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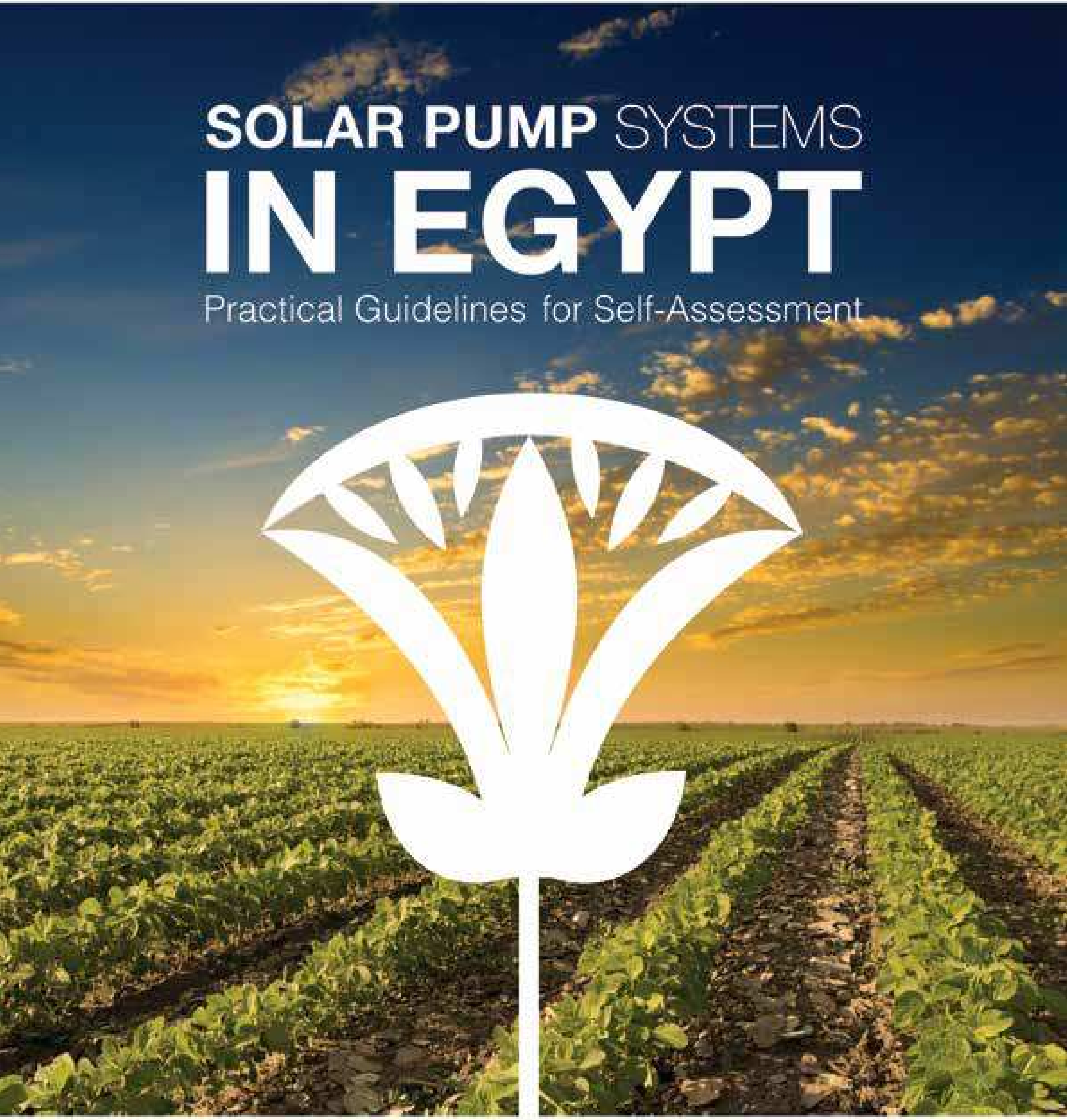
SOLAR PUMP SYSTEMS IN EGYPT

Practical Guidelines for Self-Assessment



RaSeed GREEN ENERGY IN AGRICULTURE
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SOLAR PUMP SYSTEMS
IN EGYPT
Practical Guidelines for Self-Assessment

Solar Pump Systems in Egypt

Executive Summary

Cost effective, reliable and sustainable systems for the long-term are needed to ensure essential irrigation in the agricultural sector of Egypt. The currently used diesel powered systems are becoming more and more unsustainable due to rising costs and unreliable supply of fossil fuels. With Egypt's optimal geographic location in the global sunbelt, the use of solar powered pump systems in agricultural irrigation is a viable alternative to fuel powered solutions.

These guidelines assess and provide an overview of various solar pump systems for irrigation, their optimal use and the required prerequisites.

Key factors in deciding on an optimal solar pump system are whether a farm has an existing irrigation system in place or is newly constructed, and whether a single or multiple wells are to be connected via a stand-alone or hybrid solar energy solution.

Stand-alone systems for direct irrigation provide a very simple solution, with the pump and a solar inverter being directly connected; however, no backup power source is available. Solar energy for irrigation is accessible during solar hours only. To avoid fluctuations in the irrigation schedule and to prolong irrigation hours one may prefer a hybrid system, which combines solar and diesel power.

Alternatively, to maximize independence of fuel price fluctuation, systems with energy storage in batteries or water storage tanks may be preferable. Here, excess energy produced during peak solar irradiation is either stored in batteries for later pumping activities, or directly used to pump water and store it in tanks for later irrigation.

In the future, a smart mini-grid solution is expected to be the optimal, most cost efficient solution. All active components are connected for communication and transfer of power, regardless of whether conventional generator, solar power systems at different locations, or other energy sources, such as wind energy, are used. This solution optimizes energy production adapted to the required irrigation schedule.

In the design of any system it is crucial to effectively communicate to system providers the exact requirements a new system needs to meet. Thorough communication between the solar system provider and the on-farm irrigation specialist allow the creation of efficient systems, designed to optimally fit the specific farm conditions.

The guidelines address farmers having experience with irrigation. Therefore, hydrological aspects, requirements of plants, irrigation technologies and its components such as wells, reservoirs, pumps, piping and the irrigation system itself are not discussed in this document. Instead, it focuses on eco-efficient irrigation systems. A first step to realize sustainable systems is to save water. Therefore, the considerations in these guidelines are restricted to drip irrigation. Yet, solar systems can be implemented for all irrigation systems.

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1. Introduction

Energy production in Egypt is a highly relevant topic. Fuel prices have been heavily subsidized in the past, which has led to vast overuse and unsustainable practices for electricity generation[1]. These subsidies are continuously being cut, leading to higher fuel prices and thus making formerly economically viable practices unsustainable. Egypt is experiencing a period of population growth and urbanization, which increases both, the demand for food and the demand for energy. Due to the pace of this process, the electrical grid is unreliable and fuel shortages occur. Agriculture in remote areas is especially affected by crop loss resulting from fuel shortage. Farms require large amounts of diesel to run irrigation pumps. The transportation and storage costs, combined with rising fuel prices make this practice of irrigation more and more difficult to maintain.

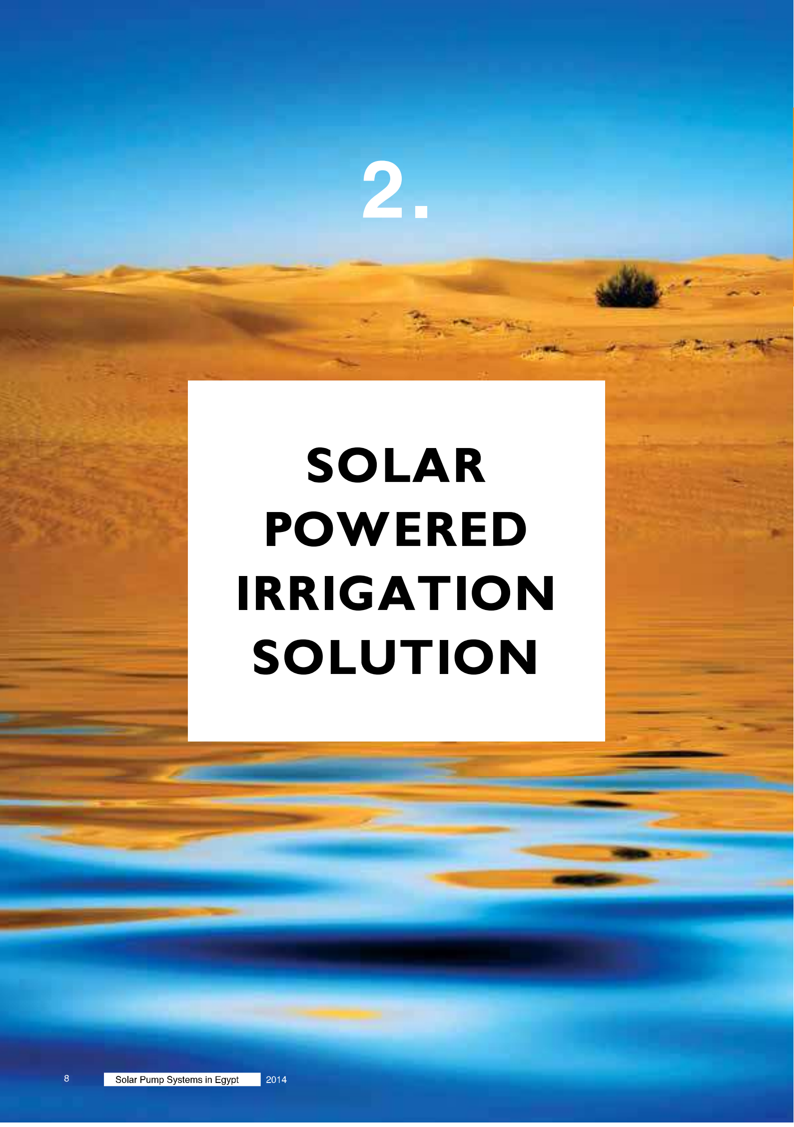
Egypt's geographic position is within the global sunbelt. Yearly, up to 2,600 kWh/m2 have been recorded. An irradiation exposure of this level, together with the country's vast empty desert area, provides an ideal condition for the use of solar power. A solar power system, also known as a photovoltaic system, generates ready to use electrical power by transferring the solar irradiation into electricity.

Solar cells, also called photovoltaic (PV) cells, convert sunlight directly into electricity. PV gets its name from the process of converting light (photons) to electricity (voltage), which is called the PV effect. The effect was first recognized in 1954 when scientists at Bell Telephone discovered that silicon created an electric charge when exposed to sunlight. Soon after, solar cells were being used to power space satellites and smaller items such as calculators and watches. Today, millions of people power their homes and businesses with individual solar PV systems. Utility companies are also using PV technology for large power stations.

While economic considerations, such as rising fuel prices or shortage of fuel, are crucial factors in the decision for solar system implementation, environmental factors also play a deciding role. The use of a solar pump system demonstrates clear superiority to a diesel generator driven system, both in terms of environmental protection and sustainable agriculture practices. Today – as from the very beginning of agriculture – natural energy and sustainable farming go hand in hand. The growing of crops is a silent process – as is solar power generation. Healthy food, alongside water, is a highly valuable good, and does not correlate with an environment of highly polluted air from diesel generators. Fresh, clean and sustainable is what we expect in healthy food, and thus also from agriculture practices. Solar pump systems are an integral part of these expectations.

The use of solar energy for pumping systems can save both water and energy. Through optimal matching of the irrigation schedule and the solar plant, an efficient system can be implemented. Considerable savings of water – and energy – are achieved. Solar pump systems have been in use in small and medium size farming applications for decades. As an economically viable alternative to fossil fuels in off-grid applications, solar pump systems reliably provide water for connected irrigation systems. Due to a vmarket responsive development of PV systems worldwide, prices have dropped substantially. Especially commercial large-scale applications profit from this development. They reduce their dependence on fossil fuels and thus limit their exposure to rising energy prices.

[1]El-Katiri, L. (2014). A Roadmap for Sustainable Energy for the Middle East and North Africa. The Oxford Institute for Energy Studies.

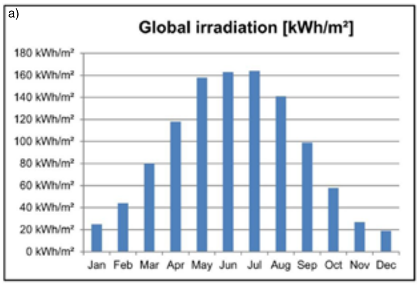


2.

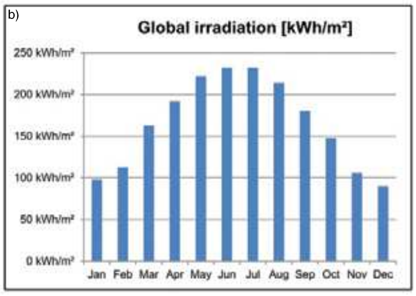
SOLAR POWERED IRRIGATION SOLUTION

A solar powered irrigation system is a complete system which provides fresh water from a well or reservoir for use in households, industries or agriculture, powered by solar energy.

Egypt is one of the richest countries in the world with regard to solar energy potential. On average there are 330 to 340 sunny days per year. This results in yearly irradiation energy in Cairo of 1,990 kWh/m2, which is the energy equivalent to 200 liters of diesel per/m2 r . In Germany this value is about two times lower, because of low irradiation during winter.



Global irradiation [kWh/m²] *	
Jan	25 kWh/m²
Feb	44 kWh/m²
Mar	80 kWh/m²
Apr	118 kWh/m²
May	158 kWh/m²
Jun	163 kWh/m²
Jul	164 kWh/m²
Aug	141 kWh/m²
Sep	99 kWh/m²
Oct	58 kWh/m²
Nov	27 kWh/m²
Dec	19 kWh/m²
Total:	1,096 kWh/m²



Global irradiation [kWh/m²] *	
Jan	98 kWh/m²
Feb	113 kWh/m²
Mar	163 kWh/m²
Apr	192 kWh/m²
May	222 kWh/m²
Jun	232 kWh/m²
Jul	232 kWh/m²
Aug	214 kWh/m²
Sep	180 kWh/m²
Oct	148 kWh/m²
Nov	106 kWh/m²
Dec	90 kWh/m²
Total:	1,990 kWh/m²

Figure 2: Global irradiation Würzburg (a) and Cairo (b). (Source: Aschoff Solar)

Throughout the year irradiation levels and the corresponding potential energy production varies (Figure 3).

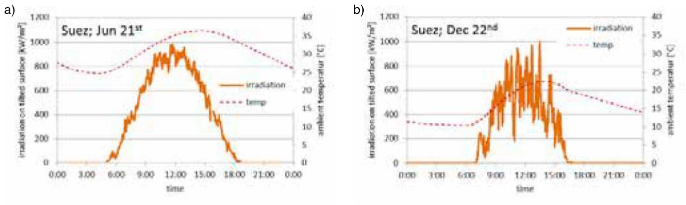


Figure 3: (a) A typical summer day / (b) A typical winter day in Suez– Egypt; latitude = 29.98°; longitude = 32.55°; height = 30 m a.s.l.; azimuth = 0°; inclination = 25°

As agricultural irrigation systems require a constant water supply, technological solutions are implemented to counteract the varying energy output of solar pump systems. Irrigation systems often call for daily operation times of up to 16,in some cases even 24 hours. However, the solar operation hours depend on latitude, date (hours of daylight in Cairo 14 hr in June; 10 hr December), weather conditions and the relation between installed PV and load. An average value from practical experiences of daily solar operations hours lies at 6-8 hr. In order to compensate for this divergence, solar pumps are integrated in a solar irrigation system designed to specific, local needs.

The challenge for both designers and operators of solar irrigation systems is to harmonize the non constant solar energy and the constant irrigation requirements via the innovative design and use of solar pump system technologies. The better the energy supply and irrigation requirements can be harmonized, the more water and cost efficient the irrigation operation will be.

An independent system, i.e. without need for back-up energy or water/energy storage, is possible when required irrigation time corresponds to the local level of solar hours and when irrigation schedules have flexible flow-rates. When longer irrigation times are required, various hybrid system solutions can be considered.

Properties of well	
Max. well withdrawal	100 m³/hr
Requirements of the plants	
Daily irrigation time	12 hr
Properties of PV-system and site, date:	
Solar operation time	8 hr

	Case I	Case II
Requirement		
actual flow-rate	60 m³/hr	90 m³/hr
Consequences		
Daily water demand	720 m³/hr	10,080 m³/hr
Flow-rate with solar system	90 m³/hr (< max. well withdrawal)	135 m³/hr (> max. well withdrawal)
Allowed flow-rate with regard to max. well withdrawal	✓	✘
Possible solar solution	PV stand-alone with water reservoir	PV hybrid system or PV-battery system

Table 1: Example: Selection of adequate PV-pump systems for two cases

Because of the boundary condition that irrigation must run 12 hours a day, Case I in the example can only be realized with a simple PV-Pump system without batteries in combination with a high-level water reservoir as storage. Precondition for such a solution is that the irrigation works gravimetrically with a high-level water reservoir and that the realization of a water reservoir on a higher level is possible at the site.

Because of the limitations of the well (maximal flow-rate of withdrawal 100 m³/hr) Case II can only be realized with an energy supply allowing an operation of the pump for at least 11 hours a day. Therefore, a PV-battery system or a PV-hybrid system can meet the requirements.

2.1. Solar Pump Concepts

Single well or multi-well systems

Single well describes a solution for one well/one pump, combined with one solar system.

Multi-well describes a solution where several wells/pumps are connected together to a small grid with a central or decentralized power supply.

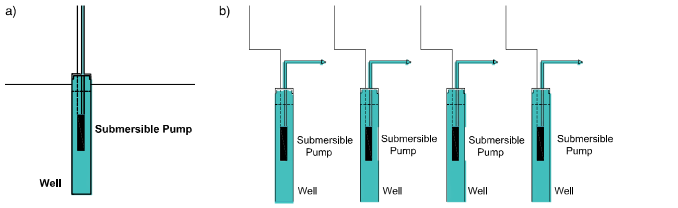


Figure 4: Single well (a) and multi-well (b) systems (Source: Jorg Steinke)

Stand-alone or hybrid systems

In a stand-alone solution, solar energy is the only source of power.

Hybrid solutions describe systems which combine solar power with other power sources, such as diesel generators, wind energy or the public grid. Although only a limited percentage of the total energy requirement can be provided through solar panels, significant fuel and thus cost savings occur. Additionally, there are decreased maintenance and replacement costs for the diesel generators, as their daily operation time is reduced.

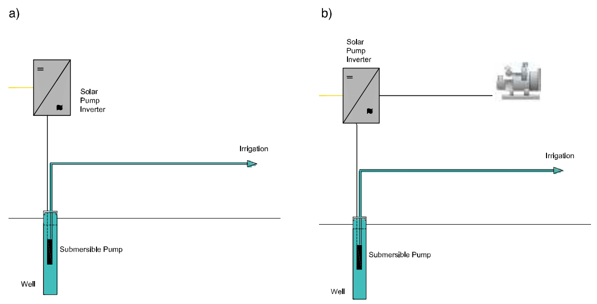


Figure 5: Stand-alone (a) and simple hybrid (b) system

Systems with or without batteries

Solar pump systems can be equipped with batteries to increase the operation time of the pump, even up to a total of 24 hours independent solutions. Batteries can be used to store electricity produced during solar hours for energy use during non-solar hours.

Systems without batteries or other storage solutions require a hybrid operation if the irrigation profile requires more water than can be supplied during solar hours, or if irrigation is required during the non-solar period.

