definition stage (choice of pump(s) and PV array), PVsyst offers a contextual graph visualizing the effective behaviour of the system with the chosen components.

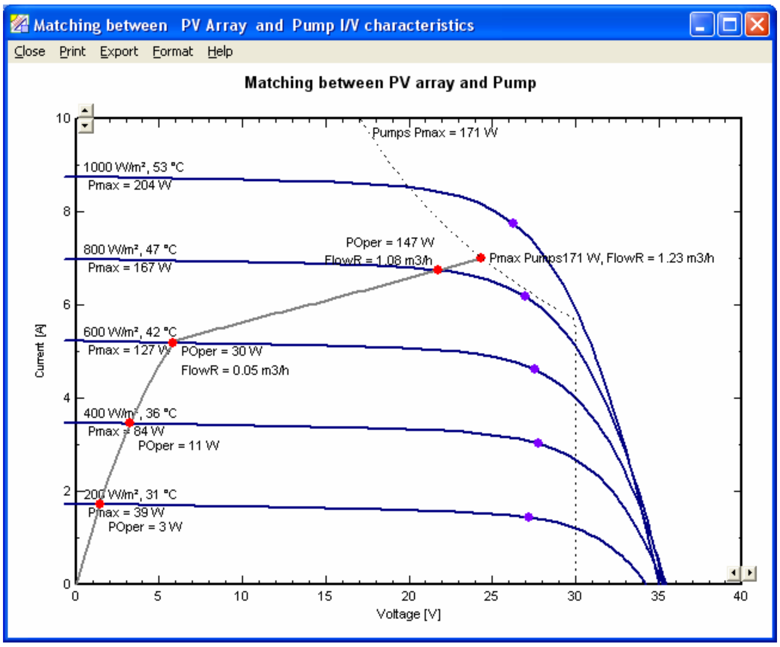

Fig 3.5. - Contextual diagram available during system definition in PVsyst.

3.2.8. - Direct coupling with Booster device

Most displacement pumps require a significant peak of current (at low voltage) when starting, in order to overcome the internal friction forces. We see on the diagram that this array configuration is not able to provide the peak unless by waiting very high insolation, still increasing the irradiance threshold.

Help is usually provided by an electronic device named "Booster", which stores the PV energy in a capacity and gives it back as an instantaneous peak of current.

This non-linear behaviour should also be reproduced in detail in the PVsyst simulation.

The booster strategy is useable with a **single pump** system. When several pumps are involved in the system, the Cascade configuration is best suited.

3.2.9. - Direct coupling with pumps cascading

If the system is equipped with **several pumps**, the regulation should switch them ON according to the available PV power, in order that each pump runs near its optimal efficiency. In practice with deep well systems, this option is difficult to realize: either there should be two wells, or a very wide one for passing the output pipe of the deeper pump next to the upper one!

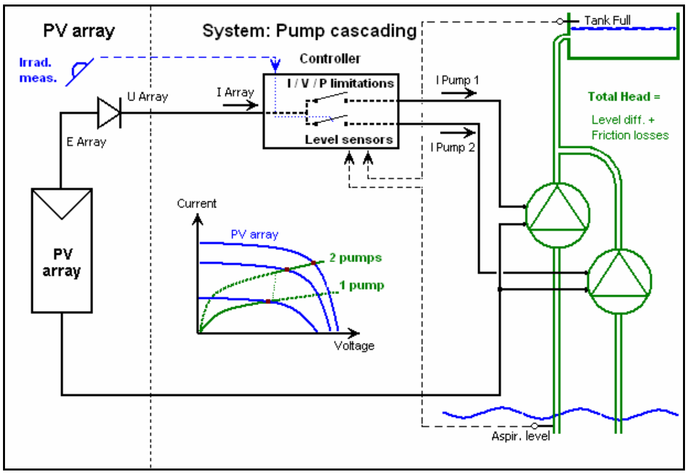

Fig 3.6. - Direct coupling with cascading

This opportunity may improve drastically the performances of the direct coupling configuration, lowering the irradiance threshold and improving the operating at high irradiances.

But be careful: the starting threshold of the second pump is a crucial setting! If too low, the starting current of the second pump will prevent the running of the first pump, while in a very efficient irradiance range.

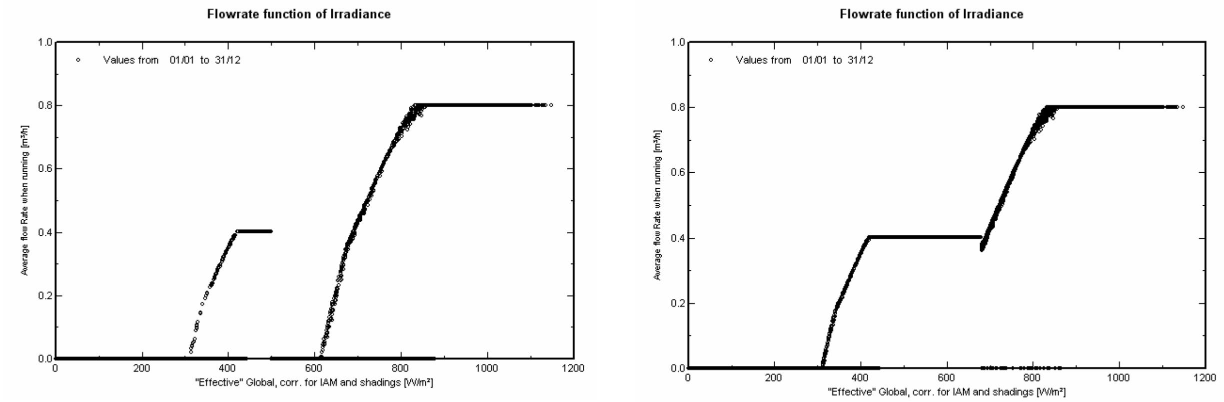

Fig 3.7. - Threshold adjustment with Cascading

The Predefined Graphs "Flowrate function of Irradiance" in the results is a suitable tool for understanding the behaviour and optimising the threshold. Here for the 500 W/m² and 680 W/m² thresholds.

With pumps with incorporated MPPT power conditioning units, the cascading cannot be used unless the MPPT algorithms are suited for "Master/slave" operation. Indeed, the operating point on the I/V characteristics of the PV array cannot of course be driven simultaneously by two independent MPPT devices.

Such an operation mode is not yet implemented in the present version of PVsyst.

3.2.10. - Direct coupling with array reconfiguration

Direct coupling mismatch may be improved by performing a PV-array reconfiguration: if we consider two identical groups of PV-modules, at low irradiance all groups are connected in parallel, providing the high currents necessary to the pump starting. From a given irradiance level, the groups are connected in series, doubling the voltage and reducing the current of the PV array. This requires an electronic switch of rather simple technology [Salameh, 1990].

