Solar Powered Irrigation Systems (SPIS)

Technology, Economy, Impacts

Deutsche Gesellschaft
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Foreword

In 2002, a project on 'Resource-saving Irrigation through Photovoltaic Pumps' carried out by the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH had completed a series of field tests on the applicability of the technology in Ethiopia, Chile and Jordan. It concluded that while interest among farmers is high, initial investment costs and a lack of adequate financing instruments hinder broad-scale adoption of the technology.

Ten years later, agricultural and energy experts at GIZ began to revisit solar powered irrigation systems (SPIS) in the light of falling costs for PV, rising costs for diesel fuel and technological improvements. It was observed that governments, extension services and technical cooperation actors in various sectors (water, agriculture, energy, agricultural finance) were actively promoting or considering promoting this technology. However, it was equally evident that the potential in terms of economic feasibility and economic performance remains highly dependent on specific circumstances and was therefore largely unknown.

Today, economic circumstances and system costs are still highly relevant in terms of a broad adoption of SPIS. Nevertheless, an increasing number of innovative business models, such as pay-as-you-go models or shared irrigation systems, owned by several smallholders, allow a continuing adoption. One of the most pressing challenges as of today is the risk of groundwater exploitation by using PV-powered irrigation systems. The urgent need to improve farmers', advisors' and system installers' capacity to sustainably manage water resources in a SPIS has become evident.

Two GIZ projects joined forces in order to fill prevailing knowledge gaps: *Sustainable Energy for Food – Powering Agriculture* and *Basic Energy Services (HERA).*

Basic Energy Services (HERA) was a sector project commissioned by BMZ. It has built on more than three decades of GIZ experience in the field of access to energy and worked in four thematic areas: Clean cooking, access to electricity, productive use of energy and cross-cutting issues. In the area of productive use of energy, HERA was working on the use of energy in agriculture, handicrafts, commerce and other value-generating areas.

Sustainable Energy for Food – Powering Agriculture is the German contribution to 'Powering Agriculture: An Energy Grand Challenge for Development (PAEGC)'. PAEGC, an international initiative, seeks to identify and support new and sustainable approaches to accelerate the development and deployment of clean energy solutions by which to increase agricultural productivity and/or value in developing countries. It is an initiative of USAID, partnering with the Swedish International Development Cooperation Agency (SIDA), Duke Energy Corporation (Duke), the Overseas Private Investment Corporation (OPIC) and the German Federal Ministry for Economic Cooperation and Development (BMZ). GIZ is implementing BMZ's contribution to this initiative.

The report at hand presents the status quo of SPIS-technology. It identifies potentials and challenges of the technology and links to hands-on tools for sustainably planning, installing and running a SPIS. Hopefully, the results may prove useful for all those, who are active in the field of solar irrigation and contribute to growing but sustainable application of this technology.

Preface

Irrigated agriculture is an important factor for local economic development in most developing countries. Reliable and affordable access to irrigation water is hence key to food security and poverty reduction.

Manual lifting of irrigation water reduces the scope for crop cultivation and the efficiency of irrigation – it does not, for example, allow for the pressurised systems that are required for water-saving micro-irrigation techniques. In the absence of reliable electricity supply due to intermittent service or even a complete lack of grid connection, farmers in developing countries often must rely on fossil fuel driven pumps for water abstraction and conveyance. This technology has low initial investment costs but incurs high operation costs and is prone to outages due to an insufficient fuel supply and frequent maintenance and repair. A reliable and cost-effective supply of irrigation water is therefore a limiting production factor in many rural areas of the developing world.

The establishment of uninterrupted and affordable electricity supply in rural areas through grid extension and centralised electricity production is a distant vision in many countries. Rural electrification in economically weak rural areas of Africa, Asia and Latin America will be largely based on investment in local off-grid solutions and independent mini grids. In regions with high solar insolation levels, electricity from photovoltaic arrays presents new options for abstracting/lifting and distributing water in an efficient, reliable, economically viable and ecologically sound way.

The technological option of solar-powered irrigation is rarely taken into consideration due to a lack of pertinent experience and the relatively high investment costs of the past. However, as prices for solar modules have fallen substantially in recent years, innovators in the farming sector, governments, extension services and technical cooperation are reconsidering photovoltaic water pumps (PVP) to be employed on a larger scale in agricultural production and beyond.

This report takes stock of and analyses the use of Solar Powered Irrigation Systems in agriculture. It brings together a timely and extensive overview of the state of the technology in terms of the water lifting, energy supply and irrigation system components, its economics and ecological boundaries, management requirements as well as potentials and barriers. The report is based on desk research and information generated by manufacturers, agrodealers, farmers and researchers worldwide. In addition, four country case studies provide information on geographical and market development differences. The preliminary findings of the report were enriched by comments and contributions from a series of workshops organised by GIZ and the Food and Agriculture Organization of the United Nations (FAO).

Complementary to this report, the Toolbox on Solar Powered Irrigation Systems was developed by GIZ and FAO. The Toolbox provides hands-on guidance for practitioners who work on or consider promoting Solar Powered Irrigation: agricultural extensionists, solar powered irrigation system providers, development practitioners and credit officers.

Both, the work on this report and the Toolbox was guided by the fact that information on technology options for SPIS – their potentials, limits and risks – is often unavailable to farmers and extension services. SPIS are often designed and planned in a simplistic way, resulting in a lack of integration of agronomic and technical as well as environmental aspects. There is a broad need for knowledge on site-specific and demand-based design of SPIS to render this technology option viable for the farmer and to avoid negative ecological and economic impacts. Both, the report and the Toolbox aim to overcome some of these shortfalls. It reflects our efforts to encourage the application of SPIS in developing countries where it is ecologically suitable and economically viable.

We wish you an interesting reading experience and hope that the report will increase your interest in the further prospects of Solar Powered Irrigation Systems in the context of rural development efforts.

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The report was prepared by Jan Sass GFA Consulting Group and Andreas Hahn (ah Advice International). It is the result of desk research enriched by the outcomes of exchanges and discussions with stakeholders in the private and public sectors, including civil society organisations.

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During the country case studies, the authors had the opportunity for exchanges and discussions with a large number of representatives of public services related to renewable energies and agriculture on both macro and meso levels.

The study has furthermore benefitted from contact management and facilitation provided by the GIZ Country Offices in Chile, India, Kenya and Morocco. The study team also benefitted greatly from support by and fruitful discussions with key GIZ staff of the Programme for Renewable Energies and Energy Efficiency in Chile, the Indo-German Energy Programme in India, the Energising Development Kenya Country Programme in Kenya and the Promoting Renewable Energy Sources and Energy Efficiency for Sustainable Development programme in Morocco.

The Delegations of German Industry and Commerce in Kenya and Morocco also provided valuable information and facilitated further contacts followed up by the study team.

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Abbreviations

AC	Alternating Current (sources)
Ah	Ampere Hour
AM	Air Mass
AZ	Solar Azimuth
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (German Federal Ministry of Economic Cooperation and Development)
BSW-Solar	German Solar Industry Association
CBA	Cost-Benefit Analysis
CNR	Comisión Nacional de Riego (National Irrigation Commission, Chile)
DASTPVPS	Design And Simulation Tool for Photovoltaic Pumping Systems
dB	Dezibel
DC	Direct Current (sources)
DGS	Deutsche Gesellschaft für Sonnenenergie e.V. (International Solar Energy Society, German Section)
Duke	Duke Energy Corporation
EC	Electric Conductivity
EPBT	Energy Payback Time
EPIA	European Photovoltaic Industry Association
EUR	Euro
EVA	Ethylene-vinyl Alcohol
FAO	Food and Agriculture Organisation of the United Nations
GFA	GFA Consulting Group GmbH
GIWR	Gross Irrigation Water Requirement
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
gph	Gallons per Hour
GSM	Global System for Mobile Communications
GWp	Gigawatt Peak
HDPE	High-density polyethylene
HERA	Poverty-oriented Basic Energy Services
HP	Horse Power
IARC	International Agency for Research on Cancer
ICID	International Commission on Irrigation and Drainage
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IFC	International Finance Cooperation
IGEN	Indo-German Energy Programme (India)
INDAP	Instituto de Desarrollo Agropecuario (Body of the Ministry of Agriculture in Chile)
INIA	Instituto de Investigaciones Agropecuarias (Body of the Ministry of Agriculture in Chile)
INR	Indian Rupee
IREDA	Indian Renewable Energy Development Agency
IRR	Internal Rate of Return
IWR	Irrigation Water Requirement
JNNSM	Jawaharlal Nehru National Solar Mission (India)
kW	Kilowatt

kWh	Kilowatt-Hour
kWp	Kilowatt Peak
LCA	Life Cycle Analysis
LPG	Liquefied Petroleum Gas
MALF	Ministry of Agriculture, Livestock and Fisheries (Kenya)
MENA	Middle East and North Africa
MNRE	Ministry of New and Renewable Energies (India)
MPPT	Maximum Power Point Tracking
NASA	National Aeronautics and Space Administration
NCWR	Net Crop Water Requirement
NIWR	Net Irrigation Water Requirement
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OECD	Organization for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPIC	Overseas Private Investment Corporation
PAEGC	Powering Agriculture: An Energy Grand Challenge for Development
PAH	Polycyclic Aromatic Hydrocarbons
PC	Pressure Compensation
PV	Photovoltaic
PVC	Polyvinylchloride
PVP	Photovoltaic (Water) Pump
RAP	Regional Office for Asia and the Pacific of the Food and Agricultural Organization of the United Nations
RE	Renewable Energy
RoHS	Restriction of Hazardous Substances
SABI	Suid Afrikaanse Besproeiing instituut (South African Irrigation Institute)
SAR	Sodium Absorption Rate
SIDA	Swedish International Development Agency
SNA	State Nodal Agency (India)
SPIS	Solar Powered Irrigation Systems
SSWM	Sustainable Sanitation and Water Management
STC	Standard Test Conditions
TC	Temperature Coefficient
TDS	Total Dissolved Solids
TWh	Terawatt-Hour
USAID	United States Agency for International Development
USD	United States Dollar
USGS	United States Geological Survey
UV	Ultraviolet
VASFA	Vashali Area Small Farmers' Association (India)
WEEE	Waste of Electrical and Electronic Equipment
WHO	World Health Organization
Wp	Watt Peak

Executive summary

Worldwide, the need for energy, the availability of renewable resources, and the falling cost of renewable energy technologies create multiple opportunities for PV technology. Photovoltaic solutions for on- and off-grid electrification are quite common and solar energy based water pumping is already widely used in drinking and livestock water supply as a low-maintenance option for rural areas. In the irrigation sector, however, the exploitation of PV-based water abstraction and conveyance technologies is still relatively rare, although the technology has proven to be a mature option – reliable and viable when properly planned and operated.

Most water pumps utilised for irrigation purposes worldwide are powered by engines running on fossil fuels (diesel, petrol, gas) or on electricity supplied from the grid (and thus produced by fossil fuel based generators). Fossil energy sources are limited in availability and the emissions from their utilisation have severe impacts on the global climate. At the same time, grid-based electricity supply tends to be insufficient and unreliable in developing countries, if not largely absent in rural areas. This context presents a **large potential to introduce PV technology** in irrigated agriculture. For India alone, it is estimated that farms operate 26 million diesel and electric pumps.

Photovoltaic powered irrigation is a **technically mature option**, even though it is not yet very widespread. From a technical point of view, photovoltaic water pumping can be integrated into most irrigation concepts. Water abstraction from ground or surface water sources is technically feasible even where large pumping heads and large conveyance quantities must be handled. PV pumps can also be employed to pressurise closed irrigation systems including centre pivots. On the side of pump manufacturers, technology development is far advanced and the market can provide a suitable pumping solution for almost any requirement and condition. This includes the integration of PV pumps into hybrid systems.

Limits upon a meaningful and feasible application of PV technology in irrigation result from agronomic and financial viability aspects. In contrast to public water supply, water pumping for irrigation has to follow an economic rationale – a farmer is an entrepreneur, no matter how small his landholding may be. The main considerations of a farm household are always production (food) security and the generation of income, hence maximisation of production and minimisation of fixed and variable production costs. Promotion efforts have to take these limits into account and must proceed from an understanding that the utilisation of PV technology requires high initial capital investment and technological know-how for system design and development.

Photovoltaic water pumping in irrigation is currently largely promoted by subsidising the technology in order to be an attractive alternative for the farmer. **Subsidisation**, however, should not result in non-adherence to principles of economic feasibility – for example, solar-powered water lifting from a deep borehole should not be employed to irrigate low yielding oilseeds in traditional basins, as can be observed in India. In this case, the costs and benefits are in no meaningful relation to each other but the equation is neglected due to subsidisation.

Based on the analysis presented in this report, photovoltaic water pumping in irrigation can be best utilised in the following contexts:

- **Surface irrigation:** Water abstraction from surface water resources (rivers, lakes) or shallow groundwater resources and injection into primary canals for onward water distribution;
- **Drip irrigation:** Water abstraction from surface or groundwater resources and (i) injection into storage facilities, (ii) direct injection into a pressurised system or (iii) injection from a storage facility into a pressurised system.

Water pumping with PV pumps from deep groundwater resources (or lifting from surface water resources up-hill with a large head) for water-intensive surface irrigation is not a feasible option due to the required dimensions of the PV generator and pump. Likewise, water pumping from groundwater or surface water resources for pressure-demanding sprinkler irrigation is not a viable option.

PV pumps have the **comparative disadvantage** that their performance is correlated to the level of radiation or rather the yield in solar energy that can be supplied to the pump. A PV pump is hence always sized larger than alternative diesel or grid-fed electric pump solutions – a PV pump must achieve an adequate performance related to irrigation needs even in the low-radiation periods of the day (morning/afternoon). This need for larger sizing usually results in over-capacity in the high-radiation periods of the day (noon).

Cost-efficient and viable operation of PV pumps in irrigation can be achieved if a number of principles are observed:

- Water-saving irrigation methods should be employed in order to reduce water pumping requirements – the most appropriate irrigation method in this sense is drip irrigation in low-pressure systems < 4 bars;
- Intermediate water storage tanks/basins (covered storage is to be preferred to avoid evaporation losses) should be integrated into the design of a Solar Powered Irrigation System (SPIS) – in particular in areas with deep aquifers – to create a low-head water source and create water autonomy for periods with low radiation; elevated storage tanks/basins that can provide onward gravity flow into the (low-pressure) network are ideal;
- Direct injection drip irrigation system designs should only be considered for smallholdings under the condition that the entire irrigated area can be irrigated at least once a day on any given day during the vegetation period;
- Irrigation systems with PV water abstraction and conveyance should be sub-divided into irrigation blocks adapted to the specific pumping performance to enable irrigation rotation between blocks (to avoid excessive over-dimensioning of the pumping system);
- PV water pumping should only be considered for high-value crops with excellent market prospects in order to recover the high initial investment;
- PV water pumps should not be used as back-up system to conventional pumping solutions, as their financial viability depends on a high utilisation rate with as little as possible additional operational expenses – if a decision is made to employ a PV pumping system, the PV pump(s) should become the primary pumping component;
- System design should incorporate flow and pressure requirements for filter and fertigation system components, even if their integration is not immediately planned;
- Every water pumping installation should be equipped with a monitoring device (at least a water flow meter, ideally also pressure gauge).

PV-based water abstraction and conveyance has a **number of positive ecological effects**, notably due to the low carbon footprint of the technology, the avoidance of emissions and the reduction of groundwater contamination risks. With regard to the sustainable utilisation of water resources, PV-based pumping solutions can have a widespread positive effect if planned in a meaningful way. The daily operational window of a solar-powered pump is up to 60 % narrower than that of a pump driven by conventional energy sources, which suggests introducing modern, water-saving micro-irrigation approaches to counter this limitation. This, combined with the fact that excessive over-sizing of PV pumps and the establishment of large water storage capacities result in financial non-viability in almost all cases (except for greenfield development), presents a barrier to excessive employment of the technology.

Experience gained in **planning and designing SPIS** shows that almost no system – not even existing turn-key solutions – is planned in such a way that system capacity is oriented towards the specific farmer's requirement and the available water resources. Most SPIS are designed and planned in a fragmented way: Water source, PV generator/pump and irrigation system, and subsequently also cropping patterns and irrigation management are seldom harmonised and often do not match. This creates system inefficiencies that may influence production and/or gross margins negatively. In some cases, this may result in system failures and/or inherent financial non-viability, in particular when the PV generator/pump is significantly over- or under-sized or when network design does not allow for appropriate irrigation management. In severe cases, this may also result in unsustainable exploitation of water resources. Based on the representative SPIS visited during this study, it has to be assumed that only a minority of systems is designed by considering actual water availability and groundwater recharge – farmers and system developers often have no knowledge of the capacities of their specific water resources.

A key demand and recommendation flowing from this report is **adherence to water governance and integrated planning** when designing and developing an SPIS, no matter what size. Planning an SPIS is a complex exercise that requires a significant level of **knowledge and skills**. These requirements often exceed the capacity and possibilities of an individual farmer and an individual extension worker or advisor. It must be assured that all components are adjusted to each other to the maximum possible extent. A promotion and planning manual is needed to provide practical orientation.

Further promotion of productive use of water in agriculture and beyond requires **accompanying measures** in support of sustainable water resource management and water governance. This cannot be regulated by market principles. It rather requires the establishment of water resource management capacities, awareness creation and capacity development.

A counter-productive instrument in this regard is the **availability of unconditional subsidies**. Besides altering the economic parameters of an SPIS as mentioned above, there are environmental concerns. As long as PV-based pumping solutions are subsidised to a large extent without demanding strict adherence to water availability and water utilisation monitoring, water-saving irrigation technologies and limitation of water storage, the risk of unsustainable utilisation of the technology will prevail in view of widespread concerns about over-pumping.

Key barriers to a larger degree of SPIS development today include up-front investment costs and the technical know-how for site-adapted design and development. Professional services for installation and maintenance are available to a growing extent. The development of operational skills for SPIS is manageable as long as system developers document the systems in an appropriate way and provide training to their clients. Key to an individual system's sustainability and success is the adaptation of the agricultural production process. Here, agricultural extension and information services need to develop their capacities in line with the demands arising from SPIS.

Suitable financing products catering for the specific needs of SPIS development (high initial capital needs, no additional collateral options, long repayment periods) are key to the dissemination of the technology. Good examples like in India and Morocco show that loan financing is an option, even though it may require special risk management.

The main opportunities related to solar powered irrigation include:

- A large untapped market potential;
- Rural electrification in developing countries continues and PV water pumps present a good off-grid alternative (possibly involving feed-in tariffs for surplus energy);
- SPIS open up opportunities with respect to agricultural productivity;
- Collective use of SPIS (group or cooperative schemes) may help overcome current financing hurdles;
- PV systems can reduce electricity costs and problems of unreliable power supply;
- As the PV market develops locally, it will create employment opportunities;
- There is scope for innovation and improvement.

The main risks for the promotion of SPIS include:

- PV systems are falsely perceived as being too expensive and are hence not considered as a technical option;
- No affordable financing services for PV systems are available yet;
- Fluctuating oil prices may create a favourable environment for conventional pumping systems;
- The use of grants and subsidies could undermine the long-term sustainability of SPIS dissemination;
- A low awareness of technological SPIS options prevails, particularly in the agricultural sector in developing countries;
- The deployment of SPIS is not accompanied by durability measures which ensure that water for irrigation is used in a sustainable manner;
- Low quality and false use of SPIS can undermine its reputation regarding technical reliability and credibility;
- Risks such as theft can negatively influence the decision-making of the farmer.

1 Overview of irrigation technologies

1 Overview of irrigation technologies

You can find a brief overview of the suitability of different irrigation methods for PV pumping on the SPIS Toolbox Module GET INFORMED – Irrigation System on Energypedia.

Water is the most important input for plant growth in agricultural production. Irrigation is the controlled application of water for agricultural purposes through manmade systems to supply water requirements not satisfied by rainfall. Crop irrigation is vital throughout the world in order to provide the world's ever-growing population with enough food (USGS 2016). Irrigation can be defined as replenishment of soil water storage in the plant root zone through methods other than natural precipitation. Irrigation water is brought to cultivated land through artificial means, such as pipes, hoses or ditches. The irrigated land usually contains crops, grass or vegetation which would not receive enough water from rainfall or other natural sources. Sometimes the reason to irrigate a portion of land is that it happens to be a dry season with less-than-average amounts of rainfall, or it might be necessary to do so because the land would never receive enough water on its own to be fertile. The water used for irrigation might be taken from nearby lakes, reservoirs, rivers or wells (Hall n.d.).

Water application for irrigation is confined in time and space, satisfying the water requirements of a crop at a given time of its vegetative cycle or to bring the soil to the desired moisture level outside the vegetative cycle. The irrigation of a field includes one watering or more per season based on the specific water requirements of the cultivated crop (ICID n.d.).

Sources of irrigation water can be groundwater extracted from springs or by using borings or wells, flood water spreading, surface water withdrawn from the flow of a stream, lake or reservoir or non-conventional sources like treated wastewater, desalinated water or drainage water. With regard to wastewater, it has to be stressed that around 90 % of wastewater/effluents produced globally remain inadequately treated, causing widespread water pollution, especially in low-income countries. Agriculture is increasingly using untreated wastewater as a source of irrigation water, in particular in peri-urban areas of water-scarce countries (ICID n.d.; UN Water 2015).

The water quality used for irrigation influences the yield and quantity of crops, maintenance of soil productivity, and protection of the environment. For example, the physical and mechanical properties of the soil, in particular the soil structure (stability of aggregates) and permeability are very sensitive to the type of exchangeable ions present in irrigation waters (ICID n.d.).

1.1 General Types of Irrigation

You can find an overview of the different irrigation methods and considerations to take before choosing one in the SPIS Toolbox Module IRRIGATE – Select Field Irrigation on Energypedia.

There are various methods that can be used for irrigation (starting from simple watering of plants), and each method needs an experienced farmer to determine the quantities of water to apply and the timing of the irrigation. The three commonly used modern irrigation methods will be briefly recalled in the following:

- Surface irrigation;
- Sprinkler irrigation;
- Drip irrigation.

The suitability of the various irrigation methods, i.e. surface, sprinkler or drip irrigation depends on a number of factors including:

Table 1.1: Factors determining the suitability of irrigation methods

Factors	Parameters	
Natural Conditions	Soil Type	Sandy soils have a low water storage capacity and a high infiltration rate. They therefore need frequent but small irrigation applications, in particular when the sandy soil is also shallow. Under these circumstances, sprinkler or drip irrigation are more suitable than surface irrigation. On loam or clay soils all three irrigation methods can be used, but surface irrigation is more commonly found. Clay soils with low infiltration rates are ideally suited to surface irrigation. When a variety of different soil types is found within one irrigation scheme, sprinkler or drip irrigation are recommended as they will ensure a more even water distribution.
	Slope	Sprinkler or drip irrigation are preferred above surface irrigation on steeper or unevenly sloping lands as they require little or no land levelling. An exception is rice grown on terraces on sloping lands.
	Climate	Strong wind can disturb the spraying of water from sprinklers. Under very windy conditions, drip or surface irrigation methods are preferred. In areas of supplementary irrigation, sprinkler or drip irrigation may be more suitable than surface irrigation because of their flexibility and adaptability to varying irrigation demands on the farm.
	Water Availability	Water application efficiency is generally higher with sprinkler and drip irrigation than surface irrigation and so these methods are preferred when water is in short supply. However, it must be remembered that efficiency is just as much a function of the irrigator as the method used.
	Water Quality	Surface irrigation is preferred if the irrigation water contains much sediment. The sediments may clog the drip or sprinkler irrigation systems. If the irrigation water contains dissolved salts, drip irrigation is particularly suitable, as less water is applied to the soil than with surface methods. Sprinkler systems are more efficient that surface irrigation methods in leaching out salts.
Type of Crop	Surface irrigation can be used for all types of crops. Sprinkler and drip irrigation, because of their high capital investment per ha, are mostly used for high value cash crops, such as vegetables and fruit trees. They are seldom used for the lower value staple crops. Drip irrigation is suited for irrigating individual plants, trees or row crops such as vegetables and sugarcane. It is not suitable for close growing crops (e.g. rice).	

Factors	Parameters
Type of Technology	The type of technology affects the choice of irrigation method. In general, drip and sprinkler irrigation are technically more complicated methods. The purchase of equipment requires high capital investment per ha. To maintain the equipment a high level of 'know-how' has to be available. Also, a regular supply of fuel and spare parts must be maintained which – together with the purchase of equipment – may require foreign currency. Surface irrigation systems – in particular small-scale schemes – usually require less sophisticated equipment for both construction and maintenance (unless pumps are used). The equipment needed is often easier to maintain and less dependent on the availability of foreign currency.
Previous Experience with Irrigation	The choice of an irrigation method also depends on the irrigation tradition within the region or country. Introducing a previously unknown method may lead to unexpected complications. It is not certain that the farmers will accept the new method. The servicing of the equipment may be problematic and the costs may be high compared to the benefits. It is often considered easier to improve a traditional irrigation method than to introduce a totally new method.
Required Labour Input	Surface irrigation often requires a much higher labour input – for construction, operation and maintenance – than sprinkler or drip irrigation. Surface irrigation requires accurate land levelling, regular maintenance and a high level of farmers' organization to operate the system. Sprinkler and drip irrigation require little land levelling; system operation and maintenance are less labour intensive.
Costs and Benefits	Before choosing an irrigation method, an estimate must be made of the costs and benefits of the available options. On the cost side not only the construction and installation, but also the operation and maintenance (per ha) should be taken into account. These costs should then be compared with the expected benefits (yields). It is obvious that farmers will only be interested in implementing a certain method if they consider it economically attractive. Cost/benefit analysis is, however, beyond the scope of this manual.
Capital Requirements and Availability	The specific capital requirements for investments and operation of an irrigation system depend on the irrigation method. Sprinkler and drip irrigation systems require a high initial investment that can only be repaid by a multi-annual return on the production. Investment into these systems usually requires existing corresponding capital resources or the availability of suitable financing products (including subsidies).

Based on Brouwer et al. 1989b

Worldwide, there are approx. 3.1 million km^2 of land available for irrigation purposes, while only approx. 2.6 million km^2 are utilised (Renner 2012). With about 95 % share of total irrigation worldwide, surface irrigation is by far the most widespread irrigation method. Surface irrigation is normally used when conditions are favourable: mild and regular slopes, soil type with medium to low infiltration rate, and a sufficient supply of surface or groundwater (Brouwer et al. 1989b).

In the case of steep or irregular slopes, soils with a very high infiltration rate or scarcity of water, sprinkler and drip irrigation may be more appropriate (Brouwer et al. 1989b). In 2012, according to FAO data, approx. 86 % of the world's irrigated area was under surface irrigation (280 million ha), 11 % was under sprinkler irrigation (35 million ha) and only 3 % under localized irrigation (9 million ha) as a primary distribution method. At least 111 million ha equipped for irrigation use a pump (FAO, AQUASTAT, 2014).

The distribution of sprinkler irrigated area by region in 2006 was:

- Americas 13.3 million ha
- Europe 10.1 million ha
- Asia 6.8 million ha
- Africa 1.9 million ha
- Oceania 0.9 million ha

The top ten sprinkler irrigated countries were USA, Russia, China, India, France, Brazil, Italy, Spain, Saudi Arabia and Ukraine. These countries together made up 75 % of the total sprinkler-irrigated area.

The highest coverage of drip irrigation is found in the Americas (1.9 million ha) followed by Europe and Asia (1.8 million ha each), Africa (0.4 million ha) and Oceania (0.2 million ha). The top ten countries in 2016 were USA, Spain, India, China, Italy, Brazil, South Africa, Russia, Mexico and Saudi Arabia. These countries made up 77 % of the total drip-irrigated area of the world. In five countries – Austria, Israel, Libya, Slovak Republic and United Kingdom – irrigation is accomplished solely through pressurised systems (Kulkarni et al. 9/13/2006).

1.1.1 Surface Irrigation

Surface irrigation is the application of water by gravity flow to the surface of the field. Either the entire field is flooded (basin irrigation) or the water is fed into small channels (furrows) or strips of land (borders) (Brouwer et al., 1989b).

Surface irrigation is widely utilised and therefore a well-known system which can be operated without any high-tech applications. "In general, it is more labour-intensive than other irrigation methods. Proper design of surface irrigation systems takes into account the soil type (texture and infiltration rate), slope and levelness of the field, stream size, and length of run. It is generally more difficult to obtain high uniformity of water distribution in long fields on coarse textured soils (gravel and sands) than on fine textured soils (loams to clay). Levelling the fields and building the water ditches and reservoirs might be expensive, but once this is done, costs are low and self-help capacity is very high." (Stauffer & Spuhler).

Basin Irrigation
Basins are flat areas of land, surrounded by low bunds. The bunds prevent the water from flowing to the adjacent fields. Basin irrigation is commonly used for rice (paddy) grown on flat lands or in terraces on hillsides. Trees (e.g. citrus, banana) can also be grown in basins, where one tree is usually located in the middle of a small basin. Other crops which are suited to basin irrigation include:

- Pastures, e.g. alfalfa, clover;
- Broadcast crops, e.g. cereals;
- Row crops such as tobacco to some extent.

Figure 1.1: Paddy cultivation in an irrigated basin, China
Source: GIZ / Guenay Ulutunçok, 2005

Basin irrigation is generally not suited to crops which cannot stand in wet or waterlogged conditions for periods longer than 24 hours. These are usually root and tuber crops such as potatoes, cassava, beet and carrots which require loose, well-drained soils (Brouwer et al., 1989b).

The soil types suitable for basin irrigation depend on the cultivated crop. A distinction has to be made between rice and non-rice or other crops. Paddy rice is best grown on clayey soils which are almost impermeable, as percolation losses are then low. Rice could also be grown on sandy soils but percolation losses will be high unless a high water table can be maintained. Such conditions sometimes occur in valley bottoms. Although most other crops can be grown on clays, loamy soils are preferred for basin irrigation so that waterlogging (permanent saturation of the soil) can be avoided. Coarse sands are not recommended for basin irrigation as, due to the high infiltration rate, percolation losses can be high. Soils which form a hard crust when dry (capping) are also not suitable (ibid.).

Furrow Irrigation

Furrows are small channels which carry water down the slope between the crop rows. Water infiltrates into the soil as it moves along the slope. The crop is usually grown on the ridges between the furrows. This method is suitable for all row crops and for crops that cannot stand in water for long periods (e.g. 12–24 hours). Irrigation water flows from a field channel into the furrows by opening up the bank of the channel (breach), or by means of siphons or spiles[1] (ibid.).

1 Siphons are small curved pipes that deliver water over a ditch bank. Spiles are small pipes buried in the ditch bank.

To manage irrigation with the traditional breach system, the farmer has to open and close the embankment of the water-conveying channel. This is the most common method of releasing water from a channel, but it can also be the most damaging. Not only is it difficult to control the discharge, but there can be serious erosion of the channel embankment. If other more controllable methods are available, then these should be used in preference. Breaches can be most easily controlled on clay soils which do not erode easily. On sandy and loamy soils cutting a breach may cause serious erosion and leakage problems. In this case, it is better to use siphons or spiles (Brouwer et al., 1989b).

For siphons and spiles to work properly, the water level in the farm channel must be higher than in the field furrow. When the water level in the farm channel is much higher than in the field, the outlet from the siphon or spile may be above the water level in the field (free discharge). When the water level in the farm channel is lower, then the outlet may be below the field water level (drowned discharge). Both modes of operation are acceptable. The discharge through siphons and spiles depends on the diameter of the pipe and the hydraulic head:

- For free discharge, the head is the difference between the water level in the farm channel and the outlet from the pipe;
- For drowned or submerged discharge, the head is the difference between the water level in the farm channel and in the field.

The discharge can be adjusted by a change in pipe diameter or a change in the head (ibid.).

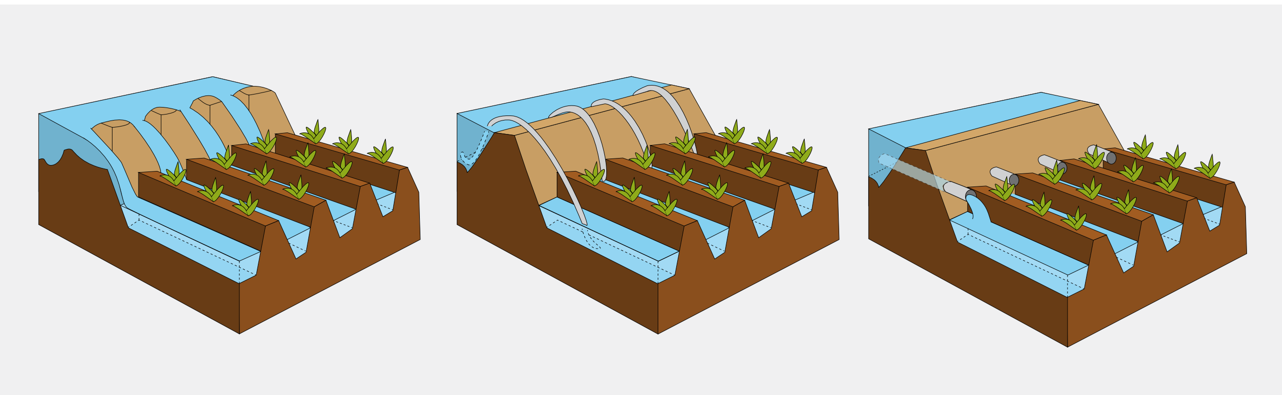


Figure 1.2: Water conveyance into furrows – breaches, siphons and spiles Adapted from FAO / Brouwer et al., 1989b

Border Irrigation

Borders are long, sloping strips of land separated by bunds. They are sometimes called border strips.

Irrigation water can be fed to the border in several ways: opening up the channel bank using small outlets or gates or by means of siphons or spiles. A sheet of water flows down the slope of the border, guided by the bunds on either side (see Figure 1.2). When the desired amount of water has been delivered to the border, the stream is turned off. This may occur before the water has reached the end of the border. There are no specific rules controlling this decision. However, if the flow is stopped too soon, there may not be enough water in the border to complete the irrigation at the far end. If it is left running for too long, the water may run off the end of the border and be lost in the drainage system (ibid.).

Border irrigation is best suited to the larger mechanised farms as it is designed to produce long uninterrupted field lengths for ease of machine operations. Borders can be up to 800 m or more in length and 3–30 m wide depending on a variety of factors. Border irrigation is less suited to small-scale farms involving hand labour or animal-powered cultivation methods (ibid.).

Border slopes should be uniform, with a minimum slope of 0.05 % to provide adequate drainage and a maximum slope of 2.0 % to limit problems of soil erosion. Deep homogenous loam or clay soils with medium infiltration rates are preferred. On heavy clay soils, border irrigation may cause problems because of the low infiltration rates (basin irrigation is more suited on these soil types). Close growing crops such as pasture or alfalfa are preferred (ibid.).

The surface irrigation approaches introduced above can be further sub-divided according to the specific characteristic and shape of the underlying land preparation. Furrows or border strips can be level or graded or follow contour lines; they can also be laid out in zigzag patterns to reduce flow rates.

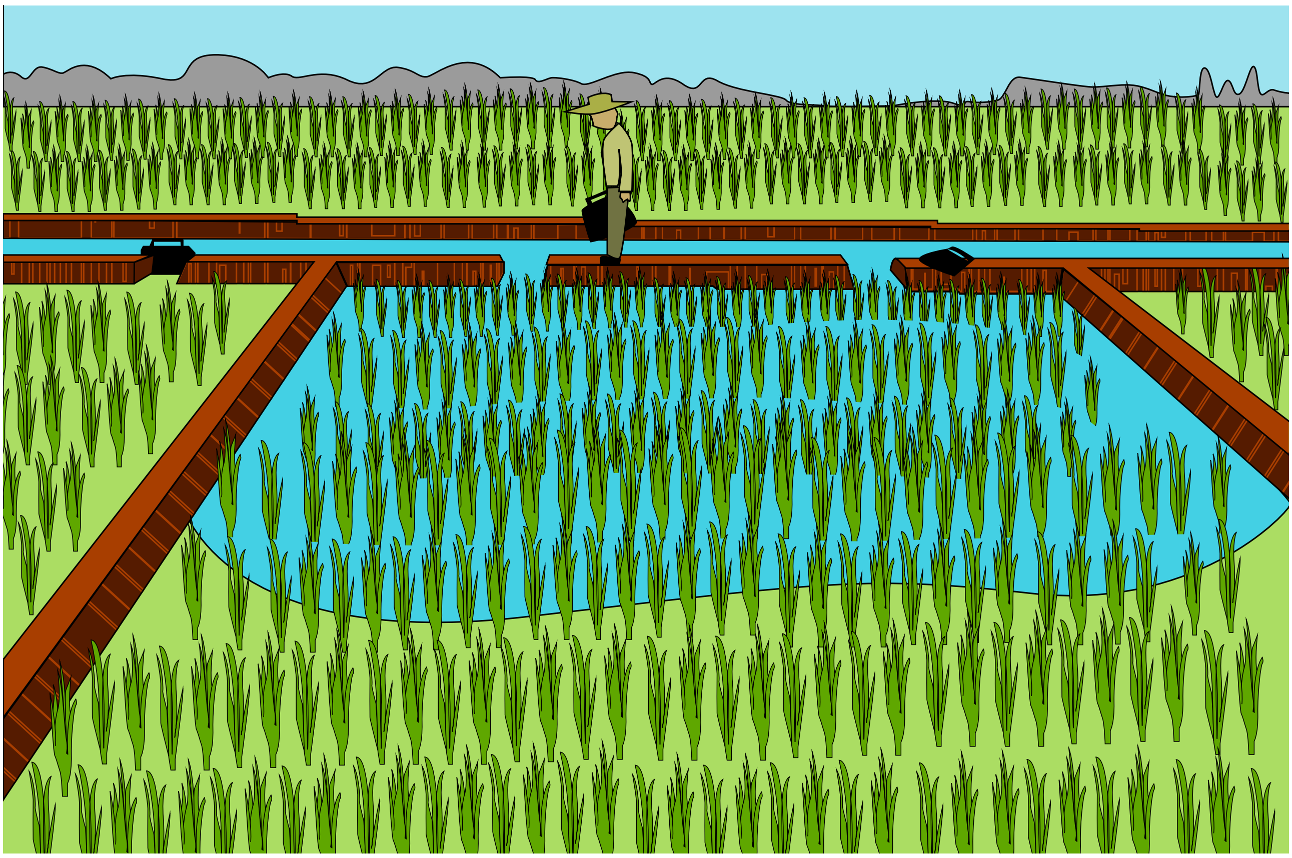


Figure 1.3: Layout of border irrigation

Adapted from FAO / Brouwer et al., 1989b

Level surface irrigation means that water is ponded on an enclosed level field and allowed to infiltrate in basins, borders, or furrows. Graded surface irrigation means that water is fed into the high end of a field and is allowed to run slowly to the low end. The advantages and disadvantages of these land preparation characteristics are summarised below:

Table 1.2: Advantages and disadvantages of level and graded surface irrigation

Land Preparation System	Advantages	Disadvantages
Level Surface Irrigation	▸ Irrigation management is easy and does not require modern technology and can largely build on local traditional knowledge ▸ Adapts well to small land holdings and does not require high financial input ▸ Adapts easily to flat topography and can function without outlet drainage facilities ▸ Works well with short-term water supplies ▸ Irrigation allows full utilization of rainwater and can achieve high application efficiencies ▸ Adapts well to moderate to low infiltration rates and allows easy leaching of salts	▸ Requires level land to achieve high efficiencies (maximum land elevation fluctuation should not be greater than half the applied irrigation depth) ▸ Soils with high infiltration rates require small field sizes, which interfere with mechanization ▸ Difficult to apply small irrigation quantities and to evacuate excess water, particularly during times of excess rainfall ▸ Plants are partly covered with water sometimes over extended periods (in low infiltration rate soils) ▸ Small basins require extensive delivery channels and are not easily adaptable to tractor mechanization
Graded Surface Irrigation	▸ Requires low capital and energy costs ▸ Allows irrigation on sloping land (as is found in many irrigated areas) ▸ Allows irrigation of long fields with relatively small flows ▸ Is applicable to soils with moderate to fairly high infiltration rates ▸ Field drainage of excess water is made possible	▸ A high degree of management and water control is required to achieve high irrigation efficiencies ▸ High irrigation efficiencies require uniformly graded and shaped land ▸ With moderate to slow infiltration rates, long irrigation times are required (irrigation time must be close to the required infiltration opportunity time) ▸ Except for soils with high infiltration rates, a drainage outlet must be available from every field to dispose of tail water and rainwater ▸ Labour intensive

Based on Conradin et al. 2010; Walker 1989

A special and rarely used approach is subsurface irrigation: Water is directed to the subsoil (crop root zone) in the area to be irrigated. The water is used to artificially control the groundwater table, and is normally delivered through perforated pipes buried in the ground. In some Latin American countries, porous clay pots are buried in the ground and filled with water that slowly seeps into the subsoil to moisten the roots of crops.