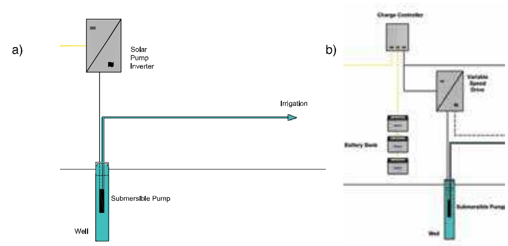


Figure 6: Systems without (a) or with batteries (b) (Source: Jorg Steinke)

With or without water storage

Systems, which include a water reservoir, save all excess water pumped during solar hours in tanks. When needed during non-solar hours, the water is supplied from these storages either via small booster pumps (ground level tank) or gravity (high level tank). This system requires a high performing well, as the pump runs at high capacity during peak solar hours. If the well is limited, the amount of water cannot be extended during solar hours and hence may be insufficient for storage. When designing new farms, the maximum flow rate of water withdrawal of each well must be assessed carefully. As a rough rule of thumb, the ratio of feddan[2] to well is typically 100 feddan/well. This value of the irrigated area per well depends on the performance of the wells, the crops and their water demand, the irrigation technology and a lot of other parameters. Well performance and water demand of the plants both usually vary throughout the year.

Figure 8 shows the effect of using water storage together with a stand-alone PV-Pump system without batteries. A system without a storage option can only directly use the pumped water for irrigation. In the first example (Figure 8 ii) iii)) a constant flow rate of the irrigation system over 24 hr can be realized, despite of a fluctuating profile of the water withdrawal from the well. Figure 8 iii) shows that the total amount of water used for 24 hr-irrigation is equal to the amount, which was pumped from the well to the high-level tank by the PV-Pump system during more or less 8 hours. In the second example (Figure 8 iv) v)) irrigation takes place in the early morning and in the evening. The high-level reservoir allows such an irrigation profile independently from the pump flow rate. Figure 8 v) shows the effect of storing water even for a longer period if the daily demand is lower than the amount of pumped water.

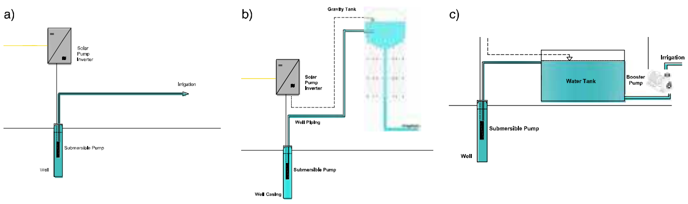
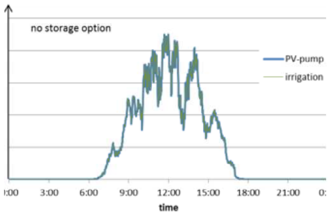


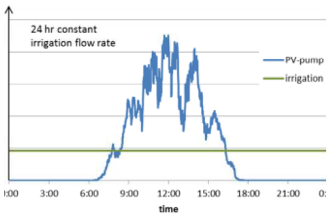
Figure 7: Systems without water storage (a); with high-level tank/reservoir (b), with low-level reservoir and booster pump (c). (Source: Jorg Steinke)

[2]Feddan is a unit of area, used in Egypt. 1 feddan = 24 kirat = 4200 m^2 = 0.42 hectares = 1.038 acres

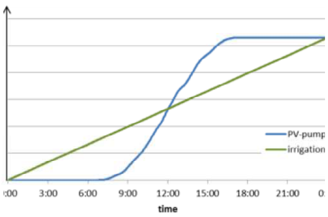
i)



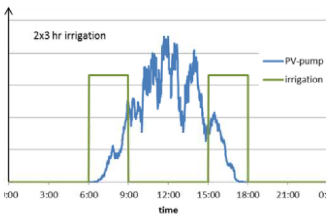
ii)



iii)



iv)



v)

Figure 8: Effect of using a high-level reservoir together with a PV-pump system; Example (i) without storage option; flow rate of pump and irradiation are equal; Example (ii): with water reservoir; flow rate of irrigation can be constant for 24 hr; the total amount of pumped water (cumulated flow-rate or volume) and total amount of water for irrigation are equal (iii); Example (iv): with water reservoir; special irrigation profiles can be realized; the total amount of pumped water is higher than the amount of water used for irrigation(v).

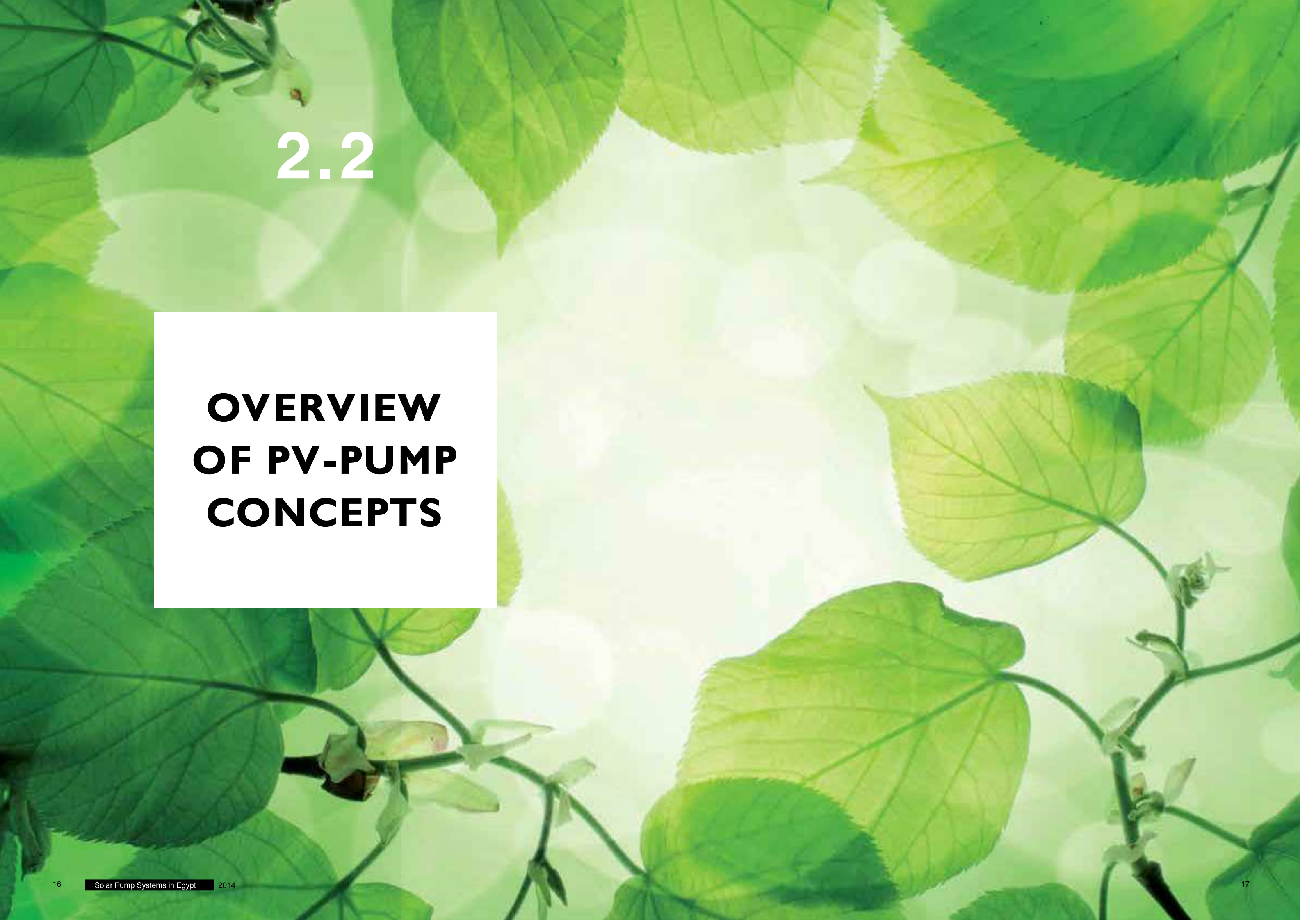
Design for Existing Farms and Wells

When solar energy systems are implemented onto existing farms, the implemented system design is not always free to exploit maximum cost saving potential. Due to currently owned components, such as generators or pumps, compromises may be required. Thus, the solar system is often designed as a fuel saving add-on by constructing a hybrid system with switch operation, or as stand-alone system with batteries.

Existing farms often serve 100 feddan per well. The flow rates of these wells can often not be increased because of issues such as salinity of the ground water. Another limiting factor is the need for free space to install solar arrays.

Design for New Farms and Wells

The design of new farms or irrigation systems offers the opportunity for efficient and cost effective designs. The ratio of irrigated feddan per well are flexible and adaptable according to the required schedules and the well performance. On new farms it is possible to realize single well concepts, especially if the conditions on site (e.g. distances, accessibility of a well etc) do not allow a clustering of wells. But the full potential of solar energy can be best utilized with multi-well concepts combined with integrated storage concepts of underground, on-ground or high level storages.



2.2

OVERVIEW OF PV-PUMP CONCEPTS

A. Stand-Alone System for Direct Irrigation

Basics of system design

Stand-alone systems for direct irrigation are the simplest way to set up a solar pump system. The pump is directly connected to a solar pump inverter and starts to operate in the mornings when the solar output is higher than the minimum power required to start the pump. The solar system keeps the pump running as long as sufficient irradiation is available. The pump stops before sunset, when the solar output power is less than the minimum input power required for the pump. During the day the flow-rate of water varies with the solar irradiation. Throughout the year, the daily water volume changes with the daily and seasonal profile of solar irradiation.

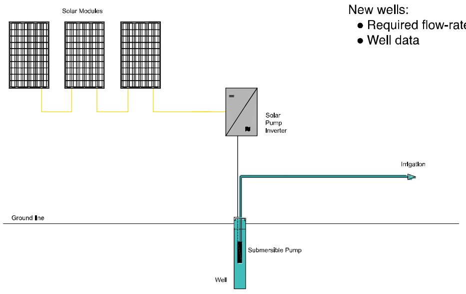


Figure 9: System scheme – Stand-alone system for direct Irrigation (Source: Jorg Steinke)

Suitable applications

- Existing or new wells
- Irrigation systems using a demand profile similar to the solar irradiation profile
- Irrigation for non-critical crops (as output is dependent on amount of solar hours)
- Realized systems where the fluctuating pumping power is not a problem for the irrigation systems (pressure and flow-rate)

Data needed to enable design

New wells:
- Required flow-rate
- Well data

Existing wells:
- Hydraulic power of the pump[3]
- Type and characteristics of wells[4]
- Location

Required components

- Submersible pump (new or existing)
- For smaller systems (< 5 kw) with high pump head and moderate flow-rate, positive displacement pumps such as screw-pumps are recommended
- Solar pump inverter[5] or conventional variable speed drives (VSD) with external or internal possibility to realize maximum power point tracking (MPP tracking)
- String combiner box, if required by the solar pump inverter
- Array with pv modules
- Support structure for the pv modules
- Dc and ac wiring

Design outcomes

- Daily and/or monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation

[3] Pump head from well (dynamical pump head, seasonal dependency of pump head, pressure loss from piping and irrigation system
[4] Characteristic curve of whole system (seasonal dependency); max. flow-rate of withdrawal
[5] See also chapter 4.1.3 „Solar Inverters"
[6&7] See Glossary

Limitations

- Irrigation only during solar hours, according to solar irradiation
- Variable water delivery throughout day and year
- Limitation through nominal pressure of piping system

Advantages

- Low costs
- No special automated control necessary
- Easy to install and maintain

Maintenance

- Cleaning of modules every 1 to 3 months, according to environmental conditions
- System check every 6 months

Cost structure

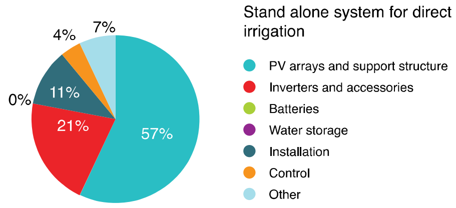


Figure 10: Cost structure – Stand-alone system for direct irrigation

Table 2: Assessment of economics – Stand-alone system for direct irrigation

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[8]
New installation				

System essentials

- Solar pump inverter or similar power electronic devices (e.g. conventional VSDs) should allow MPP tracking
- Adaptation of the pumping power to the solar power supply should be used
- Pump should run with VSD in a wide range of flow-rate[9]
- Certain ratio between PV size and pump size is necessary to ensure full operation time throughout the year and for the expected lifetime

[8] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.
[9] Startup of pump at low frequency, ability to reach high frequency to create maximum energy

B. Stand-Alone System for Direct Irrigation with Batteries

Basics of system design

Stand-alone systems with batteries used for direct irrigation prolong the operating time of solar pump systems, as compared to systems without batteries. For systems with an equal fraction of installed solar power and power demand of the pump, a relatively small battery can store the energy which is not sufficient yet for the solar pump to run in the morning and afternoon. This energy can later be used to prolong the operation time of the pump. In this system, the total operation time will not be significantly increased, but rather the efficiency of the whole system will be improved. In stand-alone systems with higher solar power and higher battery capacity, up to 24h continuous operation can be realized. Solar power is either stored in the battery or drives the pump directly when solar power is sufficient to run the pump. In case of lower solar power or during the night, the pump is driven by the battery power. The pump continues to run as long as sufficient irradiation or battery power is available.

Suitable applications

- Existing or new wells
- Irrigation systems with a required irrigation time longer than solar hours
- Limited well capacity (flow-rate of withdrawal)

Data needed to enable design

New wells:
- Required flow-rate
- Well data
- Irrigation schedule
- Location

Existing wells:
- Hydraulic power of the pump
- Type and characteristics of wells
- Irrigation schedule
- Location

Required components

- Submersible pump (new or existing)
- Solar pump inverter or conventional vsd with external or internal possibility to realize mpp tracking
- String combiner box, if required by the solar pump inverter
- Batteries and battery charge control
- Array with pv modules
- Support structure for the pv modules
- Dc and ac wiring

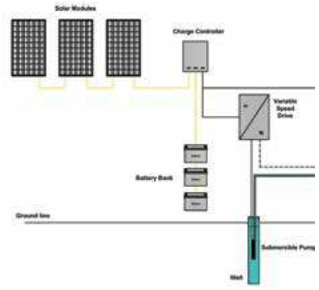


Figure 11: System scheme – Stand-alone system for direct Irrigation with batteries (Source: Jorg Steinke)

Design outcomes

- Daily and/or monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation

Limitations

- Irrigation limited according to solar system design and battery capacity
- Higher costs due to batteries and charge control
- Limited lifetime of standard battery technologies

Advantages

- Fully independent irrigation system
- Higher solar fraction than systems without batteries
- Easy to install
- Standard inverters can be used in combination with frequency inverters for the pump

Maintenance

- Cleaning of modules every 1 to 3 months, according to environmental conditions
- System check every 6 months
- Battery check according to battery technology

Cost structure

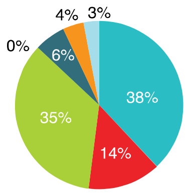
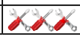


Figure 12: cost structure - Stand-alone system for direct irrigation with batteries

Table 3: Assessment of economics – Stand-alone system for direct irrigation with batteries

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[10]
New installation				

System essentials

- Charge control and battery dimensioning need to avoid deep discharge within the daily cycle, as the level of discharge has strong influence on the lifetime of the batteries
- Protection against total discharge of batteries must be ensured
- Use of suitable batteries which fit to the environmental circumstances

[10] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.

C. Stand-Alone System with High-Level Water Storage

Basics of system design

Stand-alone systems with high-level storage are the most popular systems in Asia. The operation time of the irrigation system is independent from the pumping operation. The full day demand for irrigation is pumped into the high-level water reservoir and released under constant pressure based on gravity (no booster pump). The pump operation and daily profile of water flow-rate to the tank is similar to stand-alone systems for direct irradiation (see System A).

Suitable applications

- Existing or new wells
- Any irrigation profile

Data needed to enable design

New wells:

- Required flow-rate
- Well data
- Irrigation schedule
- Information on ground/soil
- Location

Existing wells:

- Hydraulic power of the pump
- Type and characteristics of wells
- Irrigation schedule
- Information on ground/soil
- Location

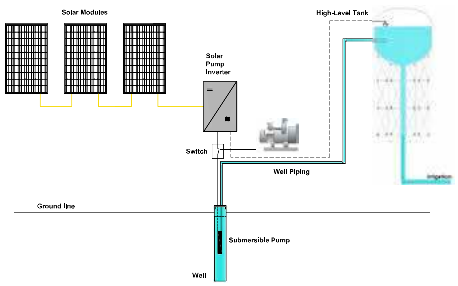


Figure 13: System scheme – Stand-alone system with high-level water storage (Source: Jorg Steinke)

Required components

- Submersible pump (new or existing)
- Solar pump inverter or conventional VSD with external or internal possibility to realize mpp tracking
- String combiner box, if required by the solar pump inverter
- Array with PV modules
- Support structure for the pv modules
- Dc and ac wiring
- Foundation for high-level tank
- Infrastructure for high-level tank
- High-level water tank/reservoir with water level sensor

Design outcomes

- Daily and/or monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation

Limitations

- Terrain must be suitable to support concept with high-level tank/reservoir
- Performance of well must allow to pump total daily demand during the solar hours
- Height of high-level tank must meet pressure requirements of irrigation system

Advantages

- Lower storage costs than for batteries
- No special control necessary
- Constant pressure on irrigation system
- No booster pump for irrigation required
- Irrigation schedule independent from pumping profile

Maintenance

- Cleaning of modules every 1 to 3 months, according to environmental conditions
- System check every 6 month
- Check tank/reservoir for corrosion; frequency depends on material and technology used

Cost structure

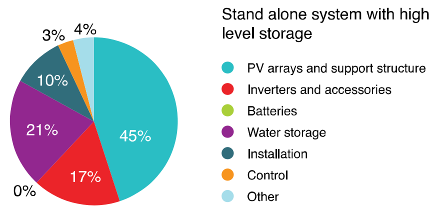


Figure 14: Cost structure - Stand-alone system with high-level water storage

Table 4: Assessment of economics – Stand-alone system with high-level water storage

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[11]
New installation				
Existing farm	[12]	No difference		

System essentials

- Solar pump inverter or similar power electronic devices (e.g. conventional VSDs) allowing MPP tracking and adaptation of the pumping power to the solar power supply should be used
- Pump should run with VSD in a wide range of flow-rate
- Certain ratio between PV size and pump size is necessary to ensure full operation time throughout the year and throughout the expected lifetime
- Tank/reservoir has to be protected against corrosion

[11] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.
[12] If high-level storage already exists

D. Stand-Alone System with Ground-Level Storage, Batteries & Booster Pump

Basics of system design

Combining a stand-alone system with a ground-level storage tank and booster pump are used to reduce the construction costs of the storage tank, or when high-level tanks cannot be built due to unstable terrain on the farm. The operation time of the irrigation system is independent from the pumping operation.

The full day water demand for irrigation is pumped into the water reservoir on the ground and then extracted from the tank with the help of a booster pump. The booster pump is driven by the solar system during solar hours and from batteries during the night. The advantage of this system, as compared to full battery systems (see system B), is that battery capacity can be lower and thus costs are decreased. Only the pressure and flow-rate for the irrigation have to be included in the design, as the energy to pump the water to the surface is completely supplied during daytime from the solar system. The pump operation and daily profile of water flow-rate to the tank is similar to stand-alone systems for direct irrigation (see system A).