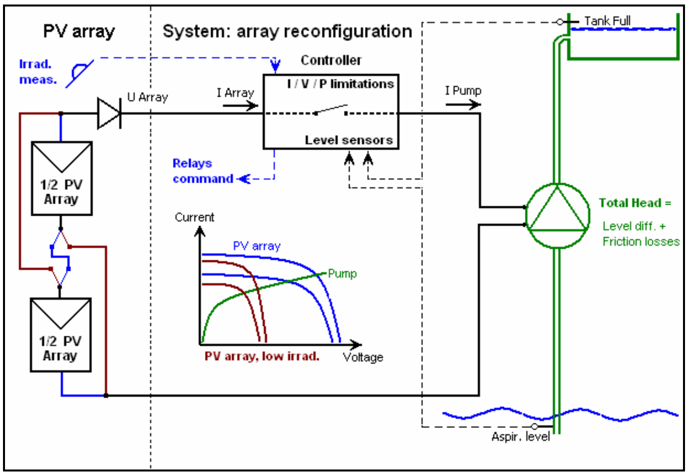

Fig 3.8. - Direct coupling with array reconfiguration

This strategy is not advised when several pumps are used: the Cascading operation is probably more suited in this case.

As for cascading, the irradiance threshold for commuting the arrays is of great importance for the final performances, and should be determined carefully using the "Flowrate function of Irradiance" diagram in the simulation results.

3.2.11. - Power converter (MPPT or Fixed DC input)

Use of a DC-DC converter (Power Conditioning Unit, PCU) shows a much favorable figure than direct coupling. This (now cheap) electronic device absorbs the power of the PV array at an optimal voltage, and behaves as a current generator for feeding the DC-motor of the pump.

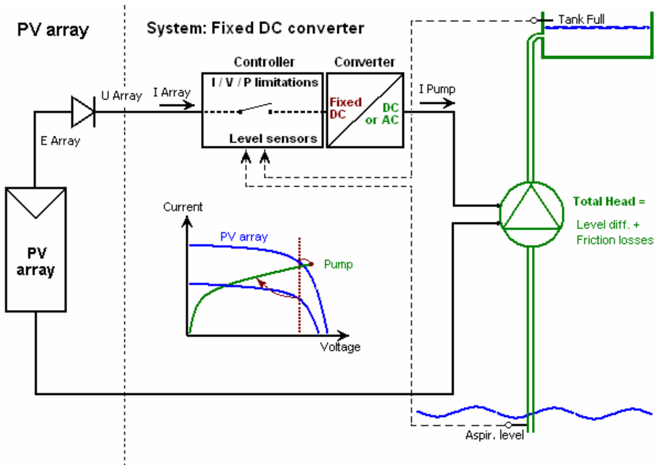

Fig 3.9. - DC-DC power converter

Most pump manufacturers propose now converters with Maximum Power Point Tracking (MPPT) capabilities, adjusting continuously the input voltage at the optimum of the array.

But this is not quite necessary. A simpler (and cheaper) device with fixed voltage DC-input may show very good performances if the voltage is well adjusted. As in real conditions the MPP voltage is indeed very stable (it increases slightly with irradiance, but this increase is compensated by the module temperature effect), the fixed voltage can be chosen near this value. On most commercial DC-DC devices, the input voltage may be adjusted by hardware.

PVsyst includes a specific tool for determining the optimal fixed DC voltage setting at a given site, performing a quick simulation over the whole year, and therefore all situations. This shows that the voltage optimum value is not very critical.

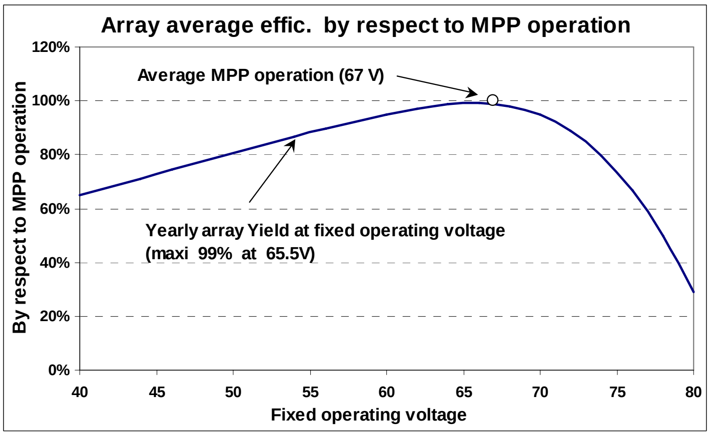

Fig 3.10. - DC fixed operation yearly performance

When the converter definition is included in the pump's model, the electrical input definition of this converter-motor-pump aggregate is only based on the power. The only information on the input voltage/current behaviour is the MPPT or fixed VDC input parameters (minimum and maximum voltage of the tracking range, absolute maximum voltage).

At the output side, the power is supposed to be transmitted to the motor at the optimal current/voltage point corresponding to the available power.

For **AC motor pumps**, a Power Conditioning Unit (DC or MPPT inverter) suited for a given pump is usually proposed by the pump's manufacturer. It is supposed to fit the pump's requirements (voltage and frequency) for proper operation.

With Power Conditioning Units, the overall performances of the pumping system are only related to the PV array power and meteo conditions. They don't depend anymore on the detailed pump electrical characteristics. The system sizing - and the robustness of the design - is therefore much better !

Efficiency

Nowadays, the converter efficiency is usually of the order of 95% or more in the high power region. It drops toward low powers as other similar devices like inverters. It is treated as such in PVsyst: an efficiency profile is constructed using the maximum and "euro" efficiency data, defined in a similar way as for inverters.

By the way, efficiency drop often arises at powers which are below the hydraulic threshold of the pump; therefore it doesn't affect much the normal running.

Of course the DC-DC converter also plays the role of a "Booster". The starting high current is usually required under very low voltage, therefore low power. This is automatically provided by the converter.

Step-down technology

We have to point out here a special design constraint: most of the DC-DC converters operate on "step-down" principle. This means that they cannot deliver a voltage greater than the input voltage. Therefore the PV-array MPP voltage should be over the maximum voltage required by the pump at the maximum desired flowrate.

This "step-down" limitation can be taken into account by the simulation only when the voltage behaviour of the pump is well defined. With pumps specified only by power curves, it is neglected.

DC – AC inverter

Pumps driven by an AC motor require of course a power converter (inverter) in any case. Manufacturers of AC pumps especially designed for solar use usually propose their own suitable inverter. In these cases, they don't specify the intermediate values (voltage, current, frequency) between the output of the converter and the input of the pump: the simulation process should consider the set converter-motor-pump as a whole.

A very promising design is also based on the use of **standard frequency converters** (FCs), coupled to **standard submersible centrifugal pumps** [Alonso-Abella 1998,2003]. This allows for choosing any commercial pump, not dedicated to solar use. As the market for these materials is much greater than the solar market, this results in cost reductions (the cost of a standard FC is typically half the cost of a PV inverter), improvement in reliability and service, extended power range availability, etc.

Again, DC-AC inverters are often "step-down" devices. This implies that the array MPP voltage should be greater than the peak AC values of the sinus (about nominal voltage * 1.4, i.e. 325V for standard 230V pumps); otherwise the signal will be distorted, resulting in motor inefficiencies. This limitation doesn't hold if the device includes a LF transformer at the output.

As a consequence, as use of standard materials often involves high voltage array, it is best suited for rather high power systems.