1.1.2 Sprinkler Irrigation

Sprinkler irrigation is a method of providing rainfall-like irrigation to the crops. Water is distributed through a system of pipes, usually by pumping. Spray heads at the outlets distribute the water over the entire soil surface.

A typical sprinkler irrigation system consists of the following components:

- Pump unit;
- Mainline (and sometimes sub-mainlines);
- Lateral lines;
- Sprinklers.

The pump unit is usually a centrifugal pump, which takes water from the source and provides adequate pressure for delivery into the pipe system (Brouwer et al. 1989b).

Mainline and sub-mainline pipes deliver water from the pump to lateral pipes. In some cases these pipelines are permanent and are laid on the soil surface or buried below ground. In other cases they are temporary, and can be moved from field to field. Pipe materials used are mainly PVC- and corrugated-iron-based today, but asbestos cement or aluminium alloy materials are also in use. The laterals deliver water from mainlines or sub-mainlines to the sprinklers. They can be permanent, but more often they are portable and made of aluminium alloy or PVC in order to be moved easily (ibid.).

There are different types of sprinkler heads in use, depending on irrigation purpose and plot size:

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

An impact sprinkler is mounted on a bearing that allows the entire sprinkler body to spin in circles. It is rotated by the impact of a swinging arm repeatedly striking the body of the sprinkler, causing it to rotate slightly each time. Cam drive or ball drive sprinklers are also impact sprinklers, but the impact is caused by either a cam or a ball bearing inside the body of the sprinkler. With ball and cam drive rotors only the nozzle moves. Ball and cam drive sprinklers are no longer present on the market, but may be still in use.

Figure 1.4: Example of impact sprinkler heads from India

Source: AUTOMAT INDUSTRIES PVT. LTD, 2015

Figure 1.5: Examples of gear-drive sprinkler heads

Source: Alupus, 2011, licensed under CC BY-SA 3.0

Source: unknown, picture from pxhere.com, free of copyrights under Creative Commons CC0

Figure 1.6: Example of a centre pivot sprinkler irrigation system
Source: Scott Bauer, USDA Agricultural Research Service, 2004

As impact sprinklers tend not to rotate in a uniform manner, they are replaced by gear-driven rotors on the market. As with cam and ball drives, only the nozzle on a gear-driven sprinkler head moves. The water moving through the sprinkler spins a turbine, which turns a set of gears, which again turn the nozzle. These gear-drive rotors have one or more streams of water rotating. In agricultural irrigation, these sprinklers are usually in operation on very large plot sizes. They require a higher input pressure.

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

A **linear move** (also called lateral move) irrigation system is built the same way as a centre pivot; the main difference is that all the towers move at the

Figure 1.7: Example of a linear irrigation project, Keudell Farm, Marion County — Source: Tracy Robillard (NRCS), 2019, via flickr.com, licensed under CC BY-ND 2.0

same speed and in the same direction. Water is pumped into one of the ends or into the centre (Stauffer & Spuhler, 2019a).

A **travelling big gun** system uses a large capacity nozzle and high pressure to throw water out over the crop as it is pulled through an alley in the field. Travelling big guns come in two main configurations: hard-hose or flexible-hose feed. With the hard-hose system, a hard polyethylene hose is wrapped on a reel mounted on a trailer. The trailer is anchored at the end or centre of the field. The gun is connected to the end of the hose and is pulled towards the trailer. The gun is pulled across the field by the hose winding up on the reel. With the flexible-hose system, the gun is mounted on a four-wheel cart. Water is supplied to the gun by a flexible hose from the main line. A cable winch pulls the cart through the field towards the cart (Stauffer & Spuhler, 2019a).

Figure 1.8: Example of a travelling big gun irrigation system from the USA — Source: Cadman Power Equipment, 2013

Figure 1.9: Example of a side roll sprinkler irrigation system from the USA Source: Wade Rain Irrigation Systems / Chase Berrier, 2015

A **side roll** (also called wheel roll) system consists of long lateral pipes mounted on 1 to 3 m wheels in diameter and the pipe serving as an axle. When the desired amount of water has been applied to an area, a gasoline engine at the centre is used to move the side roll to the next. The sprinklers are generally mounted on weighted, swivelling connectors so that no matter where the side roll is stopped, the sprinklers will always be on top (Stauffer & Spuhler, 2019a).

Due to high capital investment, centre pivots, linear moves, travelling big guns and side roll systems are used in high-value crops such as potatoes and vegetables. A higher level of expert knowledge is necessary to carry out irrigation with these systems, even though the labour requirement is relatively low due to automation. Motors, water supply pipes/hoses and all mechanical components have to be maintained systematically to avoid damage and high repair costs.

Sprinklers provide efficient coverage for small to large areas. Sprinkler irrigation is suited for most row, field and tree crops and water can be sprayed over or under the crop canopy. However, large sprinklers are not recommended for irrigation of delicate crops such as lettuce because the large water drops produced by the sprinklers may damage the crop (Brouwer et al. 1989b).

Sprinkler irrigation is adaptable to any farmable slope, whether uniform or undulating. Lateral pipes supplying water to the sprinklers should always be laid out along the land contour whenever possible to minimise the pressure changes at the sprinklers and provide a uniform irrigation. A good clean supply of water, free of suspended sediments, is required to avoid problems of sprinkler nozzle blockage and spoiling the crop by coating it with sediment. The pump supply system, sprinklers and operating conditions must be designed to enable a uniform application of water (ibid.).

Sprinkler irrigation can also be adapted to nearly all irrigable soils since sprinklers are available with a variety of discharge capacities. However, sprinklers are best suited to sandy soils with high infiltration rates. The average application rate from the sprinklers (in mm/hour) is always chosen to be less than the basic infiltration rate of the soil so that inundation/flooding and runoff can be avoided. Sprinklers are not suitable for soils which easily form a crust (ibid.).

1.1.3 Drip Irrigation

Drip irrigation, also referred to as micro-irrigation, trickle irrigation or localised irrigation, involves dripping water onto the soil at very low rates (2-20 l/hour) from a system of small diameter plastic pipes fitted with outlets called emitters or drippers. Water is applied close to plants so that only the part of the soil in which the roots grow is wetted, unlike surface and sprinkler irrigation, which involves wetting the entire soil profile. With drip irrigation, applications are more frequent (usually every 1-3 days) than with other methods, thereby providing a favourable high moisture level in the soil for the plant (ibid.). As long as the application rate is below the soil's infiltration capacity, the soil remains unsaturated and no free water stands or runs over the surface (Hillel 1997).

A typical drip irrigation system consists of the following components:

- Pump unit;
- Control head;
- Mainlines and sub-mainlines;
- Lateral lines;
- Emitters or drippers

(Brouwer et al. 1989b).

The system may include additional features, such as reservoir tanks, filters and fertigation devices.

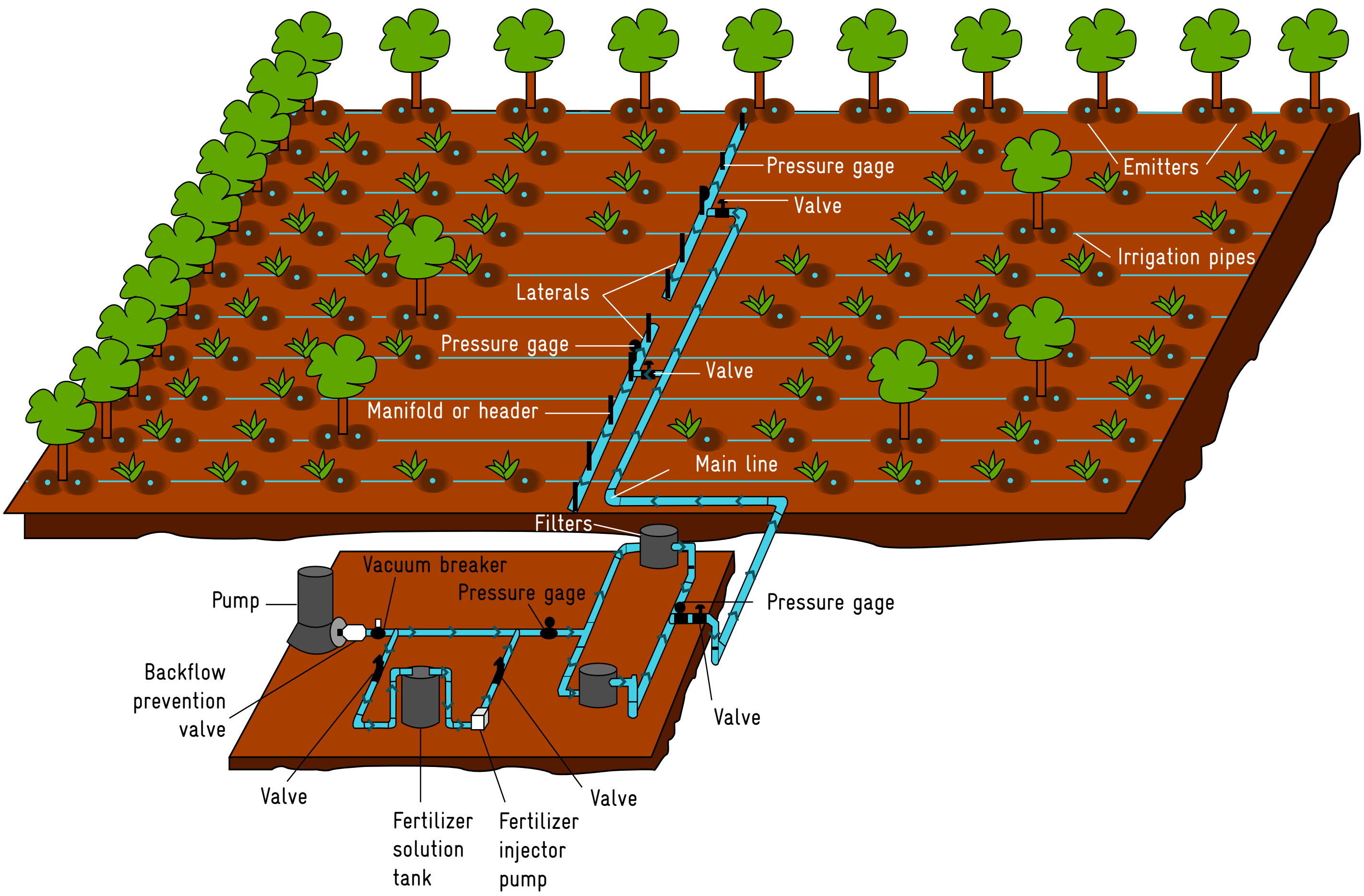


Figure 1.10: Typical layout of drip irrigation Adapted from USDA

The pump unit takes water from the source and provides the right pressure for delivery into the pipe system.

The control head consists of valves to control the discharge and pressure in the entire system. It may also have filters to clear the water. Common types of filter include screen filters and graded sand filters that remove fine material suspended in the water. Some control head units contain a fertiliser or nutrient tank. These slowly add a measured dose of fertiliser into the water during irrigation. This is one of the major advantages of drip irrigation over other methods (Brouwer et al. 1989b)

Mainlines, sub-mainlines and lateral lines supply water from the control head into the fields. They are usually made of PVC or polyethylene hose and should be buried below ground because they easily degrade when exposed to direct solar radiation (ibid.). Water distribution to the plants is effected through lateral lines hosting the specific drip devices or emitters. In principle, there are two types of drip irrigation:

- **Sub-surface drip irrigation:**
  Water is applied below the soil surface;
- **Surface drip irrigation:**
  Water is applied directly to the soil surface.

Figure 1.11: Example of subsurface irrigation drip line
Source: SISTEMA AZUD, SA & USDA

Sub-surface irrigation is a more sophisticated and hence expensive and rare method, which employs narrow plastic tubes of about 2 cm diameter. These are buried in the soil at a depth between 20 and 50 cm, deep enough so as not to interfere with normal tillage or traffic. The tubes are either porous throughout, or are fitted with regularly spaced emitters or perforations. If porous, the tubes exude water along their entire length. If fitted with emitters, they release water only at specific points. The released water spreads or diffuses in the soil. The pattern of wetting depends on the properties of the surrounding soil, as well as on the length of the interval between adjacent emitters and their discharge rates (Hillel 1997).

A potential problem with this technology is that the narrow orifices of the emitters may get clogged by roots, particles, algae or precipitating salts. Such clogging is difficult to detect when the tubes are placed over the surface in above-ground drip irrigation. Occasionally injecting an acidic or herbicidal solution into the tubes may help to clear some types of clogging, though the problem may recur periodically. Slit sections of plastic tubes may also be used to cover the emitter and thus inhibit clogging by roots without substantially reducing discharge (ibid.).

In underground drip irrigation, the delivery of water in the feeder tubes can be constant or intermittent. For uniformity of application, there should be some means of pressure control. If the lines are long or the land is sloping, there can be considerable differences in the hydraulic pressure and therefore in delivery rate, unless pressure-compensated emitters are used. However, such emitters tend to be expensive (Hillel 1997).

Experiences from Israel, California, Spain and elsewhere have shown that this method of subsurface irrigation is feasible in plantations of fruit trees and other perennial row crops. It may also be applicable to annual crops grown in regular beds when high maintenance intensity can be assured (ibid.). The employment of modern subsurface drip irrigation technology in developing countries is rare and is often not feasible due to unfavourable framework conditions.

Surface drip irrigation is much more common and uses a very large range of drip emitter devices. Lateral lines, supplied from a field main, are laid on the surface. They are commonly 10 to 25 mm in diameter and are either perforated or fitted with special emitters. The latter are designed to drip water on the soil at a controlled rate, ranging from 1 to 10 l/hour per emitter. The operating water pressure is usually in the range of 0.5 to 2.5 atmospheres. This pressure is dissipated by friction in flow through the narrow passages or orifices of the emitters, so the water emerges at atmospheric pressure in the form of drops rather than a jet or spray (ibid.).

Emitters or drippers are devices used to control the discharge of water from the lateral to the plants. They are usually spaced more than 1 m apart with one or more emitters used for a single plant such as a tree. For row crops more closely spaced emitters may be used to wet a strip of soil. Many different emitter designs have been produced in recent years; there are hundreds of different emitter designs on the market. The basis of design is to produce an emitter that will provide a specified constant discharge that does not vary much with pressure changes, and does not block easily (Brouwer et al. 1989b).

Commercial emitters are either in-line (spliced into the lateral supply tubes), or on-line (plugged on to the tubes through a hole punched into the tubing wall). Commercial emitters are usually pre-calibrated to discharge at a constant rate of 2, 4, 8 or 16 l/hour. The discharge rate is always affected by changes in pressure, but less so in the case of pressure-compensated emitters. The frequency and duration of each irrigation period are controlled by means of a manual valve or a programmable automatic valve assembly. Metering valves are designed to shut the flow automatically after a pre-set volume of water is applied (Hillel 1997).

Irrigation water tends to spread sideways and downwards in the soil from the point where it is dripped. The fraction of the soil's total volume that is actually wetted depends on the density of the drip points (the grid) as well as on the rate of application and the internal water-spreading properties of the soil. The wetted zone, and hence the active rooting volume, is usually less than half of what would be the normal root zone if the entire soil were wetted uniformly (ibid.).

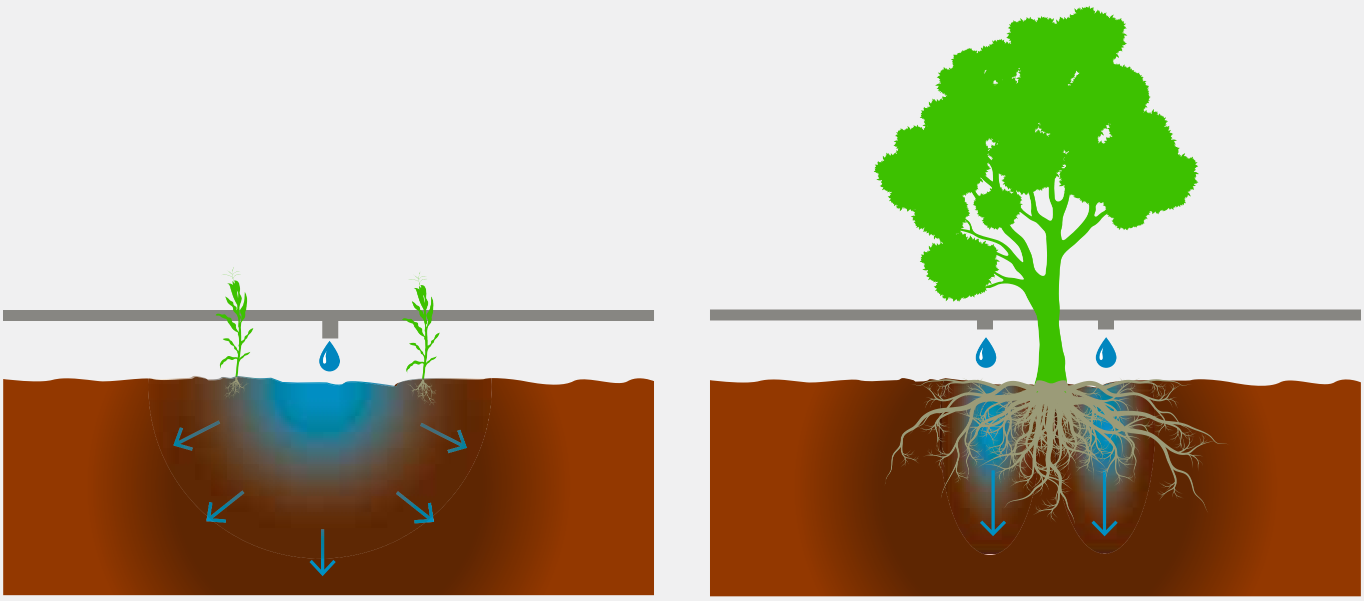


Figure 1.12: Patterns of soil wetting under drip irrigation

Adapted from FAO / Hillel, 1997

Under frequent drip, the wetted portion of the soil is maintained in a continuously moist state, though the soil is unsaturated and therefore well aerated. This creates a uniquely favourable soil moisture regime. Drip irrigation thus offers a distinct advantage over flood irrigation and also over less-frequent sprinkler irrigation, especially for sandy soils of low moisture storage capacity and in arid climates of high evaporative demand. In contrast to sprinkler irrigation, drip irrigation is practically unaffected by wind conditions. Compared to surface irrigation, it is less affected by soil texture, topography or surface roughness (ibid.).

Types of Drip Irrigation Emitters

Emitters (also referred to as 'drippers') are classified into groups based on their design type and the method they use to regulate pressure. Emitters are installed on the pipe and act as small throttles, assuring that a uniform rate of flow is emitted. Some are built into the pipe or tubing, others attach to it using a barb or threads. The emitter reduces and regulates the amount of water discharged.

Figure 1.13: Drip irrigation pipes with mounted (on-line) emitter
Source: Jeff Vanuga/ USDA Natural Resources Conservation Service / Public Domain, 2011

Drip irrigation emitters are offered in two basic categories: Pressure compensating and non-pressure compensating. Generally speaking, all drip irrigation emitters are pressure compensating to some degree and most are designed to work best at 1.5 to 2.0 bars of pressure (Stryker 1997).

Pressure compensating (PC) emitters are designed to discharge water at a very uniform rate under a very wide range of water pressures; they give the same flow under varying input pressure and landscape conditions. PC emitters are best used on plots that have drops in elevation which then cause an increase in pressure. For pressure compensation, diaphragm type emitters are employed – a silicone diaphragm inside the emitter flexes to regulate water output.

Non-pressure compensating emitters output varies with changes in elevation and pressure. As pressure increases, the drip emitter emits more flow. These drip emitters are best used where the landscape terrain is flat and level with very little elevation changes and consistent pressure. Non-pressure compensating emitters use an internal labyrinth design to reduce the velocity in the flow of water over a very short distance.

In response to the vulnerability of emitters to clogging (due to particles transported with the irrigation water), some drip irrigation emitters are built with a self-flushing (self-cleaning) mechanism reducing the clogging risk. These are usually PC diaphragm or turbulent flow emitter types.

Table 1.3: Main types of surface drip irrigation emitters

Type of Emitter	Description
Long-Flow Path Emitters	Water is rooted through a very long, narrow passage or tube. The small diameter and great length of this path reduces the water pressure and creates a more uniform flow. A typical long-path emitter has a long water path that circles around and around a barrel shaped core. Long path emitters tend to be fairly large in size due to the need to fit the long tube in.
Soaker Hose, Porous Pipe, Drip Tape, Laser Tubing	Soaker hose, porous pipe, drip tape, and laser tubing are various adaptations of the "extremely small hole in a pipe" type of drip system. They only have very small holes drilled (usually using a laser) into a tube, or are made from materials that create porous tubing walls that the water can slowly leak out of. The advantage is their very low cost. The disadvantage is that the tiny holes are very easily clogged, especially with hard water containing lots of minerals, and for some products watering uniformity can be uneven. These types of systems are most often used in systems with portable irrigation (tubes are removed and thrown away or recycled at the end of each growing season).
Short-Flow Path Emitters	Similar to the long path emitters with a shorter and smaller water path. Advantages: Low costs and operating on very low-pressure systems, such as gravity flow drip systems fed by water from rain barrels. Disadvantages: Clogging up easily and poor water distribution uniformity compared to other emitter types.
Tortuous-Path or Turbulent-Flow Emitters	Water runs through a path similar to the long path type, but the path has sharp turns and obstacles in it. These turns and obstacles result in turbulence in the water, which reduces the flow and pressure. By using the tortuous path the emitter water passages can have a shorter length and larger diameter.
Vortex Emitters	Water runs through a vortex (whirlpool) to reduce the flow and pressure. The pressure drops at the centre of a vortex. By swirling the water around the outlet hole a drop in pressure and a lower flow through the hole is caused. Vortex emitters are small in size (about the size of a large pea) and inexpensive, but they clog up easily.
Diaphragm Emitters	A flexible diaphragm is used to reduce the flow and pressure. All models use some type of flexible part that moves or stretches to restrict or increase the water flow. Very accurate in controlling the flow and pressure than the previous types, but wearing out after some time.
Adjustable Flow Emitters	Adjustable flow emitters have an adjustable flow rate. Typically the emitter has a dial that you turn to change the flow rate. The design of most of these is very similar to the short-flow path emitter. Adjustable flow emitters tend to vary greatly in flow and have little pressure compensation.
Dripline, Dripperline	Drip line, dripper line and other variations on that name are used to describe a drip tube with factory preinstalled emitters on it. Often the emitters are actually moulded inside the tubing and all that is visible on the outside is a hole for the water to come out. The emitters are typically the tortuous-path or diaphragm type, but may be other types as well. The emitters are uniformly spaced along the tube; often several different spacing options are available. The primary advantage of drip line is ease of installation due to the preinstalled emitters.

Source: Authors

Drip irrigation is most suitable for row crops (vegetables, soft fruit), tree and vine crops where one or more emitters can be provided for each plant. Generally only high-value crops are considered because of the high capital costs of installing a drip system.

It is adaptable to any farmable slope. Normally, the crop would be planted along contour lines and the water supply pipes (laterals) would be laid along the contour. This is done to minimise changes in emitter discharge as a result of land elevation changes.

Drip irrigation is also suitable for most soils. On clay soils, water must be applied slowly to avoid surface water ponding and runoff. On sandy soils, higher emitter discharge rates will be needed to ensure adequate lateral wetting of the soil (Brouwer et al. 1989b).

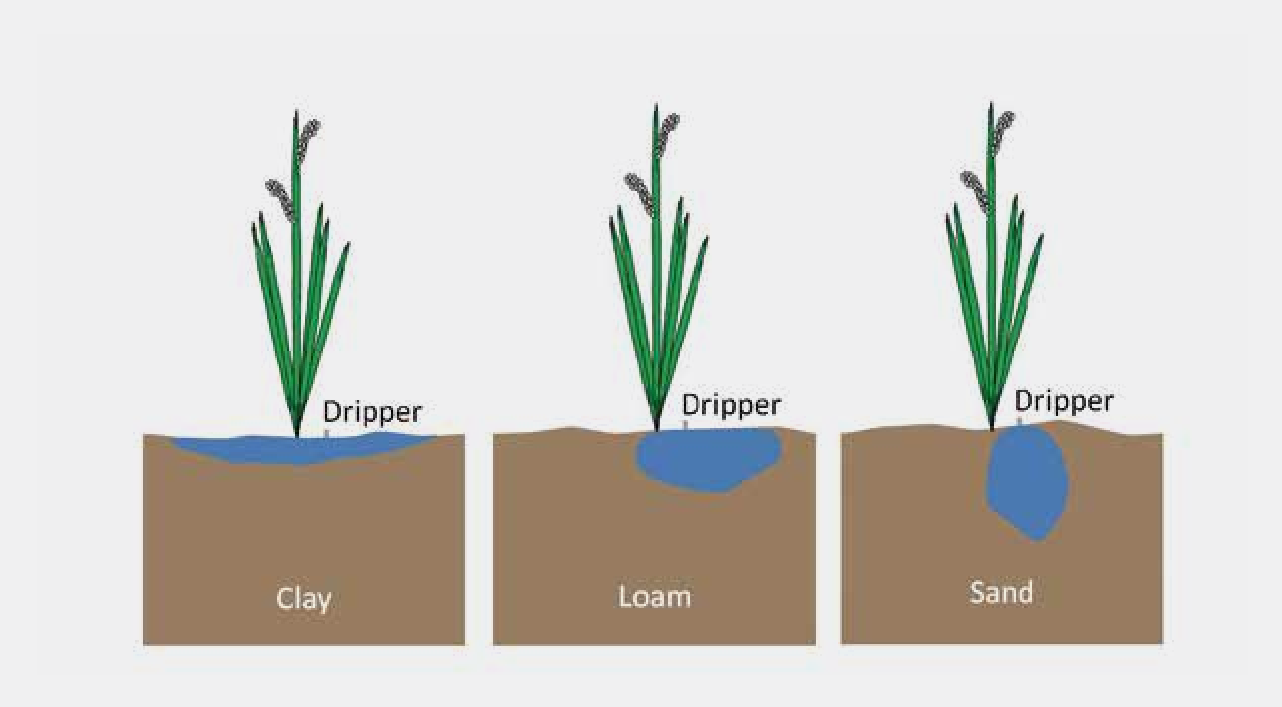


Figure 1.14: Moisture distribution under drip irrigation in different soil types Adapted from FAO / Hillel, 1997

One of the main problems with drip irrigation is blockage of the emitters. All emitters have very small waterways ranging from 0.2-2.0 mm in diameter and these can become blocked if the water is not clean. Thus it is essential for irrigation water to be free of sediments. If this is not the case, then filtration of the irrigation water will be needed. Blockage/clogging may also occur if the water contains algae, fertiliser deposits and dissolved chemicals which precipitate (e.g. calcium and iron). Filtration may remove some of the materials but the problem may be complex to solve and requires an experienced engineer or consultation with the equipment dealer (Brouwer et al. 1989b).

1.1.4 Comparison of Sprinkler and Drip Irrigation

Advantages and disadvantages of sprinkler irrigation and drip irrigation systems are summarised in Table 1.4:

Table 1.4: Advantages and disadvantages of sprinkler and drip irrigation systems

Irrigation System	Advantages	Disadvantages
Sprinkler Irrigation	▸ Expansive land levelling or terracing is not required ▸ No loss of cultivable area due to channel construction ▸ Suitable for almost all soil types ▸ Water saving irrigation intensity can be changed in accordance with the infiltration capacity of soil and crop water requirements ▸ High efficiency due to uniform water distribution, crop water management can be adapted to growth stage and conditions ▸ Possibility of adding fertilizers or pesticides to irrigation water in an economic way ▸ Possibility of irrigating for other purposes: sprouting, frost protection or cooling during hot periods ▸ Lower labour requirements as compared to traditional surface irrigation approaches	▸ High initial capital costs (investment in equipment – sprinklers and pipes) and high operation costs due to energy requirements for pumping and labour costs ▸ Sensitivity to wind, causing evaporation losses (under high wind condition and high temperature distribution and application efficiency is poor) ▸ Unavoidable wetting of foliage in field crops results in increased sensitivity to diseases ▸ Highly saline water (>7 millimhos/cm) causes leaf burning when temperature is higher than 35°C ▸ Debris and sediments in irrigation water can cause clogging of sprinkler nozzles
Drip Irrigation	▸ Extensive land levelling and bunding is not required ▸ Irrigation water can be used at a maximum efficiency level and water losses can be reduced to a minimum ▸ Soil conditions can be taken into account to a maximum extent and soil erosion risk due to irrigation water impact can be reduced to a minimum ▸ Fertilizer and nutrients can be used with high efficiency; as water is applied locally and leaching is reduced, fertilizer/nutrient loss is minimized (reduced risk of groundwater contamination) ▸ Weed growth is reduced as water and nutrients are supplied only to the cultivated plant ▸ Positive impact on seed germination and yield development ▸ Low operational costs due to reduced labour requirement, in particular energy cost can be reduced as drip irrigation is operated with lower pressure than other irrigation methods	▸ High initial investment requirements ▸ Regular capital requirement for replacement of drip irrigation equipment on the surface (damage due to movement of equipment, UV-radiation) ▸ Drip irrigation emitters are vulnerable to clogging and dysfunction (water filters required, regular flushing of pipe system) ▸ High skill requirements for irrigation water management in order to achieve optimal water distribution ▸ Soil salinity hazard

Based on Brouwer et al. 1989b

1.1.5 Micro-Sprinkler Irrigation

Micro-sprinkler irrigation systems are a cross-over between conventional sprinkler irrigation technology and the more water efficient drip irrigation. These systems are usually referred to as mini-sprinkler and micro-spray systems. They deliver water under pressure by an emitter which is connected to a lateral pipe. There is generally one lateral pipe per row and these are connected to a sub-mainline (Goodwin 2010).

These systems are commonly employed on smaller orchards to irrigate tree crops. They are not suitable for larger plots due to the high capital and labour requirements.

Emitters available are commonly known as micro-sprinklers, micro-jets, mini-jets, mini-sprays and spray-jets. Such terms are best understood by realising that a sprinkler uses a moving part to distribute the water, while a jet or spray has no moving part but rather interferes with the water stream to cause it to be distributed over an area (ibid.).

Almost all above-mentioned emitters operate on pressures as low as 0.75 bar up to 4.0 bars. Their usual operating range is between 1.0 and 1.5 bars due to pumping cost considerations. Commercially available emitters discharge water at rates from 20 to 200 l/hour. This wide range allows the selection of an emitter to suit the particular requirements of irrigation frequency and soil type (ibid.).

There are as many patterns of water distribution as there are emitters. For this reason, it is essential in the design of the irrigation system to be familiar with the various types of emitters. Most of the spray or jet emitters apply water over small areas (diameters of 2 m) within which are localised areas receiving much heavier applications. Consequently, it is important that the areas receiving the bulk of the water are in the vicinity of the plant roots. Mini-sprinklers generally apply water over a larger area (diameters from 4-10 m) and, apart from an area near the emitter which receives more water, the water is uniformly distributed. Such emitters can be used for a wide range of crops and planting distances. Application rates can vary from 2 to 50 l/hour. Many mini-sprinklers apply water at an average rate of 2 to 5 l/hour (Goodwin 2010).

As these emitters discharge water at a greater rate than most drip emitters, the piping has to be larger. Furthermore, most mini-sprinkler and

Figure 1.15: Examples of micro-sprinkler devices

Nelson Irrigation Corporation

Source: GIZ / Kilian Blumenthal, 2016

micro-spray emitters do not compensate the flow rate in response to a variation in pressure. This leads to increased cost of the system. By increasing the pressure the variation in flow rate can be reduced and systems can be designed with smaller pipe sizes, minimising the capital cost. However, the running cost will increase proportionally with increase in pressure (ibid.).

Because mini-sprinkler and micro-spray emitters use orifices of diameters of 1 mm or more, blockages caused by silt sized particles or algae should not occur as frequently as with drip irrigation. However, filtration is still required since plant fibre in the water is very often of 1 mm size and can become lodged in the orifice (ibid.).

The main difference between mini-sprinkler/micro-spray systems and drip systems of irrigation is the wetting of a larger soil volume by the spray or jet emitters. This occurs by virtue of the water being distributed over a larger area of soil; drip systems apply water to one point and rely on the soil properties for distribution of the water. The wetting of a larger surface of soil is important on sandy soils where little lateral movement occurs within the soil, and also on some clay soils where cracking of the soil is severe (ibid.).

All forms of micro-irrigation offer advantages over conventional sprinklers by applying water to each plant individually along the line where the concentration of roots is the highest. Compared with sprinklers, there is considerably less evaporation because less of the soil surface is wetted (ibid.).

Systems usually work on the principle of one mini-sprinkler per tree (or two trees in case of close plantings), plus hilled-up tree-lines for maximum root growth and surface drainage.

1.2 Modern Water-Saving Irrigation Solutions

You can find an overview of considerations to make about water management before planning your irrigation design in the SPIS Toolbox Module IRRIGATE – Irrigation Efficiency Tips on Energypedia.

It is imperative to save water to achieve higher productivity per unit of water consumed and to provide water for the environment. However, low commodity prices do not necessarily allow investment in higher technologies, largely owing to government subsidies and international market competition (RAP 2006).

Technical options for a more efficient use of available water supply for irrigation include:

- Adoption of on-farm water-saving methods (from soil water monitoring to pressurised irrigation systems) to improve water productivity;
- Reducing conveyance losses in the water delivery systems through canal lining and piping;
- Matching water-saving investments with higher value cropping systems;
- Removing salinity constraints from farm to regional levels through efficient leaching of soils;
- Promoting sustainable multiple use of water (ibid.).

The relative economic and environmental merits of adopting water-saving options for overall water saving and water productivity are largely unknown due to a lack of integration of existing data sets (RAP 2006). In principle, it would be required to identify water-saving options by adopting a system approach for accounting for all surface water and groundwater uses, losses and interactions at the catchment, irrigation area and farm levels.

The individual farmer is primarily concerned with efficiency at farm level. Ultimately, these considerations have an impact on the irrigation and catchment area. Investment decisions, however, are not based on these latter impacts unless prescribed by legal and regulatory frameworks. Reflections in the stocktaking and analysis study are limited to farm level.

Numerous studies from the irrigation research sector (in developing and developed countries) reveal that conventional irrigation methods for food crops are characterised by net crop water requirements (NCWR) well below the actual irrigation application. There are usually also major differences between the minimum and maximum crop yields, as well as the overall amount of water consumed and the NCWR. These findings suggest that there is a potential to increase farm profitability at a range of levels, which include:

- Better matching of soils and groundwater conditions with cropping systems;
- Improving irrigation efficiency;
- Increasing crop yields by removing the management, nutrient and salinity constraints (ibid.).

On-farm irrigation technology conversions can provide potential water savings ranging from 10 to 50 % depending on the system and the crop if on-farm surface irrigation methods can be replaced with pressurised irrigation systems.

1.2.1 Cropping Pattern Requirements

You can read more about the different crop revenues in the SPIS Toolbox Module DESIGN – Analyze Agricultural Production Options.

Use the SAFEGUARD WATER – Water Resource Management Checklist Tool on Energypedia.

On-farm technology changes resulting in water savings have a significant impact on the individual farm's management. This may include, but not necessarily cause, changes in the specific cropping patterns.

In the first place, water-saving should result in secured and/or increased yield levels of the prevailing crops. If irrigation water availability was in deficit prior to the change in technology, for example, the saved quantities of water may not allow any intensification and/or expansion of cropping. In extreme cases, it may also be that water savings are still not sufficient to sustain the current crop rotation and intensity.

In most parts of the world, cropping patterns depend largely upon irrigation facilities. Wherever water is available, not only can a different crop be grown but even double or triple cropping will be possible. When new irrigation facilities are provided, the whole method of cultivation may change. However, there are many factors outside of the availability of irrigation water that influence the choice of crops, their rotation and the cropping intensity on farm level:

- Physical characteristics (soil, climate, environmental hazards, etc.);
- Availability and ownership/tenure of arable land;
- Farm size;
- Subsistence needs of the farm household and market access for cash crops;
- Market dynamics for cash crops;
- Education and skill level of the farmer;
- Availability of farm labour and level of mechanisation;
- Availability of inputs (seeds, fertiliser, plant protection products, etc.);
- Access to capital/financing and subsidies;
- Legislative and administrative policies.