Suitable applications

- Existing or new wells
- Any irrigation profile
- Any irrigation technology

Data needed to enable design

New wells:

- Required flow-rate
- Well data Irrigation schedule
- Information about existing tank (volume, material etc.), or space for new tank
- Location

Existing wells:

- Hydraulic power of the pump
- Type and characteristics of wells
- Irrigation schedule
- Information about existing tank (volume, material etc.), or space for new tank
- Location

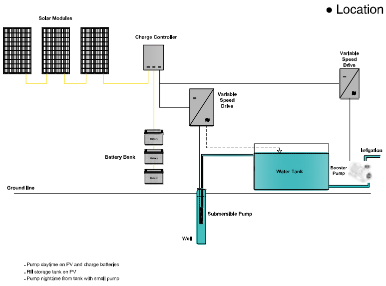


Figure 15: System scheme – Stand-alone system with ground-level storage, batteries and booster pump (Source: Jorg Steinke)

Required components

- Submersible pump (new or existing)
- Booster pump
- Automation
- Solar pump inverter or conventional VSD with external or internal possibility to realize MPP tracking
- String combiner box, if required by the solar pump inverter
- Batteries and battery charge control
- Array with PV modules
- Support structure for the PV modules
- Dc and AC wiring
- Infrastructure for ground-level reservoir
- Ground-level water tank/ reservoir with water level sensor

Design outcomes

- Daily, monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation

Limitations

- Terrain must be suitable to support concept with ground-level tank/reservoir
- Well performance must allow to pump total daily demand during solar hours

Advantages

- Reduced battery costs
- Constant pressure on irrigation system
- Simple construction of ground reservoir
- Irrigation schedule independent from pumping profile
- Standard inverters can be used in combination with frequency inverters to operate the pump
- Energy management possible

Maintenance

- Cleaning of modules every 1-3 months, according to environmental conditions
- System check every 6 months
- Check of tank/reservoir for corrosion; frequency depends on material and technology used
- Battery check according to battery technology
- Maintenance for booster pump according to supplier guidelines

Cost structure

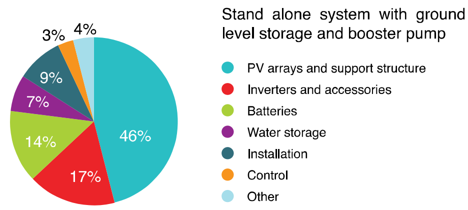
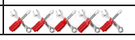


Figure 16: Cost structure - Stand-alone system with ground-level storage, batteries and booster pump

Table 5: Assessment of economics – Stand-alone system with ground-level storage, batteries and booster pump

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[13]
New installation				
Existing farm	 [14]	No difference		

System essentials

- Charge control and battery dimensioning need to avoid deep discharge within the daily cycle
- The level of discharge has strong influence on the lifetime of the batteries
- Protection from a total discharge of battery must be ensured
- Batteries need to fit to the environmental circumstances
- Tank/reservoir has to be protected against corrosion

[13] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.
[14] If high-level storage already exists

E. Solar / Diesel Hybrid System with Switch Operation (and high-level storage)

Basics of system design

Hybrid systems with switch operation are simple to set up within existing farms, as only a solar system is added to the well. During solar hours the solar system runs the pump with the same principle as for a stand-alone system. During the irrigation, the solar system runs the pump directly at varying flow-rates according to the available irradiation. If no solar power is available, the system switches to the diesel generator operation. The switch can be done manually or automatically, depending on the diesel generator control options. The operation time of the irrigation system is independent from the solar pumping operation. Savings of fuel, and therefore of costs are achieved dependent on the total required irrigation time and the designed operation time of the solar system.

If the system additionally allows the use of a high-level reservoir this is a good solution when the well performance does not allow pumping the total daily demand during daytime. The water storage allows an irrigation schedule which differs from the pumping schedule, e.g. when irrigation is mainly required during evening and at night, while the pumping mainly occurs during daytime. The solar system pumps as much water as possible into the high-level tank during day light hours and the remaining required amounts are pumped by diesel generator operation. The water for irrigation is taken out under constant pressure conditions based on gravity (no booster pump)

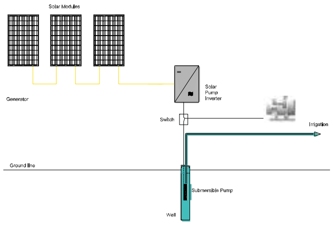


Figure 17: System scheme - Solar / Diesel hybrid system with switch operation (Source: Jorg Steinke)

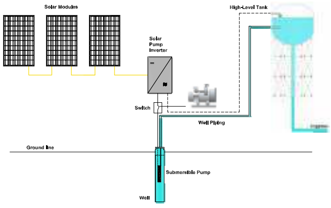


Figure 18: System scheme - Solar / Diesel hybrid system with switch operation and high-level storage (Source: Jorg Steinke)

Suitable applications

- Existing or new wells
- Any irrigation profile

Data needed to enable design

New wells:
- Required flow-rate
- Well data
- Irrigation schedule
- Data of current or planned diesel generator
- Location

Existing wells:
- Hydraulic power of the pump
- Type and characteristics of wells
- Irrigation schedule
- Data of current or planned diesel generator
- Location

Limitations

- Diesel generator needs to allow automated control
- Solar fraction limited, depending on irrigation time
- For option with high-level reservoir:
  - Terrain must be suitable to support concept with high-level tank/reservoir
  - Well performance must allow to pump total daily demand during solar hours

Required components

- Submersible pump (new or existing)
- Solar pump inverter or conventional vsd with external or internal possibility to realize MPP tracking
- String combiner box, if required by the solar pump inverter
- Array with PV modules
- Support structure for the pv modules
- Dc and AC wiring
- Diesel generator and switch control
- Or a VSD which allows to feed in DC solar power directly into the DC intermediate circuit for option
- With additional high-level reservoir:
  - Foundation for high-level tank
  - Infrastructure for high-level tank
  - High-level water tank/reservoir with water level sensor

Design outcomes

- Daily and/or monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation
- Solar fraction regarding water supply and energy

Maintenance

- Cleaning of modules every 1-3 months, according to environmental conditions
- System check every 6 months
- Check tank/reservoir for corrosion; frequency depends on material and technology used
- Diesel generator maintenance, according to supplier guidelines

Advantages

- Lower costs than battery solutions
- Easy to install
- No booster pump for irrigation required
- Operation time not limited to solar hours
- Reduced maintenance
- Longer diesel generator lifetime
- Existing diesel generators can be used
- In case of using a high-level reservoir:
  - No booster pump for irrigation required
  - Constant flow-rates and pressure on irrigation

Cost structure

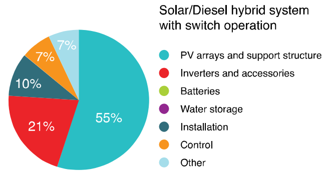


Figure 19: Cost-structure - system scheme - Solar / Diesel hybrid system with switch operation

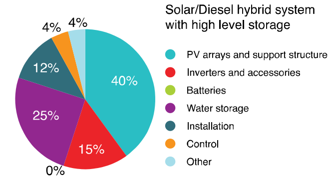


Figure 20: Cost structure - System scheme - Solar / Diesel hybrid system with switch operation and high- level storage

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[15]
New installation (in brackets: with high-level storage)	$$$ ($$$$)	$$	🔧🔧	☀☀
Existing farm (in brackets with high-level storage)	$$ ($$$)	$$$	No difference	

System essentials

- Solar pump inverter or similar power electronic devices (e.g. conventional VSDs) should allow MPP tracking
- Adaptation of the pumping power to the solar power supply should be used
- Pump should run with VSD in a wide range of flow-rate
- Certain ratio between PV size and pump size is necessary to ensure full operation time throughout the year and throughout the expected lifetime
- In case of using a high-level tank:
  - Tank/reservoir has to be protected against corrosion

[15] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.

F. Solar / Diesel Hybrid System with Batteries

Basics of system design

Hybrid systems with batteries can be designed to provide up to 100% solar solutions, with a diesel generator as a backup for critical crops. This system is normally designed to provide a reasonable solar fraction. A large fraction provided by the solar system, with the diesel generator running in case of longer non-solar periods or periods with low irradiation. During the irrigation time, the solar system runs the pump directly via the solar pump inverter. If none or too little solar power is available to run the pump, the system is driven by energy from the batteries. The batteries are always kept in optimized charge level by the solar system and/or the diesel generator. The operation time of the irrigation system is independent from the solar operation. Achievable savings of fuel and therefore of costs depend on the total required irrigation time and the designed operation time of the solar system and batteries.

Suitable applications

- Existing or new wells
- Any irrigation profile

Data needed to enable design

New wells:
- Required flow-rate
- Well data
- Irrigation schedule
- Data of current or planned diesel generator
- Location

Existing wells:
- Hydraulic power of the pump
- Type and characteristics of wells
- Irrigation schedule
- Data of current or planned diesel generator
- Location

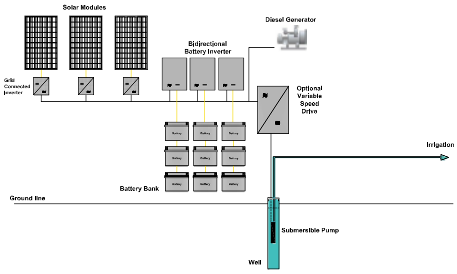


Figure 21: System scheme - Solar / Diesel hybrid system with batteries (Source: Jorg Steinke)

Required components

- Submersible pump (new or existing)
- Solar pump inverter or conventional VSD with external or internal possibility to realize MPP tracking
- String combiner box, if required by the solar pump inverter
- Batteries and battery charge control
- Array with PV modules
- Support structure for the PV modules
- DC and AC wiring
- Diesel generator and switch control

Design outcomes

- Daily and/or monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation
- Solar fraction regarding water supply and energy

Limitations

- Diesel generator needs to allow automated control
- Solar fraction depends on irrigation time and design of solar system and batteries

Maintenance

- Cleaning of modules every 1-3 months, according to environmental conditions
- System check every 6 months
- Battery check according to battery technology
- Diesel generator maintenance, according to supplier guidelines

Advantages

- Higher solar fraction than switch systems
- Possible to use smaller diesel generators than those used for switch operation
- Operation time not restricted to day time
- No booster pump required for irrigation
- Reduced maintenance and increased diesel generator lifetime
- Standard inverters can be used in combination with frequency inverters for the pump
- Existing diesel generators can be used

Cost structure

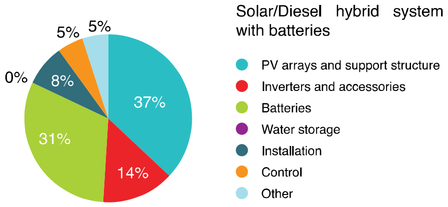


Figure 22: Cost structure - Solar / Diesel hybrid system with batteries

Table 7: Assessment of economics – Solar / Diesel hybrid system with batteries

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[16]
New installation	$ $ $ $	$ $ $	🔧🔧🔧🔧	⛅⛅⛅
Existing farm	$ $ $	$ $ $ $	No difference	

System essentials

- Charge control and battery dimensioning needed to avoid deep discharge within the daily cycle
- The level of discharge has strong influence on the lifetime of the batteries
- Protection from a total discharge of battery must be ensured
- Batteries need to fit to the environmental circumstances

[16]The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.

G. Solar / Diesel Hybrid Systems with Ground-Level Storage & Booster Pump

Basics of system design

Hybrid systems with ground-level storage tank and booster pump are chosen when a compromise is needed to reduce the costs of storage tanks, or if high-level tanks cannot be built due to unsuitable terrain on the farm. The operation time of the irrigation system is independent from the pumping operation.

The total daily demand for irrigation is pumped into the water reservoir on the ground and then extracted from the tank with the help of a booster pump. The booster pump is driven by the solar system during daytime and during the night by batteries. Compared to full battery systems (see systems B and F), the advantage of this system is, the required battery capacity is lower and thus costs are lower. Only the pressure and flow-rate for the irrigation needs are supplied by the battery, while the energy to pump the water to the surface is completely supplied from the solar system during daytime. The batteries are always kept at the necessary charge level by the solar system and/or the diesel generator.

Suitable applications

- Existing or new wells
- Any irrigation profile
- Any irrigation technology

Data needed to enable design

New wells:
- Required flow-rate
- Well data
- Irrigation schedule
- Data of current or planned diesel generator
- Information of existing tank, or space for new tank
- Location

Existing wells:
- Hydraulic power of the pump
- Type and characteristics of wells
- Irrigation schedule
- Data of current or planned diesel generator
- Information of existing tank, or space for new tank
- Location

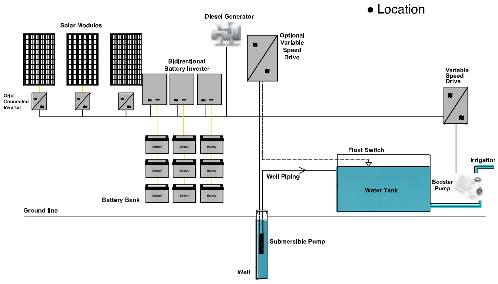


Figure 23: System scheme - Solar / Diesel hybrid systems with ground-level storage and booster pump (Source: Jorg Steinke)

Required components

- Submersible pump (new or existing)
- Booster pump
- Automation
- Solar pump inverter or conventional VSD with external or internal possibility to realize MPP tracking
- String combiner box, if required by the solar pump inverter
- Batteries and battery charge control
- Array with PV modules
- Support structure for the PV modules
- DC and AC wiring
- Diesel generator and switch control
- Infrastructure for ground-level reservoir
- Ground-level tank with water level sensor

Design outcomes

- Daily and/or monthly profile of water supply
- Costs per m³
- Savings compared to diesel operation
- Solar fraction regarding water supply and energy

Limitations

- Terrain must be suitable to support concept with ground-level tank/reservoir
- Diesel generator needs to allow automated control
- Solar fraction depends on irrigation time and design of solar system and batteries
- Well performance must allow to pump total daily demand during solar hours

Advantages

- Higher solar fraction than switch systems
- Possible to use smaller diesel generators than used for switch operation
- Operation time not limited to solar hours
- Constant pressure and flow-rate on irrigation system
- Reduced maintenance, increased diesel generator lifetime
- Existing diesel generators can be used

Maintenance

- Cleaning of modules every 1 to 3 months, according to environmental conditions
- System check every 6 months
- Check of tank/reservoir for corrosion; frequency depends on material and technology used
- Maintenance for diesel generator, according to supplier guidelines
- Maintenance for booster pump, according to supplier guidelines

Cost structure

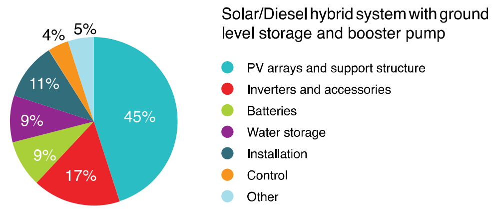
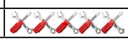


Figure 24: Cost structure - System scheme - Solar / Diesel hybrid systems with ground-level storage and booster pump

Table 8: Assessment of economics – Solar / Diesel hybrid systems with ground-level storage and booster pump

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[17]
New installation				

System essentials

- Charge control and battery dimensioning need to avoid deep discharge within the daily cycle
- The level of discharge has strong influence on the lifetime of the batteries
- Protection from a total discharge of battery must be ensured
- Batteries need to fit to the environmental circumstances
- Tank/reservoir has to be protected against corrosion

[17] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.

H. Solar / Diesel Hybrid System

(fuel saver concept for limited solar fraction and managed system for higher solar fraction)

Basics of system design

Fuel saving solutions can be easily set up in either existing or new farms if several wells are connected to a centralized generator driven grid (multi-well hybrid systems). The solar system is not connected to the pumps directly, but rather to the main distribution board of the grid. This system setup is similar to commonly used system configurations when using solar energy to support other energy sources and to achieve fuel savings. Standard inverter technology for grid connected systems can be used without additional control systems, as long as the solar fraction is in a range which allows the diesel generators to reduce their power based on their internal control mechanism according to the output of the solar system. Depending on the diesel generator, solar power up to 30% of the total load can easily be achieved. In case of higher solar fraction, active management and control of the solar power system and the generators is required.

The passive fuel saver concept for multi-well systems and the multi-well hybrid management system distinguish themselves by the solar fraction. In the passive fuel saver concept, PV is fed in with standard grid inverters up to a share of about 30%. For higher fractions of PV, active control measures have to be carried out to stabilize the energy supply (hybrid management system).

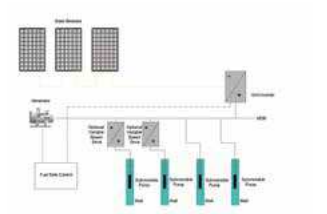


Figure 25: System scheme – Solar / Diesel hybrid system (fuel saver concept for limited solar fraction) (Source: Jorg Steinke)

Required components

- Grid connected inverter
- String combiner box, if required by the inverter
- Array with PV modules
- Support structure for the PV modules
- DC and AC wiring
- In case of higher solar fraction (multi-well hybrid management systems):
  - Power management system
  - Diesel generators allowing part load operation
  - Variable speed drives for the pumps (VSD)

Multi-well hybrid management systems can reach high solar fractions and can be implemented in either existing or new farms when a centralized, diesel generator driven grid is available and the diesel generators can be included in the control management led by the solar system. Both the output of the solar system and of the diesel generator units can be controlled according to the actual load and the availability of solar power. De facto the power from the solar system is throttled down, once the actual load of the diesel generator declines to values lower than 30% of its nominal power. Diesel engines should not run with a load lower than 30% of their nominal power due to incomplete combustion and lowering expected life time of the diesel generator. Only special diesel generators with a sophisticated injection technology can cope with the part load. Solar power of up to 70 or 80% of total power demand is possible, dependent on the diesel generators and the irrigation schedule. Within certain limits, the sizing of the systems can be independent from the total load, as long as the system is large enough to justify efforts and costs for a special control system.

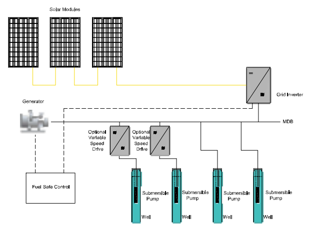


Figure 26: System scheme - Solar / Diesel hybrid system (managed system for higher solar fraction) (Source: Jorg Steinke)

Data needed to enable design

- Power demand profile of grid
- Accurate design data of existing or planned diesel generator is important (flexibility and sizing)
- Location

Suitable applications

- Existing or new farms
- Any irrigation profile
- Especially when a centralized grid is available

Design outcomes

- Lower costs per m³
- Solar fraction regarding power generation

Limitations

- Diesel generator needs to allow automated control
- Solar fraction depends on irrigation time and design of solar system
- Solar fraction depends on flexibility and sizing of diesel generators
- Diesel should not run with a load lower than 30% of its nominal power as incomplete combustion lowers expected life time of the diesel generator
- If the load for the diesel generator declines below 30%, PV has to be throttled down
- In case of higher solar fraction (multi-well hybrid management systems):
  - Special diesel generators need to allow good part load operation and automated control

Advantages

- Sizing of solar power system independent from individual hydraulic power demand of the pump
- Easy to install
- Reduced maintenance, increased diesel generator lifetime
- Aging effect can be neglected
- Standard components for grid connected systems can be used
- No oversizing needed when the solar system is not directly connected to the pump
- Solar fraction naturally decreases from year to year of far less than 1%

Cost structure

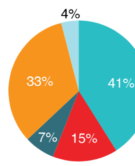


Figure 27: Cost structure - System scheme - Solar / Diesel hybrid management system (managed system for higher solar fraction)

Maintenance

- Cleaning of modules every 1 to 3 months, according to environmental conditions
- System check every 6 months
- Diesel generator maintenance according to guidelines

Table 9: Assessment of economics – Solar / Diesel hybrid system (managed system for higher solar fraction)

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[18]
New installation (in brackets: managed system)	\$ \$	\$ \$ (\$ \$ \$)		
Existing farm (in brackets: managed system)	\$	\$ \$ \$ \$ \$ (\$ \$ \$ \$)	No difference	

System essentials

- The load profile of a diesel generator is essential for an accurate design of a solar power system
- Diesel generators should not be oversized
- Diesel generators should be flexible regarding load adjustment
- Diesel generators should not run with a load lower than 30% of its nominal power

[18] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.