3.2.12. - Battery buffered configuration

This can be understood as a regulating device like a very big capacity, which operates over the time:

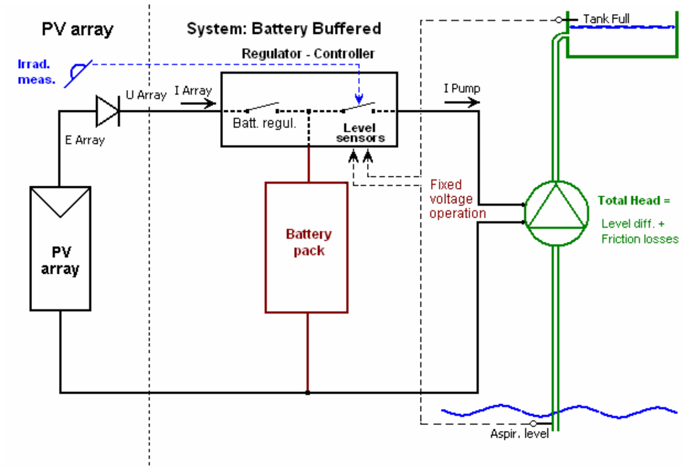

Fig 3.11. - Battery buffered system

Conceptually, in this operating mode, the battery should not be sized for storing energy over a medium or long period - the water storage in the tank is far more efficient for this task.

It should be meant for yielding a power complement when the sun's power doesn't reach the pump's power threshold, and also absorb the excess energy when it overcomes the pump's maximum power. This way the battery capacity may be reduced to a few operating hours.

In practice the pump is connected to the battery, and operates at the fixed battery voltage at any time, avoiding the need of a power converter. It could be regulated in the same way as any other consumer in a stand-alone system, i.e. turned OFF according to the battery discharge threshold protection. But this would lead to a very intensive use of the battery, in a domain (low charge state) where the wearing is very important.

It would be far better to turn the pump ON only when the sun already yields a significant power, but just not sufficient for activating the pump. This way the battery may be understood as a "power regulating" device.

Therefore the regulating device should act according to an irradiance level sensor (in conjunction of course with the discharge protection of the battery), with a threshold carefully chosen, in such a way that it starts a little before the pump's threshold.

The detailed simulations should help for determining this threshold in each given situation, in order to optimize both the water yield and the battery wearing conditions.

4. - Simulation Results

4.1. - System definition

We would like to give here an example for comparing the performances of the different possible configurations of the system. This corresponds to the project given as Demo Project for pumping systems in the software.

We have imagined a Deep Well system at Dakar (Senegal, 15° latitude), with a static level depth of 32m, and a tank feeding altitude of 6m. The water needs are set at 4 m^3/day, constant over the year.

The system includes a set of 2 pumps of 100 W each, positive displacement with DC motor, supplied by 4 PV modules of 60Wp, i.e. 240Wp. This configuration is not an ideal system of course: one only bigger pump would probably be better in this case. Nevertheless this configuration allows for applying all the system configurations with the same components.

Annex 3 shows the whole report provided by PVsyst after simulation. It includes the detailed definition of all parameters involved in the simulation, an eventual graphical presentation of horizon or near shadings if any, graphs and table of the main results, and a detailed loss diagram. The detailed economical evaluation (Annex 4) may also be part of the report if defined and if desired.

Many other special graphs, and tables of monthly values (of more than 40 variables accumulated during the simulation) are also available for deep analysis of particular aspects of the system behaviour.

For example, the daily production as function of irradiance (input/output diagram) gives a "signature" of the system type and sizing.

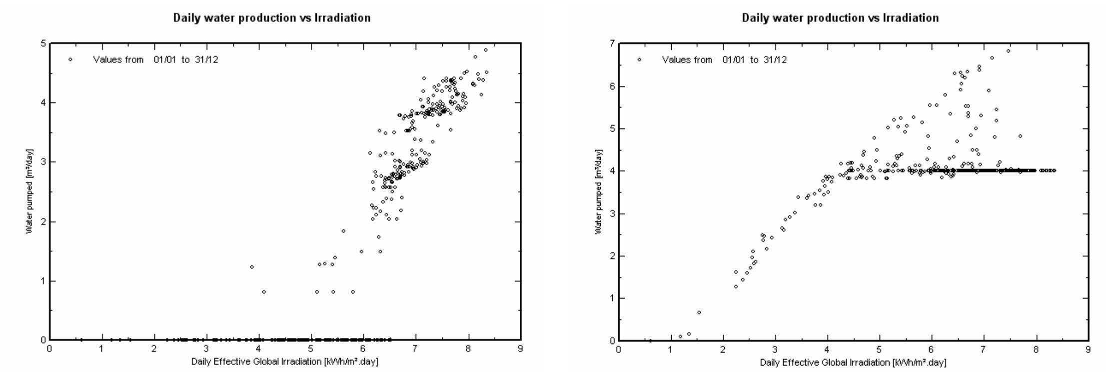

Fig 4.1. - Daily water production with direct coupling and MPPT converter

The performance difference between these two configurations is really impressive. While the direct coupling doesn't produce anything during days below 5-6 kWh/m², the MPPT system fills the tank almost every day, and a lot of potential water is "lost" (NB: the productions over the needs of 4m^3/day are when the previous day was not good, and the tank was not full at the beginning of the day).

4.2. - Loss diagram

A particularly interesting output is the detailed loss diagram at each stage of the system, which allows in one quick view to identify the system's design weaknesses. We show here an example of this for the two extreme configurations: the simple direct coupling, and the system with MPPT converter.