If traditional considerations are neglected, economic motivation is the most important factor for determining cropping patterns. Basically any farm household strives to employ its resources (this includes irrigation water as a farm input) with the objective to achieve the best economic outcome, be it subsistence food security or income from market sales of agricultural products.

The assessment of irrigation potential, based on soil and water resources, can only be done by simultaneously assessing irrigation water requirements (IWR) (Hillel 1997).

Net irrigation water requirement (NIWR) is the quantity of water necessary for crop growth. It is expressed in mm/yr or in m^3/ha per year (1 mm = 1 l/m^2 = 10 m^3/ha). It depends on the cropping pattern and the climate. Information on irrigation efficiency is necessary to be able to transform NIWR into gross irrigation water requirement (GIWR), which is the quantity of water to be applied in reality, taking into account water losses. Multiplying GIWR by the area that is suitable for irrigation gives the total water requirement for that area (Hillel 1997).

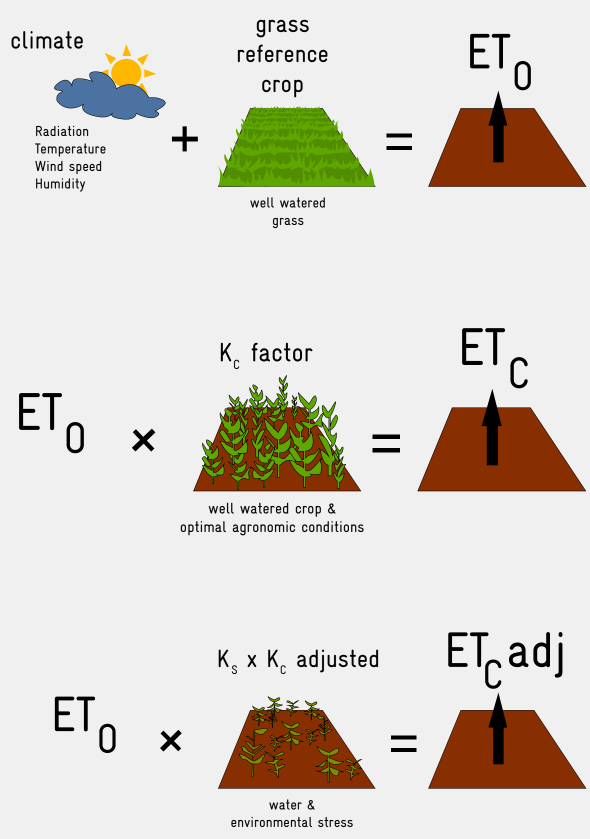
Each crop has its own specific water requirements. NIWRs in a specific scheme or on a specific plot for a given period of time are thus the sum of individual crop water requirements (CWR) calculated for each irrigated crop. Multiple cropping (several cropping periods per year) has to be taken into account by computing crop water requirements for each crop (Frenken 1997).

Calculation of crop water requirements

Find a brief overview about crop water requirements and different software tools for calculation in the SPIS Toolbox Module DESIGN – Determine Water Requirements and Availability on Energypedia.

Crop water requirements for a given crop depend on the prevailing local reference evapotranspiration (ET_0) representing the environmental demand in a given location. This value represents the evapotranspiration rate of a short green crop (grass) completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available

Figure 1.16: Calculating crop evapotranspiration (ETc)



Adapted from FAO/Allen et al., 1998

to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere (Pond et al. 2009).

A crop coefficient relates crop water use at a particular development stage of a specific crop to the amount of evapotranspiration (ET_0) calculated from weather data: $ETcrop = Kc \times ET_0$. Crop coefficients vary between crops and growth stages which reflect the changing characteristics of a plant over the growing season. Crop type and growth stages are major factors influencing the crop coefficient. As the crop grows, ground cover, crop height and leaf area change (Brouwer, Heibloem 1986).

The difference between the CWR of different crops can be significant and is also subject to variation between different locations as the local ET values differ. Traditional food crops such as sorghum, millet, wheat and other cereals are usually at the lower end of the table, whereas fodder and tree crops have much higher requirements. Table 1.5 gives an example of three locations in Morocco for the main local crops:

The figures illustrate that higher value market crops have usually higher water requirements as compared to traditional cereal crops. As long as the crop water requirements are not satisfied from rainfall or from water flowing directly to the field without additional effort required, irrigation water would have to be actively extracted from a source and conveyed to the field, thereby causing operational expenditure.

As outlined in section 1.1.1, traditional surface irrigation methods are only suitable for some crops. Basin irrigation is suitable for fodder production, cereals including paddy and maize and leguminous crops, but is not suitable for vegetables and other cash crops with higher sensitivity to waterlogging, which require furrow irrigation, which again is not a feasible solution for broadcast crops (cereals, leguminous crops).

High crop water requirements of high-value crops also force the farm manager to consider the efficiency of available irrigation methods (see section 1.2.2 below) due to the operational expenditure related to water extraction and conveyance. Introducing sprinkler irrigation to

Table 1.5: Crop water requirements at different locations in Morocco

Crop	CWR Aoulouz (Souss-Massa) (m^3/ha)	CWR Yacoub (Souss-Massa) (m^3/ha)	CWR Afenssou (Haut Atlas) (m^3/ha)
Durum Wheat	2,825	2,655	---
Wheat	2,678	2,505	3,524
Barley	2,643	2,470	3,487
Maize	5,129	5,057	5,454
Vegetables (Winter)	---	---	3,272
Vegetables (Spring)	4,678	4,555	4,698
Vegetables (Summer)	2,632	2,514	---
Broad Bean	---	---	2,748
Lucerne	10,066	9,674	9,414
Olive Plantation *	5,662	5,198	3,091
Almond Plantation *	5,144	4,681	2,248
Other Tree Crops *	6,327	5,896	3,250

* Stocking rate: 100 plants/ha

Source: Authors

cereal and fodder production (except for paddy) is a technically feasible option and would result in water savings due to the higher application efficiency. It may, however, be not a viable option if the incremental benefit of the production is lower than the additional investment costs and operational expenses linked to the establishment and running of a sprinkler irrigation system.

High-value tree and vegetable crops, floriculture and other special cultivations usually have high requirements in terms of the conditions they are cultivated in:

- High water demand throughout the vegetation period with high sensitivity to water stress (drought and waterlogging);
- High nutrition requirements;
- Sensitivity to siltation;
- Sensitivity to splash water.

These parameters influence the choice of irrigation system. Modern agriculture with high-value crops is increasingly turning towards micro-irrigation methods as these systems have the highest efficiency and accuracy in water distribution and offer optimal plant management conditions.

From a different perspective, once a farm manager has opted for a modern micro-irrigation system and invested accordingly, the induced capital and operational expenditure requires the production of high-value market crops with an increased intensity. This may require the farm household to change its cropping patterns radically over time based on actual market dynamics.

1.2.2 Efficiency and Durability

Use the SPIS Toolbox DESIGN Pump Sizing Tool on Energypedia to identify leaks and pressure losses and make your system more efficient. Read more about Irrigation Efficiency and Crop Water Requirement in the Module GET INFORMED – OVERVIEW: Irrigation Principles.

The term **irrigation efficiency** is used to express the percentage of irrigation water actually used by the cultivated crop. Each irrigation system has its particular scheme efficiency depending on the water losses in its primary, secondary and lateral components. The scheme irrigation efficiency (in %) is that part of the water pumped or diverted through the scheme inlet, which is used effectively by the plants. It can be sub-divided into:

- **Conveyance efficiency**, which represents the efficiency of water transport in canals or pipes;
- **Field application efficiency**, which represents the efficiency of water application in the field (Brouwer et al., 1989a).

Conveyance efficiency mainly depends on the length of the canals, the soil type or permeability of the canal banks and the condition of the canals (surface irrigation) – or on the type and length of the pipelines used in pressurised systems. Naturally, the risk of water losses in canal systems is very high (evaporation, seepage/infiltration etc.), whereas in modern pressurised systems this risk tends to be minimal as the water is distributed in a closed pipeline system. Pressurised irrigation systems have the potential to avoid the water loss related to surface irrigation, thereby increasing irrigation efficiency from 45–60 % in open surface irrigation schemes to 75–95 % in closed pressurised irrigation systems.

In terms of irrigation water usage, **field application efficiency** is highest with modern drip irrigation methods, where 90 % of the supplied water is actually used by the plant. Sprinkler irrigation systems achieve a field application efficiency of 75 %, whereas surface irrigation approaches (furrow, basin, and border) achieve not more than 60 % field application efficiency.

Table 1.6: Typical efficiencies of irrigation application systems

Application System	Irrigation Efficiency
Drip Systems	90 %
Micro Sprinkler Systems	80 %
Permanent Sprinkler Systems	75 %
Moving Sprinkler Systems	80 %
Movable Quick Coupling Sprinkler Systems	70 %
Travelling Sprinkler Systems	65 %
Surface Irrigation Systems (Piped Supply)	80 %
Surface Irrigation Systems (Earth Channel Supply)	60 %

Source: SABI 2014

Please note that the actual measured efficiencies can vary widely from the typical values shown in Table 1.6 due to conditions such as wind, humidity, and cultivation, operation and maintenance practices of the producer (SABI 2014).

Both irrigation water quality and proper irrigation management are critical to successful crop production. The **quality of the irrigation water** may affect both crop yields and soil physical conditions, even if all other conditions and cultural practices are favourable/optimal. In addition, different crops require different irrigation water qualities. It is critical to test the irrigation water prior to selecting the site and the crops to be grown. The quality of water sources may change significantly with time or during certain periods (such as in dry/rainy seasons). It is recommended to have more than one sample taken in different time periods (Sela n.d.).

The parameters that determine irrigation water quality are divided into three categories: chemical, physical and biological.

Chemical characteristics of irrigation water refer to the content of salts in the water as well as to parameters derived from the composition of salts in the water; parameters such as EC/TDS (Electrical Conductivity/Total Dissolved Solids), SAR (Sodium Adsorption Ratio), alkalinity and hardness (Sela n.d.).

Table 1.7 summarises the main chemical parameters of irrigation water:

Table 1.7: Chemical parameters of irrigation water[NRG12]

Chemical Parameter	Description
Salinity	The primary natural source of salts in irrigation water is mineral weathering of rocks and minerals. Other secondary sources include atmospheric deposition of oceanic salts (salts in rain water), saline water from rising groundwater and the intrusion of sea water into groundwater aquifers. Fertilizer chemicals, which leach to water sources, may also affect the irrigation water quality. The main problem related to irrigation water quality is the water salinity. Water salinity refers to the total amount of salts dissolved in the water but it does not indicate which salts are present in it. A high level of salts in the irrigation water reduces water availability to the crop (because of osmotic pressure) and causes yield reduction. Above a certain threshold, reduction in crop yield is proportional to the increase in salinity level. Different crops vary in their tolerance to salinity and therefore have different thresholds and yield reduction rates. In case the irrigation water salinity exceeds the threshold for the crop, yield reduction occurs. Equations were developed to estimate the yield potential, based on the irrigation water salinity. $\% \text{ Yield (of maximum)} = 100 - b * (EC_e - a)$ Where (b), is the percent loss in relative yield per unit increase in salinity, (a) the EC threshold the crop can tolerate and ECe is the electrical conductivity of the saturated soil paste, which is measured in the laboratory. ECe is proportional to the electrical conductivity of the irrigation water, depending on the percentage of irrigation water leached below the root zone.
Sodium Hazard and Irrigation Water Infiltration	The parameter used to determine the sodium hazard is SAR - Sodium Adsorption Ratio. This parameter indicates the amount of sodium in the irrigation water, in relation to calcium and magnesium. Calcium and magnesium tend to counter the negative effect of sodium. $SAR = \frac{Na\ (meq/l)}{\sqrt{\frac{CA\ (meq/l) + Mg\ (meq/l)}{2}}}$ High SAR levels might result in a breakdown of soil structure and water infiltration problems. Soil tends to seal and become hard and compact when dry. Higher salinity reduces the negative effect of sodium on the soil structure. With high sodium levels in the soil in relation to calcium and magnesium, flushing the soil with good irrigation water quality will only worsen the problem.
Toxicity of Specific Ions	The quality of the irrigation water can be also determined by toxicity of specific ions. The difference between a salinity problem and a toxicity problem is that toxicity occurs within the plant itself, as a result of accumulation of a specific ion in the leaves. The most common ions which might cause a toxicity problem are chloride, sodium and boron. The same as with salinity, crops differ in their sensitivity to these ions. Special attention should be given to boron because its toxicity occurs in very low concentrations, even though it is an essential plant nutrient. Toxic levels of even a single ion in the irrigation water might make the water unsuitable for irrigation. There are some management practices that can help in reducing the damage. These practices include proper leaching, increasing the frequency of irrigations, avoiding overhead irrigation, avoiding the use of fertilizers containing chloride or boron, selecting the right crops, etc.
Alkalinity and pH	Alkalinity is the sum of the amounts of bicarbonates (HCO_3^-), carbonates (CO_3^{2-}) and hydroxide (OH^-) in water. It is expressed as mg/l or meq/l $CaCO_3$. Alkalinity buffers the water against sudden changes in pH. If the alkalinity is too low, any addition of acidic fertilizers will immediately lower the pH. In container plants and hydroponics, ions released by plant roots may also rapidly change the pH if alkalinity is low.

Based on Abrol et al. 1988

Irrigation water of low quality in terms of its chemical parameters requires consideration of risk management or alleviation measures. Unless a farm invests in active cleaning of its irrigation water from salts and other unwanted nutrients by means of an (expensive) reverse osmosis filter system, irrigation management approaches have to be developed. This may include fresh water blending from higher quality sources. However, these approaches increase the capital and operational expenditure of irrigated production.

Physical and biological impurities of irrigation water are a cause for concern, especially in micro-irrigation (clogging of pipes and emitters). Here, the systematic integration of filter devices is mandatory (see section 2.2.4). In addition, regular maintenance routines need to be established to clean fittings and emitters from particles and to flush out sediments from the pipe system.

The possible contamination of irrigation water with pathogens is a highly sensitive issue. This may include water-borne diseases, food-borne pathogens and faecal pathogens. Open water sources such as rivers, lakes, supply channels and open wells are subject to micro-biological contamination from drainage and wastewater and from influx of human and livestock faeces. Such contamination may also include the shallower layers of the aquifer, particularly in peri-urban areas.

Developing countries usually report much higher levels of pathogens in irrigation water than developed countries, as untreated raw wastewater is often used for irrigation. Wastewater irrigation provides a quarter of all vegetables produced in Pakistan. In most parts of Sub-Saharan Africa, but also in larger urban agglomerations in the Middle East, irrigated urban and peri-urban farming with highly polluted water sources contributes 60-100 % of the perishable vegetables sold in most cities (Raschid-Sally et al. 2004). Faecal indicator concentrations in such waters can reach levels typical of manure and faeces. Surveys identified concentrations of faecal coliforms from 10^5 to 10^9 PN/100 ml in waters of the Indo-Gangetic riverine system used for irrigation of leafy greens. Irrigation water containing raw sewage or improperly treated effluents from sewage treatment plants may contain hepatitis A, Norwalk viruses, or enteroviruses in addition to bacterial pathogens (Pachepsky et al. 2011).

Farmers can achieve significant energy savings through reviewing and modifying their irrigation and other water distribution systems. The relationship between water efficiency and **energy efficiency** is a key factor when designing or modifying irrigation solutions. Opportunities for savings include devising efficient pipe layouts, sizing pumps correctly, introducing variable speed drives and switching from diesel to electric pumps. Electricity is generally more cost-efficient for pumping than diesel or other hydrocarbon fuels; hence the energy source needs to be considered (New South Wales Farmers Association 2013).

Irrigated farms typically move many m^3 of water every year, with application rates for different crops ranging from 20,000 to 100,000 m^3/ha. Energy used in irrigation can account for upwards of 50 % of a farm's overall energy bill. Additionally, many farms pump water for stock and domestic needs.

Energy efficiency in irrigation has three key aspects:

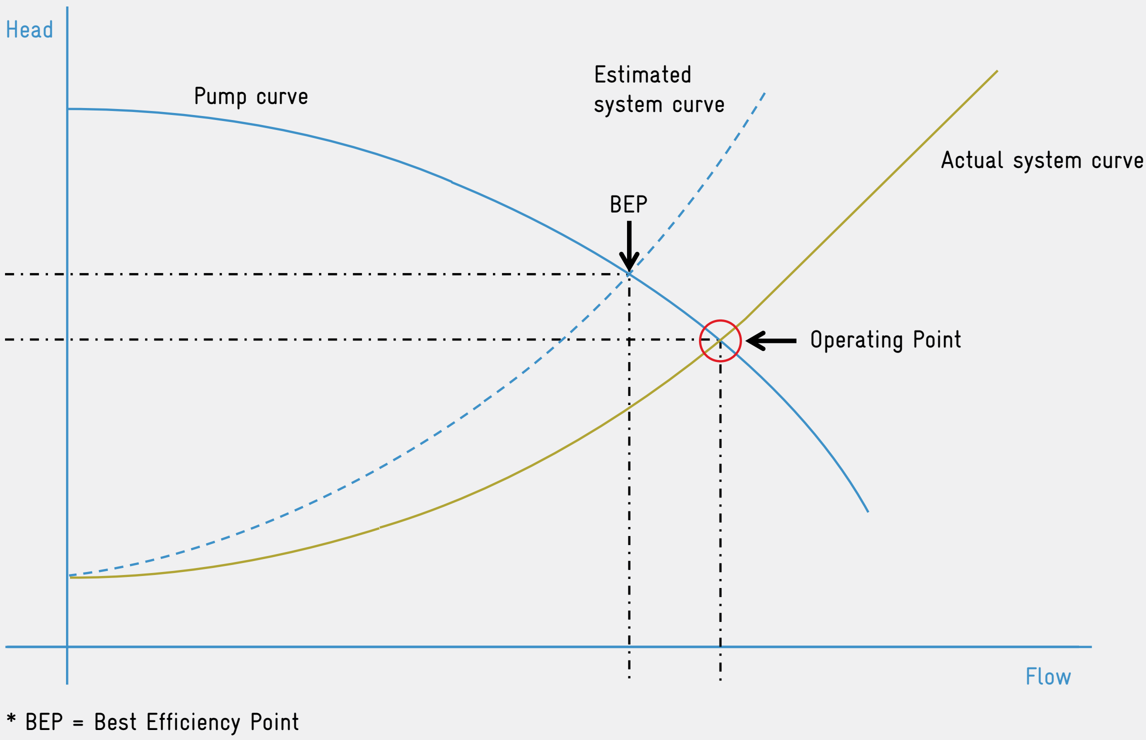
- **Needs analysis, design and planning** – it is essential that farmers and irrigation planners consider and balance water and energy efficiency;
- **Optimising equipment** – it should be ensured that pumps and control systems optimise return on energy inputs;
- **Energy source** – electricity is more cost-efficient for pumping than diesel but not all farms are able to connect to the grid. Alternative energy sources, such as solar, may be a viable option in such cases (New South Wales Farmers Association 2013).

In areas where ground and surface water availability is diminishing, efficient irrigation tools, such as drip, trickle and lower-flow sprinkler systems save energy as well as water and thus money. Some common causes of wasted energy in irrigation systems are worn or improperly sized pumps, worn nozzles, and improperly sized or designed fittings. Problems with irrigation equipment and maintenance tend to go hand in hand. Pumps, motors and engines that are badly designed or poorly maintained reduce the irrigator's degree of control over water applications, making it impossible to maintain correct soil moisture levels. This leads to crop stress, reduced yields, runoff, erosion and other problems (eXtension 2015).

The key variables affecting energy efficiency for water conveyance are gravity, pressure and friction. When designing water distribution systems and specifying pumps, engineers consider the distance the water has to be lifted and transferred, the depth below and height above sea level, and the friction caused within pipes and channels by layout, diameter and operating pressures. Further complications may arise from policy constraints on pump size, pipe diameter and allowable pumping hours. A further consideration is the trade-off that may occur between water efficiency and energy efficiency aims. For example, forcing water through a drip irrigation network will use more energy that running it through channels and furrows, but this type of system will apply water more efficiently than a more energy-efficient centre pivot irrigation system (New South Wales Farmers Association 2013).

Figure 1.17 illustrates the correlation between pumping head and flow in terms of actual operating performance versus the theoretical best efficiency point.

Figure 1.17: Actual operating performance versus the theoretical best efficiency point



Adapted from New South Wales Farmers Association, 2013

In terms of the **durability** of irrigation systems, no uniform assessment can be articulated. Any irrigation system comprises several key components starting at the head with its water abstraction to the actual tail where water is applied (and perhaps even excess water/drainage recollected). Each of these components would have a specific lifespan under ideal conditions, subject to variability based on changing local conditions.

Key to the durability of different irrigation system components are their original manufacturing quality, the degree to which they are properly installed (as per design), the intensity of use, climatic conditions and, last but not least, the degree to which operation and maintenance is carried out regularly and professionally.

Table 1.8 gives a generalised overview of the typical lifespan of irrigation system components used for planning purposes and for capital cost considerations:

Table 1.8: Typical lifespan of irrigation system components

Irrigation System Component	Typical Lifespan (Years)
Earthen Weirs/Dams, Farm Ponds	20
Unlined Canals	15
Civil Works Structures (Head portion)	40
Civil Works Structures (Field Level)	20
Underground Primary and Secondary Pipe System	15 – 20
Unburied Pipe System	5 – 10
Fittings, Filter and Metering Devices, etc.	5 – 10
Centre Pivot System	20
Other Travelling Sprinkler Systems	10 – 15
Impact Sprinkler Head	8 – 10
Drip Tape	1 – 2
Drip Tube, Porous Pipes	3 – 5
Drip Emitters, Micro Sprinklers	3 – 5
Natural Gas Engine/Generator	8 – 10
Diesel Engine/Generator	6 – 12
Petrol Engine/Generator	2 – 5
Electric Motor	7 – 10
PV Generator	15 – 20
PV Controller	3 – 5
PV Pump (Submersible)	5 – 7
PV Pump (Surface)	3 – 5

Based on South African Irrigation Institute 2014

1.3 Energy Sources for Water Abstraction and Pressurised Irrigation Systems

You can compare different energy sources using the SPIS Toolbox INVEST Payback Tool on Energypedia.

Don’t forget to also check the chapter on Water Extraction in the Module SAFEGUARD WATER.

1.3.1 General Classification and Description

Motor-driven water abstraction and conveyance requires a reliable energy source – or a reliable combination of energy sources. Worldwide, many types of pumps and pump motors are in use. The majority of water pumping for irrigation purposes is currently effected by diesel or petrol motors or electric motors fed from the grid or from diesel generators. The utilisation of renewable energy sources to power pump motors is steadily increasing, but is still on the minority side.

Table 1.9 gives an overview of the main energy sources for water abstraction and conveyance in irrigated agriculture:

Table 1.9: Overview of energy sources for irrigation water pumping

Source of Energy	Description
Petrol Engine	Small petrol-driven pumps are a very common option for smallholder agriculture. The pump motors have usually an output in the range of 1.5 to 5.0 horse powers (HP), but are also available with higher performances. Petrol-driven pumps are characterized by low initial costs, low weight, comparatively small lifespan, high fuel consumption and high maintenance requirements.
Diesel Engine	Diesel engine-driven pumps are generally available with higher capacities and outputs starting from 3.5 HP. Higher performance engines are available and cater also for medium-size farms. Diesel-driven pumps are characterized by their high initial costs and the high costs for spare parts and maintenance. Their lifespan is much higher than that of petrol-driven pumps. Operational expenses are quite low due to the good fuel efficiency of diesel engines and the low price (often subsidised for agricultural use) for diesel in most countries.
Natural Gas Engine	In some countries like Morocco propane gas engine-driven pumps are in use due to a heavy subsidization of propane household gas and lacking utilization restrictions. Here, small petrol-driven pump engines are converted to run on propane gas with similar characteristics as petrol engines. Operational expenses are much lower compared to petrol engines due to the large price difference between propane gas and petrol.
Electric Engine	AC or DC electricity-driven pumps are quite common with a large variety in the actual source of electricity. Their output starts as low as 0.5 HP and can extend flexibly to large scale purposes. Electric pumps are generally very efficient and low on maintenance requirements (if operated within their designed input power range). A distinction has to be made according to the actual source of electricity: ► Network/grid-supplied electricity; ► Generator (diesel, petrol)-supplied electricity; ► Photovoltaic-generated electricity; ► Electricity generated from other off-grid RE-sources (biogas, biomass generators).
Wind Powered Pumps	In remote areas around the world windmills have been in use as a common technology to lift water from wells and aquifers for agricultural purposes. This technology has partly been used for irrigation on smallholdings in connection with an intermediate water storage high tank enabling gravity flow into a low pressure system (or traditional surface irrigation). This technology is characterized by an extreme variation of water availability due to varying wind speeds and a high maintenance requirement for the mechanical system of the windmill. Initial costs are low.

Source: Authors

1.3.2 Hybrid Solutions

Renewable energy (RE) based water abstraction and conveyance is still in its early stages as far as the larger scale utilisation of PV technology is concerned. Very often, PV water pumping is integrated within a multiple energy source mix on farm level, rarely as a standalone solution. Hybrid solutions can generally be distinguished in two categories:

Separated systems usually comprise a RE option (predominantly PV) as the preferred source of energy for the water pump(s). A conventional energy option, mostly a diesel or petrol engine-driven pump or a grid-supplied (or generator-supplied) electric pump, are available as a back-up or stand-by option (in case the RE source is not available). This set-up is often chosen by farm managers to minimise risks.

Parallel operation of the RE option with conventional energy options is also quite common to reduce operational expenditure.

Integrated systems combine two or more RE sources or combinations of renewable and conventional energy sources. These systems are usually quite sophisticated and capital-intensive, as they require investments in several modern technologies (e.g. PV and wind generators) or automated or semi-automated system integration of conventional and RE technologies.

Integrated high-end products (e.g. AC/DC compatible PV pumps) are available on the market.

1.4 Pumping Technology for Water Abstraction and Irrigation

You can find additional information on structures, conveyance and distribution options in the SPIS Toolbox Module IRRIGATE – Plan Intake Structures, Conveyance and Distributions on Energypedia.

Irrigation pumps are categorised according to their design. There are two main classifications of irrigation pumps:

- Positive displacement pumps apply force to a liquid in a contained vessel, creating pressure which moves the liquid;
- Rotodynamic (centrifugal) pumps are equipped with an impellor that rotates in the liquid and imparts energy to the liquid to create pressure. This pressure then moves the liquid. Rotodynamic pumps can be further classified by the different shape of their impellor: radial flow, mixed flow and axial flow.

Almost all irrigation pumps fall into the category of **centrifugal pumps**. Centrifugal pumps may be 'multi-stage', which means they have more than one impeller and casing, and the water is passed from one impeller to another with an increase in pressure occurring each time. Each impeller/casing combination is referred to as a 'stage' (Stryker 2003).

End-suction centrifugal pumps are typically mounted right on the end of the motor's drive shaft and the pump case is bolted straight into the motor so that it looks like a single unit. The water typically enters the pump through a suction inlet centred on one side of the pump, and exits at the top. Almost all portable pumps are end-suction centrifugal type pumps. End-suction centrifugal pumps are designed to push water, hence they are widely used as irrigation booster pumps and for pumping water from any source where the water level is higher than the pump (where the water can flow down an intake pipe to the pump using gravity). End-suction centrifugal pumps are not the best choice for drawing water from a water source that is lower than the pump (Stryker 2003).

Figure 1.18: Example of an end-suction centrifugal pump (single stage) mounted with motor

Source: Grundfos, 2015

Figure 1.20: Example of a centrifugal (turbine) pump

Source: Lorentz, 2019

Submersible pumps are installed completely underwater, including the motor. The pump consists of an electric motor and a pump combined in a single unit. Typically the pump will be shaped like a long cylinder so that it can fit inside a well casing. Although most submersible pumps are designed to be installed in a well, many can also be laid on their side on the bottom of a lake or stream. As the power cable runs down to the pump through the water it is very important that it is protected from accidental damage (Stryker 2003).

A **turbine pump** is basically a centrifugal pump mounted underwater and attached by a shaft to a motor mounted above the water. The shaft usually extends down the centre of a large pipe. The water is pumped up this pipe and exits directly under the motor. Turbine pumps are very efficient and are used primarily for larger pump applications. Often they consist of multiple stages, each stage essentially being another pump stacked on top of the one below.

A **jet pump** is similar to a turbine pump but it works by redirecting water back down to the intake in order to help lift the water (Stryker 2003).

Figure 1.19: Example of a submersible centrifugal pump

Source: Grundfos, 2015

1.5 Comparative Financial Analysis of Irrigation Solutions

You can compare investment options of different pumping technologies and economic profit scenarios using the SPIS Toolbox INVEST Payback Tool on Energypedia.

1.5.1 Generic Costs of Irrigation Solutions

You can read more about loan assessment, profitability and credit risk in the SPIS Toolbox Module INVEST – Loan Assessment on Energypedia.

Costs and financial implications of different irrigation solutions available at any given location around the world vary according to the specific system design and the local prices for the system components. The impacts of the different irrigation solutions on farm management vary accordingly.

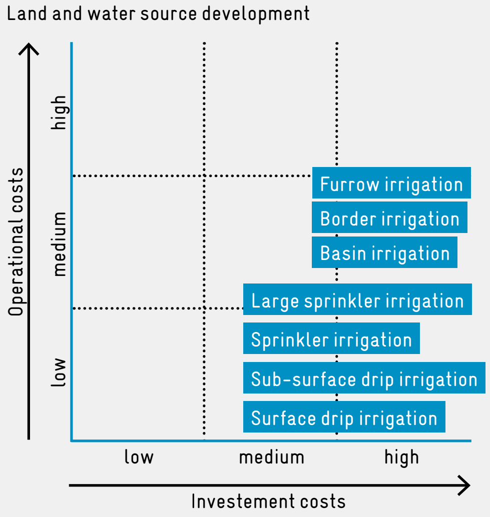
The cost of a specific irrigation solution is an aggregate of a number of factors that need to be assessed financially:

Table 1.10: Main cost factors and cost components to be considered for irrigation systems

Cost Factor	Cost Components
Land Development / Earthworks, Grading	► Capital costs (acquisition, investment) ► Financing costs (loan services)
Water Source / Headworks, Well	► Capital costs (investment) ► Financing costs (loan services) ► Depreciation costs (replacement)
Pumping System	► Capital costs (investment) ► Financing costs (loan services) ► Depreciation costs (replacement)
Water Conveyance System / Canal, Pipeline	► Capital costs (investment) ► Financing costs (loan services) ► Depreciation costs (replacement)
Water Distribution System	► Capital costs (investment) ► Financing costs (loan services) ► Depreciation costs (replacement)
System And Irrigation Management	► Fixed costs (subscriptions) ► Variable operation costs (fuel/electricity, fees)
Labour	► Labour costs (system operation, irrigation management)

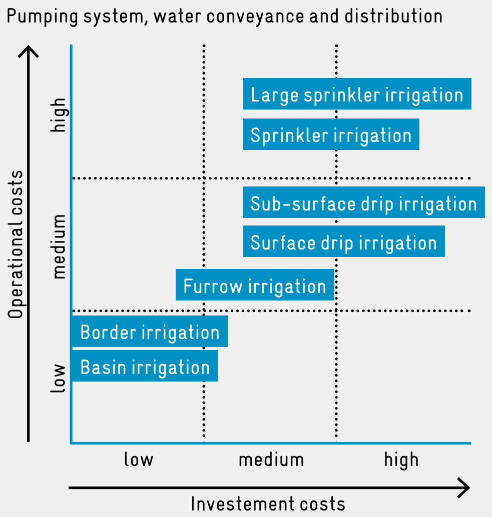
Source: Authors

Figure 1.21: Impact of irrigation methods on investment and operational costs related to land and water source development



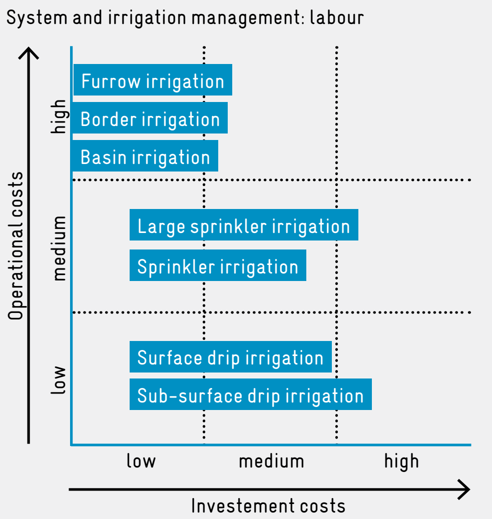
Source: Authors

Figure 1.22: Impact of irrigation methods on investment and operational costs related to pumping system, water conveyance and distribution (no bulk supply)



Source: Authors

Figure 1.23: Impact of irrigation methods on system and irrigation management and labour requirements



Source: Authors

These factors cannot be compared in a globalised manner, but the impact of different irrigation solutions on these factors can be generalised as illustrated in the figures:

Surface irrigation approaches require a high degree of land development, as outlined above (see section 1.1.1), but they usually work with simple water abstraction installations such as derivation weirs or riverside intakes. Pressurised systems often require a bore well or a deep dug well, implying higher initial investment costs. Sprinkler and drip irrigation do not require sophisticated land development (Figure 1.21).

As for the pumping system, water conveyance and water distribution (Figure 1.22), pressurised systems require higher investment and induce moderate to high operational expenses due to the energy consumption for pumping. Sprinkler irrigation implies high operational expenditure as the systems operate at higher pressure rates as compared to drip irrigation and require regular replacement of mechanical sprinkler equipment. Surface irrigation methods do not induce high operational expenditure as water flow is usually distributed through gravity and secondary level distribution is done manually.

The actual cost of operation of pressurised irrigation systems is low due to automation. Micro-irrigation systems in particular can be operated with a minimum of personnel. Sprinkler irrigation systems require a higher degree of labour input due to the need to move the sprinkler units. Surface irrigation methods are labour-intensive due to the manual water management on field level (Figure 1.23).

The consideration of all relevant factors and components of capital and operational expenditure will always result in a specific value for the cost of water in a given system, which is one of the key parameters when comparing irrigation development options. Traditionally, such a comparison was mostly made based on the cost per m3 irrigation water. However, when comparing gravity flow and lift irrigation systems the specific pump head would have to be considered. It is hence useful to calculate the cost per m^3 x head (m) = m^4.

1.5.2 Financial Impact on Farm Budgets

You can use the SPIS Toolbox PROMOTE & INITIATE – Impact Assessment Tool on Energypedia and calculate the socio-economic as well as environmental impacts of SPIS.

Irrigation water is an important production factor in agriculture. Market-oriented agricultural production without irrigation is not possible in many parts of the world. The extent to which farm households depend on irrigation for their production depends on their geographical or rather agro-climatic location, local hydrological and soil conditions, and actual crop water requirements.

The importance of irrigation may range from zero (in temperate regions with a positive water balance throughout the year enabling rain fed agriculture) over a gradually increasing importance of occasional and temporary supplementary irrigation (in regions with periodic water deficit/water stress) to the point of essentiality in semi-arid and arid regions with quasi permanent negative water balance and inherent drought/water stress conditions.

As illustrated above (see section 1.5.1), the actual irrigation method or rather the capital and operational costs related to the specific irrigation method are linked to three parameters via a number of factors:

- Capital costs and related financing service charges;
- Operational costs;
- Labour costs.

These costs impact the farm budget on several levels. Capital costs and financing service charges for investments (land development, irrigation infrastructure and irrigation equipment) are often budgeted on an aggregate level, not specifically allotted to individual crop margins as they constitute fixed costs of the farm enterprise.

In practical terms, it would be more pertinent to calculate dynamic costs per unit irrigation water including capital costs and related financing services in order to have a clear allocation of these costs to the actual crop margin calculation. This can only work, however, if the annual quantities of irrigation water utilised by a farm enterprise do not vary too much.

Operational costs and specific labour requirements are usually taken into account on the level of crop gross margins as they constitute variable costs depending on the actual cultivation.

The share of irrigation water costs within the total production costs of a crop budget varies depending on the irrigation method and local cost levels. Simple surface irrigation services can account for as little as 5-10 % of total production charges in subsidised public irrigation schemes. Here, the farmer usually pays a water tax that may be a flat rate or a small volumetric charge. At the other end of the scale, in commercially operated pressurised irrigation schemes irrigation charges can account for up to 60 % of the production costs of a crop. Common percentages are 20-30 % in surface irrigation systems and 30-40 % in pressurised irrigation systems.

The level of charges obviously determines the choice of crops and their rotation to a very large extent: the higher the variable charges, the greater the need for increased productivity.

1.5.3 Financial Services Requirements

Capital employed in a farm enterprise is seldom available from the equity of the farm owner or household, particularly in the case of small and medium size enterprises. Large holdings, which often produce in an industrialised way, are an exception in this regard.

Farm households usually must borrow money to finance investment in infrastructure or land extension/development or sometimes also to replace machinery and equipment. These financing needs are usually covered by collateral-based long-term lending. The utilisation of short-term production loans to bridge liquidity gaps between harvest periods is also common. Corresponding financing products are available from banks, private lenders and micro finance institutions in most, but not all rural areas around the globe. As these financing products entail certain default risks, their costs are usually quite high (= high interest rate and demanding repayment conditions).

Due to high interest rates and short repayment periods, loans often constitute a severe problem for the cash flow of a farm household, in particular in years with moderate and sub-average yields and negative market price dynamics.

The very high investment costs associated with modern pressurised irrigation systems are usually beyond the financing capacity of small and medium size farms as the underlying capital requirement outpaces the annual earnings of these households by a wide margin. These households always depend on subsidies and/or financing services to handle such an investment.

A common occurrence and hence problem is the failure to consider depreciation of investments in view of their replacement at a later stage. Farm households are usually not in a position to make savings to cover the replacement of equipment, putting at risk the business model on which they base their operations.

1.6 Financial Calculation Models

You can calculate a Farm Income Statement with the SPIS Toolbox INVEST – Farm Analysis Tool on Energypedia.

Very few models and tools are available for farm budgeting and the financial analysis of investment in irrigation infrastructure. Mostly, local calculation models are programmed as Excel calculators catering for specific sector needs.

The SPIS INVEST – Farm Analysis Tool (as introduced above) allows for assessment on farm productivity and profitability through its average annual agricultural production. The tool is useful for establishing a baseline or to assess the impact of planned investments and allows SPIS advisors (suppliers, development practitioners, extension officers) to support a farm enterprise towards identify unnecessary costs, determine best value agricultural activities and correctly monetize different farm inputs.