I. Smart Mini-Grid Solutions

Basics of system design

Smart mini-grid solutions will surely be the most optimal solution for farms in the future. They offer the full potential of optimized and efficient irrigation and energy supply. All active components in the grid are connected for exchanging basic information about their state of operation and transfer of power, regardless of conventional diesel generators, solar power systems at different locations, or other energy sources such as wind energy are used. All pumps in the wells are also connected to the grid, as well as to any required batteries. This optimal system is combined with adequate sensors regarding load, irradiation, solar output, as well as the actual needs of the irrigation systems. The central management system decides which of the resources to use and how to distribute the energy. The smart mini-grid solution is already being implemented at the housing and village level, either in the form of on-grid or off-grid. The costs of the current technology is the major limitation at present, especially when battery storage is included. However, a smart mini-grid solution is the key for the future design of new farms, and awareness of opportunities to convert to such systems is essential.

Suitable applications

- New farms
- Any irrigation profile
- Any irrigation technology

Data needed to enable design

- A detailed concept, and thorough communication between operator and system provider

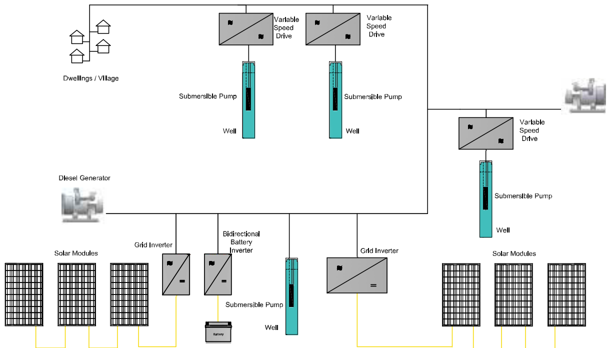


Figure 28: System scheme - Smart mini-grid solutions (Source: Jorg Steinke)

Required components

- Solar inverters
- String combiner box, if required by the solar pump inverter
- Arrays with PV modules
- Support structure for the PV modules
- DC and AC wiring
- Grid management with master slave control
- Slaves control units at each generating or consuming unit
- Diesel generators
- Batteries as option

Design outcomes

- Daily and/or monthly profile of water supply and power generation
- Costs per m³
- Savings compared to diesel operation
- Solar fraction regarding water supply and energy

Limitations

- Accurate data and intensive design period for suitable design is important

Advantages

- Flexible energy and water management
- Modular extendable structure
- Best performance from all components

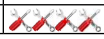
Maintenance

- Cleaning of modules every 1-3 months, according to environmental conditions
- System check every 6 months
- Diesel generator maintenance, according to supplier guidelines

Cost structure

- The cost structure of smart mini-grid solutions is specific for each project. A general estimate of the cost structure cannot be calculated.

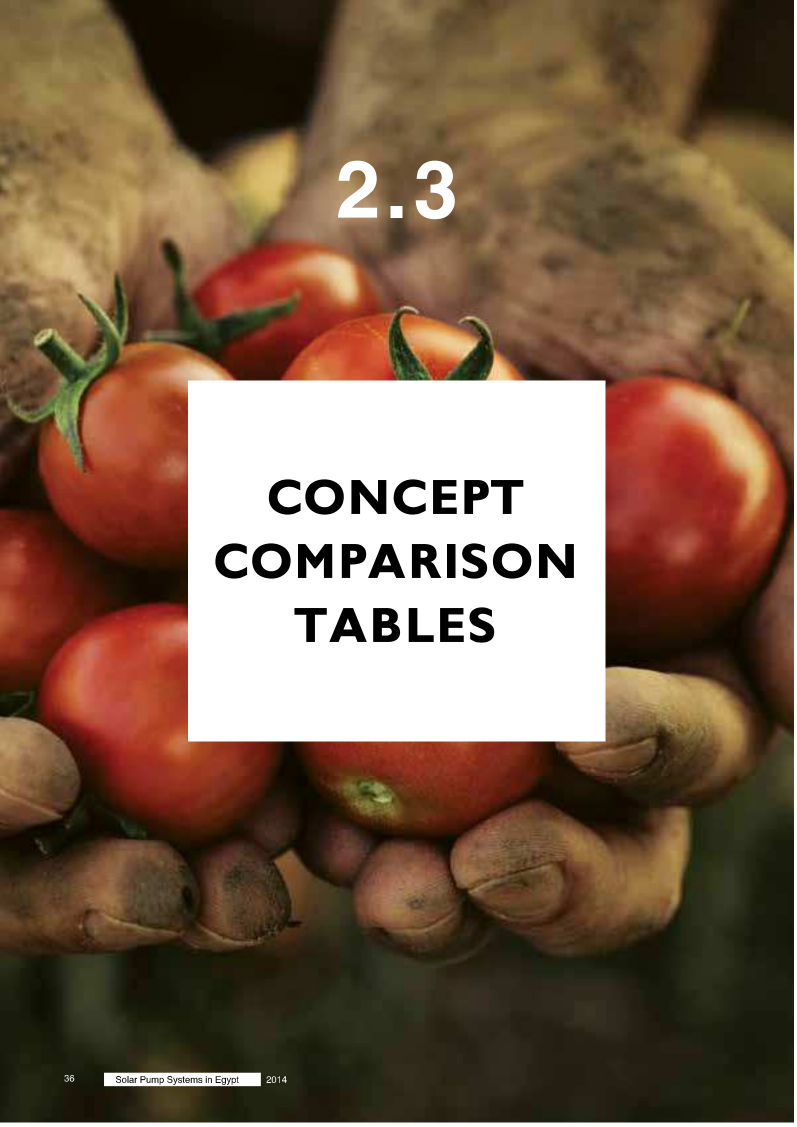
Table 10: Assessment of economics – Smart mini-grid solutions

	Investment costs	Operating costs	Maintenance effort	Solar Fraction[19]
New installation				
Existing farm		No difference		

System essentials

- In depth communication between operator and system provider is essential
- An individual design for each system is necessary
- No standard design is available
- Design has to fit specific circumstances including environmental conditions
- Use efficient components which can be integrated into a flexible structure

[19] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.



2.3

CONCEPT COMPARISON TABLES

2.3 Concept Comparison Tables

New Farm

Table 11: Comparison of concepts for new farms

Solar Pump System	Limitations (Irrigation)	Investment costs	Operating costs	Maintenance effort	Solar Fraction[20]
A. Stand-alone system for direct irrigation	1	$	$	🔧	☀☀☀☀☀
B. Stand-alone system for direct irrigation with batteries	2	$$$	$$	🔧🔧🔧🔧	☀☀☀☀☀
C. Stand-alone system with high level storage	3	$$$	$$	🔧🔧🔧	☀☀☀☀☀
D. Stand-alone system with ground-level storage, batteries and booster pump	2	$$$$$	$$$	🔧🔧🔧🔧🔧	☀☀☀☀☀
E. Solar / Diesel hybrid system with switch operation (and high-level reservoir)	0 (3)	$$$ ($$$$)	$$	🔧🔧	☀☀
F. Solar / Diesel hybrid system with batteries	0	$$$$	$$$	🔧🔧🔧🔧	☀☀☀
G. Solar / Diesel hybrid system with ground-level storage and booster pump	0	$$$	$$$	🔧🔧🔧🔧🔧	☀☀☀
H. Multi-well – Solar / Diesel hybrid system (Fuel-saving solution or managed system)	0	$$	$$$$$ ($$$)	🔧🔧	☀ (☀☀)
I. Smart-mini-grid solution	0	$$$$$	$$	🔧🔧🔧🔧	☀☀☀

Existing Farm

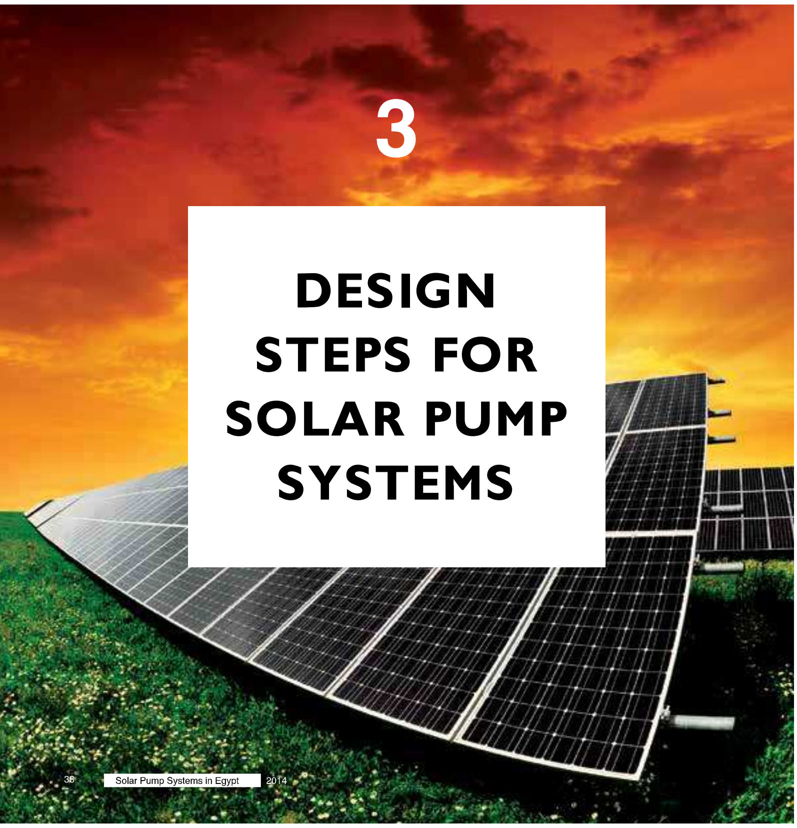
Table 12: Comparison of concepts for existing farms (only differences to Table 11)

Solar Pump System	Limitations (Irrigation)	Investment costs	Operating costs	Maintenance effort	Solar Fraction
A. Stand-alone system for direct irrigation					
B. Stand-alone system for direct irrigation with batteries					
C. Stand-alone system with high level storage		$ [22]			
D. Stand-alone system with ground-level storage, batteries and booster pump		$$$			
E. Solar / Diesel hybrid system with switch operation (and high-level reservoir)		$$ ($$$)	$$$		
F. Solar / Diesel hybrid system with batteries		$$$	$$$$		
G. Solar / Diesel hybrid system with ground-level storage and booster pump		$$$	$$$$		
H. Multi-well – Solar / Diesel hybrid system (Fuel-saving solution or managed system)		$	$$$$$ ($$$$)		
I. Smart-mini-grid solution		$$$$			

[20] The ratio of the amount of input energy contributed by a solar energy system to the total input energy required for a specific application.
[21] If high-level storage already exists
[22] If high-level storage already exists

Legend

Limitations:
0: No limitations with regard to irrigation and well
1: Irrigation profile coupled with solar irradiation profile (no control of maximum flow-rate of well withdrawal, irrigation time and flow-rate
2: Limited control of maximum flow-rate of well withdrawal, irrigation time and flow-rate depending on PV-battery dimensioning
3: High-level reservoir feasible; height of reservoir must fit to irrigation system
Investment costs: very low $ to very high $$$$$
Operating costs: reverse parameter of savings: very low x to very high xxxxx
Maintenance effort: very low i to very high iiiii
Solar fraction: very low *to very high *****



3

DESIGN STEPS FOR SOLAR PUMP SYSTEMS

A variety of designs to implement a solar pump system are possible. Accurate information in a standardized format given to the system provider helps assessing which system shows the best fit at an early stage of the project.

Possible approaches for the investor

- Invest the maximum budget available to achieve maximum optimization of the system
- Achieve maximum savings regarding fuel cost
- Install a completely independent system, replace current diesel generators
- Start with a small system, with later upgradeable potential
- Select the most cost-efficient solution
- Use the maximum available space for solar arrays

A step by step guide

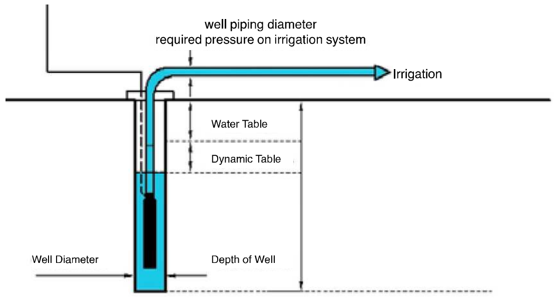
Step 1:

Describe
- The conditions of the existing well/farm or
- The concept of the new farm

Standard questionnaires from suppliers can often be used as checklists to ensure sufficient information is obtained[24].

Important information to include:

- Basic project data
  - Location
  - Site map with geographic direction
  - Free space for solar installation, wells and diesel generators
- Well characteristics
  - Depth
  - Water table
  - Dynamic table
  - Well performance (if available)
- Information on water quality
- Pump characteristics of existing pumps and to-be-purchased pumps (if applicable)
  - Type
  - Power
  - Design flow-rate and pump head
  - Data sheet
- Required irrigation schedule
  - Daily and seasonal profile
- Required pressure on irrigation system or height of storage tank for storage systems
- Information regarding single well with own diesel generator
- Information regarding multiple wells with central diesel generator, grid availability or individual diesel generators
- Diesel generator information
  - Type
  - Size
  - Fuel consumption
- Set standard frame for calculation of economics for suppliers
  - Equity
  - Interest
  - Fuel costs, etc[25]



[24] Appendix II: PV Request for Proposal of Solar Pump System
[25] To request a dynamic model for economic calculations, please contact info@raseed-giz.com

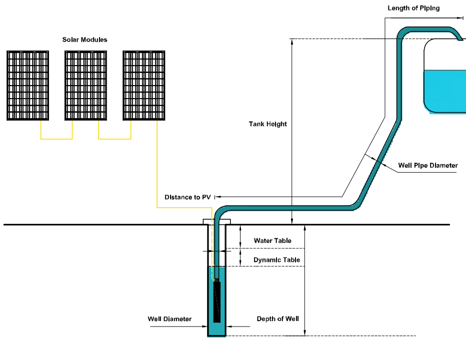


Figure 29: Well characteristics for direct irrigation and storage systems – composition of the pump head (Source: Jorg Steinke)

Step 2:
- Contact system providers to work out a proposal based on the above information
- Collect quotations and proposals

Step 3:
- Evaluate quotations based on technical concept, used components and financial projections

Step 4:
- Pursue a deeper technical discussion with limited group of potential suppliers to discuss different concepts and quotations
- Undertake a field trip with each supplier to the perspective farm

3.1 Single well concepts

- Check well and/or pump characteristics and information regarding water quality
- Check irrigation or load schedule
- Select suitable pump to fit water volume and pump head
- Select suitable inverter to match pump and system concept
- Select PV array and string dimensioning to match the inverter requirements
- Design battery bank, if battery solution required
- Check terrain/soil regarding adequacy of foundation
- Confirm PV array installation requirements, available space, and array arrangements
- Define the control system for hybrid systems
- Define necessary safety devices (lightning and overvoltage protection)
- Define the necessary accessories (cable ducts, wiring, protection pipes, etc.)
- Recheck for ways the water flow for irrigation can be reduced under the current system

3.2 Multi-well concepts

- Check grid structure characteristics and information regarding existing or designed power generation
- Check load schedule
- Check control system of diesel generators
- Select suitable inverter to match the grid and system concept
- Choose PV array and string dimensioning to match the inverter requirements
- Design battery bank, if battery solution required
- Check of terrain/soil regarding adequacy of foundations
- Confirm PV array installation requirements, available space, and array arrangements
- Define control system for hybrid systems
- Define necessary safety devices (lightning and overvoltage protection)
- Define necessary accessories (cable ducts, wiring, protection pipes, etc.).

3.3 Recommendations for the solar design on existing farms

For single wells, the first requisite to install a solar system is availability of space. The existing diesel generators need to be checked that they allow automatic control and integration into the whole control system. It is possible to achieve 100 % solar operation for some non-critical crops if irrigation is only required during the day. When pumps need to be replaced at existing wells, only highly efficient pumps with a wide range of possible frequency control should be selected. Such pumps allow the usage of variable speed drives (VSD), which allow a smooth starting and a power limitation of the pump. If possible and/or available, flexible diesel generators that can be controlled externally should be chosen. Also, oversizing of diesel generators should be avoided by using VSDs for the pumps. Taking these aspects into account, the diesel generators don't have to deliver high power to overcome the breakaway torque when starting the pump.

On an existing farm with several wells already connected to a small diesel generator driven grid, several cost and fuel efficient solutions are possible by adding a grid connected PV system (up to 30% of the total demand). Depending on the demand profile 5 – 15 % fuel savings are possible. If the grid connected inverter allows active management by a fuel saver, higher solar fractions and higher fuel savings can be realized.

3.4 Recommendations for the solar design on new farms

Multi-well concepts have the considerable advantage of being able to equalize diverse irrigation needs, especially with integrated water storage. Additionally, as the exact PV sizing for minimum power is not required, a farm starting from zero can gradually build up solar power to a full solar capacity as allowed by the farm budget, the market situation and energy prices. In contrast, single well concepts normally require a minimum PV size[26] based on the pump used.

To enable solar solutions with optimal performance and cost-efficiency to be set-up on newly designed farms, alongside consideration for future expansion, the following criteria should be considered:

- Use the most efficient irrigation technology available
- Aim to reduce water consumption
- Choose efficient pumps with a VSD allowing operation over a wide range of flow-rate
- Fix ratio of feddan per well based on the total daily water demand and a solar operation time of 6 to 8 hours
- Ratio of feddan per well should not be based on the irrigation schedule and maximum well output
- Keep free space next to wells and/or diesel generators to allow solar installation (space requirement approx. 8 to 10 m^2 per kwp[27] solar power).
- Avoid oversizing of diesel generators
- Use cascades of diesel generators (base load, peak load) and intelligent management rather than oversized diesel generator units
- Use diesel generators with an external control option

[26]Direct systems always must be designed on the point with solar power > power demand of the pump. If PV is too small, operation won't run. Multi well systems can start with 1% solar up to maybe 30% for fuel safer and 100% for managed systems.
[27]See Glossary

4

TECHNICAL SPECIFICATIONS

4.1 Effects reducing PV Output Power

Degradation

Degradation of the output power of PV modules is a physical effect which cannot be avoided. All manufacturers cover this effect with the so-called output performance warranty. Manufacturers' datasheets indicate 0.5 % yearly degradation for crystalline and 1% for thin film PV modules. The long-term monitoring experience of Fraunhofer ISE show that these values in reality are lower with about 0.25% for crystalline and 0.6% for thin film yearly degradation.

Temperature effect

Module temperature is a significant factor which reduces the output power with a coefficient in %/K from Standard Test Conditions (STC). For crystalline modules this negative factor is about 0.4 – 0.5 %/K, for thin film modules it is lower with about 0.2 - 0.45 %/K. The temperature of a PV module can be calculated with the following rule of thumb:

T_module = Ambient temperature (°C) + 25°C x Solar irradiation (W/m2)/1000W

For an ambient temperature of 35°C and a solar irradiation of 1000W/m2 this results in a module temperature of 60°, which causes a reduction of 17.5 % of the STC output power value for a crystalline module.