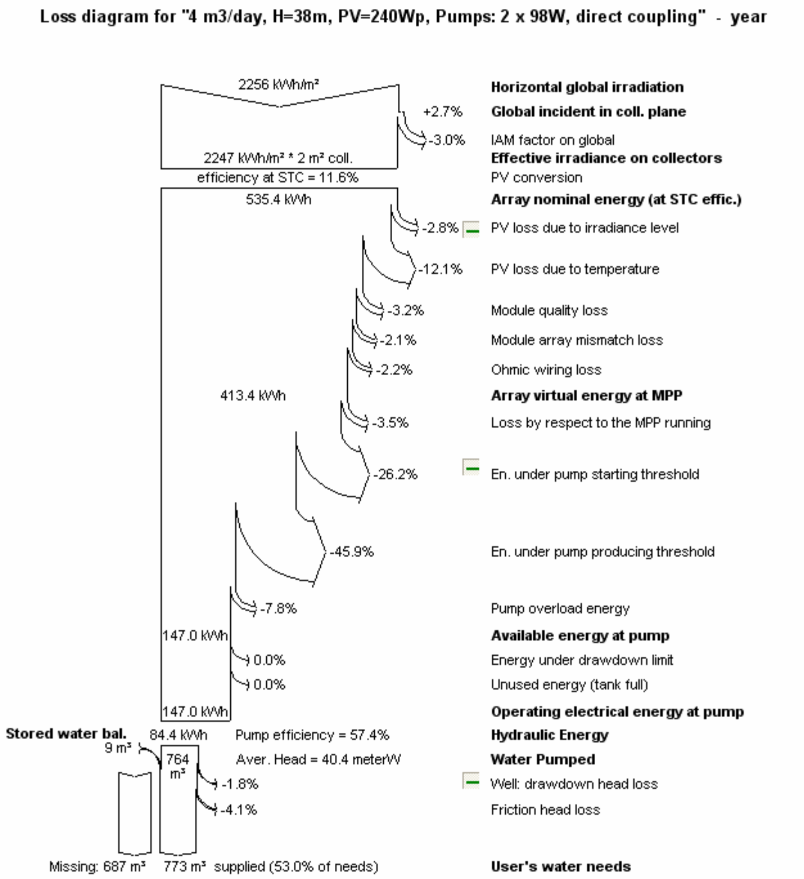

Fig 4.2. - Loss diagram for direct coupling system

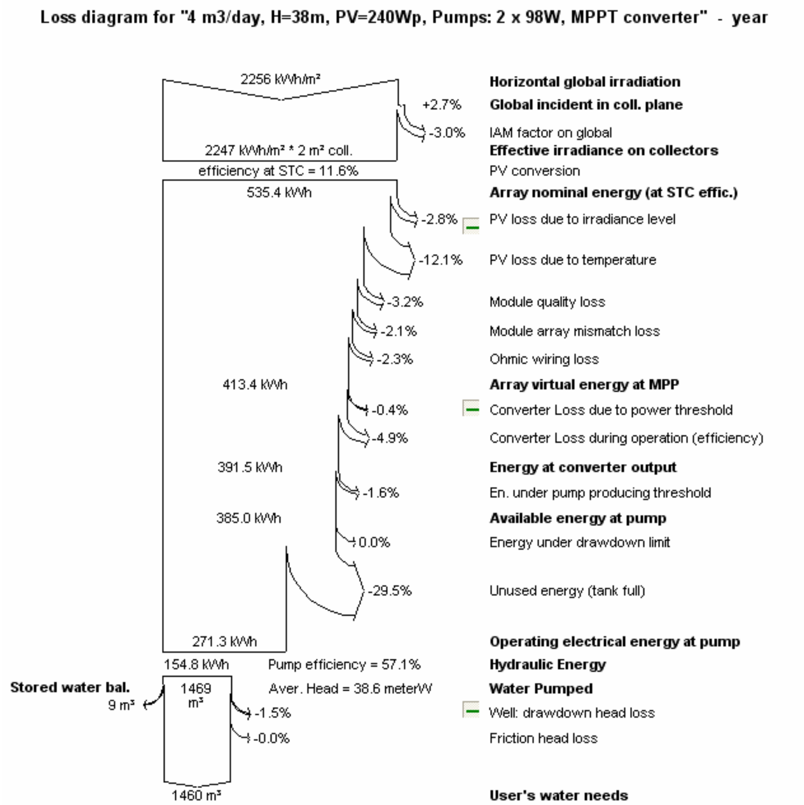

Fig 4.3. - Loss diagram for system with MPPT converter

4.3. - Performance comparison between all configurations

We simulated this system will all configuration options available in PVsyst. This gives the following results:

Needs 4 m3/day	Direct coupling	Direct with Booster	Cascade 500 W/m²	Cascade 680 W/m²	Array Reconfig	MPPT Conv.	26V DC Conv.	28V DC Conv.	30V DC Conv.	Battery 400 W/m²	Battery 680 W/m²
Threshold			500 W/m2	680 W/m2	680 W/m2					400 W/m2	680 W/m2
Water pumped	775	1161	983	1399	1436	1469	1469	1469	1469	1469	1171
Missing water	676	290	469	53	23	0	0	0		0	280
Energy at pump	521	782	660	932	946	977	978	977	975	988	786
Unused PV energy	0	5	0	88	108	409	371	395	341	389	550
Unused PV energy	0.0%	0.6%	0.0%	8.6%	10.2%	29.5%	27.5%	28.8%	25.9%	26.1%	36.9%
System efficiency	35.0%	52.5%	44.4%	62.6%	63.6%	65.6%	65.7%	65.7%	65.5%	66.4%	52.8%
Pump efficiency	56.6%	56.4%	56.5%	56.9%	57.5%	57.1%	56.9%	57.0%	57.1%	56.5%	56.7%
Loss under pump starting	26.2%		27.3%	5.9%	6.1%						
Loss under prod. threshold	45.8%	36.6%	28.6%	9.5%	9.9%	2.0%	2.3%	2.3%	2.3%		
=> Loss under thresh	72.0%	36.6%	55.9%	15.4%	16.0%	2.0%	2.3%	2.3%	2.3%	0.0%	0.0%

Table 4.1. - Performance comparison between pumping system configurations

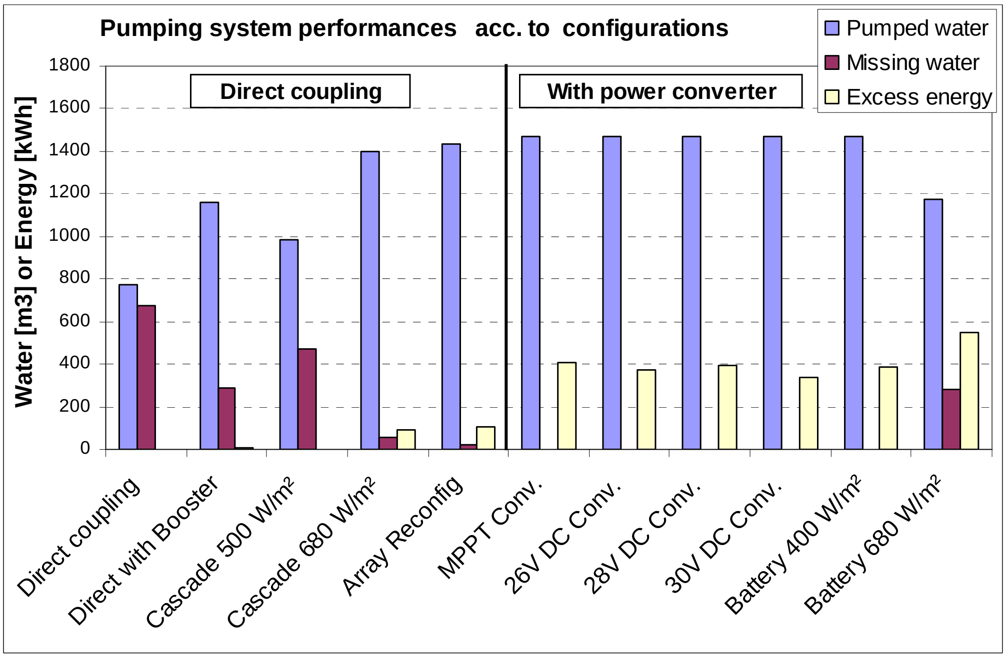

Fig 4.4. - Comparison between different system configuration performances

We can observe that all direct coupling configurations obtain lower performances than systems with power converters, and can't meet the water requirements in this project.

The **direct coupling** yields half the needs only. Although it is very dependent on the PV array sizing, the performances of such a configuration are always deceiving and strongly depend on details of the system sizing. Here the starting peak current requirement penalizes the running by 26% loss.

Introducing a **booster device** improves the situation; this overcomes the starting over-current set at 1A for this pump (in the lack of manufacturer's information, we have fixed this value arbitrarily; this corresponds to half the normal threshold current for this head).

Cascading of the two pumps can be an efficient improvement (but in practice needs 2 wells - or a very wide one for passing output pipes near the higher pump). But as we have seen (§ 3.2.9, p 24) the starting threshold of the second pump is a crucial setting, which should be adjusted precisely using for example PVsyst simulations.