After calculating the different crop and livestock water requirements with the SAFEGUARD WATER – Water Requirement Tool, the INVEST – Farm Analysis Tool provides an indicative assessment of farm profitability based on the increased yields made possible by implementing a specific irrigation system.

INVEST – Farm Analysis Tool					
8 FARM INCOME STATEMENT					
			Farm code	Mary Wanjiku's Farm	
+	Gross value of seasonal crop production	500.000	KES	+	53%
+	Gross value of seasonal crop by-product production	0	KES	+	0%
+	Gross value of perennial crop production	0	KES	+	0%
+	Gross value of perennial crop by-product production	0	KES	+	0%
+	Gross value of livestock production:	0	KES	+	0%
+	Gross value of livestock by-product production:	450.000	KES	+	47%
+	Gross value of other income:	0	KES	+	0%
-	Anticipated losses of total sales (reduction factor)	10%	%		
=	**GROSS FARM INCOME**	**855.000**	**KES**	=	100%
-	Total fixed costs	347.780	KES	+	55%
-	Total variable costs	289.450	KES	+	45%
=	**TOTAL COST**	**637.230**	**KES**	=	**100%**

Figure 1.24: SPIS INVEST Farm Analysis Tool for farm income statement calculation Source: GIZ / FAO 2019

Another calculator named INCA was developed by GTZ in the 1990s. It caters in particular for the financial analysis of photovoltaic pump irrigation solutions as an alternative to conventional pumps and provides for a number of important analysis functions that are automated and available upon entry of key system data:

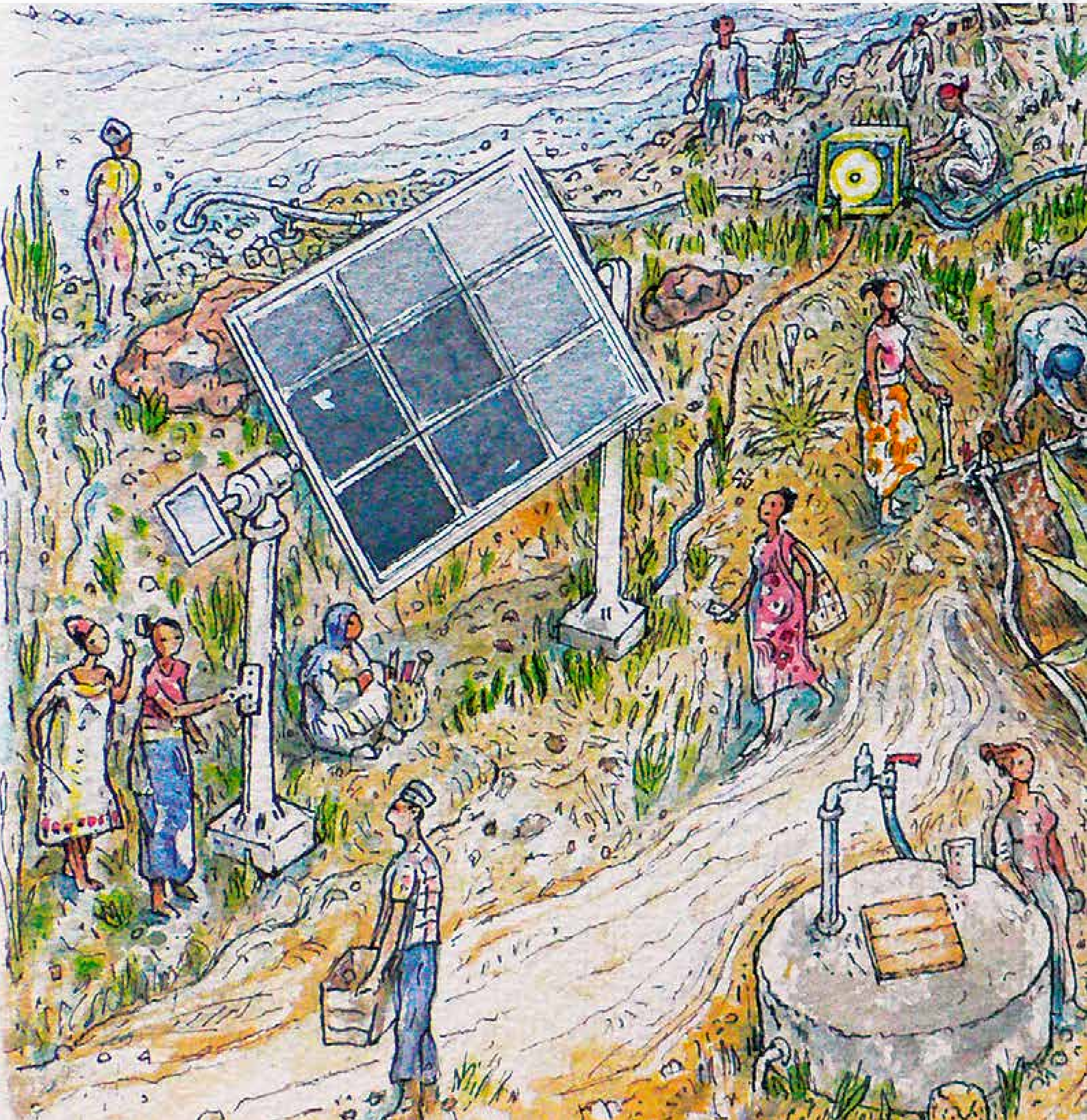
- Imputed investment costs for all system components and their depreciated values;
- Calculation of operation costs and estimation of production value;
- Annual operation costs, loan repayment rates and life-cycle costs of equipment;
- Net Present Value (NPV) of the investment and imputed break-even point.

The calculator works with approximated standard unit costs for all major system components, but can also be used with real costs for goods and services. The weakness of this calculator is the lacking consideration of crop gross margins, either as input data or as an integrated function.

In terms of financial analysis none of the calculation tools caters for the calculation of Net Present Value (NPV) and Internal Rate of Return (IRR) as the most commonly used decision criteria of Cost-Benefit Analysis (CBA).

In summary, no tools integrating all major parameters and calculation needs for the financial (or economic) analysis of irrigation systems exist, especially with regard to the requirements of modern irrigation solutions. Available calculators and tools tend to either simplify the investment side or the production side of the analysis.

2 Technical characteristics and design of SPIS



2 Technical characteristics and design of SPIS

2.1 Components of Photovoltaic Pumping Systems

To find out which SPIS suits your site the best make a suitability analysis using the SPIS Toolbox DESIGN Site Data Collection Tool

and the SPIS Suitability Checklist Tool on Energypedia.

2.1.1 Solar Generator

Find a brief overview about the solar generator in the SPIS Toolbox Module GET INFORMED – Solar Generator on Energypedia.

A solar generator provides the necessary energy to operate the motor pump unit. It is made of individual solar cells which employ the photovoltaic effect, which converts solar radiation directly into electricity.

Solar cells are made of specially prepared semiconductor materials such as silicon, gallium arsenide, cadmium telluride and copper indium di-selenide. When light falls on the surface of the semiconductor, an electric field develops. By connecting a wire to the back and front side of the solar cell, the voltage of the electric field causes a current to flow, which can be used to drive a load. Crystalline silicon solar cells are the most commonly used variety; they currently dominate the global photovoltaic market. About 90 % of all solar panels are made of crystalline silicone (DGS 2013).

To protect the cells against mechanical stress and humidity, the cell strings are embedded in a transparent bonding material (e.g. EVA) that also isolates the cells electrically. For structural stabilisation and electrical insolation, embedded solar cells are usually placed between a plastic cover on the rear side and a glass cover on the front side. Panels fabricated in a laminating process are also described as laminates. To protect the fragile laminate and to provide a mounting possibility, standard solar panels usually come with a rigid aluminium frame.

Depending on the required electrical output (voltage, current and power), several solar panels are connected in series and/or in parallel to form the solar generator (see Figure 2.1) (Schmidt, 2012).

Solar panels are rated in peak watts (Wp) according to their output under internationally defined Standard Test Conditions (STC: irradiance = 1,000 W/m²; cell temperature = 25°C; air mass (AM) = 1.5).

The panel's electrical power mainly depends on the solar irradiance captured by the panel and the solar cell temperature. Solar cell temperatures increase significantly under normal operation and may easily reach 40–65°C, depending on the site-specific conditions. This leads to a lower electrical power output, as compared to STC. The temperature coefficient (TC) describes the power reduction for each degree Celsius increase in temperature; for crystalline silicone cells and it is approximately -0.5 %/°C (DGS 2013).

The relation between the solar irradiance and electrical output of the PV generator is almost linear. Nevertheless, the effect of temperature increase, described above, must be taken into account. This can be done by a correction factor (FCp), which varies between 0.8 and 0.9.

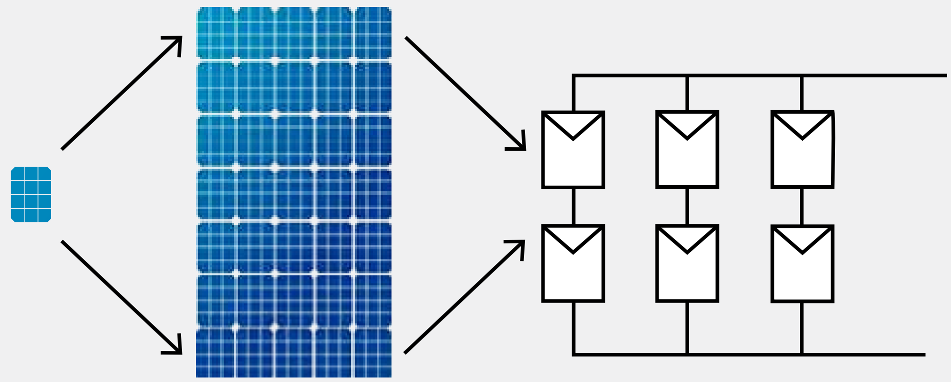


Figure 2.1: From the solar cell to the solar generator   Adapted from R. Schmidt, 2015

Quite a good estimation of the reduced electrical power is given by Schmidt (2012):

$$P_{el} = FC_P * \frac{P_{peak}}{1{,}000 \frac{W}{m^2}} * S$$

With
S = measured solar irradiation in Watt/m^2

The output of a solar panel is not only dependent on the irradiance and cell temperature. The orientation and tilt angle of the panel surface is also important. To maximise output, the site-specific optimal orientation has to be chosen.

2.1.2 Mounting and Solar Tracking Systems

Find a short description of the mounting structure on the SPIS Toolbox Module GET INFORMED – Mounting Structure on Energypedia.

Solar panels are usually mounted on a metal structure with the following alternatives:

- Installation with a fixed tilt angle with north or south orientation;
- Installation on a solar tracker with varying orientation;
- Installation with a fixed tilt angle and east-west orientation;
- Installation with a fixed tilt angle on a float.

Installation with a fixed tilt angle with north or south orientation
This is the classical installation for solar panels. In the northern hemisphere the panels should be facing south to maximise energy yield. Consequently, in the southern hemisphere panels should be facing north. Deviations from true north/south are possible but will result in a reduced energy yield.

The solar generator is always inclined at the tilt angle α which allows optimal solar radiation capture on the panel surface. The tilt angle α should be selected in accordance with the latitude at which the pumping system is installed. Typical values for the tilt angle can be estimated to:

A = absolute value of geographic latitude + / – 10°

For applications with a focus on the winter months, the tilt angle might be increased up to +10°, for summer months the tilt angle might be reduced up to -10°. But to allow rain water and accumulated dirt to run off the panel surface, the tilt angle should be at least 15°, even if the system is installed close to the equator.

Standardised mounting systems can be purchased at specialised solar companies in the region/country, but from an economic and logistical point of view, local production of support structures should be given priority.

Installation on a solar tracker with varying orientation

Mainly two advantages favour the use of trackers in solar pumping:

- Gain of additional solar radiation – the amount of solar radiation received by the solar panels increases significantly. The surplus of solar radiation varies between 25 % and 35 % (annual mean value), depending on solar tracker type and installation site (Schmidt, 2012);
- Even distribution of solar irradiance over the day – the generated electricity and thus the pump's water flow is almost constant over the day. This is quite important for direct driven solar irrigation (without water storage tanks).

There are several types of solar trackers available on the market (see Figure 2.2). For most applications, a one-axis tracker with inclined north/south axis is the best and cheapest solution (Figure 2.2 e).

Two-axis trackers are able to achieve even higher yields, but they are more expensive and because of additional maintenance requirements, they do not represent the right choice for remote applications in developing countries.

While fixed solar generators are almost maintenance free (except regular panel cleaning), tracking systems with an electrical motor and other mechanical parts need regular upkeep, maintenance and spare parts. This has to be kept in mind in particular for installations that are planned for remote areas or areas with limited technical services. If tracking devices fail or are not correctly adjusted, the yield will decline significantly. There are hence operational risks of tracked mounting solutions especially for remote areas.

By plotting measured irradiance data, the advantage of tracking on a clear sunny day is obvious (refer to Figure 2.4, dark green curve). In comparison, the light green curve shows the daily course of solar irradiance on a fixed panel surface. The area under the curves corresponds to the daily energy yield (in kWh/d).

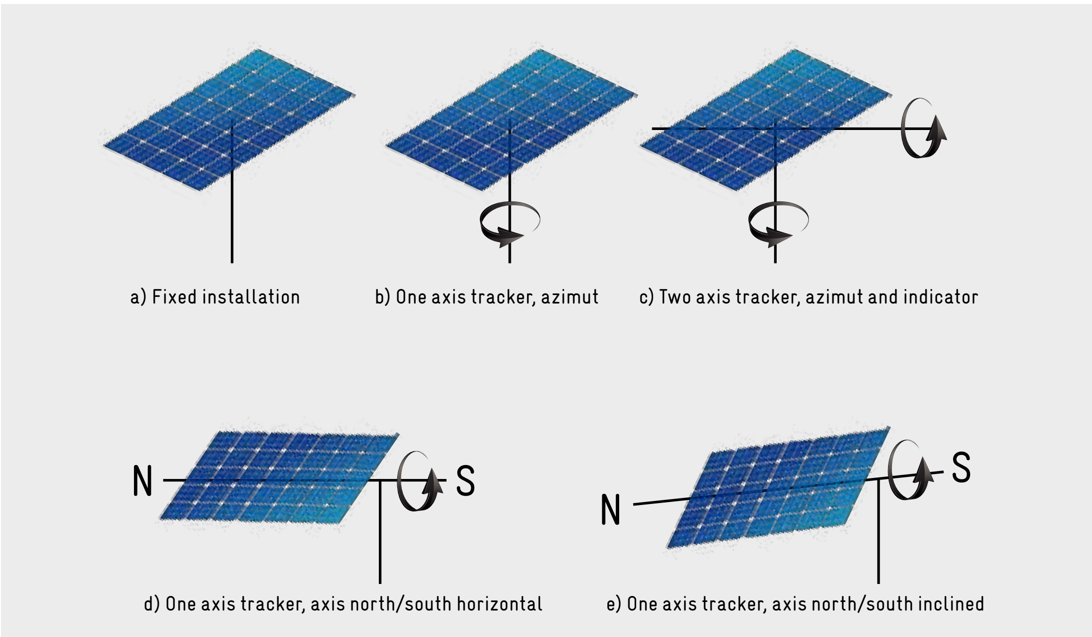


Figure 2.2: Technical options for solar tracking Adapted from R. Schmidt, 2015

Figure 2.3: A SPIS project in Northern Chile, carried out in cooperation with the farmer and the ministry of energy. The tilted one-axis tracker generates 1kW for a groundwater pump that irrigates 2 ha of pomegranate farmland. Source: Reinhold Schmidt, 2012

Using a single-axis tracker as shown in Figure 2.3, the irradiance on the solar panel surface is almost constant between 9 am and 6 pm. As already mentioned, the typical gain of solar tracking varies between 25 % and 35 %, as an annual mean. In this example, the measured data clearly show that the daily average can even be significantly higher (Schmidt, 2012):

- Global solar radiation with fixed installation: 7.4 kWh/m² day;
- Global solar radiation with solar tracker: 10.9 kWh/m² day;
- Surplus: 47 %.

In order to operate the solar tracker, a control unit is necessary to activate the driving motor and to orientate the solar generator towards the sun. This can be done by a simple time controlled unit or an irradiance sensor. Even manual operation of small generator sizes is possible. The electrical energy required to operate the tracker is very low and is realised by a small PV battery system, in most cases a 12 Volt solar panel (10–20 Wp), a charge regulator and a battery, typically with a capacity in the range of 20–40 Ah.

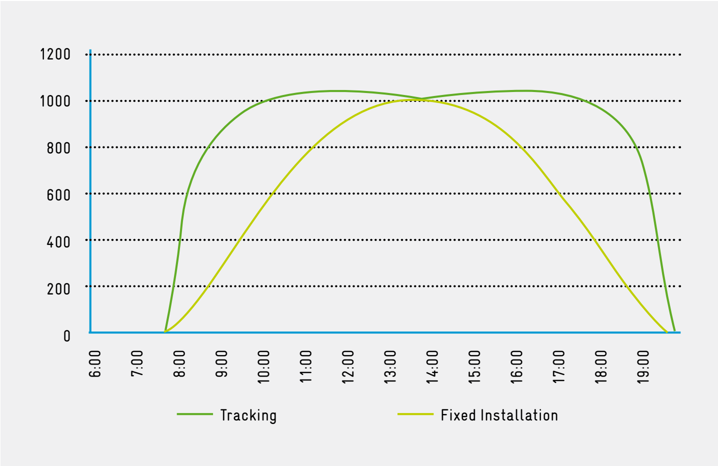


Figure 2.4: Measured solar irradiance with tracker and fixed installation Adapted from R. Schmidt, 2015

Installation with a fixed tilt angle and east-west orientation

Another, relatively new, alternative is the possibility to install a solar generator in east and west direction. Here, instead of using a solar tracker, more solar panels are applied facing east and west.

With decreasing panel prices, this technical solution could be interesting for regions with lacking maintenance structures and spare part supply.

Depending on the tilt angles chosen, the course of solar generator output and water flow is at least similar to an installation with solar tracker. Figure 2.5 shows a pilot installation in Chile with a 30° tilt angle.

Installation with a fixed tilt angle on a float

Photovoltaic systems have been successfully deployed on land for many years, so it was only a matter of time before water-based PV systems emerged on larger scales. Over the past eight years floating systems have evolved in varying degrees for use in ponds, canals and lakes and could be an interesting option for SPIS applications using open reservoirs for irrigation water storage.

The main impetus for developing floating PV systems as an alternative to land-based systems stems from the need to preserve precious land for farming, tourism and other land-intensive activities. In some countries with a booming solar market (e.g. India, Japan) prices for undeveloped land with good solar potential are rising rapidly. In some cases, this price increase even undermined the economic viability of solar projects. In contrast, water-based facilities would not face the same pressure because of much lower competition of potential sites.

Within the last years, several pilot but also large-scale floating PV systems have been installed.

Floating PV generators provide a series of benefits:

- By installing solar panels over a pond, the panels are naturally cooled, resulting in improved power production and energy yield. The company Ciel & Terre claims that due to the cooling effects of water, its floating PV systems generate about 10 % more electricity than rooftop or ground-mounted systems of the same size. Nevertheless, the economic advantage over conventional solar systems is yet to be proven since the number of existing floating PV systems is still small;

Figure 2.5: Simulation of tracking effect by east/west installation of solar panels — Adapted from R. Schmidt, 2015

Figure 2.6: Floating photovoltaic modules of the patented floating solar solution Hydrelio®. Sheeplands Farm, UK – 200 kWp Source: Ciel & Terre International

- By lowering the water temperature and reducing the size of the water area exposed to air, floating solar panels can reduce water evaporation. The company SPG Solar says that the pond array helps reduce water evaporation by 70 %, which is valuable in areas with erratic or limited rainfall (Thurston 2012). Nevertheless, these figures are site-specific and need to be calculated case by case;
- Floating PV systems can also improve water quality. As water bodies are exposed to the sun, photosynthesis promotes growth of organic matter, including algae (see Figure 2.16). By shading the water, algae growth is reduced, reducing the associated water treatment and labour cost;
- No excavation work or concrete foundations are necessary to install floating solar platforms. Usually made of HDPE plastic, they can safely be installed on drinking water reservoirs;
- With the increased number of photovoltaic installations worldwide, also the risk of theft is increasing. Especially solar panels are in demand and need to be protected against theft. Installed on water, floating PV systems provide a relatively high level of security.

When designing and installing a system on floating devices, an additional protection of the electric components has to be foreseen due to the potentially higher humidity the PV generators are exposed to. Generally, floating installation induces higher investment costs. Depending on the specific installation set-up, a floating installation may also induce higher operational expenditure (i.e. cleaning, frequency of replacement of protection for electrical components, sealing etc.).

2.1.3 Controller and Motor

Find a short description about controllers and motors in the SPIS Toolbox Module GET INFORMED – Controller & Inverter on Energypedia.

Figure 2.7 shows a simplified block diagram of a photovoltaic pumping system. The pump controller is the link between the PV generator and the motor pump and adjusts the output frequency in real time according to the prevailing irradiation levels. Modern controllers incorporate high-efficient power electronics and utilise Maximum Power Point Tracking (MPPT) technology to maximise power use from the PV generator.

In recent years, innovations in DC/AC inverter technology have led to the development of specially designed pump inverters that can drive conventional AC motors. It is important to know that non-compatible inverter/motor combinations may reduce the expected lifetime of the conventional AC motor. Therefore, well-matched and tested controller/motor combinations are the preferred option to increase system reliability.

Figure 2.8: Pump controller with display and LED fault indicators
Source: GIZ / Andreas Hahn, 2015

Electric motors of solar water pumps are generally powered by direct current (DC) sources, or by alternating current (AC) sources. DC motors are mainly used for small to medium size irrigation schemes, while AC motors gain importance in applications where higher output/head combinations are required. Since DC motors tend to have overall higher efficiency levels than AC motors of a similar size, they are often the first choice of solar pump manufacturers. In particular, water-filled brushless DC motors are gaining importance because they are maintenance-free and do not suffer from frequent starts/stops, typical in solar-powered systems.

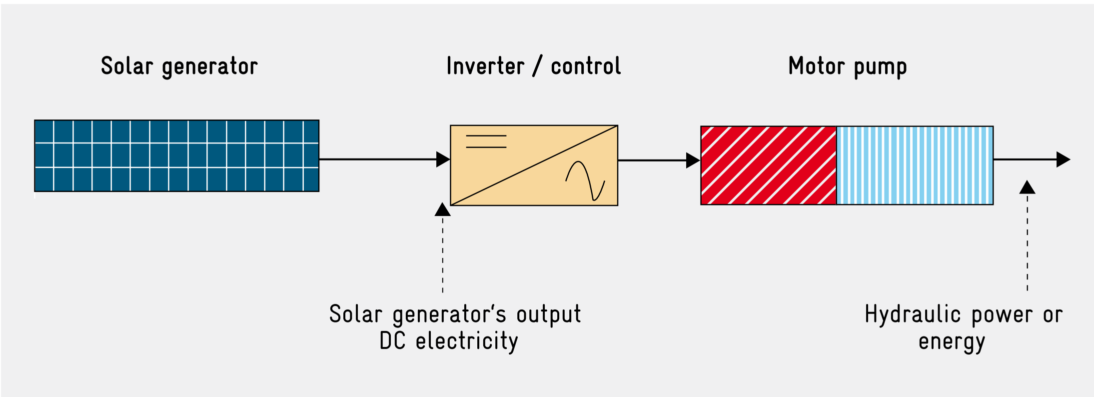


Figure 2.7: Block diagram of a photovoltaic pumping system installation of solar panels
Adapted from R. Schmidt, 2015

2.1.4 Water Pump

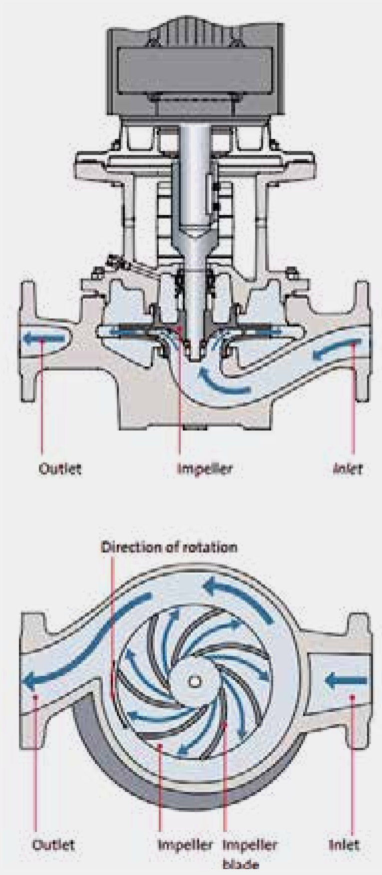
You can find a short description about the different water pumps and their respective (dis-)advantages in the SPIS Toolbox Module GET INFORMED – Water Pump on Energypedia.

The electric motor provides the rotational energy to drive the pump unit. Generally two types of pumps can be found in today's solar pumping systems – centrifugal and helical rotor pumps. Figure 2.9 describes the functional principle of a single-stage centrifugal pump.

A centrifugal pump creates an increase in pressure by transferring mechanical energy from the motor to the fluid through the rotating impeller. The fluid flows from the inlet to the impeller centre and out along its blades. The centrifugal force hereby increases the fluid velocity and consequently also the kinetic energy, which is transformed to pressure. The pressure can be increased by simply adding several stages in series (Grundfos n.d.).

A helical rotor pump is a type of progressive cavity pump which works by the rotation of a helical rotor, when sealed against a helix wall, pushing discrete sections of material through the device. This corkscrew-like action provides a pulse free flow, and valves are unnecessary as the helical rotor seals the discrete sections of material. The flow rate is determined by the rotor speed, and is independent of outlet pressure (Mining & Hydraulic Supplies n.d.).

Figure 2.9: Working principle of a centrifugal pump



Source: Grundfos

Figure 2.10: Working principle of a helical rotor pump

Source: Lorentz, 2019

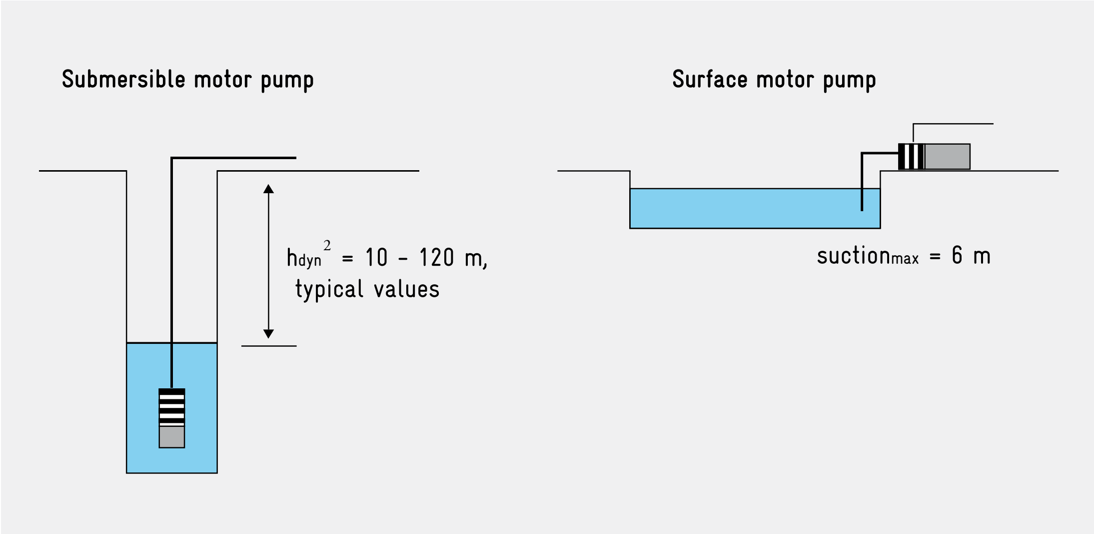


Figure 2.11: Options for water pump installation — Adapted from R. Schmidt, 2015

Depending on the water source, there are two different possibilities for pump installation – submersible or surface.

2 h_{dyn} = Dynamic Head

Centrifugal pumps are generally applied where pumping heads are low and water demand is high. For this reason centrifugal pumps are the preferred option for use in irrigation systems. Helical rotor pumps are typically found in applications with high pumping heads and low water flow rates, such as for drinking water supply.

Figure 2.12: Submersible multistage centrifugal pump with integrated inverter — Source: GIZ / Andreas Hahn, 2015

Figure 2.13: Surface-mounted single-stage centrifugal pump with AC motor Source: GIZ / Jan Sass, 2015

Figure 2.13 shows an example of a single-stage surface pump at a farm site in Morocco. Here, farmers typically pump large volumes of irrigation water from an open reservoir directly to the drip irrigation system.

Another important parameter is the pump efficiency which describes the relation of hydraulic power and electric power at the inverter input. Typical efficiency values for centrifugal pumps vary between 40 % and 50 % (Authors):

$$\eta = \frac{P_{hydraulic}}{P_{electric\ (inverter\ input)}} \approx 40 - 50\,\%$$

In order to select the right type of pump which meets the requirements regarding efficiency, head and flow, manufacturers provide simple and illustrative diagrams, as shown in Figure 2.14.

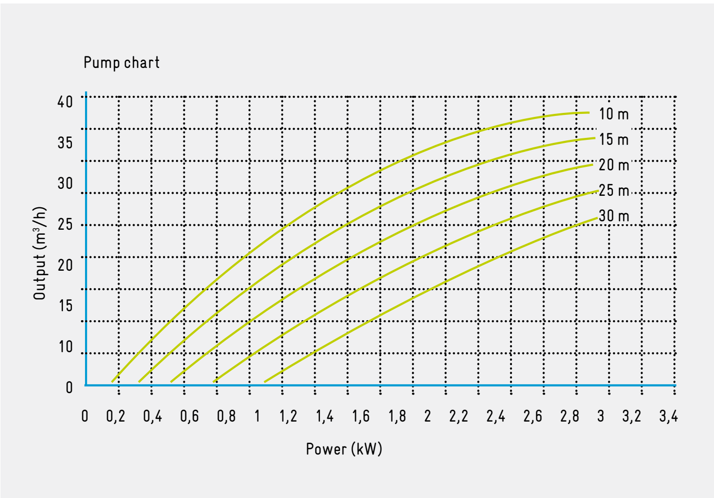


Figure 2.14: Example of a motor pump characteristic
Adapted from Lorentz GmbH & Co. KG, 2015

2.1.5 Water Storage Tank

You can find a short description about different water storage options in the SPIS Toolbox Module GET INFORMED – Reservoir on Energypedia.

You can also find more information about how to determine your water storage requirements in the SPIS Toolbox Module IRRIGATE – Calculate Water Requirements.

A water storage tank accumulates the water provided by the pump unit during sunshine hours. There are numerous ways to store the water, which can range from simple open dug reservoirs, concrete and plastic tanks to expensive and elevated metal tanks. Some examples are shown in the following figures.

Open reservoirs are inexpensive and relatively easy to construct, but the big disadvantages are the extremely high evaporation losses of water and the easy entry of debris and sediments.

Open tanks made of concrete as shown in Figure 2.16 are more advanced but also suffer from evaporation of water, entry of debris and sediments as well as algae growth. These effects can be significantly reduced by covering the tank as shown in Figure 2.17.

Figure 2.15: Example of an open plastic foil-lined reservoir often used in Morocco Source: GIZ / Jan Sass, 2014

Figure 2.16: Example of an open water tank made of concrete in Chile Source: GIZ / Reinhold Schmidt, 2015

Figure 2.17: Concrete tank covered with a metal lid Source: GIZ / Reinhold Schmidt, 2015

Figure 2.18: Example of relatively inexpensive plastic tanks Source: GIZ / Reinhold Schmidt, 2015

Figure 2.19: Example of a large water storage tank made of corrugated iron sheet in Chile Source: GIZ / Andreas Hahn, 2015

Ready-to-use plastic tanks, as shown in Figure 2.18, are available in different sizes, easy to install and often constitute a viable option for small irrigation schemes.

It is also worth considering water tanks which are made of corrugated iron sheet, as shown in Figure 2.19. Such water tanks are currently being promoted and subsidised by the Instituto de Desarrollo Agropecuario (INDAP), a body of the Ministry of Agriculture in Chile.

2.1.6 Monitoring

Find a short description about monitoring options in the SPIS Toolbox Module GET INFORMED – Monitoring System on Energypedia.

A monitoring system is a helpful tool to supervise and manage a Solar Powered Irrigation System. The main tasks of the measuring system are:

- Provide system data for the acceptance test after installation;
- Observe the system's operation and performance at any time;
- Control water provision and consumption;
- Evaluate the socio-economic impacts (e.g. acceptance of SPIS technology).

Depending on the site-specific conditions and objectives, a monitoring system can be quite sophisticated or simple.

In order to provide the farmer with a minimum of system information, the deployment of a basic monitoring system is highly recommendable.

Figure 2.20 presents the concept of a basic monitoring scheme.

The basic system is composed of:

- Water flow meter;
- Pressure gauge at the filter inlet (P1);
- Pressure gauge at the filter outlet (P2).

In case of a direct driven irrigation system (see section 2.2.2) the measured pressure at P2 is the input pressure of the irrigation system. This simple and basic monitoring system, operated by the farmer on site, allows manual readings of pressure and water flow and helps to assess the performance stability of the SPIS.

For more detailed information and deeper analysis of system performance, this basic monitoring can be supplemented with sensors to measure:

- Solar irradiance (e.g. on horizontal and inclined surface);
- Dynamic water level;
- Rainfall;
- Wind speed.

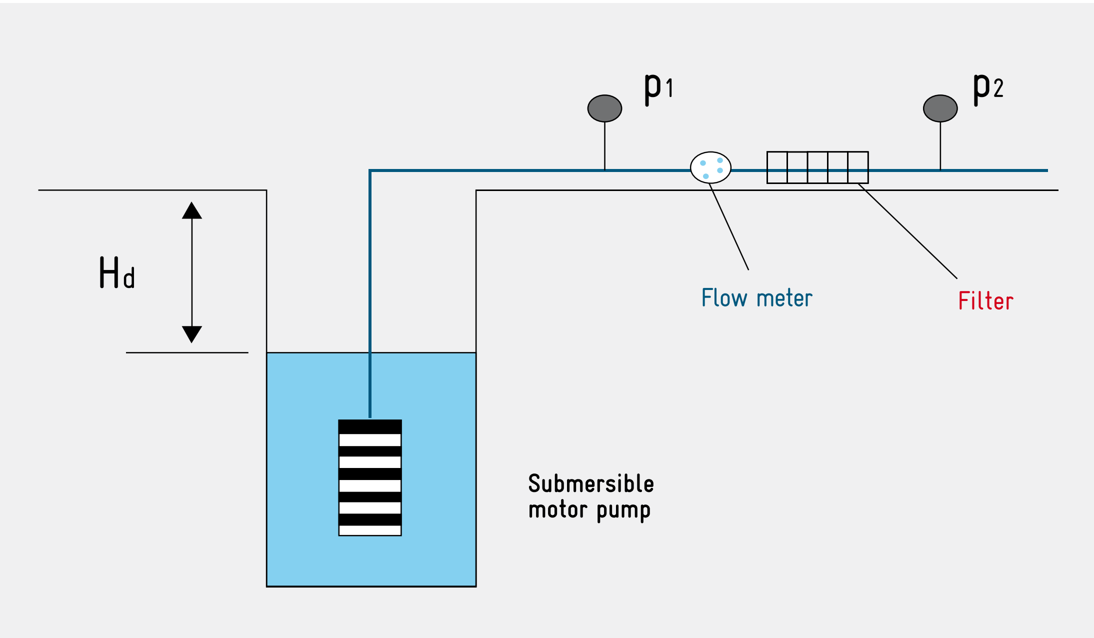


Figure 2.20: Concept of basic monitoring of system performance   Source: GIZ / Reinhold Schmidt, 2015

Figure 2.21: Basic monitoring system, installed on site Source: GIZ / Reinhold Schmidt, 2015

Figure 2.22: Performance test of solar generator Source: GIZ / Reinhold Schmidt, 2015

Very often, farmers are not aware of the dynamic behaviour of their wells. This includes seasonal variations of the water level as well as daily variations during pumping (see also section 5.1.4). The water level dipper shown in Figure 2.23 shows a simple tool by which to check the water level. Once the metal electrode reaches the water table, a light will flash and the exact value can be read from the dipper tape.

More sophisticated and expensive monitoring devices may include automatic data logging. The data logger continuously records and stores all system parameters over a longer period of time. Special evaluation software allows for quick data analysis on site. In remote areas not connected to the public grid, data loggers are usually solar-powered and may even include modern GSM communication devices with the option to check system performance via smart phones.

Figure 2.23: Dipper measuring device for easy water level readings

Source: Solinst Canada Ltd., 2015

2.2 SPIS Plant Concepts

2.2.1 Variability of Global Solar Radiation

Find a short description about the specifics of Solar Energy in the SPIS Toolbox Module GET INFORMED – Specifics of Solar Energy on Energypedia.

Compared to conventional energy systems, solar energy has some specific characteristics, which need to be considered in all solar energy applications.

Solar radiation captured by a solar panel is never constant. As described in Figure 2.24, the sun rises in an easterly direction, reaches maximum height when it crosses the meridian at noon, and sets in a westerly direction. On average, it takes the sun 24 hours to go from noon position to noon position the next day.

As the sun moves through the sky, the elevation angle (measured from the horizon) changes during the day, and also over the course of the year. The sun's altitude can be described at any location by the solar altitude (a) and the solar azimuth (AZ).