Soiling effect

Sand storms and dust in the air cause a dust deposition on the surface of PV modules. In Egypt the dust deposition on the glass surface of south oriented modules with an approximate inclination of 30% causes a monthly power reduction of up to 20%. To avoid abrasion or clouding of the PV modules by sand storms, it is strongly recommended to use only modules with glass surface. Monthly cleaning helps to diminish this problem.

Inclination

The output energy of the PV modules depends on the module inclination. An inclination within a location's latitude range maximizes yearly output. Egypt is located between 25 and 30 degree of latitude. Thus, to achieve a maximum yearly energy output, an inclination of 25° is optimal. To reach maximum power in winter, an inclination of 35° is recommended, in summer 15° are sufficient.

4.2 System Technology

The PV modules are orientated towards south (azimuth = 0°) and mounted at a fixed inclination to the horizontal, facing the sun, allowing them to capture most of the sunlight during the day throughout the whole year. Numerous solar panels combined together create one system, a solar array (Figure 30 c). A certain number of modules are connected within the array to a so-called string (Figure 30 b). For large electric utility or industrial applications, hundreds of solar strings are interconnected to form a large utility-scale PV system.

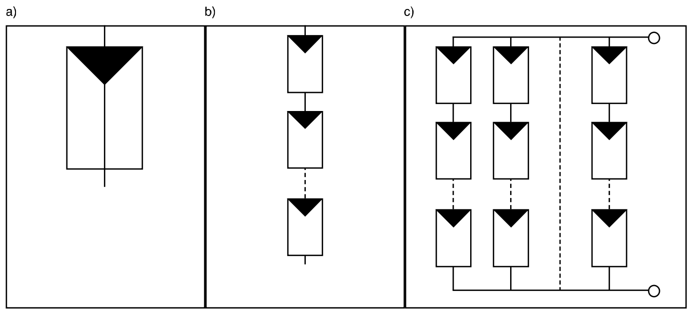


Fig 30: Composition of a solar array

The strings are connected via DC[29]wiring to a generator connection box or to the inverters directly. If string inverters are used, separated inputs for each string are provided. Inverters are necessary to transfer the solar DC power into useable AC[30]power. In industrial applications this is normally done via the three-phase level with 380/400 V and 50 or 60 Hz. The inverter stabilizes the output voltage and frequency and synchronizes the solar power with the power from public grid or generators. The special pump inverter adapts power to the pump at a usable voltage and frequency.

As the inverter is the interface between solar power and the grid, it ensures safe operation and includes other important safety functions such as over-voltage and over-frequency protection. In grid-connected systems, several inverters can combine connection boxes with additional safety devices and circuit breakers. Those are then connected to the main distribution board of the farm, the generators or the public grid. In the case of feed-in systems, additional meters are installed to measure the feed-in electricity.

The size of solar power systems is normally described in kWp (kilowatt peak). The kWp gives the output of the system under certain test conditions. It allows comparison of different systems in addition with the so called specific solar yield[31] in kWh/kWp per year when the pure energy output of the systems is concerned. Normal solar power systems can be simulated for the whole year based on local irradiation and weather data, using available standard software, such as PV Sol from Germany. Weather data is available from different sources, e.g. Meteonorm, Switzerland (weather stations worldwide) or NASA (satellite data). The information provided is of very high standard and based on long-term statistical data.

Solar pump systems, which directly use solar energy to run the pump, cannot use all the irradiation-generated energy during the day, unless battery storage is used within the system. This is due to characteristics of the pumps, which can only be operated within a specific range of power and frequency. Due to the function of bearings and cooling of the pumps, there is always a minimum speed/frequency needed for the pump to start operating smoothly when a frequency inverter or variable speed drive is used. The solar energy intensity in the early mornings and sunsets is lower than this minimum, thus it cannot be used directly and is lost unless stored in batteries (Figure 31).

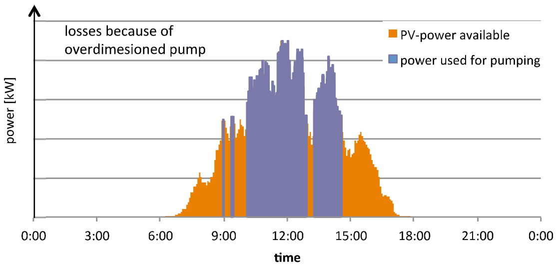


Figure 31: Power used for pumping and available PV power- the power cannot be used in the morning and evening, also midday if the pump is oversized

It is essential to use professional software for accurate simulation of standard solar power systems and input for the calculation of the individual well. The pump characteristics and the required irrigation schedule are also taken into account.

To guarantee a high system performance after a certain time period, customer and supplier should agree in advance on the expected lifetime of the different system components.

[29]Direct current
[30]Alternating current
[31]See Glossary

4.2.1 Direct Coupling via VSD and AC-coupling

The PV modules deliver DC (direct current). As the diesel generator delivers three-phase AC also the pump needs three-phase AC to operate. Therefore, you need to convert DC into AC via an inverter.

In the direct-coupled system the VSD is on the input side connected to the PV modules and on the output side connected to the pump (see concept A). Additional needed batteries are also connected on the input side of the VSD (see concept B). The VSD acts as an inverter and at the same time as the controller of the pump. If no battery is included the VSD must include MPP tracking on the solar side to adjust the solar power to the demand of the pump. An additional diesel generator can be connected via a switch to the pump (see concept E).

In an AC-coupled system two types of inverters are needed; the PV inverter and the battery inverter. Both inverters as well as the pump are connected on the AC side. The PV modules are connected to the PV inverter and the additional needed batteries are connected to the battery inverter. Also, for the AC-coupled systems diesel generators can be used as a backup system to lower the amount of batteries and therefore costs (See Fig 32 B).

AC systems offer a wider range of possible applications starting from pure fuel saving systems with certain solar fraction up to completely independent systems running solely on renewable energies.

The advantage of AC systems is a higher achievable well performance and their easier combination with existing diesel generator systems and wells. Yet, you need an additional inverter.

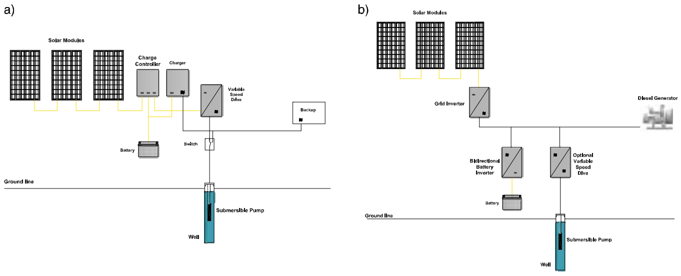


Figure 32: System scheme of a typical DC-coupled system (a) and a typical AC coupled system (b) (Source: Jorg Steinke)

4.2.2 Elaboration on Pumping Technology

Regarding the pumping of water, there are several basics of power and energy which are important to understand.

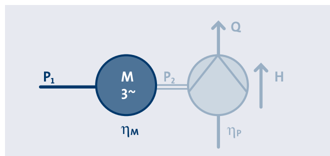


Figure 33: Definition of P1 - electric power and P2 - hydraulic power at a pump

$P_{hydr} = p \times Q = \rho \times g \times H \times Q$ [W]

p: pressure [Pa] the static pressure of a water column can be expressed by:

$p_{static} = \rho \times g \times H$ [Pa]

ρ: density of water at water temperature in operation (20°C and around 1.000 kg/m3)

g: gravity acceleration (9.81 m/s2 or N/kg)

H: pump head [m]

Q: flow-rate [m³/s]

The pump head H can easily be converted into pressure using the constant parameters of density and gravity acceleration and vice versa.

The required pressure for the irrigation system consists of following pressure losses:
Pressure at the emitter -

+ Friction losses in the lateral line
+ Friction losses in the manifold
+ Friction losses in the sub mains and in the main line
+ Friction losses in the valves and pipe fittings and minor losses (usually up to 15% of the total losses in the pipes)
+ Difference in elevation (+ or -)
+ Loss of pressure in the head control together with the dynamic pump head of the well (consider seasonal and daily dependency)
+ Dynamic pump head of well
= Total pressure head of system

In case of water at 20°C, the term can be simplified to:

P_{hydr} (kW) = 2.72 [N*hr/m³*s] x Q [m³/hr] x H [m] / 1,000

This is only the power which works on the water within the pump. The mechanical power required at the shaft of the pump is calculated based on the specific efficiency of the pump. It is normally in a range of 50 to 85% and is depending on the type of pump and the accuracy of sizing. This mechanical power is normally given as P2 in kW in data sheets.

P_{shaft} (P2) [kW] = P_{hydr} [kW]/ η_{pump}

It is very important when sizing and choosing the pump for a well to have the operating point at the top of the efficiency curve of the pump. The operating point depends on the flow-rate and pump head. It is crucial to choose pumps with high efficiency in order to optimize the system.

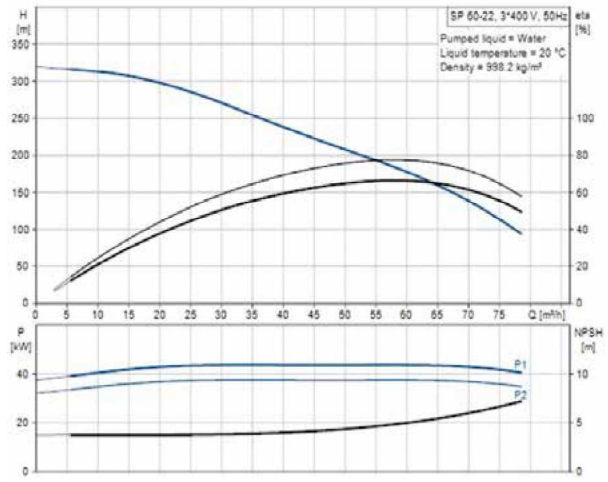


Figure 34: Characteristic curve of a typical multi-stage submersible pump (Grundfos 14A15622 SP 60-22 50 Hz); rated flow: 60 m³/h; rated head: 176 m; rated power - P2: 45 kW; source: Printed from Grundfos Product Center [2014.07.030]

The electric power, which is the decisive factor for the power supply and consumption, is calculated by the motor efficiency. Electric power is dependent on each pump/motor combination, as well as the appropriate choice of pump for the specific well. Motor efficiency ranges between 70 to 90% in normal applications with qualified pumps/motors. The motor power is normally given as P1 in data sheets.

$P_{electric}$ (P1) [kW] = P_{shaft} [kW] / ηmotor

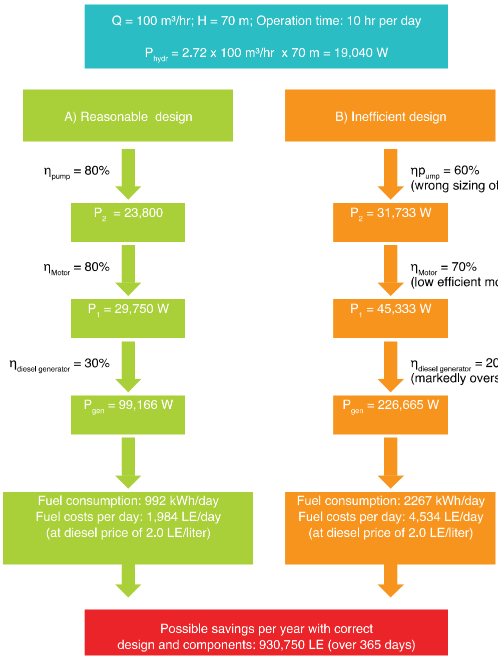
Regarding diesel generators, the fuel consumption must be calculated based on the efficiency of the diesel generator under real operation conditions e.g. partial load if oversized, ambient temperature, etc. The efficiency of the diesel generator is normally in a range of 15 to 30%, depending on type, age and size.

Power demand for diesel generator:

P_{gen} [kW] = $P_{electric}$ [kW] / ηgen

Energy consumption of diesel generator in kWh = Pgen[kW] x operating time [hr]

Fuel consumption [litre] = Energy consumption [kWh] / 10 kWh/litre (simplified for diesel)



As shown above, a mismatch of design and components can make a difference in fuel costs of more than 700,000 LE per year – for a single well. This illustrates the importance of accurate design for pumping systems. Every m³ of water not pumped saves energy. For example, even in efficient systems the energy input for the diesel generator (fuel) can be more than for times the amount than what is required (hydraulically) to pump water to the surface.

For solar pump systems, the efficiency of irrigation, pumps and motors is important for the optimal sizing of the solar system. The lower the required electric power (P1) for the pump, the smaller the solar system needed and thus the lower the investment.

The dimensioning of the PV system for a pump can be done in three different ways:

1. Dimensioning by rule of thumb
2. Dimensioning by using Nomograms
3. Dimension by using simulation programs

Dimensioning by rule of thumb
Based on extensive field experiences across Egypt, a rule of thumb for stand-alone systems for direct irrigation has been developed.

Peak power of PV

Ppv [kWp] = 4.23 x H [m] x Q [m3/d] / Gd[kWh/m2 x year]

Using the values from the example above:

Q = 100 m3/h;
H = 70 m;
Operating time:10 h/day.
*If no storage is included, solar power = 7h per day for pumping;
*Mean global irradiation, see chapter.2, Gd = 1990 kWh/m2 x yPpv = 104 kWp

With a 104 kWp PV system about 700 m3/d can be pumped. To achieve 700 m³/d a bigger pump with about 75 kW is needed, because the pump must be able to handle the power of the PV at noon of about 75 kW.

Dimensioning by using Nomograms
Nomograms are available from pump manufactures and allow the sizing of the PV system to be done graphically.

Dimension by using simulation programmes
The best way for dimensioning is to use a computer based simulation program. Pump manufacturers offer such programs and services to develop dimensions on demand by using your input data. For stand-alone systems for direct irrigation the simulation programme DASTPVPS from Oliver Mayer is suggested. For hybrid systems with storage more complex simulation programmes, such as Insel, Homer, PVSyst, PVSOL, Retscreen (see IEA PVPS task 11 publication "Worldwide overview about design and simulation tools for hybrid PV systems") are necessary.

4.2.3 Main Components of Solar Pump Systems

Important cautions

The operating voltage of solar power systems can reach up to 1000 V DC!

- Whenever there is sunshine, the system is under high voltage
- Only specialized personnel is allowed to work at the solar system
- Only tested and certified components are to be used
- Only tested and certified components for the specific environmental conditions in the desert can be used

The lifetime of PV modules reaches 20 or more years. After that time span the system runs on approx. 88% efficiency. All materials and components should be designed and installed according to the same projected lifetime.

[32] Demo version available at http://www.ibom.de/dastpvps.htm
[33] http://iea-pvps.org/index.php?id=227

PV modules

The photovoltaic modules, also called PV panels, are the driving engine of a solar power system. Solar irradiation is transferred in the modules into electric energy, and several modules are connected to form strings, which generate power on the level of 60 to 1000 V DC.

Figure 35: Installed PV modules

The choice of suitable modules, the number of modules per string and the number of strings in parallel to build up the solar array are key decisions for the system provider. The overall aim is to ensure operation and safety in combination with the inverters over a wide range of possible conditions at the project.

On their backside, PV modules are equipped with so-called module connection boxes, which are the interface to the complete system. The boxes include important bypass diodes, which ensure operation of all single cells. Also included is the module wire, which connects different modules to each other, to the string box, or to the inverter directly. These module wires need to be long enough to allow installation without tension and need to be equipped with a certified, water-tight, standard photovoltaic connector.

Each module has its own characteristics in regards to the voltage U (Volt) and current I (Ampere) under different operation condition e.g. irradiation and temperature. The power P (Watt) is the product of current and voltage. The power curve plotted in dependency from the voltage reach a maximum at the so called maximum power point MPP. The MPP is most intense power reached by the PV module in a certain time span. The maximum power point is an important factor in combination with MPP tracking[34], i.e. a key function of the solar inverters. These characteristics are normally given in data sheets as diagrams and numbers

Figure 36: Module connection box at the backside of PV modules

[34]See Glossary

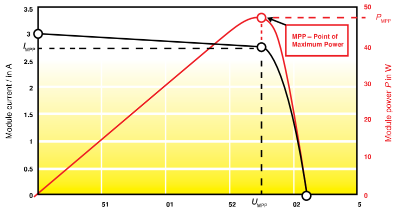


Figure 37: I-U diagram with MPP of a PV panel

Each solar panel, regardless of brand or technology, has similar characteristics. For all solar panels, the higher the irradiation is, the higher the output current of the panel will be. When designing a solar system, local irradiation conditions need to be taken into account. This is to include not only perfect irradiation conditions, but also the minimum and average irradiation conditions to ensure a stable and safe operation and optimal efficiency.

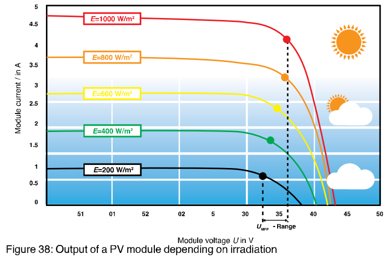


Figure 38: Output of a PV module depending on irradiation

Each solar panel, regardless of brand or technology, has similar characteristics. For all solar panels, the higher the irradiation is, the higher the output current of the panel will be. When designing a solar system, local irradiation conditions need to be taken into account. This is to include not only perfect irradiation conditions, but also the minimum and average irradiation conditions to ensure a stable and safe operation and optimal efficiency.

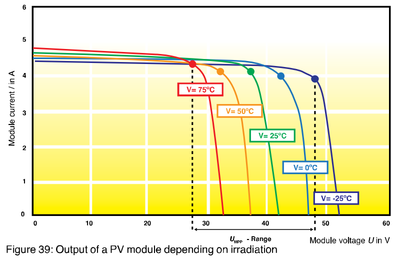
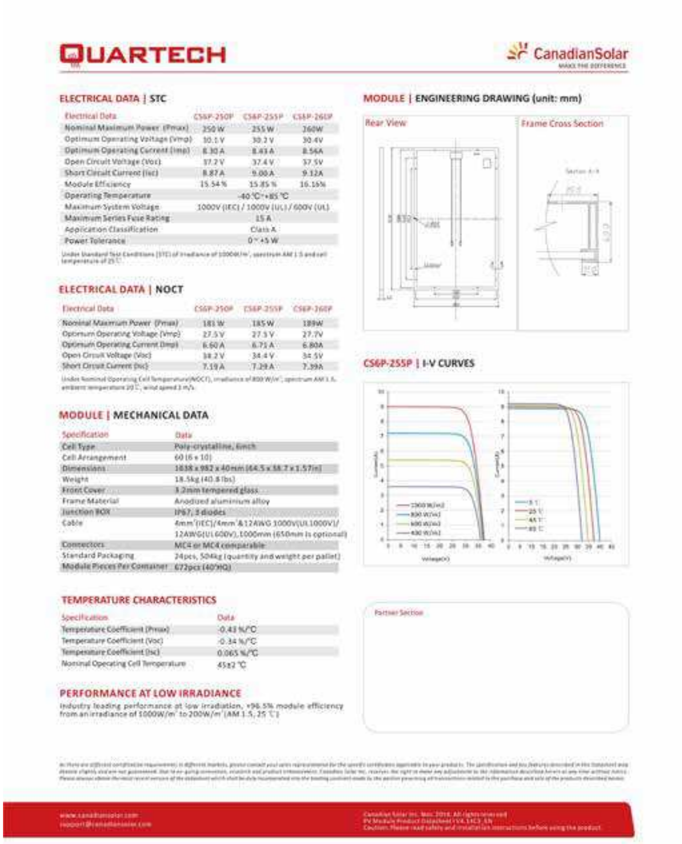


Figure 39: Output of a PV module depending on irradiation

Another constant in solar panels is the higher the module temperatures, the lower the output will be. This is a very important issue with regard to voltages in the solar system and the correct string design. It has to be adjusted with the suitable input range of the used inverters. Solar designs require both know-how and experience to optimize systems for extreme weather conditions in the deserts.