The **array reconfiguration** option shows quite similar performances as pump cascading. Although suitable controllers seem to be not available on the market (except one only manufacturer at our knowledge), it is very easy to construct without deep investment in sophisticated electronics. And it may be used with one only pump, which avoids this practical disagreement of the pump's cascading.

As for cascading, the threshold determination is very important and should be carefully determined with the same tools in PVsyst.

Power converters offer of course the best results. And as expected, the **MPPT** converter is the more efficient.

But we can observe that DC-DC converters with **fixed input voltage** are almost as efficient, and that the fixed voltage value is not critical. This could lead to cheaper converters, without MPPT algorithm implementation. It also allows to use standard converters, with standard (not solar) pumps; this may have a big impact on the prices, either of the converter, and of the pump !

Finally, the **Battery Buffered** system gives equivalent results as power converters. At the condition that the Pump starting threshold (by respect to irradiance) is set sufficiently low. Otherwise the pump is not running sufficiently often, and the battery becomes often over-charged. But of course it involves the use of a (little) battery pack, which have to be replaced periodically.

Water needs increase

As this system is oversized for all converter configuration, we tried to increase the water needs to 5 m3/day, the limit for not missing water with the MPPT, in order to better analyse the differences.

The results are given below: They are quite similar, and confirm that all the converter technological options are rather equivalent. The results of Cascading and Array Reconfiguration are a little worse (but not dramatically) by respect to converters.

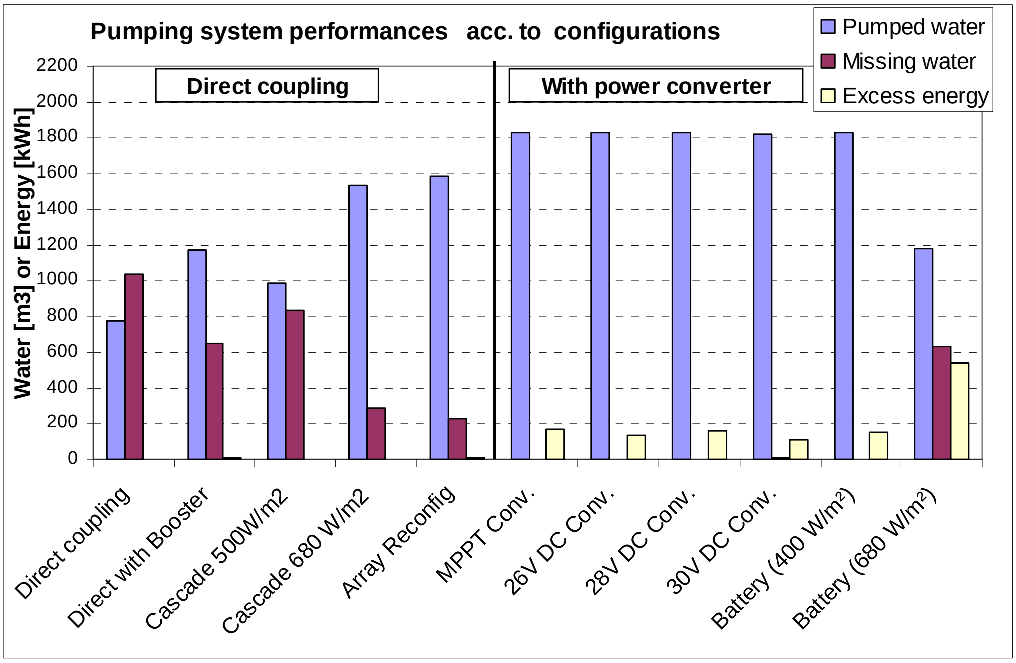

Fig 4.5. - Comparison with Water needs increased to 5 m^3/day

5. Conclusions

Proper design of solar pumping systems requires a lot of expertise. Design rules, optimal options and best practices are disseminated in many specialist documents. This program aims to gather this information and to offer an integrated environment presenting the main available design possibilities, and allowing to closely compare the performances of different technological options for any specific pumping project.

Quantitative studies of a pumping system - and especially simulations - require of course a general model of the pump device behaviour under any operating conditions. We have developed a phenomenological pump model, based on performance data sets directly available from the usual manufacturer datasheets or from measurements. The model accepts a great variety of presentations of data sets. When the original data set is limited, extension to unusual operating conditions is calculated using general behaviours established with measurements on pumps of similar technology. Of course, the model accuracy will increase if a more extended set of performance values is available.

The model covers all pump technologies: centrifugal or positive displacement, with DC or AC motors, with or without integrated power converter. It has been developed using detailed experimental measurements on several pump devices, and has proven to be very reliable over the whole operating range if good input parameter are available (errors of the order of 5 to 10%). When the set is restricted, the model stays robust around the known data region, but its performances may become worse (by 10-20%) in marginal operating regions.

In the first edition (version 4.0), the database delivered with PVsyst includes about 100 pump models. The overall precision of the data in general cases is limited by the basic available performance values from manufacturers, sometimes over-estimated in the data sheets.

The design and simulation part treats 3 types of pumping systems (deep well, from lake/river or pressurization). It gives the choice for defining almost any pumping system configuration (direct coupling, with its improvements like booster, pump cascading or array reconfiguration; systems with power converter and battery buffered).

In pumping systems, design values and their interdependence, as well as their implications on the overall system performances, are often not intuitive. The software checks the coherence of the parameters specified by the user and produces graphs for guidance and warnings for incompatibilities. This "expert" part of the software is the more difficult subject of the package, and will be progressively improved according to the experience gained when using the software (and with the remarks and suggestions of the users).

Results - and particularly the detailed loss diagram - show the overall performance and the weaknesses of a particular design. Comparisons can be performed between several options, and show that direct coupling systems are more difficult to design properly, and always less efficient than solutions with power converters.

This new module of PVsyst is available in the version 4.0, since July 2006.

ACKNOWLEDGEMENTS

We thank the REPIC Swiss fund for the financial support of this project.

We also are very grateful to Mr. Alonso-Abella, from CIEMAT in Madrid, for his valuable advices and experience, as well as the very good and extensive data about pump measurements, which were of prime importance for carrying out this study.