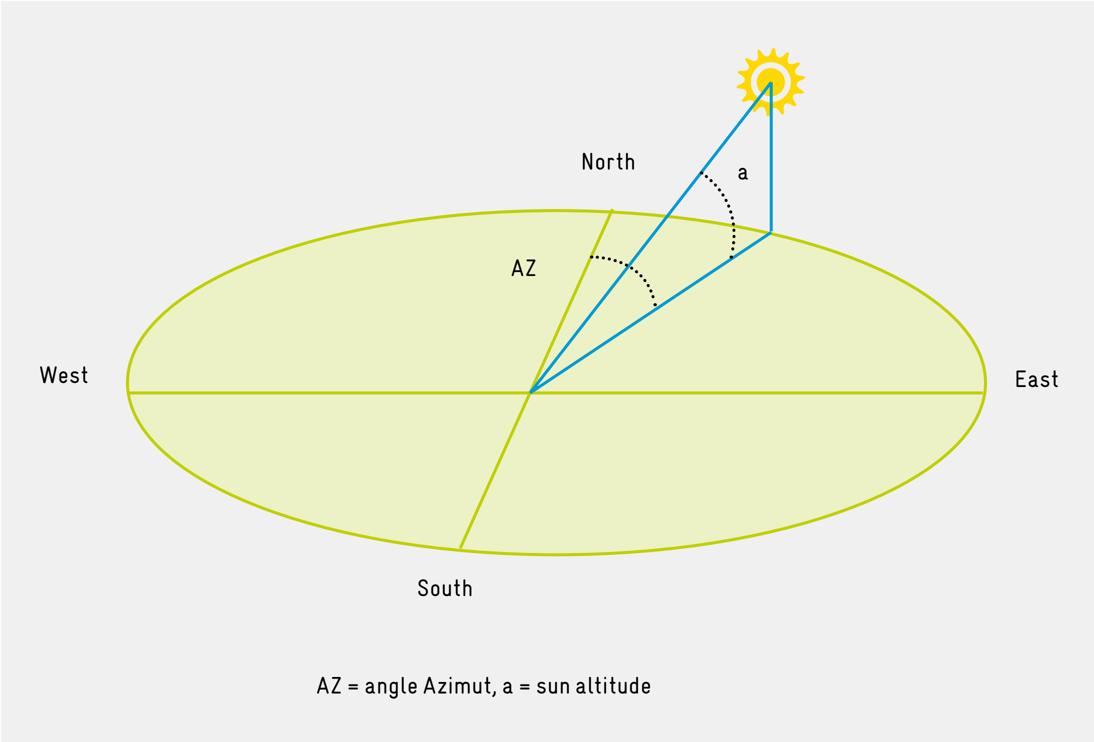


Figure 2.24: Daily movement of the sun in southern hemisphere Source: GIZ / Reinhold Schmidt, 2015

The intensity of solar radiation on a surface is called irradiance (S). The irradiance is measured in kilowatts per square metre [kW/m²]. As shown in Figure 2.25 solar irradiance varies over the course of the day with maximum values at around noon.

The energy carried by radiation to a surface over a certain period of time is called global solar radiation. It is measured by a network of meteorological stations all over the world and is expressed in kilowatt-hours per square metre [kWh/m²].

The relation between solar irradiance (S) and global solar radiation (G) gives the following equation:

$$G = \int S\, dt$$

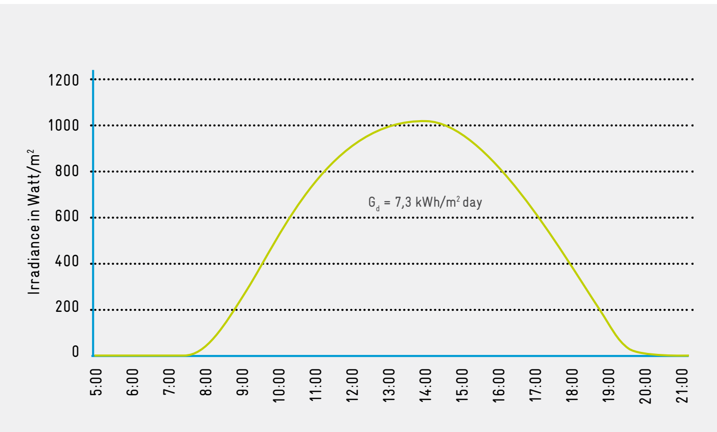


Figure 2.25: Irradiance profile on a sunny day with clear sky
Adapted from R. Schmidt, 2015

The irradiance values are instantaneous values – solar global radiation is the sum of all irradiance values multiplied by time over a defined period (e.g. over a day, month, year).

Figure 2.26 shows the daily irradiance profile on a cloudy day. It is obvious that the daily global solar radiation of 2.8 kWh/m²d is significantly smaller than on the sunny day shown in Figure 2.25 (7.3 kWh/m²d) (Schmidt, 2012).

Apart from these daily variations, seasonal changes must also be taken into account. Depending on site location, seasonal changes and differences in solar radiation between winter and summer months can be significant.

Figure 2.27 shows the monthly mean values of daily global radiation measured in northern Chile. Global radiation values on the horizontal surface can be obtained for example from public databases such as that of NASA. As already mentioned, the solar generator is generally installed with a tilt angle in order to increase the energy yield. As the optimum tilt angle is site-specific, usually tilted values for daily global radiation are not measured but have to be calculated.

The figure shows the effect of inclining the solar generator. The relatively low solar radiation in the winter months (May – August) can be significantly increased with a tilt angle of the solar generator of 45° (light green curve).

As already mentioned, the tilt angle depends on the specific project and application. The example above (light green curve) optimises the solar energy yield during winter months. In case of solar irrigation, the critical month with the highest water demand is probably in summer (November-February). Hence, in this case the tilt angle should be lower.

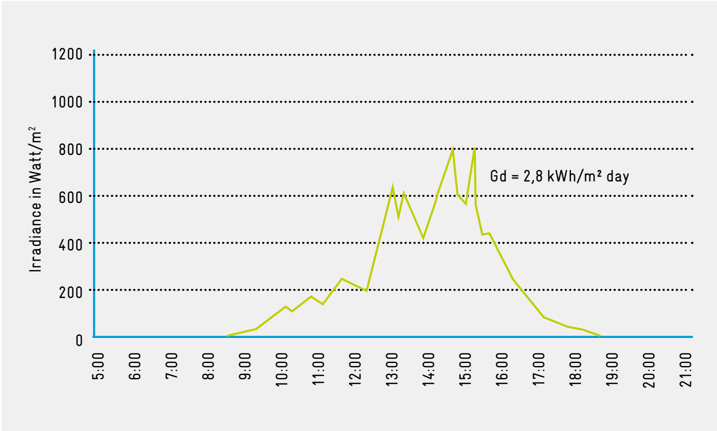


Figure 2.26: Irradiance profile on a cloudy day
Adapted from R. Schmidt, 2015

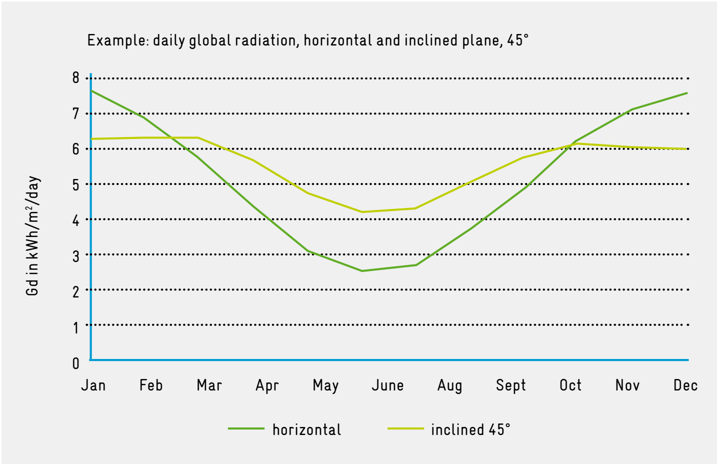


Figure 2.27: Change of global radiation over the course of the year on a horizontal and tilted surface
Adapted from R. Schmidt, 2015

2.2.2 SPIS Plant Configurations and Operation

Find a short description about the different SPIS configuration options in the SPIS Toolbox Module GET INFORMED – SPIS Configurations or for a more detailed overview in the Module DESIGN – Select SPIS Configuration on Energypedia.

Depending on the available water resource (well or surface water) and the site-specific conditions, different technical SPIS configurations are possible. Table 2.1 summarises the most common plant concepts, which will be then discussed in detail.

Configurations 1–5 are typical stand-alone applications, which differ in the following main aspects:

- ➔ Type of water source (well or surface water);
- ➔ Motor pump installation (submersible or surface);
- ➔ Use of water tanks (irrigation by gravity);
- ➔ Fertigation technology;
- ➔ Direct irrigation.

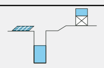
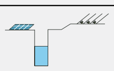
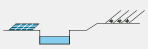
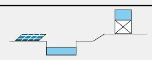
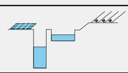
Configuration 6 is not a stand-alone SPIS, but a grid connected system with battery back-up.

Based on the results of site data collection, the best suited system configuration should be selected in close cooperation with the farmer.

#1: SPIS – Well – Water Tank

This is the classical configuration of a Solar Powered Irrigation System. The solar generator (via the controller/inverter) provides electricity for a submersible motor pump unit, installed in a well. The pumped water is stored in a water tank and irrigation is done by gravity. The irrigation system pressure depends on the height of the water level in the storage tank.

Table 2.1: Most common configurations of Solar Powered Irrigation Systems

System No:	#1	#2	#3	#4	#5	#6
						
Type	well watertank	well direct irrigation	surface direct irrigation	surface watertank	well, surface direct irrigation	PV on-grid irrigation included
Main characteristics	low head steady pressure night reservoir	head varies changing pressure only daytime	head varies changing pressure only daytime	low head steady pressure night reservoir	head varies changing pressure only daytime	system pressure 24 h / 7 days
Irrigation	gravity fed	directly operated by pump	directly operated by pump	gravity fed	directly operated by pump	gravity or direct by AC pump
	drip / micro	drip / sprinkler	drip / sprinkler	drip / micro	drip / sprinkler	all types
Solar generator	fixed installation	solar tracking or other methods	solar tracking or other methods	fixed installation	fixed installation solar tracking or other methods	fixed or tracked
Fertigation	additional equipment necessary	additional equipment necessary	simple, on suction side	simple, on suction side	simple, on suction side	additional equipment necessary
Motor pumps	submersible	submersible	surface	surface	submersible / surface	any AC pump

Source: Reinhold Schmidt, 2015

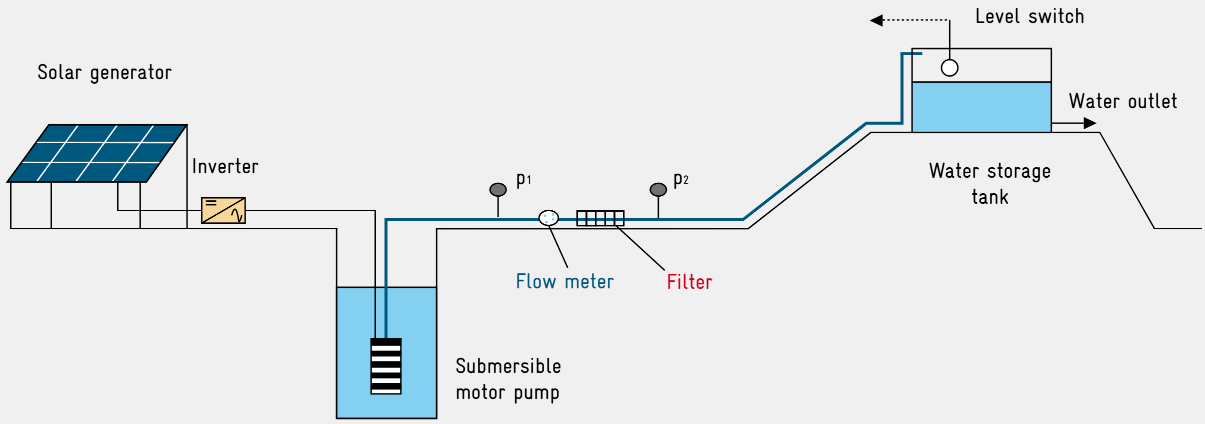


Figure 2.28: Solar powered irrigation with water storage tank

Adapted from R. Schmidt, 2015

Figure 2.29: Example of a SPIS with water tanks in Kenya Source: GIZ / Reinhold Schmidt, 2015

In order to ensure safe system operation, two safety means are necessary:

- A water level sensor, installed in the storage tank, in order to avoid an overflow by switching off the pump;
- A second water level sensor, installed in the well, to avoid dry running of the pump.

As already outlined in section 2.1.6, it is highly recommended to install a basic monitoring system to supervise and manage the Solar Powered Irrigation System.

Once installed, the operation of an SPIS using a water tank is quite easy. Figure 2.30 shows the daily course of the pump and irrigation water flow (by gravity).

The sinusoidal light green curve clearly shows that the solar generator is installed with a fixed tilt angle and azimuth. The pump water flow varies over the course of the day, according to the actual solar irradiance.

The first irrigation interval starts at 1:30 pm by opening a valve (dark green curve). The irrigation system experiences an almost constant pressure and irrigation water flow. The amount of water flowing is determined by the connected irrigation and water distribution system. The irrigation pressure is dependent on the water level in the tank. Typical values vary between 3 and 10 m (approximately 0.3–1.0 bar). A tank system even allows for night-time irrigation. The second irrigation interval starts immediately after sunset and lasts until 8:30 pm.

Although the benefits of the tank system are obvious, the main disadvantage is the relatively high

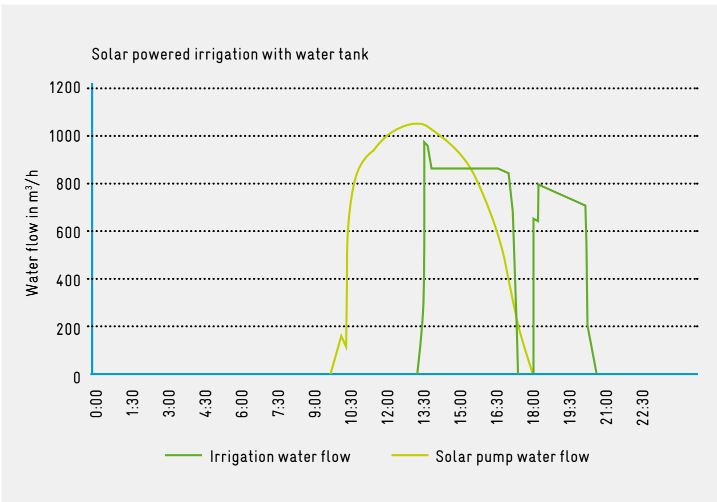


Figure 2.30: Typical daily profile of SPIS tank system in Chile
Adapted from R. Schmidt, 2015

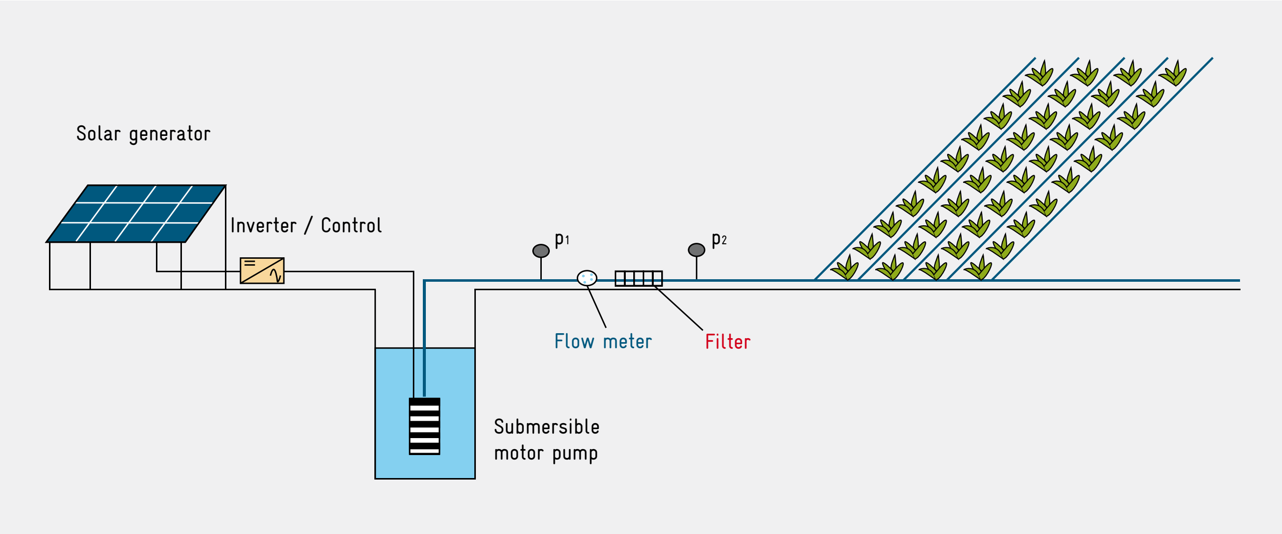


Figure 2.31: Direct irrigation system with fixed solar generator Adapted from R. Schmidt, 2015

investment costs for most water tanks. Furthermore, because of the low irrigation pressure, an electric dosing pump may be required for fertiliser application (see **Section 2.2.5**). This will increase the investment costs even further.

#2: SPIS – Well – Direct Irrigation
In configuration #2, the solar pump is directly connected to the irrigation system. Thus, the solar water flow and the irrigation water flow are the same. As no water tank is installed, investment costs are significantly reduced.

Figure 2.31 shows the corresponding plant scheme.

If a solar generator with fixed installation is chosen, the irrigation water flow corresponds to the actual solar irradiance. As a result, water flow and pressure in the irrigation system will vary over the course of the day.

The main advantage of this configuration is the simple installation and the potential for cost reduction. On the other hand, the direct connection of the solar pump and the irrigation system leads to a dynamic and varying hydraulic load. In this case, planning and operating the SPIS is far more complex as compared to the tank system. Furthermore, the use of an additional electric dosing pump for fertigation is advisable.

It is obvious that irrigating with a variable water flow and pressure as shown in Figure 2.32 does not represent a good and practical solution for the farmer, so the following alternatives can be taken into account:

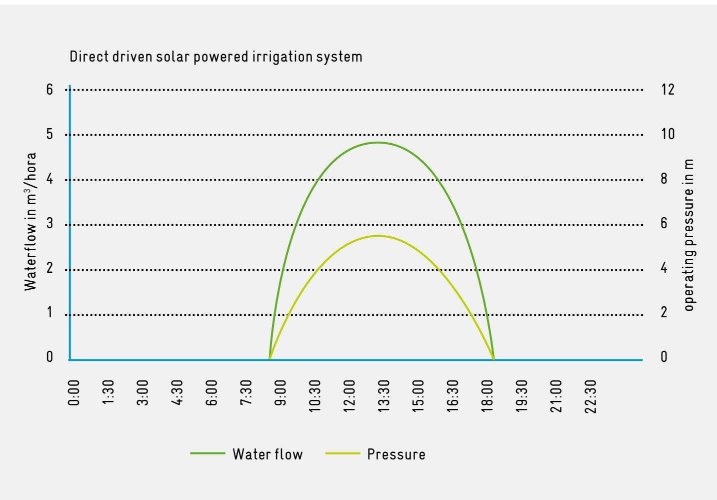


Figure 2.32: Daily profile of direct SPIS with fixed solar generator
Adapted from R. Schmidt, 2015

Automatic irrigation with water volume control
The irrigation process is usually time controlled (e.g. irrigation of subfield 1 for 2 hours/day). Nevertheless, applying the correct amount of water under variable conditions is difficult. A possible solution is the installation of an automatic irrigation system with water volume control. The farmer determines the required irrigation water amount

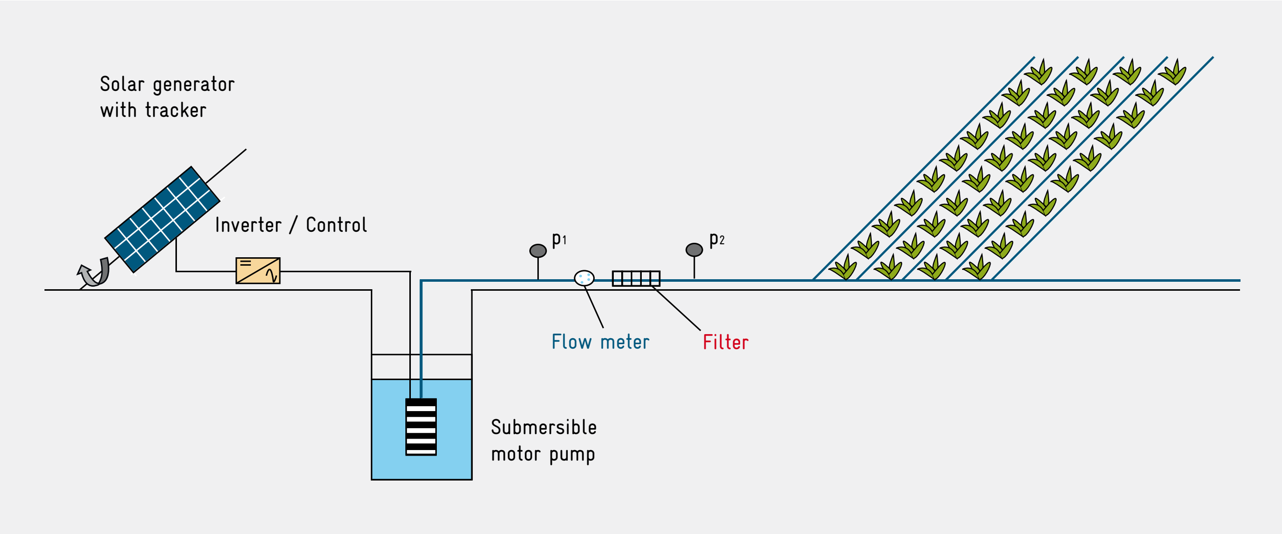


Figure 2.33: Direct irrigation system with solar tracker   Adapted from R. Schmidt, 2015

per subfield and automatic valves close as soon as the target value is reached. Although an automatic volume controlled irrigation management would be highly appreciated for direct driven SPIS, only few systems are yet available on the market. Furthermore, for smallholders located in remote areas of developing countries, automatic irrigation is probably not a technically and financially viable option.

Adapting the irrigation field size

Generally, it would be possible to adapt the size of the irrigated area to the variable output of the solar pump. This means that in the morning and afternoon with lower solar irradiance only smaller plots will be irrigated. Irrigation of larger plots is possible around noon when more solar power is available. This solution is quite demanding in terms of technical understanding and irrigation management.

Solar tracking

From today's point of view, solar tracking seems to be the best technical solution if the task is to directly pump water into the irrigation system. The corresponding plant concept is shown in Figure 2.33.

Nevertheless, it is important that the hydraulic load of the irrigation system is adapted to the motor pump capacity and that a high uniformity of water distribution on the field is achieved. This is part of the technical design process of the SPIS, described in section 2.3.

#3: SPIS – Surface – Direct Irrigation

Similar to configuration #2, the solar pump is directly connected to the irrigation system. The main difference is that surface water is used for irrigation purposes. Figure 2.34 shows a centrifugal pump which is able to pump 450 m³ of surface water per day, required to irrigate 24 ha of grape.

Figure 2.34: High performance AC surface pump with fertiliser injection valve
Source: GIZ / Andreas Hahn 2015

Figure 2.35: Lifting water to an upper reservoir in Chile
Source: iEnergía Group, 2015

Figure 2.36: Combination of submersible and surface pump in Morocco
Source: GIZ / Andreas Hahn, 2015

The pump was designed to provide a pressure of about 3 bars at the inlet of the directly connected drip irrigation system. Compared to a submersible pump, the surface pump is easier to install and to maintain. Another advantage is the possibility to install a valve at the suction side of the pump, which can be used for easy fertiliser injection.

#4: SPIS – Surface – Water Tank
The only difference as compared to configuration #3 is the use of storage tank and gravity irrigation (also compare configuration #1). A typical application is to pump water from a canal or river to an upper reservoir as shown in Figure 2.35.

#5: SPIS – Well – Surface – Direct Irrigation
This configuration represents a combination of submersible and surface pump. The submersible pump is installed in a well and pumps groundwater into an open reservoir. From there, a second pump (in this case a surface pump) directly injects the water into the irrigation system.

The solar generator for the submersible pump is typically installed at a fixed tilt angle and azimuth. To operate the surface pump, the use of a tracker is advisable.

#6: SPIS – Grid-Connected
In many cases, farms are already connected or very close to the public grid. In this case, an interesting alternative could be to install a standardised grid-connected photovoltaic system, which supplies electricity for all electrical appliances on the farm, including the irrigation water pump.

Figure 2.37 shows a possible installation scheme. The PV system is connected to the grid with preference to self-consumption of the generated electricity during daytime. If the generated solar electricity is lower than the actual demand, the grid delivers the missing electricity. If the PV generator produces more energy than the actual demand on the farm, surplus energy is fed into the grid.

There is a first pilot system installed on a 4 ha flower farm in Arica, Chile where the solar generator with a peak power of 5 kWp is connected to the electrical grid and produces around 25 kWh of electricity during the day. The solar generator supplies energy to all electrical consumers, including the irrigation system composed of two conventional 220 Volt motor pumps of 1.5 kW each.

For a purely grid-connected irrigation system, it is important that the following conditions are fulfilled:

- ➔ The electric grid is stable;
- ➔ A tariff system is established (e.g. net-metering, feed-in-tariff);
- ➔ Legal and regulatory framework allows the PV connection.

A grid failure for a longer period of time and the resultant lack of water could cause serious damage to crops so that yields may drop noticeably. If grid stability cannot be secured, a back-up solution is required.

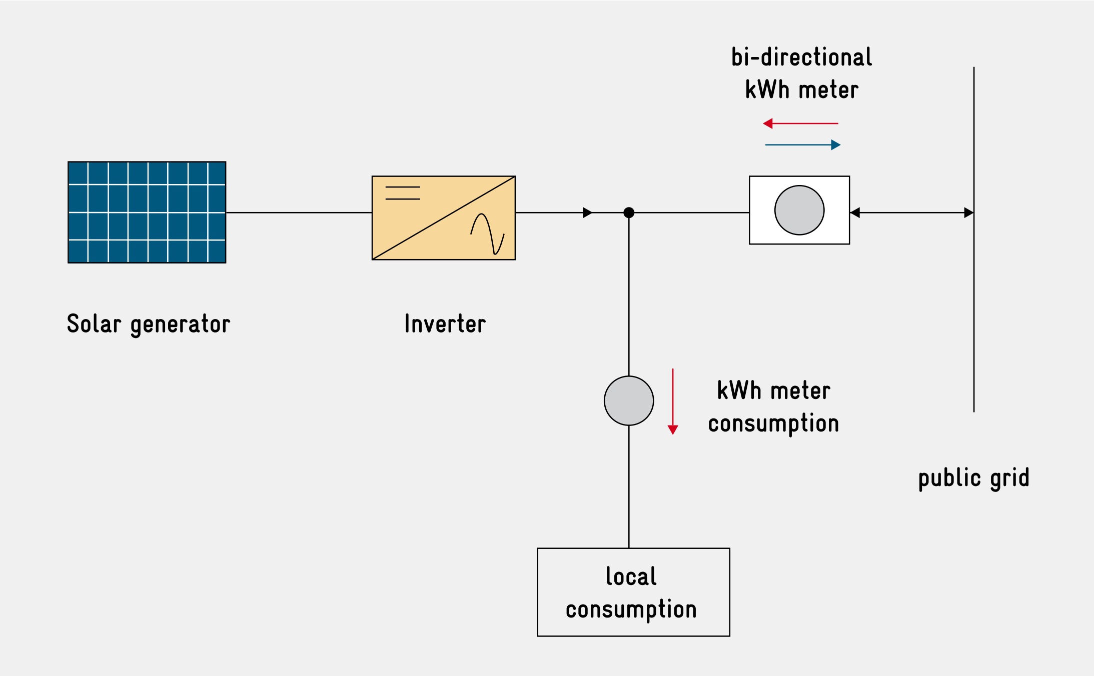


Figure 2.37: Scheme of a common grid-connected PV system with battery back-up

Adapted from R. Schmidt, 2015

2.2.3 Suitability for Drip Irrigation

Find more information about irrigation suitability in the SPIS Toolbox Module GET INFORMED – Irrigation System on Energypedia.

Almost all existing irrigation methods described in section 1.1 can generally be used in combination with photovoltaic water pumps. The size of the PV generator is mainly determined by the water and pressure requirements of the irrigation scheme. Therefore, water-saving irrigation technologies, working at relatively low operating pressures, are the preferred option in connection with PV pumping systems.

Table 2.2: Irrigation technologies and their suitability for use with PV pumps

Distribution Method	Typical Application Efficiency	Typical Head	Suitability for Use with PV Pumps
Flood Irrigation	40 – 50 %	0.5 m	Depends on local conditions
Open Channels	50 – 50 %	0.5 – 1 m	Depends on local conditions
Sprinkler	70 – 80 %	10 – 20 m	Yes
Drip/Trickle	85 – 95 %	1 – 2 m	Yes

Source: Authors

Solar-powered drip irrigation is the 'marriage' of two systems that have proven to offer an enormous independent impact:

- Drip irrigation is an extremely efficient mechanism for delivering water (and fertiliser) directly to the roots of plants. It increases yields and allows for introduction of new (potentially high-value) crops in regions where they could not be sustained by rainfall alone;
- Solar-powered (photovoltaic) pumps save potentially hours of labour daily in rural off-grid areas where water hauling is traditionally done by hand or by employing costly petrol or diesel engine-driven pumps. They are durable and immune to fuel shortages and in the medium to long term cost less than traditional diesel-powered generators (Woods Institute for the Environment n.d.).

When used in tandem in a systematic way, these technologies allow for production of market garden vegetables during the dry season, providing a much-needed source of both income and nutrition (Woods Institute for the Environment n.d.).

Drip irrigation permits economic use of water and its relatively low operating pressure makes it particularly well suited for combination with photovoltaic pumps. However, in the design of a solar irrigation pump system it needs to be taken into account that demand for irrigation system water will vary throughout the year. Peak demand during the irrigation system seasons is often more than twice the average demand.

Solar-powered water pumps have to be oversized to a certain extent to meet these peak demands, which means that they are under-utilised for most of the year. Variable water requirements during the year resulting in a low degree of system utilisation would generally favour conventional motor-driven pumps. The maximum daily output of a conventional motor-driven pump depends not only on its technical specifications but also on the (freely selectable) daily operating time. This gives a comparatively high level of adaptability to fluctuation in demand and constitutes an advantage over a PV pump.

The described drawback of PV pumps for seasonal irrigation can be balanced by adapted crop rotations (including permanent crops) and irrigation management to a certain extent, thus reducing the oversizing need for the pump and the related negative impact on the economics of such a system.

Figure 2.38: Drip irrigation in grape production in Morocco Source: GIZ / Jan Sass, 2015

Low-pressure performance of drip irrigation systems
In order to assess the suitability of conventional emitters, drip lines and other irrigation system components, the knowledge of the hydraulic characteristics is important. The performance under low operating pressures (e.g. in the early morning and late afternoon) and the uniformity of water distribution on the field are of particular interest.

Figure 2.39 presents the results of laboratory measurements. In the diagram, the water flow is plotted against the pressure. The nominal pressure of the Chapin drip line is 0.8 bar (80 kPa) but the measurements clearly demonstrate that it also works well at much lower operating pressures, down to 0.2 bar (20 kPa).

The same measurements can be done for a series of drip lines connected in parallel. This correspondsto different sizes of subfields.

Figure 2.40 shows the measurement results of 10/30/50 drip lines, each with a length of 50 m.

Knowing the hydraulic characteristic presented and the operating pressure of the irrigation system, the resulting water flow in the respective subfield can easily be determined.

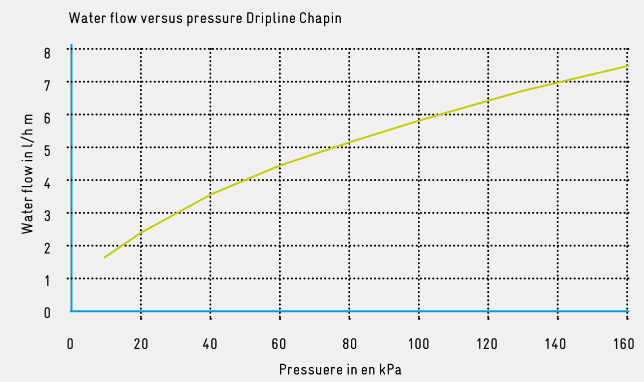


Figure 2.39: Rating curve of Chapin drip line
Adapted from R. Schmidt, 2015

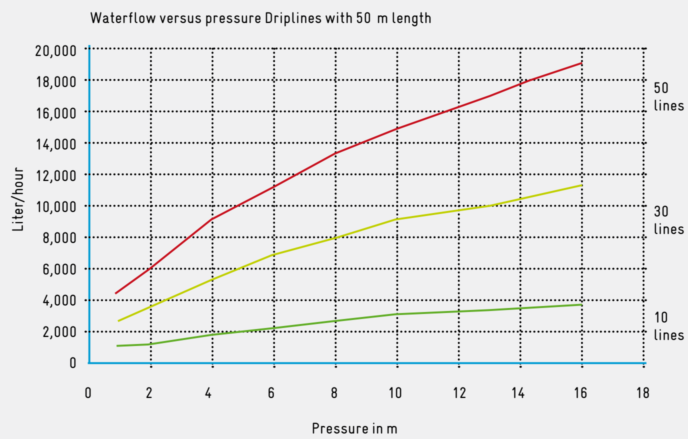


Figure 2.40: Hydraulic characteristic of drip lines connected in parallel
Adapted from GIZ / Reinhold Schmidt, 2015

2.2.4 Filter Systems

Find more information about the components of the irrigation head in the SPIS Toolbox Module GET INFORMED – Irrigation Head on Energypedia.

A general problem of micro-irrigation systems is clogging because the smaller the diameter of the drippers and mini tubes, the greater the tendency for the narrow passages to become blocked. Clogging can be the result of an accumulation process or an immediate impact and is based on non-organic material, like sand and clay, as well as organic material, like algae and bacteria.

Filters can reduce or avoid these problems and must be placed after the pump (e.g. at the well head). Filters must be adapted to the flow rate of the pump. It is important that pressure loss while passing through the filters is minimised and maintenance is easy. Normally the filters are controlled with two pressure gauges, one at the inlet and the other at the outlet of the filter system.

Figure 2.41: Example of a sand separator installation in Rajasthan, India
Source: GIZ / Andreas Hahn, 2015

Figure 2.42: Disc filter before and after manual cleaning
Source: GIZ / Reinhold Schmidt, 2015

If a critical value is reached, the filters must be cleaned manually or by back flushing. Back flush starts with a turn of the three-way valve and normal water flow is reversed. The reverse flow washes all dirt and particles into the drainage system. This must be repeated periodically, dependent on the water quality.

Surface water must be cleaned in 1–3 stages because it is often heavily loaded with dirt, and may start with a sand separator.

Initially, a water analysis can provide information about the size and amount of particles and a judgment on what filter technology is required. Different filter types are commonly used in irrigation systems, but not all of them are suitable in combination with a solar pump.

Screen Filter

A screen filter is a type of filter using a rigid or flexible screen to separate sand and other fine particles out of irrigation water. Typical screen materials include stainless steel (mesh), polypropylene, nylon and polyester. The filter intensity is often expressed in Mesh, which gives the amount of strings per inch (e.g. 160 Mesh = 160 strings/inch). Usually, the pressure loss in screen filters is quite high; therefore they are not recommendable for use in SPIS.

Disc Filter

A disc filter element contains a stack of compressed discs with an overlapping series of grooves. Unfiltered water passes through the stack of tightly compressed discs. The water is forced to flow through the interlocking grooves of the disc rings where debris is trapped, releasing only filtered water to the irrigation system (Netafim n.d.).

The dirt particles are caught on a very large surface, which is the reason for the comparatively low pressure loss of this filter technology.

For manual cleaning, the filter rings must be taken out of the enclosure and rinsed with clean water. It is not appropriate to use disc filters as a pre-cleaning unit for dirty surface water. Organic materials, like algae, can create a thin film around the disc filter in a short time and would clog the filter.

The daily course of the flow rate and pumping head of an SPIS system equipped with a disc filter is shown in Figure 2.43. At about 2 pm, the disc filter was cleaned resulting in a significant pressure drop (red) and a proportional increase in the flow rate (light green). Due to the fast accumulation of organic matter inside the disc filter, the pressure quickly increases again.

With the already mentioned back flush technology, disk filters may also be cleaned automatically.

As debris in the filter increases, the back flush process is initiated. The discs separate and jets of clean water spray and spin the discs, removing the trapped debris which is then flushed out (Netafim n.d.). Since no new particles should enter during the automatic cleaning process, in most cases a second filter element is attached and supplies filtered water for the flushing.

Regarding the use of disc filters for SPIS, it is advisable to install the next bigger model to reduce the characteristic pressure drop, which is proportional to the flow rate, or to install two filters working in parallel. The maintenance intervals should be short because this reduces the accumulated pressure loss significantly. Automatic back flush systems work with significantly higher pressure and therefore do not suit the pressure minimising concept of SPIS.

Granulate/Sand Filter

Sand filters are designed to remove organic debris and particulates from water. Sand filters are simple, effective and require very little attention. The body is a volumetric and typically metallic vessel, which can withstand higher working pressure (DripWorks n.d.).

Water is routed through the sand-filled tank where the sand traps large and small particles. Eventually the dirt accumulates in the space between the sand particles, making it harder for the water to pass through. This causes the pressure in the tank to rise, which signals that the tank needs to be backwashed by reversing the water flow (DripWorks n.d.). The working principle of a sand filter is shown in Figure 2.45.

Backwash water is used to clean the filters and flush out the suspended solids that have been trapped in the media bed. Water for backwashing can come either from the filters themselves or from an external source of clean water (such as a domestic water line or a storage tank) (Everfilt n.d.).