Important factors which describe the characteristics of specific modules are found on the product sheets of solar modules. This essential information is given as standard values and temperature coefficients in %/K, or mV/K, mA/K. These values indicate the decrease of power/voltage/current per degree deviation of operation conditions from Standard Test Conditions (STC). Any successful simulation and design of a solar system must include these factors. STC[35] stands for an irradiation of 1000 W/m2, spectrum AM (Air Mass) 1.5 and cell temperature of 25°C.

[35]See Glossary


QUARTECH

CanadianSolar

ELECTRICAL DATA | STC

Electrical Data	CS6P-250P	CS6P-255P	CS6P-260P
Nominal Maximum Power (Pmax)	250 W	255 W	260W
Optimum Operating Voltage (Vmp)	30.1 V	30.2 V	30.4V
Optimum Operating Current (Imp)	8.30 A	8.43 A	8.56A
Open Circuit Voltage (Voc)	37.2 V	37.4 V	37.5V
Short Circuit Current (Isc)	8.87 A	9.00 A	9.12A
Module Efficiency	15.54 %	15.85 %	16.16%
Operating Temperature	-40°C~+85°C		
Maximum System Voltage	1000V (IEC) / 1000V (UL) / 600V (UL)		
Maximum Series Fuse Rating	15 A		
Application Classification	Class A		
Power Tolerance	0 ~ +5 W		

Under Standard Test Conditions (STC) of irradiance of 1000W/m², spectrum AM 1.5 and cell temperature of 25°C

ELECTRICAL DATA | NOCT

Electrical Data	CS6P-250P	CS6P-255P	CS6P-260P
Nominal Maximum Power (Pmax)	181 W	185 W	189W
Optimum Operating Voltage (Vmp)	27.5 V	27.5 V	27.7V
Optimum Operating Current (Imp)	6.60 A	6.71 A	6.80A
Open Circuit Voltage (Voc)	34.2 V	34.4 V	34.5V
Short Circuit Current (Isc)	7.19 A	7.29 A	7.39A

Under Nominal Operating Cell Temperature (NOCT), irradiance of 800 W/m², spectrum AM 1.5, ambient temperature 20°C, wind speed 1 m/s

MODULE | MECHANICAL DATA

Specification	Data
Cell Type	Poly-crystalline, 6inch
Cell Arrangement	60 (6 x 10)
Dimensions	1638 x 982 x 40mm (64.5 x 38.7 x 1.57in)
Weight	18.5kg (40.8 lbs)
Front Cover	3.2mm tempered glass
Frame Material	Anodized aluminium alloy
Junction BOX	IP67, 3 diodes
Cable	4mm²(IEC)/4mm² & 12AWG 1000V(UL1000V)/ 12AWG(UL600V), 1000mm (650mm is optional)
Connectors	MC4 or MC4 comparable
Standard Packaging	24pcs, 504kg (quantity and weight per pallet)
Module Pieces Per Container	672pcs (40'HQ)

TEMPERATURE CHARACTERISTICS

Specification	Data
Temperature Coefficient (Pmax)	-0.43 %/°C
Temperature Coefficient (Voc)	-0.34 %/°C
Temperature Coefficient (Isc)	0.065 %/°C
Nominal Operating Cell Temperature	45±2 °C

PERFORMANCE AT LOW IRRADIANCE

Industry leading performance at low irradiation, +96.5% module efficiency from an irradiance of 1000W/m² to 200W/m² (AM 1.5, 25 °C)

MODULE | ENGINEERING DRAWING (unit: mm)

Rear View

Frame Cross Section

CS6P-255P | I-V CURVES

Partner Section

Figure 40: Typical data sheet of PV modules

Module temperature is a significant factor to consider in the sizing of PV systems. Module temperature can be significantly higher than the ambient air temperature. On desert farms is can reach above 75°C, which reduces the output power by about 24% (55°C/STC*0.43 %/°C, see data sheet). This means it is not only the nominal power at STC of a system that is important, but also the conditions of operation and the output under these high temperatures.

The most common used technology for PV modules is the crystalline technology based on silicon. Solar cells made by silicon are combined in one framed module onto one panel. Two different cell types are available on the market: monocrystalline and polycrystalline.

Monocrystalline cells can be identified by their homogeneous shining dark blue or black surface. As the cells are produced by very pure silicon, the cells are made from one crystal only. The efficiency of monocrystalline modules is higher than other module technologies, but the price is more expensive due to the stringent requirements for purity of material.

Polycrystalline cells are made from silicon. It is a process in which the silicon grows in several crystals. This growth is visible on the cell surface, as the borders of the crystals can be seen. The efficiency of the poly-modules is a few percent lower than mono, but its price-performance ratio often makes it the preferred choice when the space for installation is not limited.

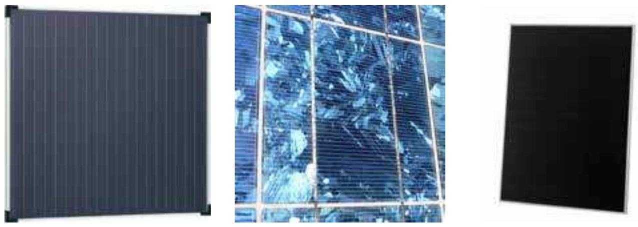


Figure 41: PV Panels – Monocrystallne, Polycrystaline and Thin Film modules

Another technology on the market is the so-called thin-film technology, in which semi-conductor materials are coated onto a carrying material such as glass, among others. This technology seems the most promising for the future, as usage of material is far less than for silicon modules. The efficiency is normally lower than for crystalline modules (around 70 %), so the necessary space to realize a certain power size is larger, which increases the costs for wiring and support structures.

Due to the effect of mass production and decreasing costs of crystalline modules in recent years, thin-film technology is currently not competitive regarding cost-efficiency and is often used in projects with high aesthetic requirements (surface colour can be flexible) or where the orientation of the solar modules is not optimal. Thin-film technology can be used in a wider range of the solar irradiation, as well as in areas with higher diffuse irradiation due to location conditions, such as fine dust in the air. Another advantage of thin-film modules in desert projects is the lower effect of temperature on the output of its panels. A disadvantage of some thin-film modules relates to its recycling and disposal options, due to the current usage of heavy metals such as cadmium or arsen in the material.

For both poly-and monocrystalline modules, a lifetime of 20 years or more can be calculated. For thin-film technology, especially the new, upcoming and potentially promising technologies, it is best to check with individual suppliers regarding warranty, as long-term data is not always available. An aging effect (degradation[36]) is normal for all types, with a loss in performance of 0.25 % to 0.6 % per year, depending on technology and supplier.

[36]See Glossary

PV cell technology		Best module efficiency [%]	Power degrada-tion [%/year]	Temperature coef-ficient of power [%/°K]	Required PV area for 1kWp
Crystalline	mono silicon	19.6%	.- 0.25	- 0.37...- 0.52	7m² - 9m²
	poly silicon	18.5%	- 0.25	- 0.37...- 0.52	7.5m² - 10m²
Thin-film	amorphous silicon	8.7%	- 0.5	- 0.10...- 0.30	14m² - 20m²
	CIGS	11.3%	- 0.5	- 0.39...- 0.45	9m² - 11m²
	CdTe	11.1%	- 0.6	- 0.20...- 0.36	12m² - 17m²

Figure 42: Various cell materials and their specifications (Source: Fraunhofer-Institute for Solar Energy Systems ISE)

Essentials for PV modules

- Good price/performance ratio
- Temperature coefficients for design as low as possible
- Range of allowed operating temperatures must fit to conditions in the desert
- Connection boxes and lamination stable under high operating temperatures
- Suitable packaging to ensure safe transportation to the farms

Required Standards for PV modules

- IEC 61215 photovoltaic modules with crystalline cells (or equal UL 1703)
- IEC 61646 thin-film photovoltaic modules
- IEC 61730 safety qualification of PV modules
- EN 50548 connection boxes for photovoltaic modules
- Module connection box IP 55 minimum
- IP 65 (category 1 acc. to EN 60259) preferred especially if location is nearby the sea (until 50 km)
  Protection class II

Support Structure

Although often neglected, the support structure of a solar power system plays a significant role, and is often decisive for the lifetime and safety of operation. The support structure should be designed according to the following criteria:

- Safe and stable structure
- Design based on the weight of modules and wind load conditions at the project
- Designed for lifetime of more than 20 years
- Only non-corrosive materials to be used

Most important for all types of support structures is the accurate choice of materials, e.g. those which can resist the local environmental conditions and are non-corrosive. Based on long-term experience in Europe, galvanized steel, high-level stainless steel and aluminium based on screwed connections with stainless steel screws are the preferable choice. It must be ensured that material mixes are safe and do not neutralize the choice of certain materials by causing contact corrosion (e.g. stainless steel screws with steel washers).

The support structures for solar power systems for application on farms can be divided into four types:

1. Pitch roof systems, such as on office, warehouse or diesel generator housing
2. Flat roof systems, such as on office or diesel generator housing
3. On-ground field installations
4. Special structures, such as vehicle or farming shelter

Pitch roof systems:

A pitch roof describes a roof with a certain inclination to the horizontal in one or two directions

Pitch roof systems:

A pitch roof describes a roof with a certain inclination[37] to the horizontal in one or two directions

For pitch roof installation, the PV modules are normally installed parallel to the roof plates on horizontal or vertical support profiles (depending on the structure under the plates). The connection between the roof structure and plates is with standard fasteners for various roof types.

Figure 43: Typical pitch roof installations

Figure 44: Support solutions for roof parallel installation

For safety reasons and to ensure the minimum of ventilation, it is important for pitch roof installations to leave space between modules and roof plates at the back of the modules. The pitch roof installation is usually the most cost-efficient solution, as no foundation or ballasting is required and the system can be fixed on an existing structure. The PV modules must be fixed to the support structure by qualified and approved module fasteners only. Available as standard fasteners for any PV module.

Figure 45: Standard module fasteners

[37] See Glossary

Flat roof systems

For flat roof installations, the PV modules are normally installed with certain inclination to optimize the solar yield and promote a self-cleaning effect via rain. Depending on the roof structure, the support structure is fixed directly under the roof, which requires special sealing technology and effort.

Simple ballasting by concrete block on rubber mats is normally used to ensure stability.

Figure 46: Typical flat roof installations

It is important for flat roof installations to keep a minimum space between the rows of the modules to avoid self-shading.[38] Even in the winter when the position of the sun to the horizontal is the lowest (e.g. in Cairo 35°), the minimum distance to avoid shading can be calculated by:

$$d_{min} = b \times \sin(180° - \beta - \gamma) / \sin \gamma$$

dmin = Minimum distance between the front edges of each module row

b = height of PV module (m)

β = inclination of modules (°)

γ = angle of sun to the horizontal in the winter (°)

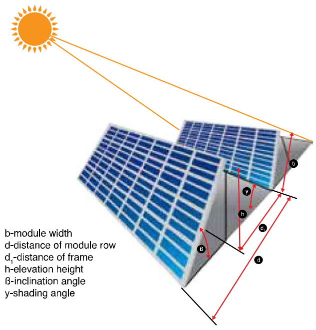


Figure 47: Distance between module rows

[38]See Glossary

Example:
Height of module b = 1.0 m
γ = 36.55° (near Cairo – 30' 2 N)
β = 15°

dmin = 1.32 m

The angle of the sun in the winter season for the northern hemisphere can be calculated in a simplified manner by:

$$\gamma = 90° - \text{latitude} - 23.45°$$

Example:
Cairo, latitude 30. 2 North

$$\gamma = 90° - 30° - 23.45° = 36.55°$$

Another important issue for flat roof systems is the check of maximum additional static load for the existing roof and the calculation of necessary ballasting. Additionally, a recheck by a statics engineer if the roof can accept the weight of the system, including additional ballasting, is necessary. In case the load is too heavy, ballasting can often be reduced by some optimized standard systems available on the market.

On-ground field installations

In farming applications, on-ground field installations are the most popular-- and are often the only possible way to create a suitable support structure. Two types of foundations can offer the necessary support structure on the ground; pile driven foundations and standard concrete strips. In the latter, the angles of support structure are fixed with screw anchors to the concrete. For both types of foundations, knowledge and analysis of the soil is required to ensure stability of the system over a long time.

For self-shading effects, the same rules as for flat roof installations apply, e.g. a minimum distance between the two front edges of each module rows. It is also important for on-ground installations to keep a minimum distance of about 0.5 m from the front edge of modules to the ground in order to avoid damage to plants and to allow cutting of grass and plants.

Figure 48: Typical on-ground field installations

Special support structures

An interesting option, especially for new farms or farms with other projects alongside planting, is to use the support structure of the solar power system for e.g. shelter for vehicles or farm materials. In Germany, farms have already installed solar systems on their available roof space. Therefore, interesting and cost-efficient solutions have been developed, many of which are now available as standard designs on the market.

Figure 49: Farming and vehicle shelters as carriers for the solar system

It is of course important for shelters to create an economic benefit via double function and usage, as seen in using power generating PV modules as a roof surface. Another double function can be the shading of the water tank or the pivot system by PV to reduce the evaporation.

A very attractive option of PV for irrigation is the combination of PV and agriculture at the same plot. This concept is called "Agro photovoltaic" (APV). Behind this idea, one can find a technological conception of double harvesting by photovoltaic installation modules elevated in approx. 3m to 6m. This technological approach uses and integrates new technologies and enables farmers to continue cultivating their land while producing renewable energy. Therefore, this conception could help to defuse land-use conflicts between energy industry and agricultural production by using the space under the photovoltaic installations. Another advantage especially for south regions is the reduction of solar irradiation and evaporation under the PV installation which is positive for the growth of several fruits and crops.

Essential for support structures
- Long lifetime
- Non-corrosive or protected against corrosion (galvanized steel if distance to sea is more than 50 km, high quality stainless steel, aluminium)
- Care in use of mixed materials regarding contact corrosion
- Static calculation of the structure
- Static check of existing roofs or structures
- If a ttsolar system is added keep enough space between rows to avoid shading effect

Required standards for the support structure
- Calculations according to din en 1991 impacts on support structures
- Din en 1990 basic standard for support structures
- Din en 1991-1 aluminium structures
- Din en 1993-1 steel structures

Solar Inverters

The solar inverter is the key component of a solar power system. It is the intelligent interface between the DC (direct current) solar power generation and the AC (alternating current) consumers.

An inverter carries out the following tasks:

- Transfers dc into useable ac power
- Adjusts the operation according to the maximum power point (mpp) of the modules
- Includes protection devices for dc and ac side
- Collects operation data and visualizes status of operation
- Solar pump inverter:
  - Adjusts solar power and demand of pump for direct connections from solar system to pump
- Island inverter:
  - Creates its own stable grid for island solutions
- Grid inverter:
  - Synchronizes solar power generation with the public or diesel generator grid

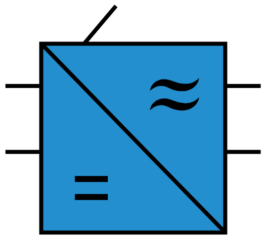


Figure 50: Symbol for a solar inverter

Figure 51: Special pump inverter for direct connection to solar system

Regarding solar pumping systems, three different kinds of inverters can be used, according to the type of system. For systems with direct connection of the pump to the inverter, only special pump inverters can be used. Such inverters are based on frequency inverters or so-called variable speed drives , VSD, which were specially developed for application with pumps or other three-phase motors with similar characteristics. VSDs for PV pumps must include MPP tracking on the solar side to adjust the solar power to the demand of the pump. The soft starting function, which is necessary due to the high current at the pump-start, is also an integral part of such inverters. Pump inverters normally include other features which are related to operations with a pump, such as connections for water level sensors in tanks or dry run protection sensors. Standard grid connected inverters, used for other household or industrial applications, are not suitable for solar pump systems with direct connection of the pump to the solar system.

Figure 52: Standard grid Inverters for grid or diesel generator connection

For multi-well systems with small solar fraction, standard grid inverters such as those used in grid connected systems for self-consumption or feed-in of power can be used. Grid inverters can only be used when other power sources, such as public grid or diesel generators, create the dominating power and the inverter can synchronize the solar power generation with voltage and frequency to this grid.

When the solar fraction is higher or with completely independent solutions based on solar power, special island inverters must be used. Such inverters are designed to create its own stable grid and play the dominating role within the power generation. Other power sources are connected with additional control and have to be synchronized with the grid of the solar power system.

Figure 53: Island Inverter for grid connection (Source: SMA Solar Technology)

Submersible Pump

In addition to the normal requirements for submersible pumps used in the farming sector, e.g. low maintenance, stable, reliable operation and low costs of operation, some special requirements for pumps used on solar pump systems need to be mentioned.

The efficiency of the pump under the specific conditions of the well is a decisive factor for the sizing of the solar power system. All costs of power modules, support structure and inverters directly correlate to the power demand of the pump. Only accurate sizing and choice of an efficient pump can allow cost efficient solutions.

Positive displacement vs. centrifugal pump
In small systems (up to 5 kW) with high pressure heads (range of 80 to 300 m) and low flow-rates (up to 10 m^3/h) screw pumps are very advantageous for solar pump applications. This type of positive displacement pump can work already with very low rotational speeds. The whole range of power provided by PV can be used for pumping with high efficiency. Yet, the stator of the screw pump has to be replaced regularly. For higher flow-rates centrifugal pumps are therefore a less expensive solution.

Range of rotary speed
Another important factor regarding the pump is the flexibility of control. If no DC pumps are used, which is normally only possible in very small scale operations, the pumps cannot be operated and controlled with an unlimited range of power and frequency. Good pumps can operate in a range of 30 to 50 Hz only, while others require a minimum frequency of 38Hz. For solar pump systems with direct irrigation, this issue has an important influence on the achievable solar operation time. The lower the minimum frequency to start and operate the pump, the longer the solar operation time and the higher the performance of the system.

If the pumps are operated at lower efficiency than recommended, the negative influence on bearings and cooling of the motor will shorten the lifetime of the pump.

Selection of pumps
The selection of a high efficient pump is quite difficult. The standard DIN EN ISO 9906 defines tolerance classes for the pump specifications. Even in tolerance class 1, the stated pump head may deviate +-3% and the flow rate +-5% to the stated specifications. These rules allow efficiencies that are 15% lower than the specification offered.

DIN EN ISO 9906 March 2013	Rotodynamic pumps - Hydraulic performance acceptance tests
ASAE EP369.1 December 1999	Design of Agricultural Drainage Pumping Plants
ANSI/ASAE S397.2 February 2003	Electrical Service and Equipment for Irrigation

Essentials for submersible pumps

- High efficiency to ensure cost-efficient sizing of solar power
- Wide range of possible frequency control
- Accurate sizing according to actual well conditions

Wiring and Accessories
Regarding the wiring of a solar power system, there are two different types: DC string wiring from power modules to the inverters and/or batteries; and AC wiring from a connection to the grid or pump directly. All wires should be sized and selected based on the environmental and operating conditions, and must be suitable for outdoor use (UV resistance, temperature resistance). Wires for DC wiring should be restricted to only special solar single wires with double insulation which are developed for outdoor application under the special conditions of a PV system (high voltage, high temperatures).

Figure 54

All wires which are used outdoors must be protected by suitable protection pipes or cable ducts.

String combiner boxes are used when several strings in the photovoltaic array need to be connected to one input of an inverter. The string boxes must include the following devices and fulfil safety requirements per local standards and according to IEC 62103 requirements:

- DC fuses for each string, if more than 2 strings are connected in parallel
- To avoid overheating space is necessary between the fuses
- DC switch, which switches off DC current with the open circuit voltage of the PV array
- DC over-voltage protection, if not provided by the inverter and the system is located in a region with a lot of thunderstorms
- Connection to earth system, if over-voltage protection is included
- Terminals for connection of strings and inverter input

In case of necessary work at the PV-input-side of the inverter, a string combiner box allows safe disconnection of the solar power modules from the inverter.