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Appendix A1. - Example of a datasheet describing a pump

PVSYST V4.03	Cuepe	19/11/06 19h59

Characteristics of a pump

Manufacturer, Model : **All Power / Meas, BU F_H + P_H 24, 36, 48, 64 V**

Data source : Ciemat measurements

File : Test_Watermax_BU_FH_PH_24_36_48_64V.PMP of 07/11/06 22h52

Pump General Characteristics Layout **Deep well pump**

Pump technology **Membrane/Diaphragm** Motor **DC motor**

Operating conditions at different heads :	**Head Min**	**Head Nom**	**Head Max**	
	10.0	**30.0**	**40.0**	**mWater**
Corresponding maximum Flow Rate	**1.45**	**1.33**	**1.24**	**m³/h**
Required power	180	280	320	W
Efficiency	22.0	38.8	42.3	%
Threshold Voltage (FlowR = 0)	14.0	16.7	18.0	V
Threshold current	3.0	4.9	6.0	A
Threshold starting peak over-current	1.6	1.8	2.0	A

Other parameters :

Absolute maximum ratings P Max abs. 350 W U max abs. 100 V I max abs. 7.0 A

Operating voltage U Min 12.0 V U nom 48.0 V U max 60.0 V

Data for the Model FlowR and Power vs Head, for some Voltages

Oper. Voltage 24 V

Head	12.0	21.8	31.5	41.5	meterW
FlowR	0.540	0.528	0.492	0.432	m³/h
Power	78	99	124	148	W

Oper. Voltage 36 V

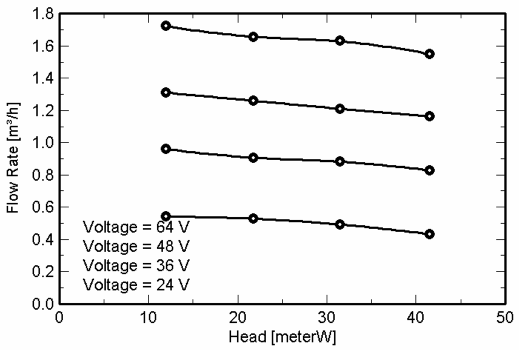
Head	12.0	21.8	31.5	41.5	meterW
FlowR	0.960	0.906	0.882	0.828	m³/h
Power	122	153	189	225	W

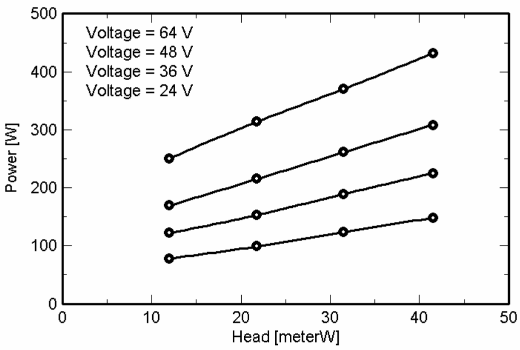
Oper. Voltage 48 V

Head	12.0	21.8	31.5	41.5	meterW
FlowR	1.310	1.260	1.210	1.164	m³/h
Power	169	215	261	308	W

Oper. Voltage 64 V

Head	12.0	21.8	31.5	41.5	meterW
FlowR	1.722	1.656	1.630	1.550	m³/h
Power	250	314	370	432	W





Appendix A2. - Typical output report for the Pre-sizing part

First example: with direct coupling

PVSYST V4.03	CUEPE	21/11/06

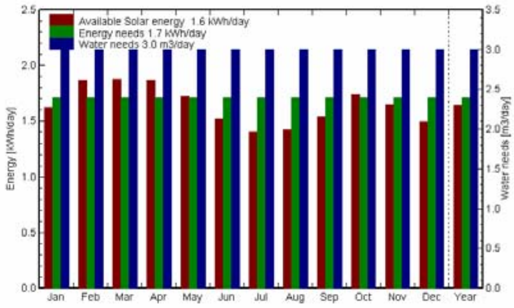
Pumping system presizing

Geographical Site	**Dakar**		**Country**	**Senegal**
Situation	Latitude	14.5°N	Longitude	17.0°W
Time defined as	Solar Time		Altitude	5 m
Collector Plane Orientation	Tilt	15°	Azimuth	0°

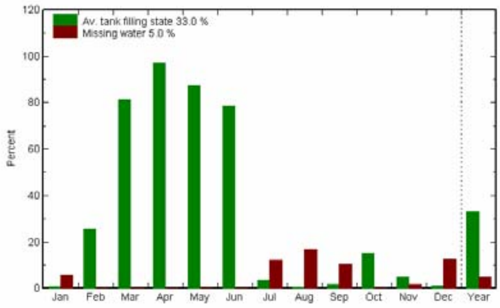
System pre-sizing evaluation

Average use of water	Daily	3.0 m³/day	Yearly	1095 m³
Required autonomy		5 days	Tank volume	15 m³
Loss-of-Load	Time fraction	5.0 %	Missing Water	55 m³
Pumping head	Average	40 meterW	Maximum	40 meterW
Pumping system configuration	Regulation	Direct coupling	Layout	DeepWell
PV array	PV Nominal power	298 Wp	Pump Power	236 W
Economic gross evaluation	Investment	4308 EUR	Energy price	0.54 EUR/m³

PV energy yield and water needs



Tank Level and Missing Water Probability



	Incid.	PV avail.	PV needs	PV Excess	Pumped W.	Missing W.	Missing	Fuel
	kWh/m².day	kWh/day	kWh/day	kWh/day	m³/day	m³/day	%	liter
Jan.	6.0	1.6	1.7	0.0	2.8	0.2	5.7	2.0
Feb.	7.0	1.9	1.7	0.0	3.3	0.0	0.0	0.0
Mar.	7.0	1.9	1.7	0.0	3.2	0.0	0.0	0.0
Apr.	7.0	1.9	1.7	0.2	3.0	0.0	0.0	0.0
May	6.4	1.7	1.7	0.0	3.0	0.0	0.0	0.0
June	5.7	1.5	1.7	0.0	2.7	0.0	0.0	0.0
July	5.2	1.4	1.7	0.0	2.5	0.4	12.4	4.4
Aug.	5.3	1.4	1.7	0.0	2.5	0.5	16.6	5.9
Sep.	5.7	1.5	1.7	0.0	2.7	0.3	10.3	3.5
Oct.	6.5	1.7	1.7	0.0	3.1	0.0	0.0	0.0
Nov.	6.1	1.6	1.7	0.0	2.9	0.1	1.7	0.6
Dec.	5.6	1.5	1.7	0.0	2.6	0.4	12.5	4.4
Year	6.1	1.6	1.7	0.0	2.9	0.2	5.0	20.8

Appendix A2. - Typical output report for the Pre-sizing part

Second example: with MPPT converter

PVSYST V4.03	CUEPE	21/11/06

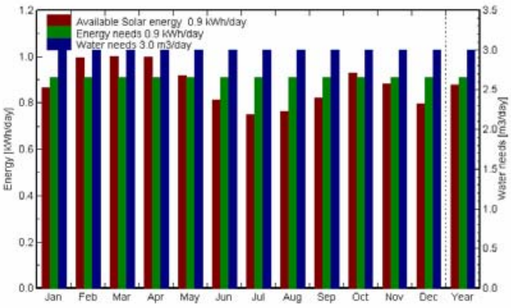
Pumping system presizing

Geographical Site		**Dakar**	**Country**	**Senegal**
Situation	Latitude	14.5°N	Longitude	17.0°W
Time defined as	Solar Time		Altitude	5 m
Collector Plane Orientation	Tilt	15°	Azimuth	0°

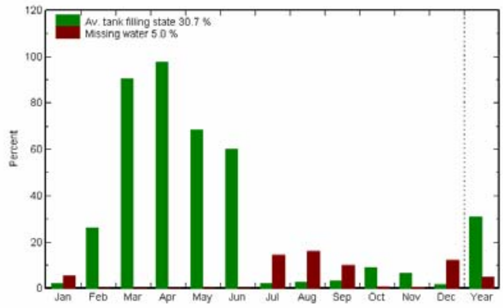
System pre-sizing evaluation

Average use of water	Daily	3.0 m³/day	Yearly	1095 m³
Required autonomy		5 days	Tank volume	15 m³
Loss-of-Load	Time fraction	5.0 %	Missing Water	55 m³
Pumping head	Average	40 meterW	Maximum	40 meterW
Pumping system configuration	Regulation	MPPT-DC converter	Layout	DeepWell
PV array	PV Nominal power	159 Wp	Pump Power	126 W
Economic gross evaluation	Investment	2515 EUR	Energy price	0.30 EUR/m³