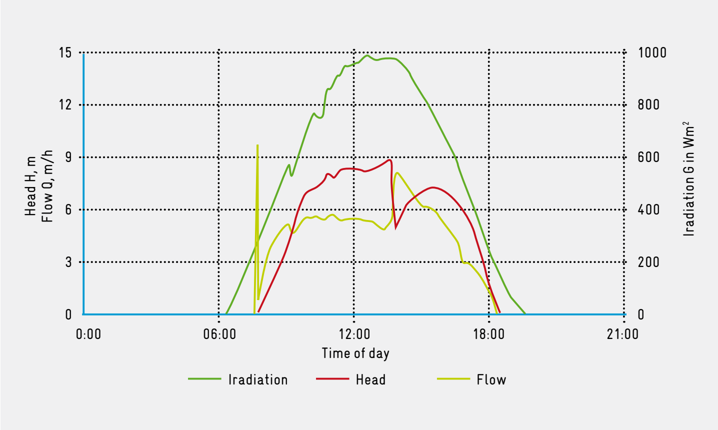


Figure 2.43: Impact of disc filter cleaning on flow rate
Source: Rivulis Irrigation Ltd, 2015

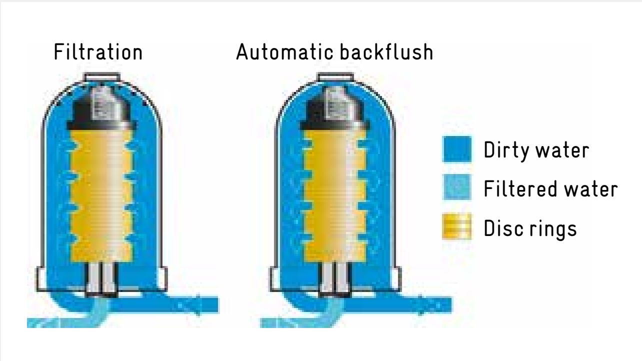


Figure 2.44: Schematic of disk filter in filtration and back flush mode
Source: NETAFIM, 2013

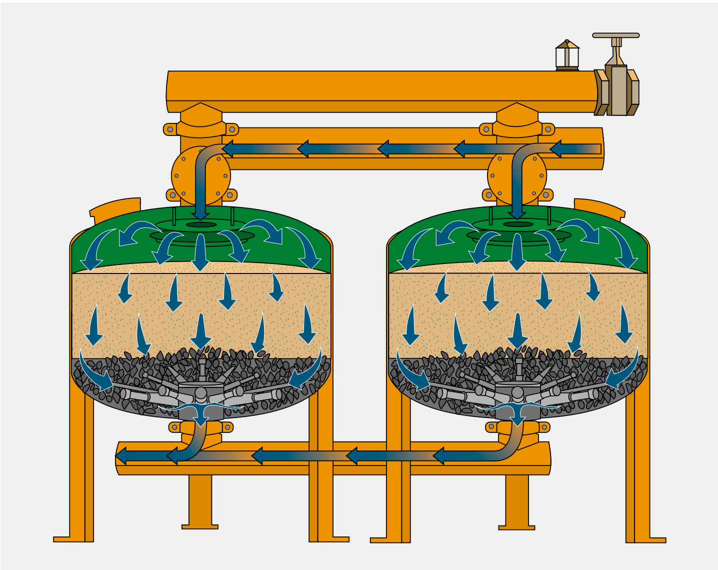


Figure 2.45: Schematic of a sand filter
Adapted from Yardney Water Filtration Systems, Inc., 2015

2.2.5 Fertigation Systems

Find a short description about fertigation systems in the SPIS Toolbox Module GET INFORMED – Fertigation System on Energypedia.

Fertigation is the injection of fertilisers, soil amendments, and other water-soluble products into an irrigation system. Fertigation is practiced extensively in commercial agriculture and horticulture and is mainly used to spoon-feed additional nutrients.

It is usually practiced on high-value crops such as vegetables and fruit trees. Especially micro-irrigation systems are well suited to fertigation because of their frequency of operation and because water application can be easily controlled by the farmer. In order to be injected, fertilisers must be soluble. Fertilisers delivered as a solution can be injected directly into the irrigation system, while those in a dry granular or crystalline form must be mixed with water to form a solution (Bevacqua, Phillips 2001).

Figure 2.46: Fertigation system at Ain Louh farm in Morocco
Source: GIZ / Jan Sass, 2014

Liquid fertiliser often adds the hazard of clogging because a chemical reaction with the organic and non-organic matter in the irrigation water happens frequently. It is advisable that after the use of liquid fertiliser an application with pure water is done to reduce the clogging effect.

In a drip irrigation system, fertigation technology can also be used to inject chemicals to dilute debris and other materials which tend to block the outlets or narrow bends. After a certain time, the treated water including the dissolved material is flushed out of each drip line. To find the right diluting chemicals is often the job of highly qualified water engineers. Certain water qualities need a permanent treatment programme and are therefore part of the regular maintenance.

There is a variety of injection equipment from which to choose, including differential pressure tanks, Venturi devices and dosing pumps. Nevertheless, often SPIS run at relatively low working pressure (0.2-0.5 bar) and the injection technology must cope with this, which is not generally the case.

Injection at the suction side of the pump
The simplest form of fertigation is the injection of liquid fertiliser through the suction side of a surface pump. Initially the liquid fertiliser must be diluted to a water equivalent concentration. Afterwards a hose with a throttle valve must be connected with the suction pipe of the pump and the other side placed into the fertiliser tank. Very often, the liquid fertiliser is corrosive and must match the material of the pump impeller and body.

Differential Pressure Tanks
Differential pressure tanks, often referred to as 'batch tanks', are the simplest of the injection devices. The inlet of a batch tank is connected to the irrigation system at a point of pressure higher than that of the outlet connection. This pressure differential causes irrigation water to flow through the batch tank containing the chemical to be injected (ibid.).

As the irrigation water flows through the batch tank, some chemicals go into solution and pass out of the tank and into the downstream irrigation system. Because the batch tank is connected to the irrigation system, it must be able to withstand the operating pressure of the irrigation system (ibid.).

While relatively inexpensive and simple to use, batch tanks do have a disadvantage. As irrigation continues, the chemical mixture in the tank becomes more and more dilute, decreasing the concentration in the irrigation water (ibid.).

If a set amount of fertiliser is to be injected and concentration during the injection is not critical, the use of batch tanks may be appropriate. If the chemical concentration must be kept relatively constant during injection, batch tanks are not appropriate (ibid.).

Venturi Nozzle

The Venturi nozzle, shown in Figure 2.47, is a common device for fertiliser injection. It makes use of the 'Venturi hydraulic effect'. Based on the reduction of the flow diameter, the flow rate is increased at this position and as result the static pressure becomes negative. The suction pressure of the Venturi nozzle is able to inject liquid fertiliser from an open container into the main pipe.

The Venturi injector is frequently installed across a valve or another point where between 10 and 30 % of the pressure is lost because of friction in the device. This means that the Venturi injector's inlet must be at a pressure 10 to 30 % higher than the outlet port. Because of these significant pressure losses, the injector should be installed parallel to the pipeline so that flow through the injector can be turned off with a valve when injection is not occurring (ibid.).

Because of the high pressure loss and the fact that the pressure provided by a photovoltaic water pump is not constant (this would cause a permanent change in the fertiliser concentration), the Venturi nozzle is not recommendable for use in SPIS unless the system pressure is regulated by means of an intermediate storage tank providing water by gravity at a uniform pressure and flow.

Dosing/Metering Pumps

Dosing pumps are the most expensive injection devices. Nevertheless, when a constant and precise injection concentration is needed, positive displacement pumps are the preferred option. They usually use pistons or diaphragms to inject the fertiliser solution into the irrigation system.

In Solar Powered Irrigation Systems in Chile, solenoid diaphragm metering pumps have proven to be very reliable.

A solenoid moves the solenoid axis back and forth by switching on and off. This stroke movement is transferred to the metering diaphragm in the dosing head. Two return valves prevent the feed chemical from f lowing back during the pumping process. The metering capacity of a diaphragm metering pump can be adjusted using the stroke length and the stroke frequency (ProMinent GmbH n.d.).

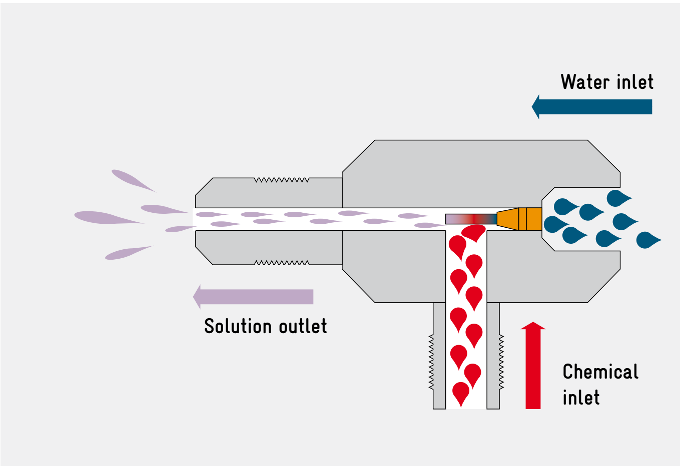


Figure 2.47: Working principle of a Venturi nozzle
Adapted from Wessmann, 2006

Figure 2.48: Solenoid metering pump for precise injection
Source: ProMinent GmbH, 2016

The pump shown in Figure 2.48 works without lubricated bearings or shafts. Energy demand, maintenance and repair costs are therefore extremely low. ProMinent is one of few manufacturers offering a version with a DC drive, which suits solar power, but requires a battery for trouble free operation. The 12V DC model is limited in capacity and is therefore only useful for smaller drip irrigation schemes.

For off-grid applications, water-driven dosing pumps, installed directly in the water supply line, are available as well.

The flowing water activates the dosing pump which takes up the required percentage of concentrate and injects it into the water. Inside the pump, the concentrate is mixed with the water, and the water pressure forces the solution downstream. Once adjusted, the dispenser requires no action or external control. The dose of concentrate will be directly proportional to the volume of water entering the dosing pump, regardless of variations in flow and pressure which may occur in the main line. The high dosing precision eliminates all risk of overdosing, thus contributing to environmental performance (Dosatron 2019). Figure 2.49 shows the friction loss of a Dosatron water powered dosing pump under low working pressure (0.2–0.6 bar), which is typical of Solar Powered Irrigation Systems. In the range of 1 to 6 m³/h flow rate, the measured pressure loss is relatively low (1–2.5 m). Thus, Dosatron injection devices are suitable for use in SPIS.

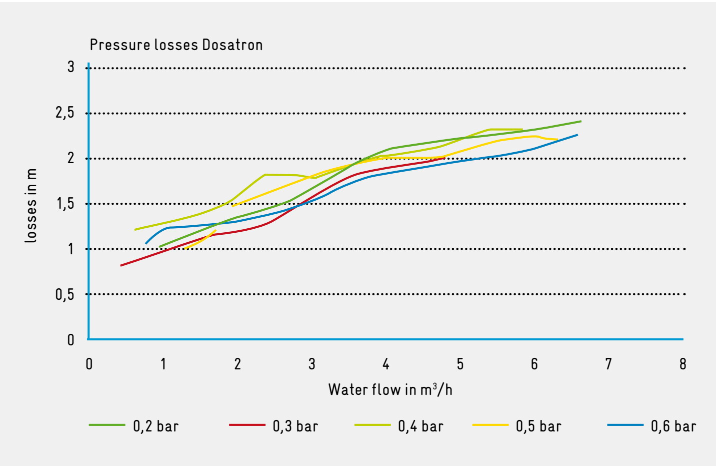


Figure 2.49: Measured pressure loss of a Dosatron pump used for fertigation
Adapted from: R. Schmidt, 2015

2.3 Planning and Sizing of SPIS

Planning and design of a solar-powered irrigation plant is a rather difficult task. The system consists of many components that have to work under constantly varying conditions due to daily and seasonal fluctuations.

Basically, system sizing means adapting the supply to the demand. A Solar Powered Irrigation System with insufficient capacity will not satisfy the farmer's needs and an over-dimensioned system will induce unnecessary operation and capital costs. Therefore, data collection and the final system design should be done in close cooperation with the farmer.

2.3.1 Design Data Collection

Find a short description about data collection in the SPIS Toolbox Module DESIGN – Collect Data

and use the interview guidelines of the DESIGN – Site Data Collection Tool on Energypedia.

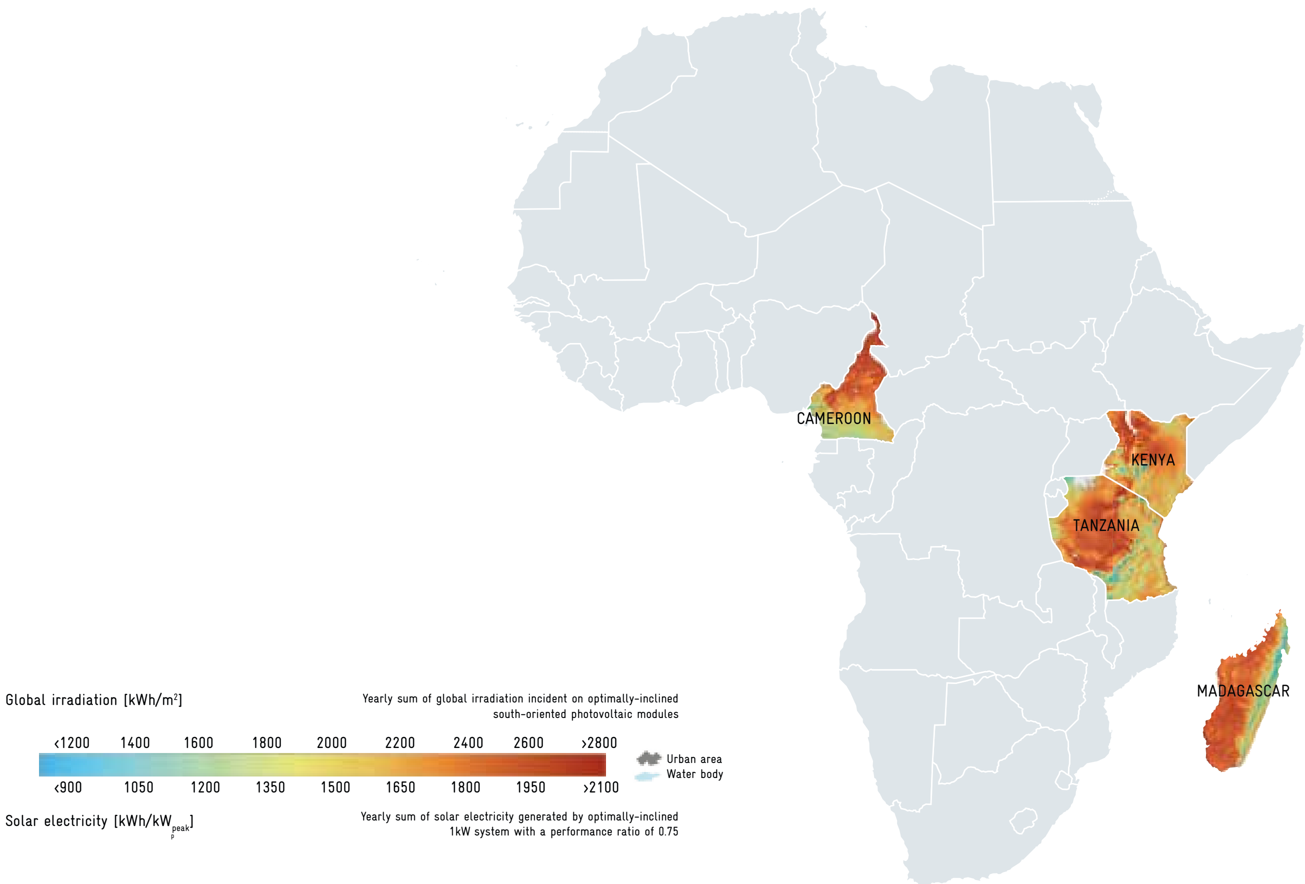
For a proper design of an SPIS, a complex set of data and information is required. This includes data on site-specific and meteorological parameters, soil conditions and water availability and quality as well as on cropping aspects:

Table 2.3: Data required to design a Solar Powered Irrigation System

Meteo Data	Site Data	Crop Data	Soil Data	Water Data
Insolation	Longitude	Crop type	Soil type	Availability
Temperature	Latitude	Growing season	Salinity	Ownership
Wind speed	Altitude	Crop rotation	Water holding capacity	Salinity
Humidity	Water source	Water demand	Organic matter content	Temperature
Evaporation	Pumping head	Root depth	Fertility	Algae content
	Shadowing	Fertiliser demand		Sediment content
	Climate			
	Terrain			

Source: ah Advice International, 2015

Any SPIS should ideally be sized on the basis of the findings from a local data survey. While an on-site survey of solar radiation and other meteorological data would be worthwhile in any case, most systems are based on the known data of a nearby reference location for which relevant measured values are available. Meteorological data can also be found on regional/national maps, or on national and international websites (e.g. Ministry of Agriculture, NASA).



Adapted from PVGIS European Union, 2001-2014 & Huld T. et al., 2012

Figure 2.50: Photovoltaic solar electricity potential in Africa

Other site-specific data, such as the dynamic pumping head, have to be collected at the potential farm. Figure 2.51 and Figure 2.52 explain how the total pumping head (with allowance for well dynamics and friction losses) can be determined.

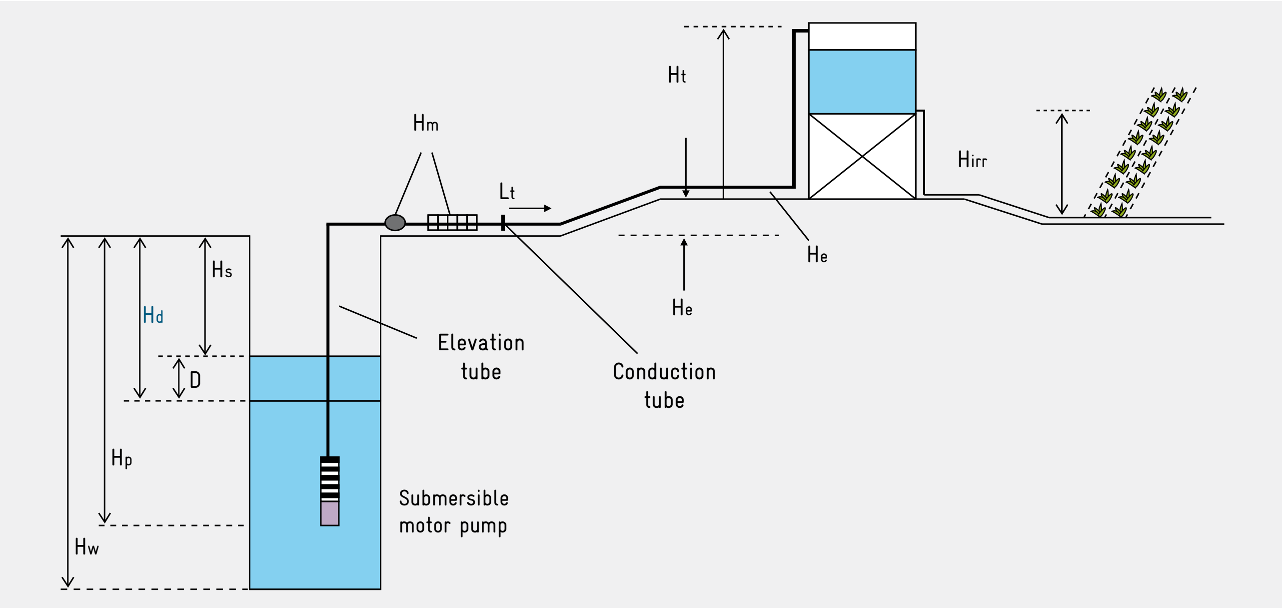


Figure 2.51: Determination of dynamic pumping head (tank system) Adapted from R. Schmidt, 2015

The dynamic pumping head is given by:

$$H_{total} = H_s + D + H_e + H_t + H_m + H_o$$

with:

H_s:	Static water level in m
D:	Draw down in m
$H_d = H_s + D$:	Dynamic water level in m
H_e:	Difference well head to tank base in m
H_t:	Water tank height in m
H_m:	Losses in flow meter and filter in m
L_t:	Length of conduction tube in m
D_t:	Diameter of conduction tube in inch

Material conduction tube:

H_o:	Losses in conduction tube, fittings in m
V:	Tank water volume in m^3
D_t:	Diameter of conduction tube in inch

Material elevation tube:

H_p:	Depth of pump in m
H_w:	Depth of well in m
D_p:	Well diameter of in m
H_{irr}:	Outlet water tank

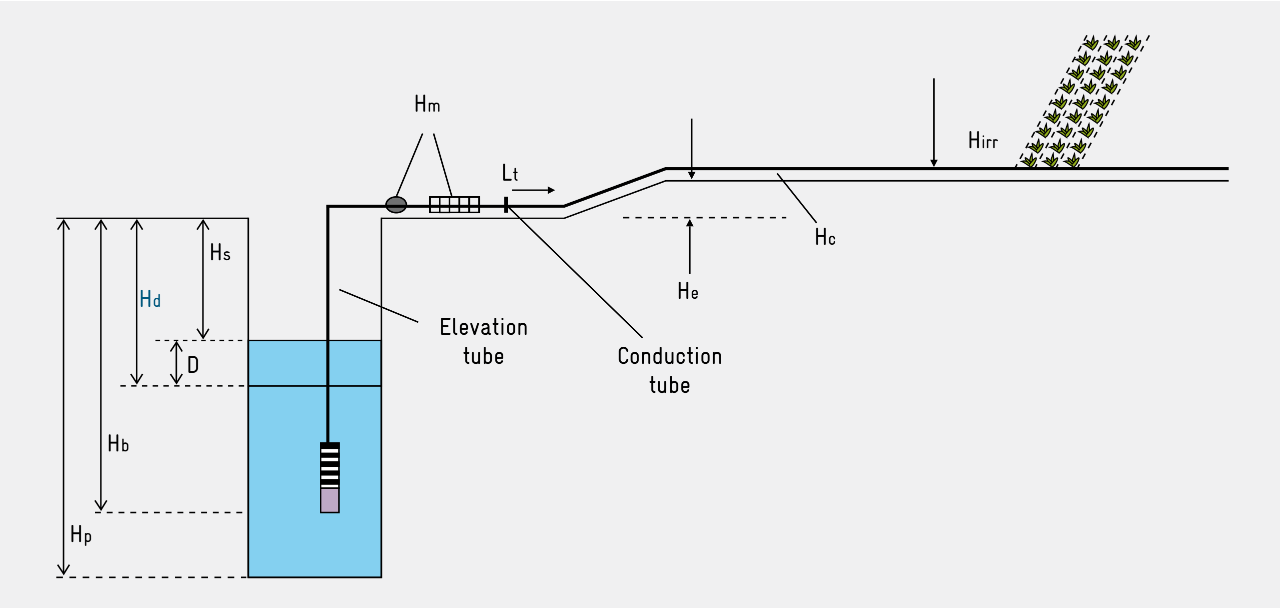


Figure 2.52: Determination of dynamic pumping head (direct input system) Adapted from R. Schmidt, 2015

An interview with the farmer allows first conclusions about the water and soil quality, as well as the water requirements for the cash crops to be planted. If required, a more detailed calculation of irrigation water demand can be done with the help of special software, such as CROPWAT. Finally, the **design month** has to be determined together with the farmer. Usually this is the month of the year with the highest water demand and/or the lowest solar radiation.

After collecting the relevant data, the design process usually starts with the solar pumping system as the main cost driver. Here, the technical planner can choose from a number of design methods of varying complexity and accuracy. Depending on the status of project development, a three-step design approach is recommendable:

Step 1: On-site estimation of PV generator size with a rule of thumb;
Step 2: EXCEL-based system sizing and pre-selection of motor pump unit;
Step 3: Complex computer-based system design and simulation.

The three different approaches are outlined below.

2.3.2 Estimation of PV Generator Size

Find a short description about PV generator size estimation in the SPIS Toolbox Module DESIGN – Estimate System Size & Costs on Energypedia.

To arrive at a first estimate of how much the planned PV pumping system will cost for a just-selected site, it is a good idea to first estimate the requisite size of the PV generator. This, however, presumes knowledge of the essential sizing data, namely:

- Daily crop water requirement Vd [m³/day];
- Total pumping head HT [m];
- Mean daily global solar radiation G_d for the design month [kWh/m² day].

A simple arithmetic formula, taking the individual system component efficiencies into account, can be used to calculate the required solar generating power P_{peak} (The Republic of Uganda, Ministry of Water and Environment 2013).

In order to understand the context, it is helpful to revisit the schematic of a photovoltaic pumping system (see Figure 2.53):

The electrical energy produced by a photovoltaic generator is given by (DGS 2013):

$$E_{el.} = \frac{FC_P}{1{,}000\ W/m^2} * P_{peak} * G_d$$

with:

P_{peak}: Peak power of solar generator in Watt
G_d: Daily global radiation in Wh/m² day
FC_P: Temperature correction of solar peak power (typically between 0.8 in hot climates and 0.9 in mild climates)

The relation between the hydraulic energy at the pump outlet ($E_{hydr.}$) and the electrical energy at the input of the inverter/control unit ($E_{el.}$) can be described with the efficiency of the inverter and motor pump unit (η).

$$\eta = \frac{E_{hydr.}}{E_{el.}}$$

thus,

$$E_{el.} = \frac{E_{hydr.}}{\eta} = \frac{FC_P}{1{,}000\ W/m^2} * P_{peak} * G_d$$

finally,

$$P_{peak} = \frac{E_{hydr.}}{\eta * FC_P * G_d} * 1{,}000\ W/m^2$$

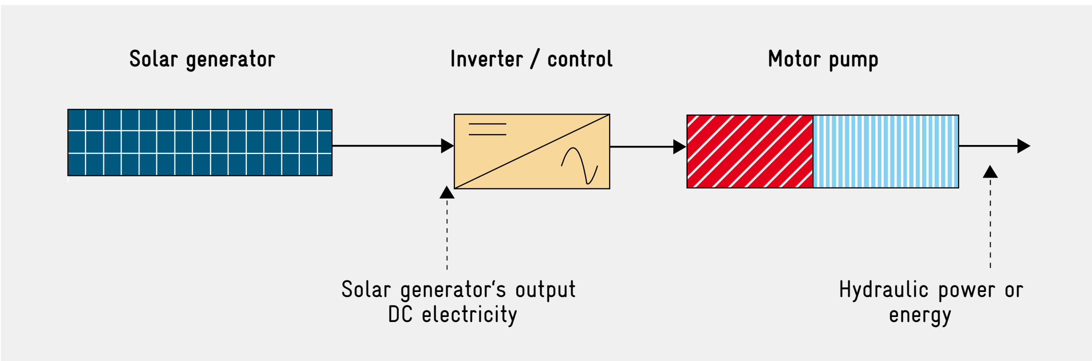


Figure 2.53: Schematic diagram for basic system design Adapted from R. Schmidt, 2015

With an assumed average efficiency of 45 % (controller & motor pump) and a temperature correction factor of 0.8 (hot climate), the solar generator size can be estimated to (Schmidt, 2012):

$$P_{peak} = 0.8 * \frac{H_T * V_{day}}{G_d}$$

with:

P_{peak} [W]
H_T [m]
V_{day} [m^3/day]
G_d [kWh/m^2 day]

According to this equation, it takes a 2.4-kWp PV generator to deliver water at the rate of 30 m^3/d at a head of 50 m for a daily total global irradiation of 5 kWh/m^2 day.

This simple equation serves to estimate the size of the PV generator and, hence, the approximate cost of the planned PV system at the time of site selection.

2.3.3 EXCEL-Based System Sizing

Find the EXCEL-based DESIGN – Pump Sizing Tool in the SPIS Toolbox on Energypedia.

Within the scope of the underlying study, a manufacturer-independent EXCEL-based worksheet was developed (as part of the planning tools) for more exact and easy system sizing.

Figure 2.54 presents the user interface of the DESIGN – Pump Sizing Tool of the SPIS Toolbox, which allows for input parameter variation of daily global radiation, total pumping head and water requirement. After entering the main system parameters, the required PV generator, pump motor size and daily water flow will be calculated.

The design tool is presented in detail in section 6.

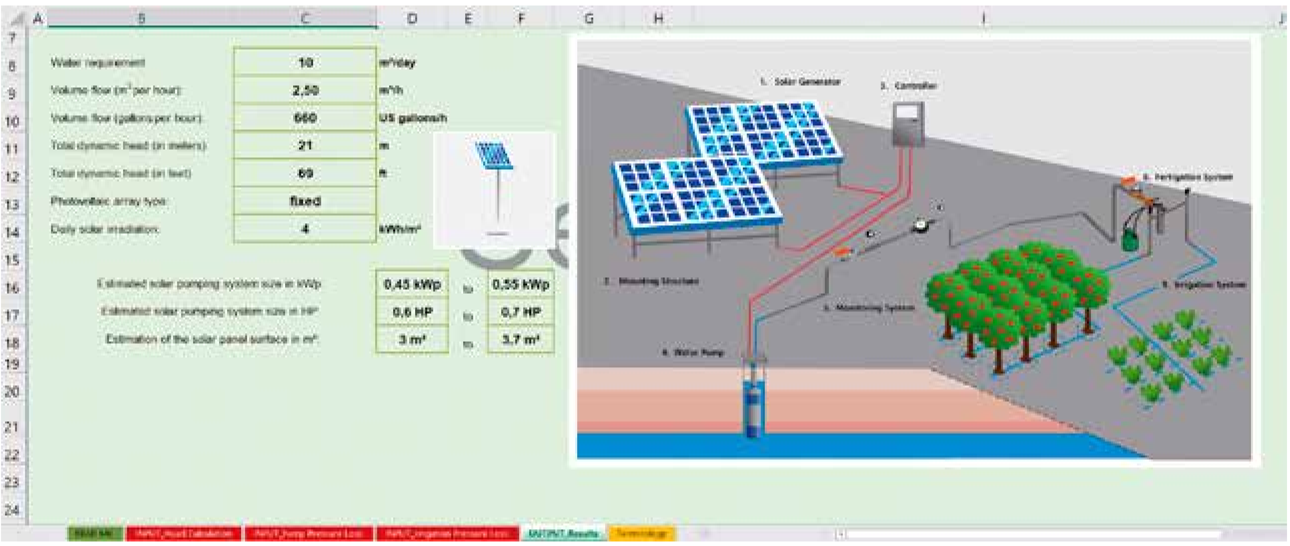


Figure 2.54: Results sheet of the SPIS DESIGN – Pump Sizing Tool. Source: GIZ / FAO, 2019

2.3.4 Computer-Based System Sizing and Simulation

For design and simulation of photovoltaic water pumps and irrigation systems, a series of software solutions can be found on the market. The available software includes everything from simple demonstration programs to highly flexible free-style programs. Most of the computer-aided design tools were developed by individual manufacturers who use the software to promote and sell their products.

Only very few manufacturer-independent solutions are offered on the market (e.g. PVSYST, DAST-PVPS). Nevertheless, such programs generally also use a data base which was provided by individual pump manufacturers. The only difference is that more than just one product variant can be selected.

Within the scope of stocktaking and analysis it became clear that there is currently no commercially available software solution on the market which integrates design features for the photovoltaic pump and the irrigation system.

A detailed overview of selected software tools is given in section 6.

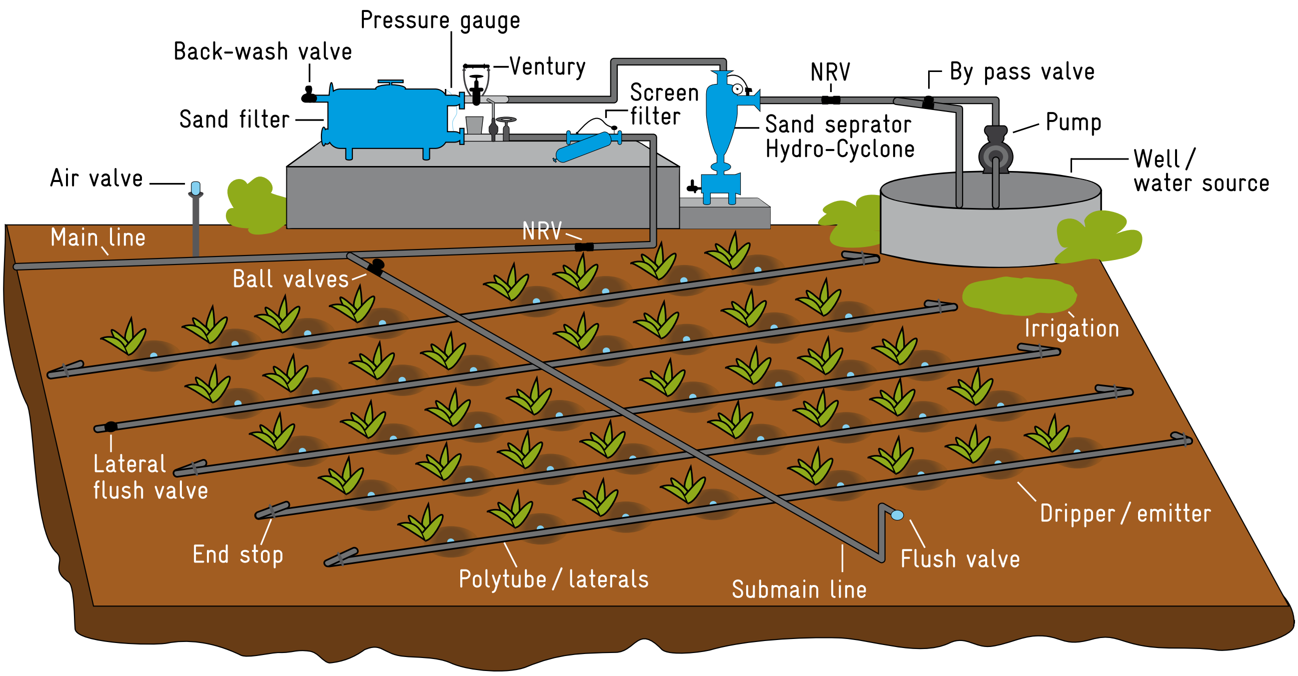


Figure 2.55: Example of a schematic layout of irrigation system design

Source: Wikipedia / Bhavarlalji Hiralalji Jain, 2006

2.3.5 Land requirements for SPIS

An important factor to consider prior to deciding on the design and installation of an SPIS is the available land resource for the system. While the main focus is on the consideration of productive arable land to be irrigated, it has to be considered that the system itself will require land resources:

- Solar panels will use farm land and need to be spaced in such a way that no shadowing occurs. Depending on system size the required land resource can be substantial, reducing the net production area of the farm;
- Pump and filter houses and water tank installations may also require land resources;
- Pipelines require land resources if they are not installed sub-surface.

The resulting land requirements for the system may be a critical issue, in particular for smallholders, and should be evaluated as part of an investment decision.

3 Management requirements of SPIS

3 Management requirements of SPIS

To assess the specific management requirements of PV irrigation systems, it is advisable to distinguish between strategic, tactical and operational management. The design and dimensioning of the overall PV irrigation system is a strategic management decision with a time frame of more than 15 years. The creation of an irrigation and fertilisation plan, however, is a tactical management function with a much shorter time frame, and whose decision framework is determined by a strategic decision. The daily operation of the irrigation valves is an example of operational management as the implementation of a tactical specification. The various levels of management are outlined below.

The most significant difference between the management of a PV irrigation system and the management of conventional systems is in the strategic area. Distinctions can also be observed with regard to tactical and operational management. These are presented in detail below.

Table 3.1: On-farm irrigation management levels

Management Level	Management Decisions
Strategic Level: **› 5–20 Years**	► Choice of farm system ► Planning and design of a SPIS ► Selection of irrigation technology ► Determination of financing strategy
Tactical Level: **‹ 1 Year**	► Planning of crop rotation ► Determination of irrigation timing and quantities ► Determination of fertilizer quantities ► Planning of operation & maintenance
Operational Level: **› 1 Day**	► Water allocation ► Application of fertilizer and plant protection ► Cleaning of filters and solar generator ► Monitoring and maintenance of irrigation system

Source: ah Advice International, 2015

3.1 Stakeholders in SPIS Management

Find an overview of this subject in the SPIS Toolbox Module PROMOTE & INITIATE – Define Target Group & Stakeholders

and use the PROMOTE & INITIATE SPIS Rapid Assessment Tool on Energypedia.

The management of an irrigation system usually requires the interaction of several stakeholders in the management field. In order to describe the management field, it is necessary to define system boundaries which, in the present case, extend far beyond the boundaries of the farm. Figure 3.1 is a simplified presentation of the main stakeholders and system boundaries as well as the flow of materials and information for a conventional irrigation system.

The manager and the farm workers act as stakeholders at the farm level in the irrigation management field. The farm workers may be family labour, but would often be migrant or foreign workers from the region or neighbouring countries. Their operational instructions for irrigation management come from the farm manager or a foreman who is responsible for tactical management in the form of planning irrigation and fertilisation cycles as well as providing necessary resources such as water, fertiliser and fuel.

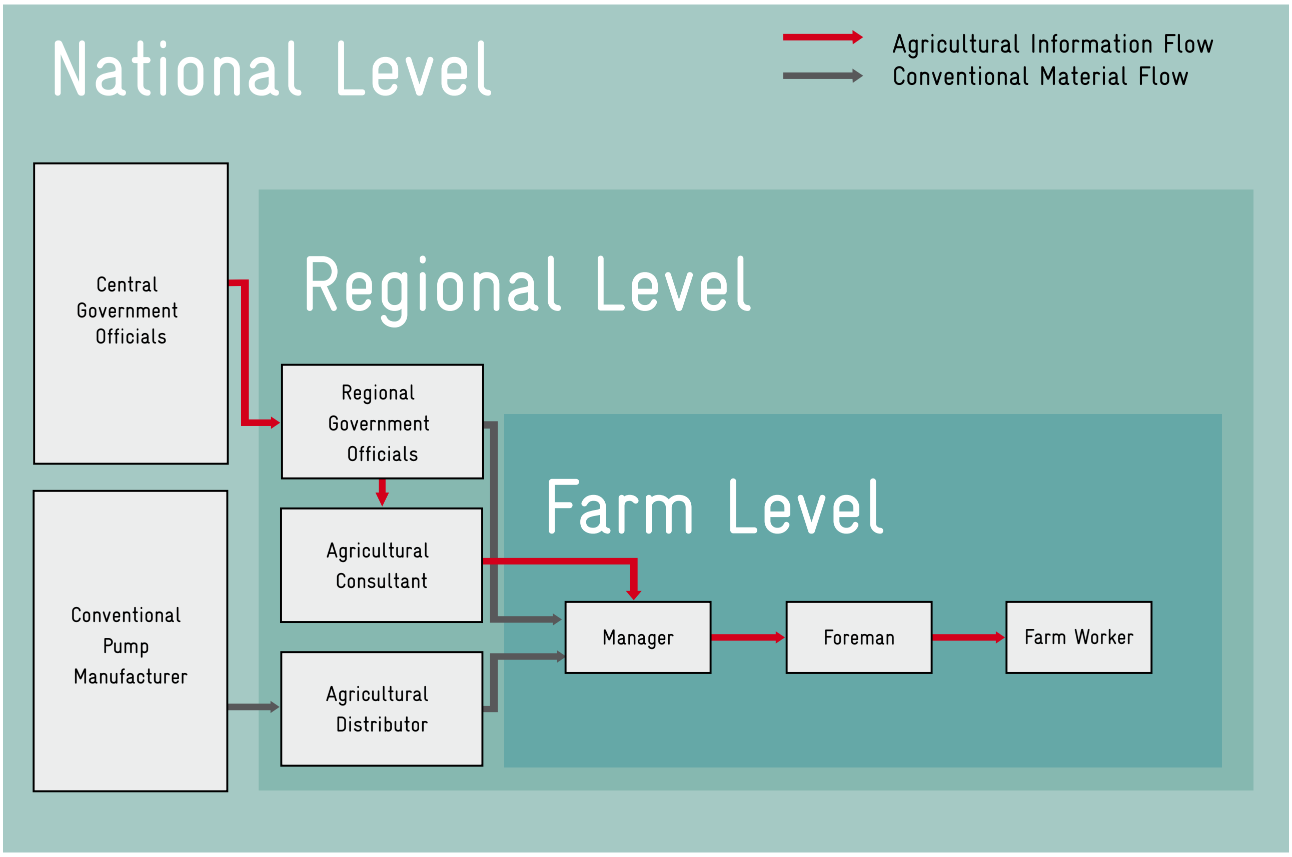


Figure 3.1: System boundaries, main stakeholders and flows of materials and information for a conventional irrigation system

Adapted from ah Advice International, 2015

Delivery of irrigation water from surface water sources can take place through a primarily state-organised system of water channels (e.g. Chile), and the relevant stakeholder is then a regionally based government official who is responsible for water allocation and possibly invoicing.