The modules and strings of a solar power system are under high voltage as long as there is solar irradiation. Disconnection of the DC side to the inverters is only effective on the inverter and AC side; PV modules remain under voltage.

Figure 55: String combiner box in a solar power system

Figure 56: AC disconnection box including lightning and surge arresters, circuit breakers and main switch

An AC disconnection box is used to connect one or several inverters to an existing grid. Its main function is to safely disconnect the solar power system from the grid in case of repair or maintenance work on the grid itself or on the solar power system. The AC disconnection box must fulfil safety requirements per local standards and according to IEC 62103 requirements. It should include the following devices:

- Circuit breakers for each phase of each connected inverter
- Avoid overheating by allowing for space between circuit breakers
- Main ac disconnection switch
- Ac overvoltage protection (only if not provided by the inverter; relevant for system locations with a high probability of thunderstorms)
- Connection to earth system, if overvoltage protection is included
- Terminals for connection of inverters and grid

Essentials for wiring and accessories

- Only use certified products for solar power systems
- Sizing according to farm's environmental conditions
- Protection level according to place of installation
- Installation protected from dirt and insects
- Safety First!

Required Standards for Accessories

- IEC 62103 - Electronic equipment for use in power installations

Batteries for Solar Pump Systems

Batteries can be used in solar pump systems to increase the efficiency of the whole system. One option is short time storage of solar over-capacity at peak solar irradiation for usage during non-solar hours, hence increasing solar pump operating time and avoiding solar energy waste. In this case, the battery capacity required is smaller and thus costs are lower. The sizing of the PV is not influenced by the batteries as only over-capacity is buffered. Another option is to adapt batteries based on the gap between the possible solar operation time and the required irrigation schedule. In this case the batteries have to be designed based on the expected pump operation time after sunset, and the PV system has to be oversized according to the required energy which has to be stored during solar hours.

Example:

Pump power:	75 kW
Expected pump operation based on batteries:	10 h
Battery efficiency:	90 %
Required energy:	75 kW * 10 h / 0.9 = 833 kWh useful capacity
DoD designed:	50%
Required nominal capacity of battery bank:	1.670 kWh

Especially in desert climate, it is crucial to take environmental conditions into account when designing the battery system. Battery efficiency and lifetime are strongly dependent on operating temperatures.

The most commonly used types of batteries in PV systems are lead acid, lithium-ion, nickel-metal-hybrid and nickel cadmium batteries.

The lead acid technology is the cheapest. All other technologies are 3 to 5 times more expensive. Lithium-ion and nickel-metal-hybrid batteries are used mainly in small portable PV applications because they are about 2 to 3 times lighter in weight, compared to lead acid. Nickel cadmium batteries are mainly used for very cold climates. This means for stationary systems, such as solar pump systems the lead acid technology is the most suitable.

a)

b)

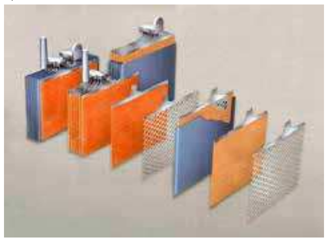


Figure 57: Typical construction of tubular OPzS (a) and grid plates OGI (b) lead acid-battery

Main requirements of lead acid batteries for PV systems:

- Long service life (6 – 10 years)
- Low self-discharge
- High duty cycle
- Highly robust to sustain integrity at extended periods at low level of charge
- Low maintenance requirements

Capacity: Generally, the capacity of batteries is given in Ampere-hours (Ah) for a certain discharge C-rate. For instance, C10 for a 100Ah battery indicates that this battery can supply a current of 10 Ampere for duration of 10 hours. To calculate the amount of stored energy (Wh) the capacity (Ah) must be multiplied with the nominal voltage (V).

Depth of discharge (DOD): The Depth of Discharge (DOD) of a battery is defined as the percentage of capacity that has been withdrawn from the battery, compared to the fully charged capacity. For deep discharge batteries, the DOD can reach up to 80%. However, less DOD results in an increased number of cycles or battery lifetime. In general, the allowable DOD is related to the number of autonomy days that battery is designed for.

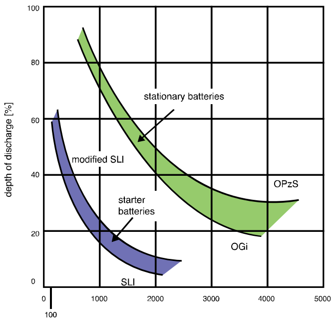


Figure 58: Life cycles vs. DOD of different types of lead-acid batteries. (Source: Varta (adapted))

For solar pump systems, it is strongly recommended to use stationary batteries which reach a higher number of cycles in comparison to starting lighting ignition (SLI) batteries. Stationary batteries are produced with two different types of positive plates. The so called tubular plate (OPzS) achieves a longer lifetime compared to the grid plate (OGI), and it is more robust against deep discharge. In many cases the so-called solar batteries are modified SLI batteries with thicker plates. They achieve more cycles compared to original SLI batteries.

The battery capacity should be adapted accurately. Three main factors must be considered: system charge and discharge current, allowable DOD and autonomy period. The autonomy period is the number of days that the battery can supply power to the load without any charging power from PV panels and before it reaches the allowable DOD. In typical sizing, it is recommended to design a system based on an allowable DOD of 80% of the nominal battery capacity, since the battery capacity declines along the lifetime. For a long battery lifetime it is recommended to keep the DOD very low. Often, a charge controller controls the battery bank's DOD. This means that, at a certain DOD, it disconnects the load or starts the diesel generator. If a DOD > 70% is reached it is important to fully charge the battery within a few days, otherwise the battery lifetime will be reduced.

Most batteries need to be maintained regularly, for example, the electrolyte has to be kept at the level assigned by the manufacturer, by adding distilled water. When using maintenance free batteries with a fixed electrolyte, it is strongly recommended to use Gel types. When AGM (absorbent glass mat) types are used, it is recommended to install them in such a way that the internal lead plates are oriented horizontally.

Influences on Battery Lifetime

The true lifetime of a battery depends on many factors.

Some likely causes of premature failure of a battery are:

- Drawing more current than the battery was designed for
- Over-discharging on regular basis
- Overcharging due to improper voltage setting
- Allowing electrolyte level in flooded cells to fall below plate level
- Topping up with other than distilled or dm water
- Operating or storing the battery in too high or too low ambient temperatures
- Subjecting the battery to excessive vibration or shock
- Too high level of discharge in operation

Essential for batteries

- Long lifetime, high number of cycles at high level of discharge
- Low maintenance
- Suitability for operation under high temperatures
- Sizing based on operation conditions such as DoD

Required Standards

- IEC 60896-11 Stationary lead-acid batteries:
  Part 11: Vented types – General requirements and method tests;
  Part 21: Valve regulated types – Methods of tests;
  Part 22: Valve regulated types – Requirements
- IEC 61427 Secondary cells and batteries for photovoltaic energy systems– General Requirements and Methods of Test
- IEC 62485-2 Part 2: Safety requirements for secondary batteries and battery installations: Stationary Batteries

Control and Metering

The operational control for a solar pump system is primarily done by the inverter. It synchronizes the generated solar power with the available grid, or in case of an island system it creates the necessary grid by its internal control. For a direct connection, the solar pump inverter adjusts the solar power to the demand of the connected pump. Additional control devices are necessary for the systems to have the following functions:

- In battery systems: charge control for batteries
- In hybrid systems with switch operation: switch control
- In hybrid systems with high solar fraction: power management

The metering depends on the requirements of the project, i.e. which data needs to be monitored. In all systems it is reasonable to install a water meter at the outlet of the well to monitor the water flow during operation. This can give an indication of the stability and performance of the solar pump system. With constant monitoring and regular checks, the meter can also indicate aging effects or other potential problems.

Figure 59: Water meter (Source: Hydrometer, Germany)

Figure 60: Example of data logging system

5

DIESEL VERSUS SOLAR: QUANTIFIED

5.1 Cost Analysis Example

LCC Comparison of Diesel- / Solar Pump System

Project name: Project location: Cairo, Egypt Date 26.Apr.2014

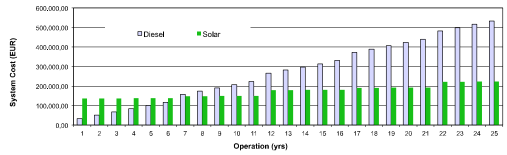
	Diesel Pump System			Solar Pump System		
Project Details	Water Demand (yr ave)	805	m3/d	Water Delivery (yr ave)	690	m3/d
	L/hr Demand	115	L/hr	L/hr Delivery max	115	L/hr
	Well Head (water table)	40,00	m	Well Head (water table)	40,00	m
	Tank Head + Pressure	4,50	bar	Tank Head + Pressure	4,50	bar
	Total Head	85,00	m	Total Head	85,00	m
	Pump	45	kW	Pump	45	kW
	Generator	160	kW	Inverter	45	kW
	Fuel Consumption (ave)	25	L/hr	PV array	73,50	kW
	New DG?	n	(y/n)			
	New Pump?	n	(y/n)	New Pump	n	(y/n)
	Operation Time (avg)	7,0	hrs/d	Operation Time (avg)	6,0	hrs/d
	Number of Pumps	1		Number of Pumps /Inverter	1	

	Item	Serv. (yrs)	Cost (€)	Cost (€)	Item	Service (yrs)	Cost (€)	Cost (€)
Setup Cost	Diesel Generator	5	16.000,00	16.000,00	Solar Pump System		128.000,00	128.000,00
	Accessories	5	1.200,00	1.200,00	Foundations Solar (local)	25	2.660,00	2.660,00
	Installation	5	1.000,00	1.000,00	Solar Installation (local)	25	5.320,00	5.320,00
	Water pump	5	8.000,00	0,00	Water pump	5	8.000,00	0,00
	Subtotal			18.200,00	Subtotal			135.980,00

	Item	Cost (€)	Interval (hrs)	Cost (€)	Item	Cost (€)	Cost /yr (€)
Operation Cost (/yr)	Fuel Cost /L	0,18		11.497,50	-	-	-
	Oil & filter	90,00	200	1.149,75	-	-	-
	Storage, Transport /wk	150,00	300	1.277,50	-	-	-
	Labour Cost /d	6,00		2.190,00	Labour Cost /d	1,00	365,00
	Subtotal			16.114,75	Subtotal		365,00

	Item	Serv. (yrs)	Cost /5yr (€)	Item	Service (yrs)	Cost /5yr (€)	Cost /10yr (€)
Replacement Cost (/yr)	Diesel Generator	5	16.000,00	Inverter	10	-	19.200,00
	Pump	5	8.000,00	Pump	5	8.000,00	8.000,00
	Accessories	5	1.200,00	Accessories	5	1.920,00	1.920,00
	Subtotal		25.200,00	Subtotal		9.920,00	29.120,00

Life Cycle Comparison 10% yr fuel/oil price hike No inflation adjustment



Specific Water Cost

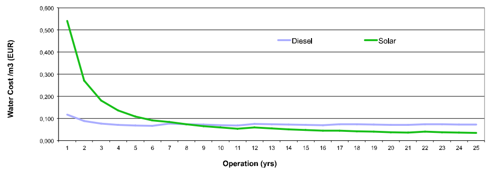


Figure 61: Example of lifecycle costs and water cost calculation – comparing diesel/solar solutions. (Source: Jorg Steinke)

5.2 Profile of Solar Water Supply

Solar Pump System Performance

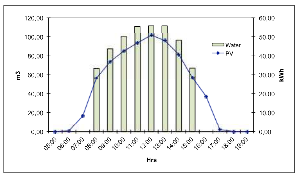
Project name: Project location: Cairo, Egypt ▼ Date 26.Apr.2014

	Diesel Pump System			Solar Pump System		
Project Details	Water Demand	805	m3/d	Water Delivery	690	m3/d
	Well head (water table)	40	m	Well head (water table)	40	m
	Tank head + Pressure	4,50	bar	Tank head + Pressure	4,50	bar
	Total Head	85	m	Total Head	85	m
	Pump	45	kW	Pump	45	kW
	Generator	160	kW	Inverter	45	kW
	Fuel Consumption	175,00	L/d	PV array	73,50	kW
	Operation Time (ave)	7,0	hrs/d	Operation Time (ave)	6,5	hrs/d

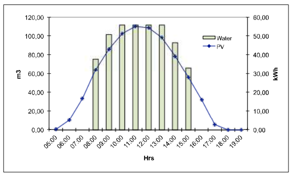
Solar Fraction 86%

Performance Analysis Seasonal

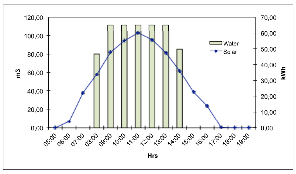
21. March 753m3/d



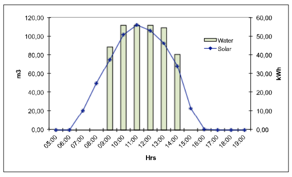
21. June 783m3/d



21. September 724m3/d



21. December 613m3/d



Yearly 251.875 m3/yr of 293.825 (86%)

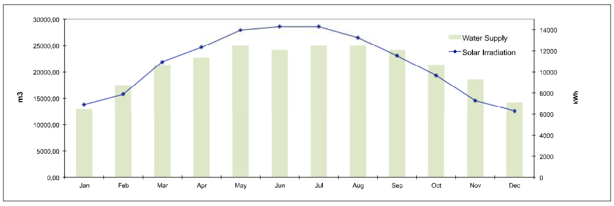


Figure 62: Example calculation (Source: Jorg Steinke)

6 Best Practices

Stand-alone systems for direct irrigation seem to be the best available choice for the situation in Egypt in 2014. Standard components, including suitable solar pump inverters, are readily accessible on the market. Such systems offer significant potential for fuel savings, for flexible crops and even allow for a completely independent solution.

Solar pumping is best applied on existing farms with fixed ratio between irrigated area and number of wells. Increases of the flow-rate during solar hours in order to store excess water however are rarely possible with this direct set-up. Therefore, it is often not feasible to increase the solar pumping fraction to more than the solar hours. For the non-solar hours a backup diesel generator is needed. While increasing the system cost, an effective way to extend irrigation time and solar fraction is the integration of batteries in the solar pump solution.

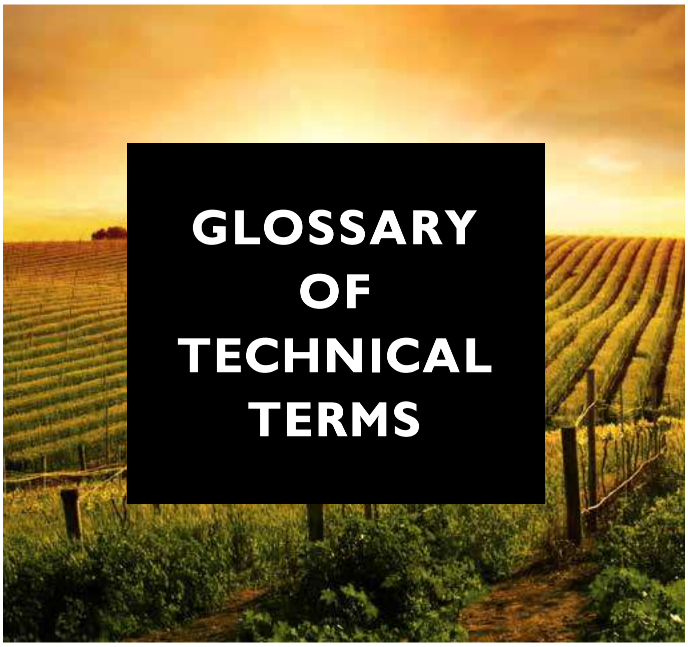
Another solution connecting several wells, is the fuel saver solution. A special control unit called "fuel saver" can be used to extent the solar pump limit. The wells are connected to a small grid and a diesel generator. When several wells are connected to a small grid and a diesel generator is continuously running, the integration of PV, by simple grid connection technology, can often be used. Such multi - well management systems or mini grids with batteries will become more and more important, as more new farms are developed or existing farms transition to PV-driven irrigation systems. To achieve the most cost-efficient solution, a professional analysis of the wells' performance, pump efficiency, irrigation schedule and of solar irradiation should be conducted ahead of deciding on a specific solar pump system. This allows to uncover and eliminate inefficient factors (e.g. an inefficient pump). Thus requirements for the design of a cost and energy efficient solution can be met.

A key part in designing a suitable systems is the inverter. Standard grid inverters, especially when imported from western countries, are designed for a stable grid connection. Also, instead of direct power to a pump or any other machinery, the grid inverters are constructed to feed into an electricity grid. Hence, grid inverters are most suitable for hybrid systems where they feed PV energy to a diesel generator grid with stable frequency and voltage.

The support structure is a significant factor in terms of system lifetime. Suitable materials and approved static calculations are crucial, independent on whether the system to be used is standardized and imported or consists of individually, locally created structures.

For solar pumping systems in Egypt, space is not a limiting factor. Instead, environmental circumstances and the climate have to be considered in the system design. Systems have to be adapted to extreme conditions such as heat and sand storms to function reliably.

In the long-term, based on the current cost development of solar power systems on the international market, battery supported systems are expected to be the preferred choice. The price of batteries is expected to drop over the next decade, thus costs for such systems will decrease and provide long-term independent solutions.



GLOSSARY OF TECHNICAL TERMS

Azimut

The azimut described the angle between direct south orientation of a PV area and the real installation.

-90° East 0° South 90° West 180° North

Degradation

As no component is in motion, PV modules and systems have a lifetime of 20 years and more, with low maintenance and operation costs. Nevertheless, the system ouput decreases over the years. The factor of lost efficiency over a time period is called degradation. It is a physical effect which cannot be avoided. Degradation is normally limited to 0.25 to 0.6% per year, so that after 20 years the output of the system is still 88% of the initial start-up output. All manufacturers cover this effect with the so-called output performance warranty. This warranty is backed up by international insurance companies to provide safety for the investment of customers.

Inclination

The term inclination describes the angle between the PV modules of a solar system and the horizontal ground in °.

kWp – kilo Watt peak

kWp is the unit to specify the system size of a solar power system. It describes the output of the system under standard test conditions (STC). As the real conditions of operation are normally different from the STC, the output power of a PV system is normally lower than the kWp value. The maximum solar irradiation of 1000 W/ is almost totally independent of the location and can be reached around noon time. However, the daily profile of the sunlight and the achievable solar energy yield is strongly dependent on the location and the manner of installation (inclination, azimut, shading factors). The closer the modules can be installed to the optimized inclination and azimut, the higher the solar yield. The higher the irradiation over the day and year, the higher the solar yield. The output power of a PV system is also dependent on the module temperature in operation. The higher the temperature is, the lower the output power will be. For roof parallel installations, it is important to keep the back of the modules ventilated and to install them at a certain distance of the roof.

PV systems can be compared by kWp size and costs, but should also be analyzed based on kWp and the solar yield in kWh/kWp or the total output of the system per year in kWh. These calculations can be determined with suitable software only.

MPP Tracking

The output voltage and current of a PV system is always changing, depending on irradiation, temperatures and shading effects. The inverter is continuously reacting to the changes via the so-called MPP tracking (Maximum Power Point) to ensure operation over a wide range at the best output performance.