PV energy yield and water needs



Tank Level and Missing Water Probability



	Incid.	PV avail.	PV needs	PV Excess	Pumped W.	Missing W.	Missing	Fuel
	kWh/m².day	kWh/day	kWh/day	kWh/day	m³/day	m³/day	%	liter
Jan.	6.0	0.9	0.9	0.0	2.9	0.2	5.5	1.0
Feb.	7.0	1.0	0.9	0.0	3.3	0.0	0.0	0.0
Mar.	7.0	1.0	0.9	0.0	3.2	0.0	0.0	0.0
Apr.	7.0	1.0	0.9	0.1	2.9	0.0	0.0	0.0
May	6.4	0.9	0.9	0.0	3.0	0.0	0.0	0.0
June	5.7	0.8	0.9	0.0	2.7	0.0	0.0	0.0
July	5.2	0.8	0.9	0.0	2.5	0.4	14.5	2.7
Aug.	5.3	0.8	0.9	0.0	2.5	0.5	16.1	3.0
Sep.	5.7	0.8	0.9	0.0	2.7	0.3	10.0	1.8
Oct.	6.5	0.9	0.9	0.0	3.1	0.0	0.6	0.1
Nov.	6.1	0.9	0.9	0.0	2.9	0.0	0.5	0.1
Dec.	5.6	0.8	0.9	0.0	2.6	0.4	12.0	2.3
Year	6.1	0.9	0.9	0.0	2.8	0.2	5.0	11.1

Appendix A3. - Typical output report of simulation results

PVSYST V4.03	CUEPE	21/11/06	Page 1/4

Pumping PV System: Basic simulation parameters

Project :	**Dakar_Pumping_DEMO**			
Geographical Site	**Dakar**		**Country**	**Senegal**
Situation	Latitude	14.5°N	Longitude	17.0°W
Time defined as	Solar Time		Altitude	5 m
	Albedo	0.20		
Meteo data :	Dakar , synthetic hourly data			

Simulation Variant : **4 m3/day, H=38m, PV=240Wp, Pumps: 2 x 98W, direct coupling**

Simulation date 30/06/06 12h51

Simulation parameters

Pumping System parameter	System type	**Deep Well to Storage**		
WellCharacteristics	Static level depth	32 m	Specific drawdown	1.00 m / m³/h
(Diameter 18 cm)	Pump depth	40 m	Max. pumping depth	38 m
Storage tank	Volume	20.0 m³	Diameter	3.5 m
Feeding by top	Feeding altitude	6.0 m	Height (full level)	2.1 m
Hydraulic circuit	Piping length	90 m	Pipes PE20 (3/4")	Dint = 22 mm
Water needs	Yearly constant:	4.00 m³/day		
Pump	Model	**9300 Series**		
	Manufacturer	Shurflo		
Pump Technology	Membrane/Diaphragm	Deep well pump	Motor	DC motor

Operating conditions	**Head Min**	**Head Nom**	**Head Max**	
	6.0	50.0	70.1	mWater
Corresponding maximum Flow Rate	0.44	0.39	0.31	m³/h
Required power	36	88	98	W

Number of pumps	in parallel	2 pumps		
Collector Plane Orientation	Tilt	15°	Azimuth	0°

PV Array Characteristics

PV module Si-mono	Model	**AP-6106**		
	Manufacturer	Astro Power		
Number of PV modules	In series	2 modules	In parallel	2 strings
Total number of PV modules	Nb. modules	4	Unit Nom. Power	60 Wp
Array global power	Nominal (STC)	**240 Wp**	At operating cond.	211 Wp (50°C)
Array operating characteristics (50°C)	U mpp	30 V	I mpp	7 A
Total area	Module area	**2.1 m²**	Cell area	0.0 m²
Control device	Model	Generic device (optimised for the system)		
	System Configuration	**Direct coupling**		

Pumping PV System: Detailed Simulation parameters

Project : **Dakar_Pumping_DEMO**

Simulation Variant : **4 m3/day, H=38m, PV=240Wp, Pumps: 2 x 98W, direct coupling**

Main system parameters		System type	**Deep Well to Storage**		
System Requirements		Basic Head	38.0 meterW	Water needs	4.0 m³/day
Pumps	2 units	Model / Manufacturer	9300 Series / Shurflo		
PV Array		Model / Manufacturer	AP-6106 / Astro Power		
		Nb. of modules	2 S x 2 P	Array Power	240 Wp
System Configuration		Control Strategy	**Direct coupling**		

System Operating Control (Generic device, params adjusted acc. to the system)

Direct coupling between the PV array and pump :
The controller only assumes the overload protections!

PV Array loss factors

Heat Loss Factor	ko (const)	29.0 W/m²K	kv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (800 W/m², Tamb=20°C, wind 1 m/s)			NOCT	45 °C
Wiring Ohmic Loss	Global array res.	135.6 mOhm	Loss Fraction	3.0 % at STC
Serie Diode Loss	Voltage Drop	0.7 V	Loss Fraction	2.2 % at STC
Module Quality Loss			Loss Fraction	3.0 %
Module Mismatch Losses			Loss Fraction	4.0 % (fixed voltage)
Incidence effect, ASHRAE parametrization	IAM =	1-bo (1/cos i - 1)	bo Parameter	0.05

Pumping PV System: Main results

Project : **Dakar_Pumping_DEMO**

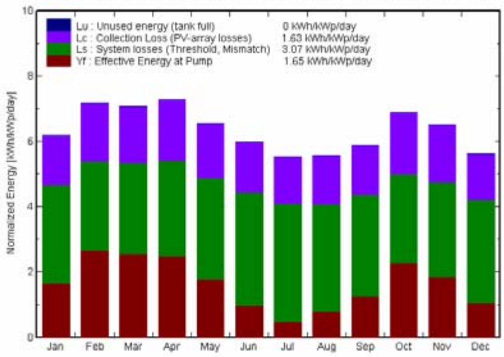
Simulation Variant : **4 m3/day, H=38m, PV=240Wp, Pumps: 2 x 98W, direct coupling**

Main system parameters		System type	**Deep Well to Storage**		
System Requirements		Basic Head	38.0 meterW	Water needs	4.0 m³/day
Pumps	2 units	Model / Manufacturer	9300 Series / Shurflo		
PV Array		Model / Manufacturer	AP-6106 / Astro Power		
		Nb. of modules	2 S x 2 P	Array Power	240 Wp
System Configuration		Control Strategy	**Direct coupling**		