Fertiliser, fuel, lubricants and the conventional pump and motor, as well as the components of the irrigation system, are sourced from agricultural distributors. The selection of the technical components is a strategic management decision on the part of the farm manager for which he can avail himself of advice from the regional agricultural consultant as well as the experience of the agricultural distributors. For pumps and irrigation components, the agricultural distributor can usually rely on domestic products or well-established import products.

With the introduction of PV irrigation, new stakeholders emerge, and there are temporary shifts in the relational structure:

As the dimensioning of the PV pumping system and the adaptation of a drip irrigation system require a high level of technical qualification and solar-specific know-how, which is often not available at the regional level in the project countries, these tasks are usually performed by specialists.

These specialists are usually local manufacturers, system integrators and distributors of photovoltaic systems. Via regional installers, the solar pumps are finally sold to the farmer. Thus, at least in the short term, the local public agricultural advisory centres pass the advisory function for strategic management over to specialised professionals.

The use of solar pumps for irrigation is relatively new, so the local agricultural distributor is currently ruled out as a supplier. The components of the adapted drip irrigation system can be differentiated, at least in part, from the usual regional requirements (e.g. dosing pumps) so that new distribution channels are also used for these. Standard components, such as drippers, tanks, etc. are generally procured from local distributors.

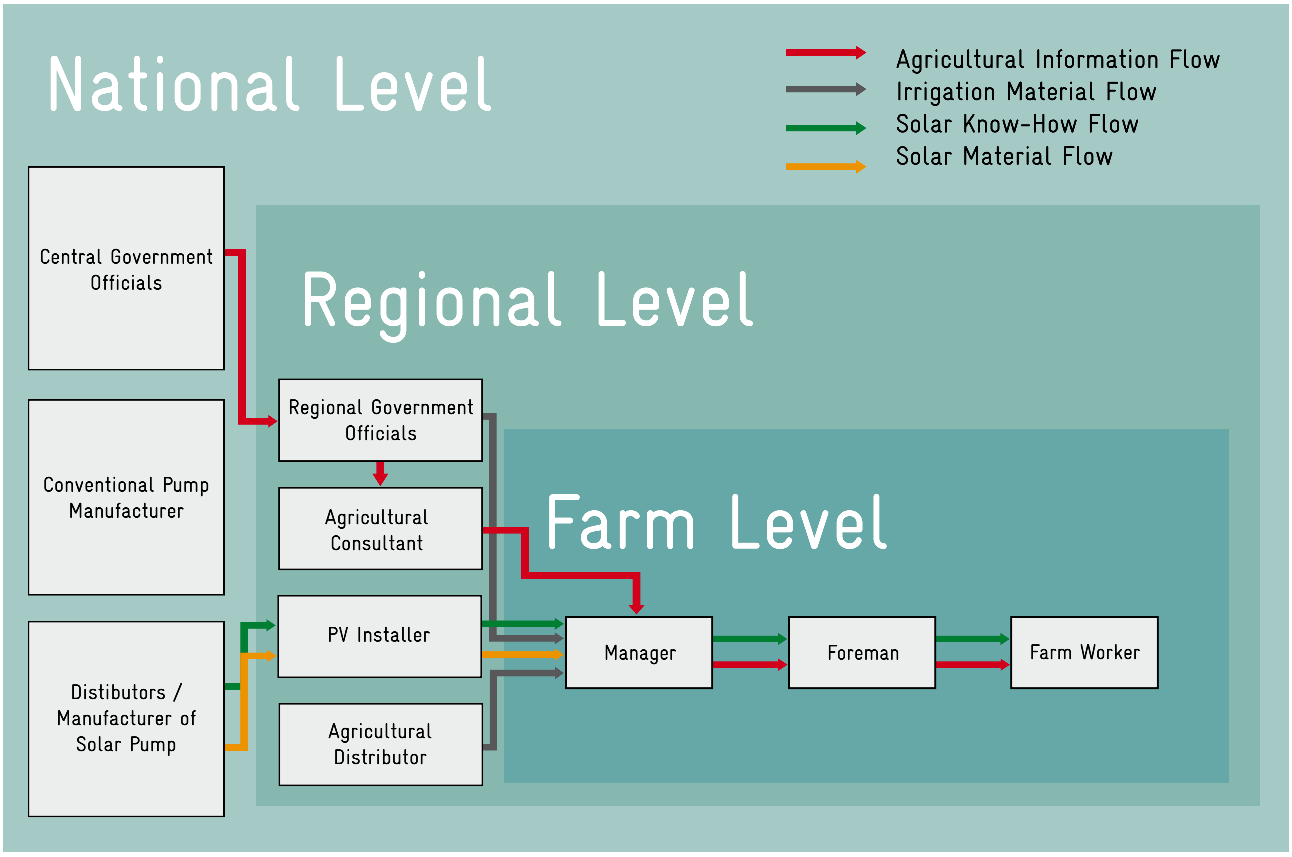


Figure 3.2: System boundaries, main stakeholders and flows of materials and information for a Solar Powered Irrigation System

Adapted from ah Advice International, 2015

Drip irrigation does not conserve water per se, but only in connection with an optimal irrigation regime in the context of tactical management via the planning of water and fertiliser quantities. The optimal adjustment of the irrigation regime to the seasonally changing needs of the crop stand requires scientific knowledge that cannot be expected from small-scale farm managers. Therefore, the calculation of water and fertiliser requirements is usually performed by agricultural consultants. There are also significant differences to conventional irrigation with regard to operational management; therefore, farm workers will require practical training.

As outlined above, the implementation of PV irrigation systems causes changes in the management field which can have a regional impact beyond the level of the farm. As the consideration of such changes is the basis of participatory approaches in any subsequent dissemination programmes, possible shifts in the different levels of management are considered in more detail below.

3.2 Impacts on Strategic Farm Management

Irrigation must be considered in the context of the entire farm's higher-level strategic decisions, such as the choice of the farm system (arable, horticultural, orchard, etc.), which have a decisive influence on the irrigation system. Hereinafter, small and medium sized farm holdings in arid areas are assumed as target group. The selection and dimensioning of the motor, pump, and irrigation system comprise the main strategic decisions regarding irrigation, as this defines the operational flow over several years.

The use of electric pumps or dry-mounted centrifugal pumps driven by conventional combustion engines is typical of the target group in the countries visited. Electrical submersible pumps are generally used only when exploiting groundwater from deeper aquifers. Diesel engines are predominantly used as drive units in remote areas not connected to the public grid. Conventional pump selection can be made by the farm manager himself, as this technique is widely used, and agricultural distributors already offer regionally appropriate product ranges.

The smallest standard diesel engines are in a power range of 5–10 kW and are often oversized for the needs of small farms. The over-dimensioning, which is dictated by market availability, is indeed uneconomical but relieves the manager of the task of calculating the required engine performance. Thus, the dimensioning of the pump system eliminates a decision within the context of strategic irrigation management. For the purposes of efficient water and fuel usage, this over-dimensioning must be offset by correspondingly shortened pump operating cycles in the context of tactical management (which is often overlooked due to a lack of knowledge regarding the actual water needs or risk avoidance).

Figure 3.3: Example of an average, maintenance-demanding diesel pump set

Source: GIZ / Andreas Hahn, 2015

Agricultural distributors usually assist farmers in selecting the appropriate irrigation system. In addition to conventional systems (incl. sprinkler equipment), agricultural distributors offer domestically produced augmented drip and micro-sprinkler technology and advice on the design of the irrigation system. A farm manager may also consult with the agricultural advisor on dimensioning and installation or learn from the experience of other farmers.

In contrast to motor-driven pumps, the dimensioning of PV irrigation systems represents a critical strategic management decision due to the high investment costs, and at the same time, due to its complexity, involves a high level of technical requirements in a relatively new field of knowledge. This task can currently be tackled only by trained specialists.

Despite all the methodological aids, the dimensioning of a PV pumping system will not be the task of the farm manager in future. The farm manager will only be able to make a decision regarding PV irrigation when he can delegate this task to a trusted professional (e.g. the agricultural advisor).

Even newer than technical knowledge on PV pumping systems is knowledge on the adaptation of micro-irrigation technologies to their variable performance under varying pressure conditions. Here, knowledge still derives from the experimental stage. In India and Chile, several operational concepts and system sizes were defined in the context of public tenders and installed in agricultural holdings with little consideration of actual requirements. In some cases this has led to acceptance problems on the part of farm workers and managers (see also section 5.2.5).

3.3 Impacts on Tactical Farm Management

For optimized farm management try the SPIS Toolbox SAFEGUARD WATER – Water Requirement Tool on Energypedia.

With conventional irrigation, tactical irrigation management on the part of the farm manager consists of ensuring access to water and the availability of other operating materials such as fertiliser, fuel, lubricants and spare parts for the motor and pump in addition to planning crop rotation and the seasonal workforce. The more remote the farm is from the corresponding supply centres, the more economic success depends on satisfactory warehouse management of operating materials.

Water and fertiliser usage are not normally scheduled but allocated by the farm workers at their own discretion. This discretion is based on the experience that the workers have acquired in the course of their farming activities (in India and Kenya very often only based on surface irrigation systems). With surface irrigation, a large amount of water is administered in a short time during a cycle of several days duration. Against this background, the quantities continuously applied in drip irrigation appear to be too low, and the primary tendency is towards over-watering.

The introduction of PV irrigation provides relief for tactical management through the elimination of supply planning with respect to fuel, lubricants and repairs. For irrigation scheduling, the water demand of crops can be calculated on the basis of weather-related potential evapotranspiration. This calculation can be performed only by qualified personnel. As opposed to the field of PV technology, the basic understanding required for this is available from the agricultural consultants and can be developed through appropriate training. Major support in this area is provided by FAO's CROPWAT computer program, which can be used to manually input current weather data and to calculate the daily water requirement for the crops (see section 6.3).

Local agricultural consultants are generally qualified with respect to fertiliser planning. However, the direct input of fertiliser into the irrigation water provides new opportunities for optimisation which can be exploited only with the appropriate training.

3.4 Impacts on Operational Farm Management

Find a short overview about operational farm management in the SPIS Toolbox Module SAFEGUARD WATER – Adjust & Planning Operation on Energypedia.

The operational management of conventional irrigation systems is usually performed by farm workers and includes the daily operation and maintenance of the motor pump (or other water extraction structures/devices) and irrigation system as well as fertilisation.

Dry-mounted centrifugal pumps must be vented before each start-up, which is a more or less time-consuming procedure, depending on the type of pump. Diesel fuel must be topped up in a timely manner, as allowing the tank to run dry may necessitate ventilation of the motor by a mechanic. Failure to maintain the lubricants causes the machine to wear prematurely.

Figure 3.4: Example of an average, maintenance-demanding diesel pump set

Source: GIZ / Andreas Hahn, 2015

Figure 3.5: Standard impact sprinkler used in combination with conventional and PV pumping in Bihar, India

Source: GIZ / Hahn, 2015

The technical skills of farm workers are sufficient for the maintenance of the machines but not for their repair, which must be carried out by a local mechanic and can lead to costly delays due to travel distances or order bottlenecks.

The operational management of sprinkler systems consists of rotating the pipes and sprinklers and occasionally spreading fertiliser. The use of drip irrigation systems eliminates the labour-intensive rotation of the pipes because the necessary lines will be permanently laid for at least the duration of the growing season. The labour effort for water allocation is reduced to the block-by-block opening of the valves.

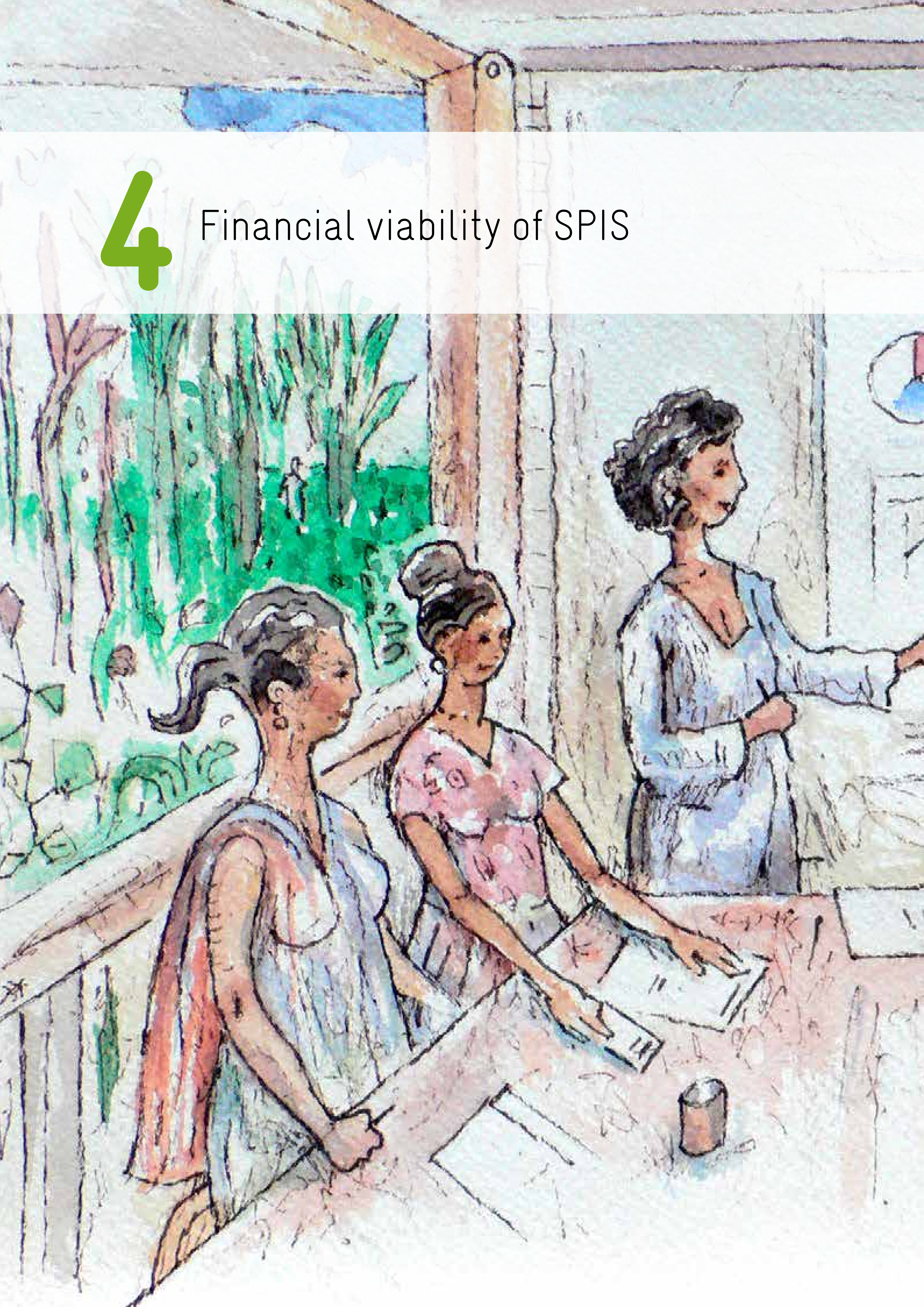
If drip irrigation is applied, the irrigation water must be filtered because the critical diameter for drip elements is much smaller than for sprinklers (see section 2.2.4). Depending on the particle load of the water, the filters must sometimes be cleaned several times a day, which requires a certain level of technical knowledge and skill.

In addition, drip lines must be flushed regularly, and the drip elements must be examined for blockages and replaced if necessary. In contrast to sprinkler irrigation, fertiliser must be added to the irrigation water because it is not dissolved by the irrigation water on the surface of the soil. The simplest method of doing this is to stir the fertiliser into an open barrel to form a solution which is fed into the suction side of the pump (see section 2.2.5).

In a PV irrigation system, the high workload and level of uncertainty associated with motor-driven pumps are eliminated. The PV pump turns on and off automatically, and even the irrigation valves can be automatically operated. The input of fertiliser can also be carried out by means of a separate dosing pump so that this procedure is significantly refined as well. Operational management is limited to cleaning the filters and solar panels, adjusting the dosing pump and monitoring the entire system. Manual labour is largely replaced by technical understanding and fine motor skills.

In addition to conserving water and energy resources, PV irrigation systems also contribute to a more efficient use of human resources. If exhausting manual labour is replaced with mentally demanding tasks, agriculture could again become more attractive for the well-educated generation currently growing up, assuming that the right income is available. This could, in turn, prevent brain-drain into urban regions.

4 Financial viability of SPIS




PAYBACK

4 Financial viability of SPIS

4.1 Parameters of Financial Viability

Find a short description of this topic in the SPIS Toolbox Module DESIGN – Assess Financial Viability

and use the INVEST – Payback Tool to define your Internal Rate of Return on Energypedia.

Financial viability is the ability to generate sufficient income to meet operating expenditure, financing needs and, ideally, to allow profit generation. Financial viability is usually assessed by using the Net Present Value (NPV) and Internal Rate of Return (IRR) approaches together with estimating the sensitivity of the cost and revenue elements. Both NPV and IRR are the most commonly used decision criteria of a Cost-Benefit Analysis:

- The **Net Present Value** of an investment is the sum of all discounted costs and benefits of this investment – the sum reflects how much the project will earn – NPV is an absolute profitability indicator.

  In technical terms, the NPV is a calculation that compares the amount invested today to the present value of the future cash receipts from the investment. In other words, the amount invested is compared to the future cash amounts after they are discounted by a specified rate of return.

- The **Internal Rate of Return** is the rate with which the discounted costs equal the discounted benefits. The IRR can then be compared with a reference value, e.g. the current interest rate or a minimum threshold expected by the investor – IRR is a relative indicator that allows a direct comparison between an investment and market interest rates.

  In technical terms, the IRR is a calculation of the interest rate at which the Net Present Value of all the cash flows (both positive and negative) from a project or investment equal zero.

Both NPV and IRR should not be used to rank project alternatives.

In a comparative assessment of project alternatives other indicators should be used. This could include:

- Comparative analysis of the **Life-Cycle Costs** of alternatives – the sum of all recurring and one-off (non-recurring) costs over the full life span or a specified period of a good, service, structure, or system (incl. purchase price, installation costs, operating costs, maintenance and upgrade costs, and remaining (residual or salvage) value at the end of ownership or useful life);
- Comparative analysis of **annual operation costs**;
- Comparative analysis of **annual financing costs**.

It is important to keep in mind that the analysis of the financial viability of an SPIS investment does not concern the choice of the pumping technology alone. The analysis should also include the entire irrigation system set-up as it may change if the water abstraction and conveyance approach are altered.

4.2 Financial Viability of Exemplary SPIS

As outlined above (see section 1.5.2), each irrigation technology choice has its limitations in terms of the range of crops it can support in production. On the other hand, the investment costs linked to the choice of technology limit significantly the range of crops to select for production. Pressurised irrigation systems in general and micro-irrigation systems in particular are on the capital-intensive side of investments for irrigation infrastructure and equipment.

The Solar Powered Irrigation Systems visited in the course of the country case studies (see section 7) adhere to a larger extent to the principle of adopting cropping patterns with higher value crops. Table 7.1 in section 7 provides an overview of these SPIS.

Below, an exemplary financial analysis of eight of these systems is summarised. All these systems are quite different in size, system configuration and production characteristics. In addition, the degree of subsidisation of these systems differs significantly, from a fully equity financed private investment to a fully subsidised community scheme.

The calculation for the example SPIS was made based on farm gate prices obtained during the interviews with the respective farm managers/owners. Some data was obtained from secondary sources, notably reference values for agricultural inputs. A 20-year life cycle of the irrigation systems was considered. In all computations of cash flows, a 2 % inflation rate was incorporated. The discount rate for NPV and IRR calculations was adopted with 6 %, which constitutes a moderate expectation on capital interest.

The life cycle of the employed PV pumps was generally assumed to be seven years, whereas that of irrigation equipment to be five years. The replacement requirement was assumed to be 20 % of the initial investment of the PV system and the irrigation system respectively.

General standing O&M requirements for system hardware were fixed at 2 % annually of the underlying initial investment sum. This caters for regular technical maintenance and spare parts/repairs.

Chile – Azapa-INIA SPIS (Arica)

This installation in the Azapa valley in Arica supports a commercial private farm with 3.5 ha of industrialised cultivation in net houses and in the open. The installed 5.0 kWp PV generator is the only source of energy for the electric pump supplying the drip irrigation system. It is connected to the grid and feeds in surplus electricity worth about EUR 95 per month. The main production is flowers, passion fruit, tomato and chilli.

The costs of the subsidised PV pumping system (80 % subsidy) was EUR 17,860, the irrigation system was valued at EUR 7,500. An additional larger investment was made in net houses, subsidised at 80 % from public sources.

Table 4.1: Financial Analysis of Azapa-INIA SPIS, Chile (Arica)

Parameter	Value
Cultivated Area	3.5 ha
Irrigation System	Drip
Pumping System	Electric Pump (PV)
Cost of Conventional Pump	Not applicable
Cost of PV-Pumping System	EUR 17,860
Cost of Irrigation System	EUR 7,500
Cost of Greenhouses	EUR 40,000
Cropping Pattern	Floriculture (2.5 ha), Passion Fruit (1.0 ha), Tomato (2.0 ha), Chili (1.0 ha) + Surplus Electricity Production
Cropping Intensity	1.9
Annual Gross Margin Production	EUR 32,543
Annual System Costs	EUR 5,625
Annual O&M Costs	EUR 1,562
System Life Cycle Costs	EUR 112,501
Net Present Value (NPV) of Investment	EUR 333,775
Internal Rate of Return (IRR) of Investment	49.6 %

Source: Authors

The production gives a high annual gross margin and profitable return on investment. Key to the high NPV and the very good IRR are the good gross margins of tomato production (EUR 13,582/ha) and passion fruit production (EUR 1,134/ha). The gross margins from floriculture (EUR 869/ha) and chilli production (EUR 732/ha) would not be sufficient to render the investment financially viable.

The limitation for a further intensification of production at this farm is the availability of farm labour. The annuity[3] of the investment is EUR 29,100.

Table 4.2 provides a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation the PV generator and pumps were replaced by (i) a 5 HP diesel engine pump and (ii) by a 3 kW electric pump supplied by the grid. The modelling shows a difference in annual costs between the PV solution and the conventional energy source options due to the reinvestment requirements for the pump sets in the diesel and grid-based options. O&M costs are at the same level. The alternatives result in quasi similar results. In this set-up, the comparative advantage of the PV-based system derives from the reduced impacts of energy price fluctuations.

As stated above, a higher profitability of the PV investment would require a change of cropping patterns and a discontinuation of the crops with a lower return.

3 The annuity of an investment is a series of fixed-amount payments paid at regular intervals over the specified period of the annuity, in this case 20 years (life cycle of the system).

Table 4.2: Comparison of financial parameters for different energy source options for Azapa-INIA SPIS, Chile (Arica)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 65,360	EUR 50,500	EUR 48,700
Annual System Costs	EUR 5,625	EUR 7,431	EUR 6,754
Annual O&M Costs	EUR 1,562	EUR 1,448	EUR 1,408
System Life Cycle Costs	EUR 112,501	EUR 148,627	EUR 135,079
Water Unit Costs*	0.0103 EUR/m^4	0.0136 EUR/m^4	0.0132 EUR/m^4
Net Present Value (NPV) of Investment	EUR 333,775	EUR 341,376	EUR 348,832
Annuity of Investment	EUR 29,100	EUR 29,763	EUR 30,143
Internal Rate of Return (IRR) of Investment	49.6 %	65.7 %	68.8 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

Chile – La Tirana SPIS (Pampa Tamarugal)
La Tirana SPIS is an installation in a remote area without grid electricity supply and difficult access to markets and farm labour. The system based on a 1.0 kWp PV generator supports a low-input commercial private farm with currently 1.2 ha of a pomegranate tree crop. The farmer has installed a 200 m^3 capacity storage tank to extend his cultivation to up to 18 ha in the future. The installed PV generator is the only source of energy for the electric pump supplying the drip irrigation system.

The costs of the subsidised PV pumping system (90 % subsidy) was EUR 7,470, the irrigation system was valued at EUR 1,500. An additional larger investment of EUR 3,500 was made in a storage tank.

The primary pomegranate production gives a high gross annual margin and profitable return on investment. Key to the high NPV and the very good IRR is the low-input cultivation based on organic nutrient supply and zero chemicals application.

Table 4.3: Financial Analysis of La Tirana SPIS, Chile (Pampa Tamarugal)

Parameter	Value
Cultivated Area	1.2 ha
Irrigation System	Drip
Pumping System	Electric Pump (PV)
Cost of Conventional Pump	Not applicable
Cost of PV-Pumping System	EUR 7,470
Cost of Irrigation System	EUR 1,500
Cost of Water Storage Tank	EUR 3,500
Cropping Pattern	Pomegranate (1.2 ha)
Cropping Intensity	1.0
Annual Gross Margin Production	EUR 5,279
Annual System Costs	EUR 1,358
Annual O&M Costs	EUR 284
System Life Cycle Costs	EUR 27,153
Net Present Value (NPV) of Investment	EUR 48,111
Internal Rate of Return (IRR) Of Investment	41.0 %

Source: Authors

Table 4.4: Comparison of financial parameters for different energy source options for La Tirana SPIS, Chile (Pampa Tamarugal)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 12,450	EUR 7,000	EUR 5,800
Annual System Costs	EUR 1,358	EUR 1,674	EUR 1,152
Annual O&M Costs	EUR 284	EUR 534	EUR 438
System Life Cycle Costs	EUR 27,153	EUR 33,473	EUR 23,039
Water Unit Costs *	0.0024 EUR/m^4	0.0029 EUR/m^4	0.0020 EUR/m^4
Net Present Value (NPV) of Investment	EUR 48,111	EUR 53,470	EUR 58,440
Annuity of Investment	EUR 4,195	EUR 4,662	EUR 5,095
Internal Rate of Return (IRR) of Investment	41.0 %	74.2 %	92.3 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

While the total return on the primary pomegranate cultivation is moderate, the farmer has started a pilot production of liquor from his pomegranate production, achieving market prices around EUR 43/l. The limitation for a further intensification of production at this farm is the availability of farm labour. In this regard, the extension of production to the envisaged 18 ha will prove a challenge.

The annuity of the investment is EUR 4,195.

Table 4.4 provides a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation the PV generator and pump were replaced by (i) a 4 HP diesel engine pump and (ii) by a 2.5 kW electric pump supplied by the grid. The latter is a theoretical reflection as there is no reliable grid supply guaranteed at this specific site. The modelling shows only minor differences in annual costs between the PV solution and the conventional energy source options. This can be largely attributed to the low production level (so far only 1.2 ha cultivated). With an extension of production, the annual cost for the diesel engine and grid electricity based options would increase significantly.

Due to the higher investment costs of the PV solution, the financial advantages are in this example on the side of the conventional system configurations. A higher financial viability of the PV-based option would require an extension/intensification of production. Due to the remote location of the system, a grid-based solution is not feasible.

India – Rajawas Smallholder SPIS (Rajasthan)

This installation in Rajasthan caters for a smallholder farm with 1.25 ha based on a 3.1 kWp PV generator and an undersized pump. The PV pumping system is employed as a back-up to the principal grid-fed electric pump for periods with no or insufficient grid supply. The PV pump was subsidised by public funds. Cultivation includes wheat, mustard, green peas, water melon and vegetables. Cereals, oilseeds and green peas (broadcast crops) are irrigated by sprinklers, 0.25 ha of the farm are irrigated by drip irrigation (water melon, vegetables).

The costs of the subsidised PV pumping system (70 % subsidy) was EUR 5,426, the irrigation equipment (sprinkler and drip) were valued with EUR 900. The value of the main grid-connected electric pump was estimated at EUR 450.

The financial analysis shows that the investment in its current set-up is basically viable as the NPV is positive and as the IRR attains a high level. The main driver behind this is the possibility to cultivate two rotations of water melon and vegetables due to the availability of irrigation water in the dry winter season. The gross margin the farm household can realise with water melons (EUR 3,104/ha) and vegetables (EUR 388/ha) is higher than the gross margin from wheat (EUR 319/ha), mustard (EUR 19/ha) and green peas (EUR 208/ha).

Table 4.5: Financial Analysis of Rajawas SPIS, India (Rajasthan)

Parameter	Value
Cultivated Area	1.25 ha
Irrigation System	Sprinkler, Drip
Pumping System	Electric Pump (Grid and PV)
Cost of Grid-Fed Pump	EUR 450
Cost of PV-Pumping System	EUR 5,426
Cost of Irrigation System	EUR 900
Cropping Pattern	Wheat (0.50 ha), Mustard (0.25 ha), Green Peas (0.25 ha), Water Melon (0.50 ha), Vegetables (0.50 ha)
Cropping Intensity	1.6
Annual Gross Margin Production	EUR 1,980
Annual System Costs	EUR 709
Annual O&M Costs	EUR 173
System Life Cycle Costs	EUR 14,177
Net Present Value (NPV) of Investment	EUR 14,961
Internal Rate of Return (IRR) of Investment	27.0 %

Source: Authors

On the other hand, the farm household is benefitting from a highly subsidised electricity supply (flat rate of EUR 12/month). Without this subsidisation, the annual gross margin of the production would be significantly reduced. This could then be countered by employing the PV pumping system to a further extent, e.g. by extending the drip irrigation section of the farm.

The annuity of the investment is EUR 1,304.

Table 4.6 provides a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation, the PV generator and pump were replaced by (i) a 8 HP diesel engine pump and (ii) by a 5 kW electric pump supplied by the grid. The modelling shows that the annual system and life cycle costs (as well as the unit costs of water) of the PV and diesel engine based options are quite similar, which is due to the standing O&M requirements calculated as 2 % annually of the initial investment amount. This can again be largely attributed to the low production level (so far only 1.2 ha cultivated). With an extension of the production, the annual cost for the diesel engine and grid electricity based options would increase significantly.

The data suggests that in this set-up with only a very small irrigated area, a grid-based electrical pumping system would be the best option providing for the best cost efficiency and return on investment. An intensification of the production would be an option to change the bias towards the PV solution.

However, due to the unreliability of the grid supply at the location of the example SPIS (only intermittent supply 46 hours per day), the PV system provides better operational security.

Table 4.6: Comparison of financial parameters for different energy source options for Rajawas SPIS, India (Rajasthan)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 6,776	EUR 2,950	EUR 1,750
Annual System Costs	EUR 709	EUR 740	EUR 336
Annual O&M Costs	EUR 173	EUR 113	EUR 104
System Life Cycle Costs	EUR 14,177	EUR 14,809	EUR 6,719
Water Unit Costs *	0.0007 EUR/m4	0.0007 EUR/m4	0.0003 EUR/m4
Net Present Value (NPV) of Investment	EUR 14,961	EUR 14,809	EUR 22,426
Annuity of Investment	EUR 1,304	EUR 1,547	EUR 1,955
Internal Rate of Return (IRR) of Investment	27.0 %	62.7 %	114.2 %

Source: Authors

* The water unit costs are indicated as EUR per m4, thereby considering the produced volume and the pumping head.

India – Lalpura Community SPIS (Bihar)

This installation in Bihar caters for a community scheme farm with 16.2 ha based on a 4.8 kWp PV generator. The PV pumping system is employed as the main source, backed up by a diesel engine driven pump set. The PV pump was subsidised by donor funds. Cultivation includes maize, mustard, green peas, water melon and vegetables in winter and paddy in summer. All irrigation is done as basin irrigation.

The cost of the subsidised PV pumping system (70 % subsidy) was EUR 6,410 no investment was made in the irrigation system. The back-up diesel engine driven pump was valued at EUR 500.

Table 4.7: Financial Analysis of Lalpura SPIS, India (Bihar)

Parameter	Value
Cultivated Area	16.2 ha
Irrigation System	Surface (Basin)
Pumping System	Electric Pump (Diesel Engine and PV)
Cost of Diesel-Engine Pump	EUR 500
Cost of PV-Pumping System	EUR 6,410
Cost of Irrigation System	Not applicable
Cropping Pattern	Maize (6.0 ha), Mustard (6.0 ha), Millet (1.5 ha), Green Peas (1.5 ha), Water Melon (3.0 ha), Vegetables (1.5 ha), Paddy (12 ha)
Cropping Intensity	1.9
Annual Gross Margin Production	EUR 15,271
Annual System Costs	EUR 790
Annual O&M Costs	EUR 287
System Life Cycle Costs	EUR 18,800
Net Present Value (NPV) of Investment	EUR 187,484
Internal Rate of Return (IRR) of Investment	221.0 %

Source: Authors

Table 4.8: Comparison of financial parameters for different energy source options for Lalpura SPIS, India (Bihar)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 6,910	EUR 2,100	EUR 900
Annual System Costs	EUR 790	EUR 1,173	EUR 1,116
Annual O&M Costs	EUR 287	EUR 631	EUR 969
System Life Cycle Costs	EUR 15,800	EUR 23,469	EUR 23,311
Water Unit Costs*	0.0001 EUR/m^4	0.0005 EUR/m^4	0.0040 EUR/m^4
Net Present Value (NPV) of Investment	EUR 187,484	EUR 191,334	EUR 196,016
Annuity of Investment	EUR 16,346	EUR 16,681	EUR 17,090
Internal Rate of Return (IRR) of Investment	221.0 %	729.1 %	1,698.8 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

This system is based on a very low investment per ha enabling high cropping intensity, hence resulting in very high NPV and IRR values. However, the low production level would have to be taken into account in an evaluation as an average gross margin of just under EUR 950 per year would only result in a very basic farm household income. Further investments in the irrigation system (change to a pressurised system) would be required in order to increase the income level, thereby changing the viability equation.

The annuity of the investment for the example SPIS already analyzed in Table 4.7 is EUR 16,346. Building upon this, Table 4.8 provides a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation, the PV generator and pump was replaced by (i) a 8 HP diesel engine pump and (ii) by a 5 kW electric pump supplied by the grid. The modelling shows that the annual system and life-cycle costs (as well as the unit costs of water) of all options are on a quite low level due to the fact that the system hardware not only comprises the pump installation. Water conveyance within the perimeter is based on open canals. In terms of the financial viability at the given low level of production, a grid-based electric pump set would be the best option as the investment costs are considerable lower than those of the PV system. This equation would change once an intensification of production is realised (increasing annual system costs due to energy charges). The same would apply to the current comparative advantage of a diesel engine driven pump.

Similar to the previous example it has to be stated that due to the unreliability of grid supply at the location of the example SPIS (only intermittent supply 4 – 6 hours per day), the PV system offers better operational security.

Kenya – Ongata Rongai SPIS (Nairobi)

Ongata Rongai SPIS is an installation close to Nairobi with intermittent grid electricity supply. The system based on a 2.5 kWp PV generator supports a high-intensity (5 – 6 rotations/year) commercial private farm with 1.5 ha of crisp lettuce production based on hydroponic film technology. The farmer has installed two separate circulation systems with a 10 m3 capacity circulation tank for each sub-system. In addition, two overhead storage tanks buffer the system. Due to the low quality of the irrigation water, a complex reverse osmosis, filter and fertigation system was installed. The system is backed up by two conventional grid-supplied electric pumps.

The costs of the privately financed PV pumping system was EUR 8,250, the irrigation system was valued at EUR 10,000. An additional larger investment of EUR 45,000 was made in the filter and fertigation system.

Table 4.9: Financial analysis of Ongata Rongai SPIS, Kenya (Nairobi)

Parameter	Value
Cultivated Area	1.5 ha
Irrigation System	Hydroponic Film (continuous flow 18 hrs/day)
Pumping System	Electric Pump (Grid and PV)
Cost of Conventional Pumps (2)	EUR 1,700
Cost of PV-Pumping System	EUR 8,250
Cost of Irrigation System	EUR 10,000
Cost of Reverse Osmosis/Filter System	EUR 45,000
Cropping Pattern	Crisp Lettuce (6.0 ha)
Cropping Intensity	4.0
Annual Gross Margin Production	EUR 24,512
Annual System Costs	EUR 11,093
Annual O&M Costs	EUR 4,447
System Life Cycle Costs	EUR 221,860
Net Present Value (NPV) of Investment	EUR 203,880
Internal Rate of Return (IRR) of Investment	**36.1%**

Source: Authors

The single crop production gives a high gross annual margin and profitable return on investment. Key to the high NPV and the very good IRR is the high intensity of the cultivation with five to six rotations per year. In addition, the lettuce produced in hydroponic channels is larger and cleaner and thus achieves a considerably higher market price as compared to conventionally produced lettuce.

The annuity of the investment is EUR 17,775.

Table 4.10 shows a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation, the PV generator and pumps were replaced by (i) two 4 HP diesel engine pumps and (ii) by two 2.5 kW electric pumps supplied by the grid. While this is a theoretical modelling as the framework conditions may not allow a full comparison of the different energy source options (questionable suitability of diesel engine pumps for hydroponic cultivation, reliability of grid), it shows the marginal comparative advantage of the conventional pumping options over the PV-based system design:

- Annual system costs, annual O&M costs and life-cycle costs of the PV-based system are lower than the diesel engine pump and grid electricity pump options;
- NPV, annuity and IRR of the investment are slightly higher for the diesel engine and grid-based options as compared to the PV option due to their lower initial investment requirement.

While the financial viability of all three alternatives is quite comparable, the main advantage of the PV-based system in the particular case of Ongata Rongai derives from the fact that independence from the unreliable grid electricity is provided. Furthermore, operation of a diesel generator or diesel driven pump engine over the long periods required for the continuous flow hydroponic system may not be feasible.