STC – Standard Test Conditions

All PV modules must be tested regarding safety and output performance before being certified. The standard test conditions are ideal conditions for solar power generation. The following fixed conditions are used for all testing to make it possible to compare different technologies and products:

Solar irradiation: 1000 W/ Module temperature: 25°C

Air Mass: 1.5 (length of transmission for the sunlight through the atmosphere, compared to direct transmission)

Shading

When solar power systems are installed, the negative influence of shading on the output must be avoided. This especially applies to directly solar driven pumps, in which the solar system needs to ensure a continuous, maximum power output to keep the pumps running. To restrict shading, first of all the environment has to be taken into account (buildings, trees). The choice of a suitable location, free of any shading, is an essential factor. Also, the solar system itself and its support structure can cause negative influence by casting shadows. A minimum distance between module areas, calculated according to the location and the minimum angle of the winter sun, must be maintained to avoid self-shading.

Solar Yield

The solar yield of a solar power system is the essential value which describes the efficiency and output of the system, and is used to compare different systems. It shows the useful generated energy of the system, whether as a specific value in kWh/kWp or as total value per year in kWh. It can be determined with suitable software, but to get the values of realized systems a technical monitoring for least one year is necessary Solar yield is the basis for any economic calculation.

System Efficiency

The system efficiency of a solar power system is defined as:

solar yield of the system / total irradiation on the PV area

The system efficiency of a standard grid connected system can reach a range about 10 %. A system with direct solar connection to the pump normally has quite a low system efficiency of about 5 %, as energy which is not yet strong enough to run the pump is internally wasted and cannot be used.

Soft Starter and Variable Speed Drive

A variable-speed drive (VSD) (also termed adjustable-frequency drive, variable-frequency drive) is a type of adjustable speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. VSDs are used in applications ranging from small appliances to the largest of mine mill drives and compressors. A variable speed drive adjusts the power input to a consumer's (such as a motor or pump) demand and is normally used to save energy in operation. In a solar pump system, it has the function to adjust the input frequency and voltage for the pump according to the available solar power. The VSD normally also includes the function of a soft starter, which is also sometimes specified as separate part when not integral to the inverter. A soft starter for pumps is necessary to avoid shut-down of an inverter, and consequently the complete solar power system, due to the high current required by the pump when it starts-up.

Appendix I: Example – Juwi Solar Pump System in Wadi El Natroun

Description of the System

Technical Data
Solar System: 50 kWp.
Wind turbines: 50 kW (4 turbines with 13 kW)
Battery: 11200 Ah / 48 V OPzS 4 Battery Banks
Inverter concept: SMA AC-coupling with Sunny Islands, 3-phase system with 4 Clusters. Max Power of Battery Inverters is 78 kW.

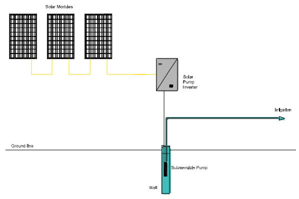
Objectives
This hybrid plant produces electricity for the local pumps for irrigation. 4 wind turbines with each 13kW and a solar field of 50kWp are coupled by AC coupling with a Sunny Island system. The batteries have enough capacity to store the produces electricity also for long sun- and windless periods. A desalination plant is also connected to the system, which desalinate the salty ground water.

Realization
The system has been built in October of 2012 with our local partners.

Appendix II: PV Request for Proposal of Solar Pump System

Checklist Solar Pump Systems

Stand Alone System for direct Irrigation



Location: ______________________

A) Irrigation System — **required irrigation time:**

summer ________ to ________ = ________ h

winter ________ to ________ = ________ h

required flow rate: ________ cbm/h

total water volume:

summer ________ cbm/day

winter ________ cbm/day

required pressure on irrigation system ______ bar

B) Pump

- Existing pump

pump type ______________________

pump power ________ **kW**

range of power control ________ to ________ **%**

- New pump

Dynamic table of well ________ m

well performance ________ cbm/h

pump head ________ m

design flow rate ________ cbm/h

pump type ______________________

range of power control ________ to ________ **%**

pipe connection of pump ________ mm

wire connection of pump ______________

Checklist Solar Pump Systems II

Stand Alone System for direct Irrigation

C) Solar Power System

size of PV system ____________ kWp

type of modules ____________________________

temperature coefficients

Pmax ______ %/K

Voc ______ %/K

Isc ______ %/K

number of strings ____________

qty of modules per string ____________

ratio of PV Power / Pump Power ______

- aging factor included for __________ years ( )
- temperature coefficients regarded in design ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

D) Solar Pump Inverter

inverter type ____________________________________

maximum PV input power __________ **kW**

range of power output __________ to __________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

version 1.0

Checklist Solar Pump Systems III

Stand Alone System for direct Irrigation

E) Support structure

- anti corrosive material ( )
- static calculations available ( )

F) Solar Pump System Data

PV Power __________ kWp

Inverter Power __________ kW

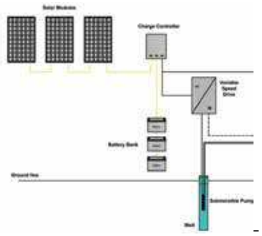
Pump Power __________ kW

	summer	winter
Required operation time	__________ h	__________ h
Solar operation time	__________ h	__________ h
Solar Fraction	__________ %	__________ %
Average Solar fraction during the year		__________ %

version 1.0

Checklist Solar Pump Systems

Stand Alone System for direct Irrigation with batteries



Location: ____

A) Irrigation System

required irrigation time:

summer ________ to ________ = ________ h

winter ________ to ________ = ________ h

required flow rate: ________ cbm/h

total water volume:

summer ________ cbm/day

winter ________ cbm/day

required pressure on irrigation system ______ bar

B) Pump

- Existing pump

pump type ____________________

pump power ________ **kW**

range of power control ________ to ________ **%**

- New pump

Dynamic table of well ________ m

well performance ________ cbm/h

pump head ________ m

design flow rate ________ cbm/h

pump type ____________________

range of power control ________ to ________ **%**

pipe connection of pump ________ mm

wire connection of pump ____________

Checklist Solar Pump Systems II

Stand Alone System for direct Irrigation with batteries

C) Batteries

expected battery operation time ________ h

necessary battery capacity ________ kWh

designed DoD ________ %

nominal battery capacity ________ kWh

battery type ____________________

calculated lifetime cycles ________

- battery suitable for operating temperatures ( )
- suitablle charge control included ( )

D) Solar Power System

size of PV system ________ kWp
(for ditect operation and charging)

type of modules ____________________

temperature coefficients Pmax ______ %/K

Voc ______ %/K

Isc ______ %/K

number of strings ________

qty of modules per string ________

ratio of PV Power / Pump Power ______

- aging factor included for ________ years ( )
- temperature coefficients regarded in design ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

Checklist Solar Pump Systems III

Stand Alone System for direct Irrigation with batteries

E) Solar Pump Inverter

inverter type ____________________

maximum PV input power __________ **kW**

range of power output __________ to __________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

F) Support structure

- anti corrosive material ( )
- static calculations available ( )

G) Solar Pump System Data

PV Power __________ kWp

Inverter Power __________ kW

Pump Power __________ kW

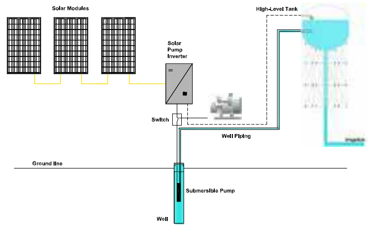
Battery capacity __________ kWh

	summer	winter
Required operation time	__________ h	__________ h
Solar operation time	__________ h	__________ h
Solar Fraction	__________ %	__________ %

Average Solar fraction during the year __________ %

Checklist Solar Pump Systems

Stand Alone System with high level storage



Location: ____________________

A) Irrigation System

required irrigation time:

summer __________ to __________ = __________ h

winter __________ to __________ = __________ h

required flow rate: __________ cbm/h

total water volume:

summer __________ cbm/day

winter __________ cbm/day

required pressure on irrigation system ________ bar

B) Pump

- Existing pump

pump type ____________________

pump power __________ **kW**

range of power control __________ to __________ **%**

- New pump

Dynamic table of well __________ m

well performance __________ cbm/h

pump head __________ m

design flow rate __________ cbm/h

pump type ____________________

range of power control __________ to __________ **%**

pipe connection of pump __________ mm

wire connection of pump ____________________

- check if necessary increase of flow rate allowed by well performance ( )

Checklist Solar Pump Systems II

Stand Alone System with high level storage

C) Solar Power System

size of PV system ______________ kWp

type of modules ______________________________

temperature coefficients

Pmax	_______	%/K
Voc	_______	%/K
Isc	_______	%/K

number of strings ______________

qty of modules per string ______________

ratio of PV Power / Pump Power ___________

- aging factor included for __________ years ( )
- temperature coefficients regarded in design __________ ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

D) Solar Pump Inverter

inverter type ____

maximum PV input power __________ **kW**

range of power output __________ to _________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

Checklist Solar Pump Systems III

Stand Alone System with high level storage

E) Support structure

- anti corrosive material ( )
- static calculations available ( )

F) High Level Storage

size of tank based on available volume _________ cbm

height of tank based on pressure for irrigation _________ m

material of tank _____________

- ground structure of field allows high level storage ( )
- corrosion protection for tank ( )
- static calculations for support structure and foundations ( )

G) Solar Pump System Data

PV Power __________ kWp

Inverter Power __________ kW

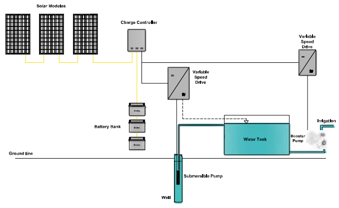
Pump Power __________ kW

High Level Storage __________ cbm

	summer	winter
Required operation time	__________ h	__________ h
Solar operation time	__________ h	__________ h
Solar Fraction	__________ %	__________ %
Average Solar fraction during the year		__________ %

Checklist Solar Pump Systems

Stand Alone System with ground level storage, batteries and booster pump



Location: ____________________

A) Irrigation System — **required irrigation time:**

summer ________ to ________ = ________ h

winter ________ to ________ = ________ h

required flow rate: ________ cbm/h

total water volume:

summer ________ cbm/day

winter ________ cbm/day

required pressure on irrigation system ________ bar

B) Pump

- Existing pump

pump type ____________________

pump power ________ **kW**

range of power control ________ to ________ **%**

- New pump

Dynamic table of well ________ m

well performance ________ cbm/h

pump head ________ m

design flow rate ________ cbm/h

pump type ____________________

range of power control ________ to ________ **%**

pipe connection of pump ________ mm

wire connection of pump ____________________

- check if necessary increase of flow rate allowed by well performance ( )

Checklist Solar Pump Systems II

Stand Alone System with ground level storage, batteries and booster pump

C) Solar Power System

size of PV system ________ kWp

type of modules ____________________

temperature coefficients Pmax ________ %/K

Voc ________ %/K

Isc ________ %/K

number of strings ________

qty of modules per string ________

ratio of PV Power / Pump Power ________

- aging factor included for ________ years ( )
- temperature coefficients regarded in design ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

D) Solar Pump Inverter

inverter type ____________________

maximum PV input power ________ **kW**

range of power output ________ to ________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

Checklist Solar Pump Systems III

Stand Alone System with ground level storage, batteries and booster pump

E) Support structure

- anti corrosive material ( )
- static calculations available ( )

F) Ground Storage

size of tank based on available volume ________ cbm

material of tank ________

- corrosion protection for tank ( )
- static calculations for support structure and foundations ( )

G) Battery and Booster Pump

flow rate of booster pump ________ cbm/h

pump head of booster pump ________ m

pump power ________ kW

pump type ________

operation time of booster pump ________ h

required battery capacity ________
(nominal capacity under DoD and operating temperatures)

H) Solar Pump System Data

PV Power ________ kWp

Inverter Power ________ kW

Pump Power ________ kW

Ground storage ________ cbm

Booster Pump ________ kW

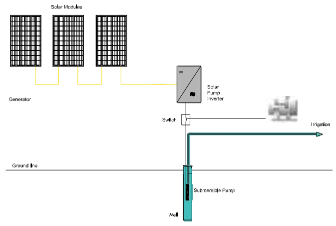
Batteries ________ kWh

	summer	winter
Required operation time	________ h	________ h
Solar operation time	________ h	________ h
Solar Fraction	________ %	________ %

Average Solar fraction during the year ________ %

Checklist Solar Pump Systems

Solar / Diesel Hybrid System with switch operation



Location: ________

A) Irrigation System **required irrigation time:**

summer ________ to ________ = ________ h

winter ________ to ________ = ________ h

required flow rate: ________ cbm/h

total water volume:

summer ________ cbm/day

winter ________ cbm/day

required pressure on irrigation system ________ bar

B) Pump

- Existing pump **pump type** ________

pump power ________ **kW**

range of power control ________ to ________ **%**

- New pump **Dynamic table of well** ________ m

well performance ________ cbm/h

pump head ________ m

design flow rate ________ cbm/h

pump type ________

range of power control ________ to ________ **%**

pipe connection of pump ________ mm

wire connection of pump ________

Checklist Solar Pump Systems II

Solar / Diesel Hybrid System with switch operation

C) Solar Power System

size of PV system ____________ kWp

type of modules ____________

temperature coefficients Pmax ______ %/K

Voc ______ %/K

Isc ______ %/K

number of strings ____________

qty of modules per string ____________

ratio of PV Power / Pump Power ______

- aging factor included for __________ years ( )
- temperature coefficients regarded in design ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

D) Solar Pump Inverter

inverter type ____________

maximum PV input power __________ **kW**

range of power output __________ to __________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

Checklist Solar Pump Systems III

Solar / Diesel Hybrid System with switch operation

E) Support structure

- anti corrosive material ( )
- static calculations available ( )

F) Solar Pump System Data

PV Power __________ kWp

Inverter Power __________ kW

Pump Power __________ kW

	summer	winter
Required operation time	__________ h	__________ h
Solar operation time	__________ h	__________ h
Solar Fraction	__________ %	__________ %
Average Solar fraction during the year		__________ %

G) Generator System

generator type ____________

power of back-up generator __________ kW

fuel consumption of back-up __________ l/h

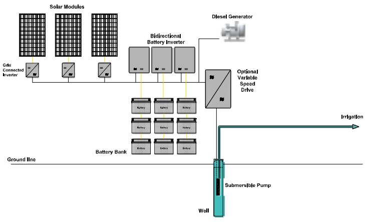
required back-up operation __________ h

total back-up fuel demand __________ l

- Switch Control available ( )

Checklist Solar Pump Systems

Solar / Diesel Hybrid Systems with Batteries



Location: ____________________

A) Irrigation System — **required irrigation time:**

summer ________ to ________ = ________ h

winter ________ to ________ = ________ h

required flow rate: ________ cbm/h

total water volume:

summer ________ cbm/day

winter ________ cbm/day

required pressure on irrigation system ______ bar

B) Pump

- Existing pump

pump type ____________________

pump power ________ **kW**

range of power control ________ to ________ **%**

- New pump

Dynamic table of well ________ m

well performance ________ cbm/h

pump head ________ m

design flow rate ________ cbm/h

pump type ____________________

range of power control ________ to ________ **%**

pipe connection of pump ________ mm

wire connection of pump ____________

Checklist Solar Pump Systems II

Solar / Diesel Hybrid Systems with Batteries

C) Solar Power System

size of PV system ________ kWp

type of modules ____________________

temperature coefficients Pmax ______ %/K

Voc ______ %/K

Isc ______ %/K

number of strings ________

qty of modules per string ________

ratio of PV Power / Pump Power ______

- aging factor included for ________ years ( )
- temperature coefficients regarded in design ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

D) Batteries

expected battery operation time ________ h

necessary battery capacity ________ kWh

designed DoD ________ %

nominal battery capacity ________ kWh

battery type ____________________

calculated lifetime cycles ________

- battery suitable for operating temperatures ( )
- suitablle charge control included ( )

Checklist Solar Pump Systems III

Solar / Diesel Hybrid Systems with Batteries

E) Solar Pump Inverter

inverter type ____________________

maximum PV input power ________ **kW**

range of power output ________ to ________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

F) Support structure

- anti corrosive material ( )
- static calculations available ( )

G) Solar Pump System Data

PV Power ________ kWp

Inverter Power ________ kW

Pump Power ________ kW

Battery capacity ________ kWh

	summer	winter
Required operation time	________ h	________ h
Solar operation time	________ h	________ h
Solar Fraction	________ %	________ %
Average Solar fraction during the year		________ %

Checklist Solar Pump Systems IV

Solar / Diesel Hybrid Systems with Batteries

H) Generator System

generator type ____________________

power of back-up generator ________ kW

fuel consumption of back-up ________ l/h

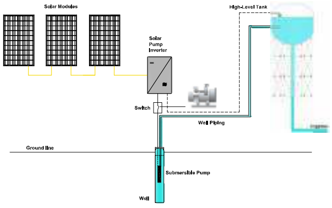
required back-up operation ________ h

total back-up fuel demand ________ l

- Switch Control available ( )
- Generator included into charge control ( )

Checklist Solar Pump Systems

Solar / Diesel Hybrid Systems with high level tank



Location: ______________________

A) Irrigation System

required irrigation time:

summer ________ to ________ = ________ h

winter ________ to ________ = ________ h

required flow rate: ________ cbm/h

total water volume:

summer ________ cbm/day

winter ________ cbm/day

required pressure on irrigation system ______ bar

B) Pump

- Existing pump

pump type ______________________

pump power ________ **kW**

range of power control ________ to ________ **%**

- New pump

Dynamic table of well ________ m

well performance ________ cbm/h

pump head ________ m

design flow rate ________ cbm/h

pump type ______________________

range of power control ________ to ________ **%**

pipe connection of pump ________ mm

wire connection of pump ______________

Checklist Solar Pump Systems II

Solar / Diesel Hybrid Systems with high level tank

C) Solar Power System

size of PV system ________ kWp

type of modules ______________________

temperature coefficients

Pmax ______ %/K

Voc ______ %/K

Isc ______ %/K

number of strings ________

qty of modules per string ________

ratio of PV Power / Pump Power ______

- aging factor included for ________ years ( )
- temperature coefficients regarded in design ( )
- modules suitable for climate conditions ( )
- modules certified according to standards ( )
- check of string voltage and power under different climate conditions ( )
- Strings can be disconnected safely and separately ( )
- string combiner boxes with suitable overvoltage protection ( )
- DC wiring with suitable solar wires ( )
- wiring in suitable cable ducts and protection pipes ( )

D) Solar Pump Inverter

inverter type ______________________

maximum PV input power ________ **kW**

range of power output ________ to ________ **%**

- MPP Tracking integrated ( )
- Frequency Inverter integrated ( )
- Inverter suitable for climate conditions ( )
- Overvoltage protection included ( )
- Motor Protection included ( )
- Inverter Housing suitable for climate and operation conditions ( )

Checklist Solar Pump Systems III

Solar / Diesel Hybrid Systems with high level tank

E) Support structure

- anti corrosive material ( )
- static calculations available ( )

F) High Level Storage

size of tank based on available volume __________ cbm

height of tank based on pressure for irrigation __________ m

material of tank ______________

- ground structure of field allows high level storage ( )
- corrosion protection for tank ( )
- static calculations for support structure and foundations ( )

G) Solar Pump System Data

PV Power ___________ kWp

Inverter Power ___________ kW

Pump Power ___________ kW

High level storage ___________ cbm

	summer	winter
Required operation time	___________ h	___________ h
Solar operation time	___________ h	___________ h
Solar Fraction	___________ %	___________ %
Average Solar fraction during the year		___________ %

G) Generator System

generator type __________________________

power of back-up generator ___________ kW

fuel consumption of back-up ___________ l/h

required back-up operation ___________ h

total back-up fuel demand ___________ l

- Switch Control available ( )

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