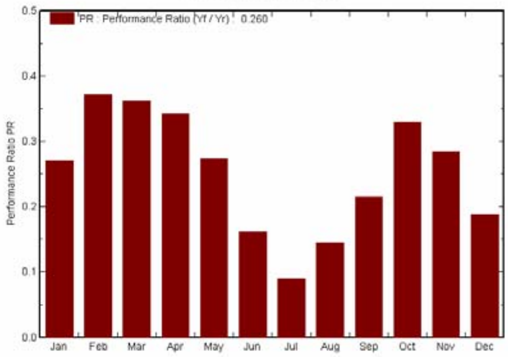
Main simulation results

System Production	**Water Pumped**	**775 m³**	Specific	850 m³/kWp/bar
	Water needs	1460 m³	Missing Water	46.9%
	Energy At Pump	521 kWh	Specific	0.67 kWh/m³
	Unused PV energy (Tank full)	0 kWh	Unused Fraction	0.0 %
	System efficiency	35.0 %	Pump efficiency	56.6 %

Normalized productions (per installed kWp): Nominal power 240 Wp



Performance Ratio PR



4 m3/day, H=38m, PV=240Wp, Pumps: 2 x 98W, direct coupling

Balances and main results

	GlobEff kWh/m²	EArrMPP kWh	E PmpOp kWh	ETkFull kWh	H Pump meterW	WPumped m³	W Used m³	W Miss m³
January	186.4	34.72	12.48	0.000	38.68	66.3	74.8	49.2
February	195.9	36.24	17.98	0.000	38.73	96.4	95.5	16.5
March	213.3	39.74	19.02	0.000	38.72	101.7	102.1	21.9
April	211.8	39.01	17.97	0.000	38.72	96.2	98.0	22.0
May	196.1	36.50	13.30	0.000	38.73	71.2	71.4	52.6
June	173.1	31.95	6.99	0.000	38.74	37.7	37.7	82.3
July	165.5	30.45	3.70	0.000	38.71	19.9	19.9	104.1
August	167.1	30.39	6.00	0.000	38.69	32.2	32.2	91.8
September	171.5	31.43	9.15	0.000	38.70	48.8	48.2	71.8
October	207.8	37.28	16.91	0.000	38.73	90.3	89.4	34.6
November	189.8	34.28	13.34	0.000	38.73	71.8	72.9	47.1
December	168.8	31.39	7.85	0.000	38.72	42.3	42.2	81.8
Year	2247.2	413.38	144.69	0.000	38.72	774.9	784.3	675.7

Legends:				
	GlobEff	Effective Global, corr. for IAM and shadings	H Pump	Average total Head at pump
	EArrMPP	Array virtual energy at MPP	WPumped	Water pumped
	E PmpOp	Pump operating energy	W Used	Water drawn by the user
	ETkFull	Unused energy (tank full)	W Miss	Missing water

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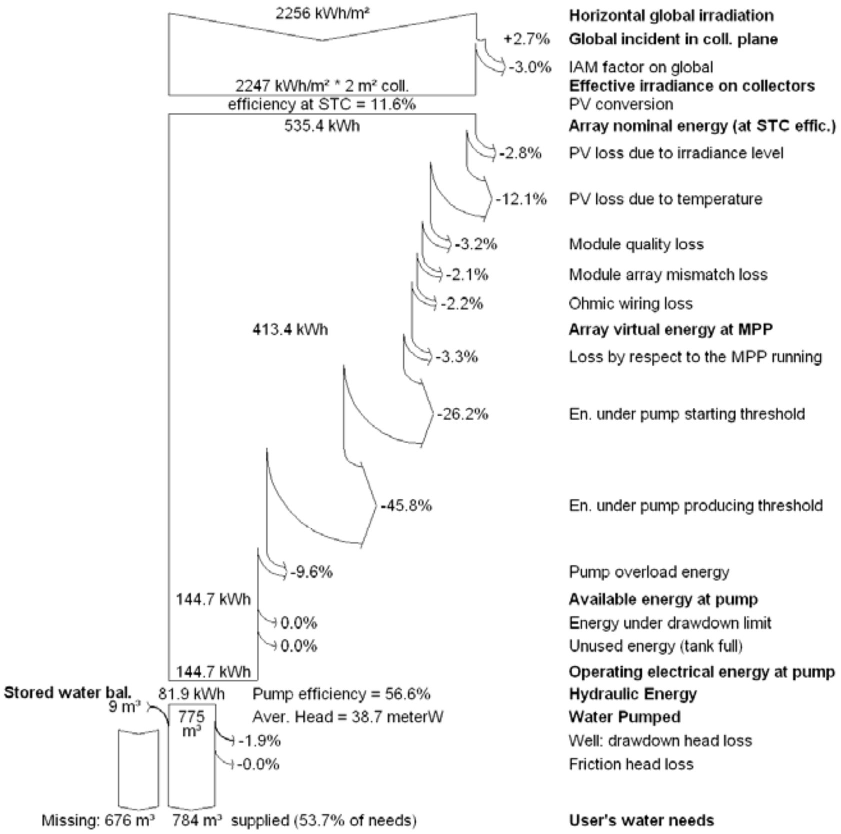
Pumping PV System: Loss diagram

Project : **Dakar_Pumping_DEMO**

Simulation Variant : **4 m3/day, H=38m, PV=240Wp, Pumps: 2 x 98W, direct coupling**

Main system parameters		System type	**Deep Well to Storage**		
System Requirements		Basic Head	38.0 meterW	Water needs	4.0 m³/day
Pumps	2 units	Model / Manufacturer	9300 Series / Shurflo		
PV Array		Model / Manufacturer	AP-6106 / Astro Power		
		Nb. of modules	2 S x 2 P	Array Power	240 Wp
System Configuration		Control Strategy	**Direct coupling**		

Loss diagram over the whole year



Appendix A4. - Typical output report of Economic Evaluation

PVSYST V4.03	Cuepe	19/11/06

Pumping PV System: Economic evaluation

Project : **Dakar_Pumping_DEMO**

Simulation Variant : **4 m3/day, H=38m, PV=240Wp, Pumps: 2 x 98W, direct coupling**

Main system parameters		System type	**Deep Well to Storage**		
System Requirements		Basic Head	38.0 meterW	Water needs	4.0 m³/day
Pumps	2 units	Model / Manufacturer	9300 Series / Shurflo		
PV Array		Model / Manufacturer	AP-6106 / Astro Power		
		Nb. of modules	2 S x 2 P	Array Power	240 Wp
System Configuration		Control Strategy	**Direct coupling**		

Investment

PV modules (Pnom = 60 Wp)	4 units	500 FS / unit	2000 FS
Supports / Integration		200 FS / module	800 FS
Pumps (Pnom = 98 W)	2 units	760 FS / unit	1520 FS
Controller			560 FS
Settings, wiring, ...			1000 FS
Transport and assembly			2500 FS
Engineering			500 FS
Substitution underworth			-0 FS
Gross investment (without taxes)			**7360 FS**

Financing

Gross investment (without taxes)		7360 FS
Taxes on investment (VAT)	Rate 20.0 %	1472 FS
Gross investment (including VAT)		8832 FS
Subsidies		-0 FS
Net investment (all taxes included)		**8832 FS**
Annuities	(Loan 5.0 % over 20 years)	709 FS/year
Annual running costs: maintenance, insurances ...		352 FS/year
Total yearly cost		**1061 FS/year**

Water and Energy cost

Energy used for pumping	147 kWh / year
Excess energy (tank full)	0.0 kWh / year
Cost of used energy	7.22 FS / kWh
Water Pumped	764 m³
Cost of pumped water	**1.39 FS / m³**