Table 4.10: Comparison of financial parameters for different energy source options for Ongata Rongai SPIS, Kenya (Nairobi)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 64,950	EUR 58,318	EUR 58,024
Annual System Costs	EUR 11,093	EUR 14,696	EUR 12,172
Annual O&M Costs	EUR 4,447	EUR 8,160	EUR 5,823
System Life Cycle Costs	EUR 221,860	EUR 293,926	EUR 243,444
Water Unit Costs *	0.0128 EUR/m^4	0.9170 EUR/m^4	0.0141 EUR/m^4
Net Present Value (NPV) of Investment	EUR 203,880	EUR 225,263	EUR 227,297
Annuity of Investment	EUR 17,775	EUR 19,639	EUR 19,817
Internal Rate of Return (IRR) of Investment	36.1 %	42.4 %	42.8 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

Kenya – Holgojo Community SPIS (Garissa)

Holgojo SPIS is a pilot multi-user project in Garissa County fully subsidised by donors. A 19 kWp PV generator supplies a pump on a raft in Tana River. 41 smallholders with an average landholding of 0.4 ha benefit from the system, cultivating bananas, tomatoes and watermelon in low-input cropping.

The costs of the donor-financed PV pumping system was EUR 56,952, the irrigation system cost EUR 48,158. An additional larger investment of EUR 8,794 was made in the raft for the PV pump in the river.

Table 4.11: Financial Analysis of Holgojo SPIS, Kenya (Garissa)

Parameter	Value
Cultivated Area	16.4 ha
Irrigation System	Surface (Basin)
Pumping System	Electric Pump (PV)
Cost of Conventional Pumps	Not applicable
Cost of PV-Pumping System	EUR 56,952
Cost of Irrigation System	EUR 48,158
Cost of Floating Raft PV Pump	EUR 8,794
Cropping Pattern	Banana (8 ha), Tomato (4.5 ha), Melons (4.5 ha)
Cropping Intensity	1.0
Annual Gross Margin Production	EUR 60,043
Annual System Costs	EUR 12,969
Annual O&M Costs	EUR 3,018
System Life Cycle Costs	EUR 259,385
Net Present Value (NPV) of Investment	EUR 589,891
Internal Rate of Return (IRR) of Investment	51.3 %

Source: Authors

Despite the low-input agricultural practices, the scheme generates a substantial gross margin and attains high values for NPV and IRR. There is a level of uncertainty as to whether economic viability may be achieved in reality as the location of the scheme is remote and market access is limited (with high transportation costs prevailing).

The annuity of the investment is EUR 51,429.

Table 4.12 provides a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation the PV generator and the pump were replaced by (i) a 30 HP diesel engine pump and (ii) by a 25 kW electric pump supplied by a grid. The latter is a purely theoretical modelling as there is no grid supply available on site. The calculation shows the impact of the low production level.

It shows that, based on the current production level, there is no comparative advantage of the PV-based system design:

- Annual system costs are comparable to those for the diesel and grid electricity based options;
- The advantage of the PV technology with regard to the annual O&M costs is compensated by the higher investment requirements for the PV generator and pump set;
- NPV, annuity and IRR of the investment are lower for the PV-based system as compared to the options, namely diesel engine pumps and grid electricity pumps. This is due to the higher investment costs while maintaining a low level of production in the system.

The main advantage of the installed PV-based system in the particular case of Holgojo is low-maintenance energy provision in this remote area. Grid electricity is not available and diesel supply is likely to be highly unreliable. Furthermore, the irrigation system provides for ample intensification options with regard to agricultural production.

Table 4.12: Comparison of financial parameters for different energy source options for Holgojo SPIS, Kenya (Garissa)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 113,544	EUR 63,552	EUR 58,652
Annual System Costs	EUR 12,969	EUR 12,355	EUR 10,339
Annual O&M Costs	EUR 3,018	EUR 4,527	EUR 4,131
System Life Cycle Costs	EUR 259,385	EUR 247,107	EUR 206,786
Water Unit Costs*	0.0049 EUR/m^4	0.0046 EUR/m^4	0.0039 EUR/m^4
Net Present Value (NPV) of Investment	EUR 589,891	EUR 666,691	EUR 686,125
Annuity of Investment	EUR 51,429	EUR 58,149	EUR 59,820
Internal Rate of Return (IRR) of Investment	51.3 %	94.6 %	103.2 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

Morocco – Alaoui SPIS (Rabat)

Alaoui SPIS is a private investment project operating on the basis of two 14.7 kWp PV generators supplying a combination of a submersible pump installed in a deep well and a surface pump pumping the irrigation water from an open reservoir directly into the drip irrigation system. Two conventional electric pumps are installed as a back-up. The systems support the production of table grape with a direct marketing approach.

The cost of the private equity-financed PV pumping system was EUR 39,450, the irrigation system cost EUR 72,650. An additional larger investment of approx. EUR 200,000 was made in a large open farm pond.

Table 4.13: Financial Analysis of Alaoui SPIS, Morocco (Rabat)

Parameter	Value
Cultivated Area	24.0 ha
Irrigation System	Drip
Pumping System	Electric Pump (Grid and PV)
Cost of Conventional Pumps	EUR 2,500
Cost of PV-Pumping System	EUR 39,450
Cost of Irrigation System	EUR 72,650
Cost of Farm Pond	EUR 200,000
Cropping Pattern	Table Grape
Cropping Intensity	1.0
Annual Gross Margin Production	EUR 78,267
Annual System Costs	EUR 60,230
Annual O&M Costs	EUR 28,186
System Life Cycle Costs	EUR 1,204,603
Net Present Value (NPV) of Investment	EUR 462,686
Internal Rate of Return (IRR) of Investment	**21.7 %**

Source: Authors

This SPIS investment is very capital-intensive largely due to the construction of a reservoir buffering the system and reducing pumping costs. The chosen irrigation system is also of very high quality. The adopted table grape crop with direct marketing from the farm is highly profitable, resulting in robust values for NPV and IRR.

The annuity of the investment is EUR 40,339.

Table 4.14 provides a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation, the PV generator and pumps were replaced by (i) a 20 HP and a 14 HP diesel engine pump and (ii) two 15 kW electric pumps supplied by the grid. The modelling shows no significant difference between the PV solution and the conventional energy source options, despite the fact that O&M costs for the conventional pumping solutions should be higher as compared to the PV option since electricity charges and diesel costs are high in Morocco. In addition, the reinvestment requirements (replacement) for the pump sets should figure in the comparative analysis.

In this set-up, also due to the large scale, the comparative financial advantage of the PV-based system design should be apparent as annual system costs, annual O&M costs and life cycle costs of the PV-based system should be lower in comparison to the diesel engine pumps and grid electricity pumps.

The fact that the current system set-up does not live up to this expectation is attributed to a significantly oversized PV configuration, thus causing high initial investment needs with a corresponding impact on the annual system costs.

Table 4.14: Comparison of financial parameters for different energy source options for Alaoui SPIS, Morocco (Rabat)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 314,600	EUR 287,200	EUR 280,300
Annual System Costs	EUR 60,230	EUR 64,406	EUR 60,012
Annual O&M Costs	EUR 28,186	EUR 31,567	EUR 29,656
System Life Cycle Costs	EUR 1,204,603	EUR 1,288,118	EUR 1,200,241
Water Unit Costs*	0.0117 EUR/m^4	0.0125 EUR/m^4	0.0117 EUR/m^4
Net Present Value (NPV) of Investment	EUR 462,686	EUR 550,186	EUR 579,166
Annuity of Investment	EUR 40,339	EUR 47,968	EUR 50,494
Internal Rate of Return (IRR) of Investment	21.7 %	26.0 %	27.3 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

Morocco – Bougleb SPIS (Casablanca)

The private investment farm Bougleb SPIS produces oranges, lemon and pomegranate on 37 ha based on a drip irrigation system supplied by electric pumps. The PV system is supported by two 21.1 kWp PV generators. Two submersible pumps are installed in an open reservoir and pump the irrigation water directly into the drip irrigation system.

The cost of the private equity-financed PV pumping system was EUR 51,300, the irrigation system was valued at EUR 86,000. An additional larger investment of approx. EUR 200,000 was made in a large open farm pond.

Table 4.15: Financial Analysis of Bougleb SPIS, Morocco (Casablanca)

Parameter	Value
Cultivated Area	37.0 ha
Irrigation System	Drip
Pumping System	Electric Pump (Grid and PV)
Cost of Conventional Pumps	EUR 2,500
Cost of PV-Pumping System	EUR 51,300
Cost of Irrigation System	EUR 86,000
Cost of Farm Pond	EUR 200,000
Cropping Pattern	Oranges (Navel) (28 ha), Lemon (5 ha), Pomegranate (4 ha)
Cropping Intensity	1.0
Annual Gross Margin Production	EUR 111,850
Annual System Costs	EUR 74,396
Annual O&M Costs	EUR 40,136
System Life Cycle Costs	EUR 1,487,920
Net Present Value (NPV) of Investment	EUR 856,024
Internal Rate of Return (IRR) of Investment	**30.7 %**

Source: Authors

This SPIS investment is also very capital-intensive, which is largely due to the construction of a farm pond, similar to the previous example.

The production is based on high gross margins, notably EUR 2,944/ha for oranges, EUR 5,044/ha for lemons and EUR 1,054/ha for pomegranates.

The annuity of the investment is EUR 74,632.

Table 4.16 presents a comparison of the financial viability analysis with different energy source options for the example SPIS. In the underlying calculation, the PV generator and pumps were replaced by (i) a 30 HP and a 20 HP diesel engine pump and (ii) two 20 kW electric pumps supplied by the grid. Very much similar to the previous example, the modelling shows no significant difference between the PV solution and the conventional energy source options despite the fact that O&M costs for the conventional pumping solutions should be higher as compared to the PV option. In addition, the reinvestment requirements (replacement) for the pump sets should also figure in the comparative analysis of this set-up.

Here again, the comparative financial advantage of the PV-based system design should normally be apparent as annual system costs, annual O&M costs and life-cycle costs of the PV-based system should be lower in comparison to the diesel engine pumps and grid electricity pumps. Similar to the previous example, it is concluded that the PV system is oversized, thus causing too high initial investment needs with a corresponding impact on the annual system costs.

Table 4.16: Comparison of financial parameters for different energy source options for Bougleb SPIS, Morocco (Casablanca)

Parameter	Value		
	PV Generator Pump	Diesel Engine Pump	Grid Electricity Pump
Total System Costs	EUR 339,800	EUR 300,550	EUR 295,500
Annual System Costs	EUR 74,396	EUR 78,246	EUR 73,630
Annual O&M Costs	EUR 40,136	EUR 44,058	EUR 41,496
System Life Cycle Costs	EUR 1,487,920	EUR 1,564,929	EUR 1,472,606
Water Unit Costs *	0.0108 EUR/m^4	0.0133 EUR/m^4	0.0107 EUR/m^4
Net Present Value (NPV) of Investment	EUR 856,024	EUR 965,090	EUR 988,637
Annuity of Investment	EUR 74,632	EUR 84,141	EUR 86,194
Internal Rate of Return (IRR) of Investment	30.7 %	36.9 %	38.0 %

Source: Authors

* The water unit costs are indicated as EUR per m^4, thereby considering the produced volume and the pumping head.

General Assessment

All of the selected SPIS represent a different context and the selection also caters for different target groups. It is convincing to see that all of the examples are financially viable. The degree of return on investment differs between the examples largely due to their size.

The example calculations also show the importance of adopting high-value crops to an increasing extent in parallel with the investment. SPIS planning and design must therefore not be based only on PV generator and pump design. The irrigation system and consequently the cropping patterns have to be adapted in order to achieve the required positive cash flow.

PV-based irrigation pumping solutions are also highly competitive in terms of their financial viability if compared with conventional pumping solutions, such as diesel engine driven pumps or grid supplied electrical pumps. However, due to the comparatively high capital requirements, correct system dimensioning and intensified agricultural production are required in order to achieve returns on investment that are higher than those of conventional solutions. Hence it must be avoided to oversize systems, which happens easily in a subsidised environment.

4.3 Business Models for SPIS

Find a short description of this chapter in the SPIS Toolbox Module INVEST – Credit Policy: Select/Develop Suitable Financial Instruments

and use the INVEST – Farm Analysis Tool to create your Farm Income Statement on Energypedia.

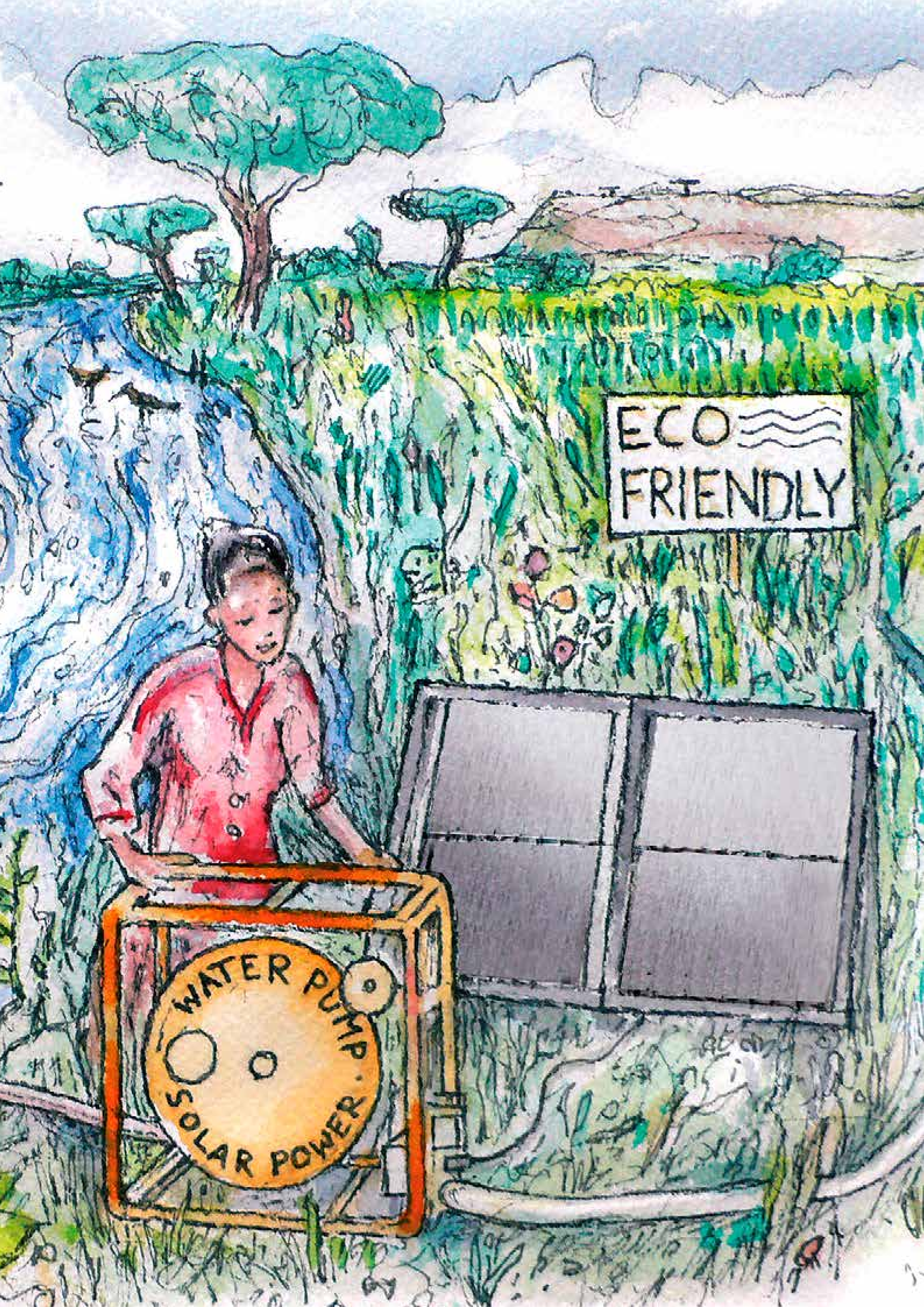
In principle, Solar Powered Irrigation Systems do not require a particular business model that differs from other irrigation technology options. The key determining factor in any technology choice is the investment need and the repayment options for the capital requirements. As mentioned above (see section 4.2), the initial capital requirements for an SPIS are considerably higher than those for investment in conventional pumping solutions.

SPIS found around the world are installed and operated on a large range of business models. The majority of installations are based on individual investments of farm owners. In addition, group schemes exist for smallholders and cooperatives. Group schemes are an interesting option for smallholders with lacking access to financial services. In the business models that exist, a fundamental distinction has to be made between three main aspects to be considered for any approach:

- Ownership model: individually owned, collectively owned, leased/rented from a third party owner;
- Operation model: individually operated, collectively operated, operated by a service provider;
- Financing model: individually equity and loan financed, collectively equity and loan financed, subsidised and granted, leased/rented.

Combinations of the above aspects are diverse. Larger farms with strong market access tend to invest with a business model involving equity or loan based individual investment, individual ownership and individual or outsourced operation. The smaller the farm, the more important the financing model becomes – medium and small farm households tend to opt for subsidy and grant financing while still maintaining individual ownership and operation. Smallholders are often required to group and opt for collective ownership and operation based on subsidies and grants.

5 Ecological impacts and sustainability of SPIS


ECO FRIENDLY
WATER PUMP
SOLAR POWER

5 Ecological impacts and sustainability of SPIS

5.1 Ecological Impacts

Find an overview of some of the environmental and socio-economic impacts of SPIS in the SPIS Toolbox Module IRRIGATE – Assess Environmental and Socio-Economic Impacts on Energypedia.

Apart from being a cost-competitive and reliable source of electricity, photovoltaic systems generate a number of ecologic benefits.

Over the past decade, the global photovoltaic market has grown at a remarkable rate. In fact, solar photovoltaic is on the way to become a major global energy source. According to the European Photovoltaic Industry Association (EPIA), the world's cumulative installed PV capacity was almost 140 GWp at the end of 2013, an amount capable of producing at least 160 terawatt-hours (TWh) of electricity every year. This is the equivalent to the electricity produced by 32 large-scale coal power plants. PV can hence be an efficient tool to replace conventional power generation and reduce climate change impacts (EPIA, 2014).

5.1.1 The Carbon Footprint of Photovoltaic Systems

Photovoltaic systems have a very low carbon footprint. The carbon footprint is expressed in terms of the amount of carbon dioxide (CO_2) and its equivalents to other greenhouse gases, emitted during the lifetime of the solar system per kilowatt-hour (kWh) (Fthenakis et al. 2011).

$$\textit{Carbon Footprint [g } CO_2 \textit{ eq/kWh]} = \frac{\textit{Total emission [g } CO_2 \textit{ eq]}}{\textit{Cumulated electrical energy produced over lifetime [kWh]}}$$

A quantitative methodology known as Life Cycle Analysis (LCA) is used when calculating the carbon footprint. LCAs help determine all environmental burdens of a product from 'cradle to grave' and facilitate comparisons of energy technologies.

Thanks to raw material savings and improvements in the manufacturing process of solar panels, the carbon footprint of PV has decreased by approximately 50 % in the last decade. Depending on the location, solar cell efficiency and technology, it ranges from 16 to 32 g CO_2 equivalent per kWh, compared to an average of 600 g/kWh produced with the current global electricity mix (Goldstein, 2019).

An off-grid solar system (i.e. SPIS) which replaces a typical diesel generator unit will save about 1 kg of CO_2 per kWh of output. This takes all emissions during the life cycle of the PV system into account (EPIA, Greenpeace 2011).

Example: In the Atacama Desert of Chile the average daily global irradiation amounts to 6.9 kWh/m^{2}d. Under these conditions a 1.0 kWp PV system will produce about 5.39 kWh of electric energy per day. With a lifetime of 25 years about 48,000 kWh will be generated and thus 48,400 kg of CO_2 emissions mitigated.

It is important to mention that PV systems do not emit any greenhouse gases during their operational lifetime. Emissions are mainly linked to the energy required during the manufacturing process and the recycling of the PV system after its useful lifetime. It is expected that the carbon footprint of PV electricity will further decrease as production technology advances.

5.1.2 Energy Payback Time

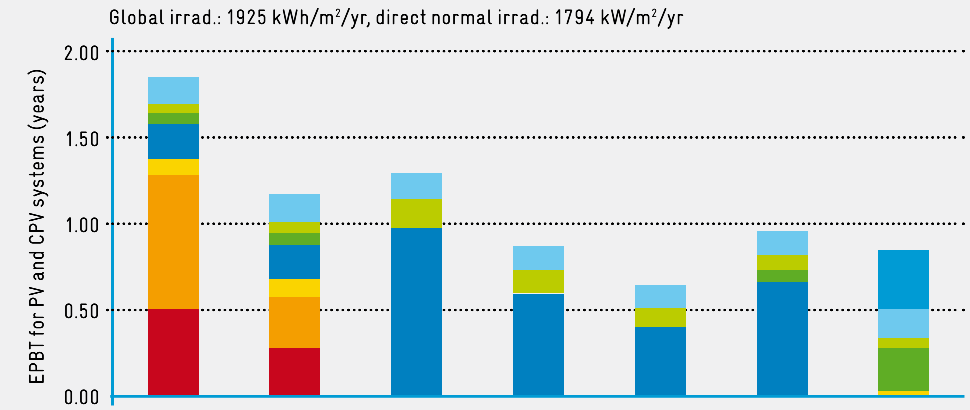
The Energy Payback Time (EPBT) of photovoltaic systems is an important criterion in understanding the sustainability of PV. The EPBT is calculated by dividing the energy required to manufacture the PV panel by the energy which it supplies annually – this gives us the time, in years, needed by the PV panel to pay back the energy required to manufacture it.

$$\textit{Energy Payback Time [years]} = \frac{\textit{Energy input [kWh]}}{\textit{Energy output [kWh/year]}}$$

Recent EPBT calculations have been made in several R&D projects funded by the European Union (EPIA, 2011) and the National Renewable Energy Laboratory (NREL 2012).

The results clearly show the improvements made in production technology. Material usage for silicon cells has been reduced significantly during the last 10 years from around 16 g/Wp to 6 g/Wp due to increased efficiencies and thinner wafers (de Wild-Scholten, Cassagne 10/3/2013).

Depending on the type of PV cell technology and geographical location, the EPBT of solar systems at present is between 0.7 and 2 years (Fraunhofer Institute for Solar Energy Systems ISE 7/28/2014).



Technology	Mono-S	Multi-Si	a-Si	pm-Si	CdTe	CIGS	CPV
Module composition	Glass-EVA-backsheet	Glass-EVA-backsheet	Glass-EVB-glass	Glass-EVA-glass	Glass-EVA-glass	Glass-EVA-or PVB-glass	Flatcon CX-75 CPV-System
Status	2011	2011	2008-2011	2013 estiamte	2010-2011	2011	2011
Efficiency	14.8%	14.1%	7.0%	10.0%	11.9%	11.7%	24.1%
Scale of production	-300 MWp	-300 MWp	33-45 MWp	120 MWp	963 MWp	20-66 MWp	-

Figure 5.1: EPBT for different PV cell technologies in Catania, Italy

Adapted from de Wild-Scholten & Cassagne, 2013

The energy payback time is even shorter in Sunbelt countries with higher solar irradiance. For example, a PV system with multi-Si modules located in India has an EPBT of about one year. Assuming a lifespan of 25 years and more, this kind of system can generate twenty-five times the energy needed to manufacture it.

5.1.3 Recycling of Solar Panels

Recycling of solar panels has positive effects on the entire energy and environmental balance of PV technology.

In the light of the European Waste Electrical and Electronic Equipment (WEEE) directive and the Restriction of the Use of Certain Hazardous Substances (RoHS) directive in electrical and electronic equipment, the PV industry started working to create solutions that reduce the impact of PV on the environment at all stages of the product life cycle.

As early as 2007, leading European manufacturers established a voluntary, industry-wide take-back and recycling programme called PV CYCLE. Similar developments in PV recycling in other growing markets such as Japan, China and USA are ongoing.

PV panels are designed to generate clean, renewable energy for +25 years. As the first significant quantities of solar panels were installed in the 1990s, significant numbers of discarded PV panels are expected in the next 1015 years (Larsen 2009).

Figure 5.2: End-of-life PV panels Source: PV CYCLE, 2015

Meanwhile, recycling technologies exist for almost all types of photovoltaic panels and recycling rates of up to 95 % are achievable (Larsen 2009).

The environmental benefits and burdens of recycling have been assessed through several pilot projects. The projects clearly show that the environmental benefits of recycling outweigh the additional environmental burdens (heat, chemical treatment to recover the basic materials enclosed in the panels) that recycling of the panels demands (EPIA, Greenpeace 2011).

5.1.4 Reducing the Risk of Groundwater Depletion

Find an overview of the ecological impacts within water resource management in the SPIS Toolbox Module SAFEGUARD WATER – Understanding Groundwater on Energypedia.

Increasing population numbers, expanding areas of irrigated agriculture and economic development are drivers of the ever-increasing demand for water worldwide. Although globally such demand can be met by surface water availability, regional variations are large, leading to water stress in several parts of the world. In regions with frequent water stress and large aquifer systems, groundwater is often used as an additional water source. If groundwater abstraction exceeds the natural groundwater recharge for extensive areas and long times, overexploitation or persistent groundwater depletion occurs (Wada et al. 2010).

In irrigated agriculture, farmers usually try to fully utilise existing land and water resources. If power supply for water pumps is available 24 hours on seven days a week, very often well capacities will be exploited to maximum limits.

Figure 5.3 shows the typical behaviour of a well during pumping. After pump start-up, the static water level will generally decrease. This 'draw down' of the water level is dependent on the water discharge and stability of the aquifer. The resulting dynamic water level will change the hydraulic head and may vary during pumping.

If the water discharge regularly exceeds the well capacity, there is a risk that the well may suffer damage. The risk of groundwater depletion may be reduced by using photovoltaic water pumps as they can only be operated during daytime in a time window of about 10 hours. Figure 5.4 shows the measured dynamic water level (dark green) and daily water flow (light green) of a Solar Powered Irrigation System installed in the Atacama Desert of Chile.

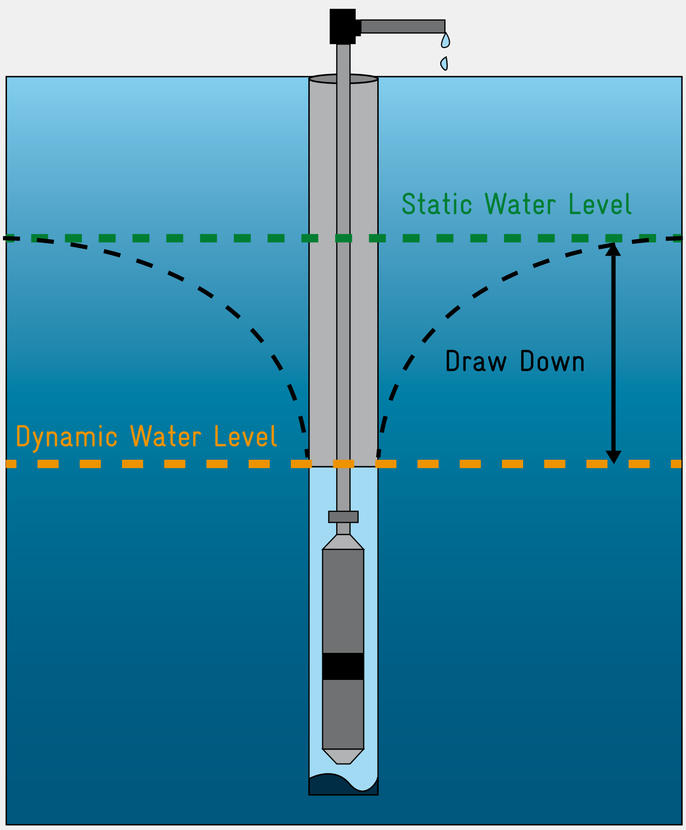


Figure 5.3: Water level variation in a well during pumping
Adapted from ah Advice International, 2015

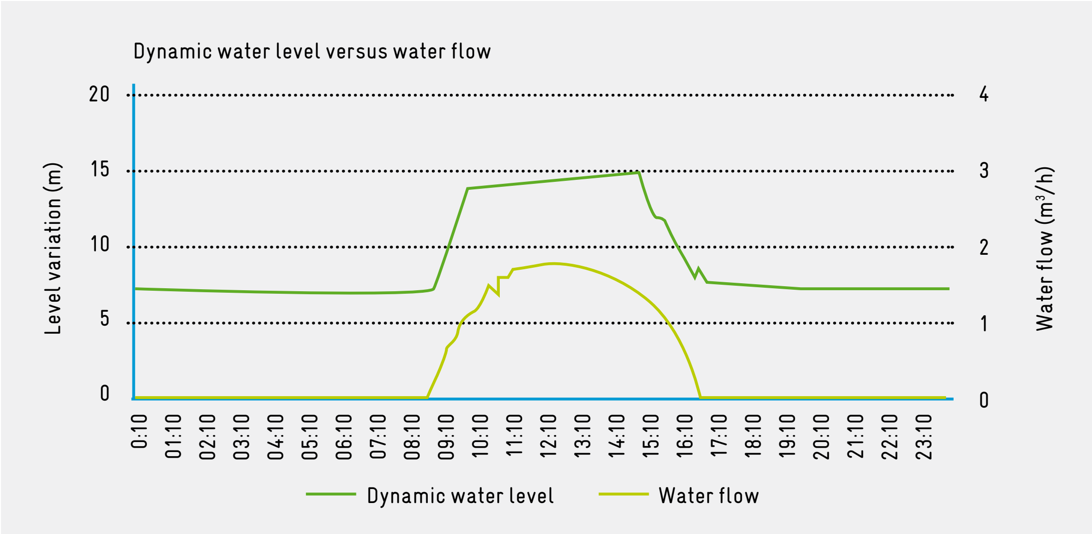


Figure 5.4: Example of dynamic water level variation in Chaca Valley, Chile

Adapted from ah Advice International, 2015

During pumping hours, the water level decreases dependent on the extraction rate. After sunset, the aquifer has enough time to recover from daily water abstraction. However, an important pre-condition is proper pump design which takes the site-specific well capacity into account.

There is a widespread concern that solar-powered irrigation (and other forms of PV-based water abstraction) may lead to an over-utilisation of available water resources. The underlying assumption is often (i) the availability of 'free energy' or 'low cost energy' and (ii) the employment of PV technology in greenfield irrigation development.

The experience made from the stocktaking and analysis exercise suggests that the vast majority of solar-powered pumping systems are actually introduced to substitute conventional pumping solutions. The financial analysis undertaken for example SPIS (see section 4.2) also reveals that an economic advantage of PV pumping solutions over conventionally driven pump sets is not given in all cases.

A few facts with regard to PV pumps need to be reiterated:

- PV pumps can only be operated during a limited period during the day (about 10 hours);
- PV pumps have to be sized larger than conventional pumps in order to compensate for the lower performance in low radiation periods, which contributes to their comparatively high investment costs;
- From an agronomic and economic point of view, PV pumps are best employed in intensive high-value cropping under water-saving irrigation approaches.

There are hence technical and economic barriers to an inherent risk of over-utilisation of water resources through the employment of solar-powered pumps. In order to be able to achieve a higher degree of water abstraction by a PV pump, significant investment is required to (i) install a large pumping capacity and (ii) establish a corresponding storage facility to host the surplus water not needed for irrigation purposes during daytime. Usually, a corresponding investment would follow economic principles. With the exception of the case of greenfield development, such an investment would be oriented towards the existing irrigation potential, which constitutes a limiting barrier to the technical expansion of a system.

Over-utilisation of water resources is, in principle, possible with any pumping option. The primary key to avoid unsustainable exploitation of ground and surface water resources is the legal and regulatory framework, hence water resource planning and management, water abstraction licensing and monitoring, and last, but not least, effective implementation of sanctions related to water resource management as well as the avoidance of unconditional subsidisation (also see **section 5.3**).

5.1.5 Avoidance of Groundwater Contamination

A prime problem associated with using diesel generators for irrigation water supply is the danger of soiling groundwater with fuels and lubricants. A diesel engine produces approx. 10 g of waste oil per kWh of delivered energy. This is about 300 kg of waste oil over the lifetime of the generator. In developing countries, an environmentally sound disposal of such amounts is unfortunately not guaranteed (Fritsche, Lenz 2000).

Figure 5.5 shows a diesel-powered surface pump installed on a farm in India. The ground close to the generator is covered with a layer of waste oil. This widespread type of installation involves unintended pollution, as escaping fuel and lubricant reach the soil and groundwater directly. In this case, one litre of waste oil can contaminate up to 1,000 m^3 of groundwater such that it is no longer usable for drinking water purposes. When PV irrigation systems are employed this problem is completely eliminated (Hahn, 2015).

Figure 5.5: Example of a diesel generator causing groundwater and soil contamination in Bihar, India

Source: GIZ / Andreas Hahn, 2015

5.1.6 Reducing Soil Salinization

Find some advice on this topic in the SPIS Toolbox Module IRRIGATE – Assess Environmental and Socio-Economic Impacts – Soil Salinity Assessment on Energypedia.

The relatively high investment costs of Solar Powered Irrigation Systems lead to a strictly demand-oriented system design. In combination with water-saving irrigation technologies (e.g. drip), no excess amounts of water will be applied to the field. Thus, the typical long-term risks of conventional surface irrigation such as the increase of the field water level with subsequent water-logging and salting of soil is reduced.

5.1.7 Avoidance of Noise and Exhaust Fumes Emissions

Like many types of rotating machinery, reciprocating engine-powered generator sets produce noise and vibration. Whether these generators run continuously or only occasionally in standby applications, their operating sound levels can approach 100 dB(A) or more. The noise produced by generator sets is usually annoying or can even be harmful to health.

Typical noise levels associated with various surroundings and noise sources are illustrated in Figure 5.6.

The noise level of typical generator sets can be compared to heavy street traffic or a jet passing by at a flight level of 300 m (Aaberg 2007).

Although generator manufacturers provide strategies for reducing generator set noise (e.g. acoustic insulation, exhaust silencers), the high cost of retrofitting a site for noise reduction usually hampers implementation, especially in developing countries.

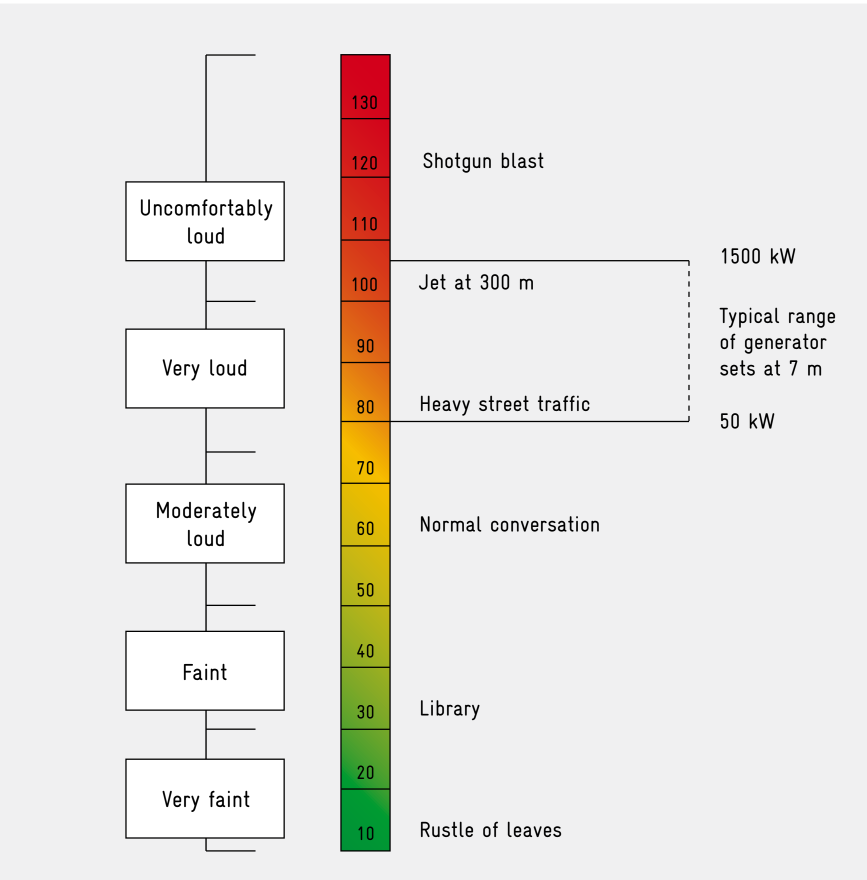


Figure 5.6: Typical noise levels of different noise sources

Adapted from Aaberg, 2007

Besides noise emission, exposure to exhaust fumes from generator sets is widespread in the developing world. Most conventional generators run on diesel fuel derived from crude oil. The exhaust from diesel engines is made up of gases and soot. The gas portion of diesel exhaust is mostly carbon dioxide, carbon monoxide, nitric oxide, nitrogen dioxide, sulphur oxides, and hydrocarbons, including polycyclic aromatic hydrocarbons (PAHs). The soot (particulate) portion of diesel exhaust is made up of particles such as carbon, organic materials (including PAHs), and traces of metallic compounds (American Cancer Society 2015).

People (e.g. farm workers) are exposed to diesel exhaust mainly by breathing in the soot and gases, which then enter the lungs. According to the International Agency for Research on Cancer (IARC) which is part of the World Health Organization (WHO), diesel exhaust is classified as carcinogenic to humans. Furthermore, diesel exhaust is believed to play a role in other health problems, such as eye irritation, headache, asthma, heart disease, and possibly immune system problems.

Compared to fossil-fuelled energy technologies, photovoltaic generators do not produce any noise or exhaust during operation. This is a feature a farmer replacing a noisy and stinky diesel generator with PV will definitely appreciate.

In summary, Solar Powered Irrigation Systems are significantly less of an environmental burden than reference systems powered by diesel engine pumps or generators.

5.2 Sustainability of SPIS

5.2.1 Technical Reliability of System Components

Find some complementary information in the SPIS Toolbox Module MAINTAIN – Establish & Refine Maintenance Plan on Energypedia.

The operating principle behind any photovoltaic irrigation system is simple: A solar generator provides the energy for an electric motor pump, which in turn pumps water into an elevated water tank or injects the water directly into the irrigation system. A specific characteristic of PV pumping systems is that generally no battery back-up is required. A water tank can be employed for storage, reducing maintenance costs and increasing the overall system reliability.

Common to most system configurations is that they are effectively maintenance-free and usually meet all expectations with regard to technical reliability. High system reliability is particularly important in combination with water-saving irrigation techniques.

Multi-year field tests conducted by GIZ have proven that a high degree of system reliability can be achieved, even under the harsh environmental conditions of many developing countries. Despite the usual ‘teething troubles’ associated with the introduction of a new technology, about 100 solar pumps tested in a worldwide demonstration programme were found to have a mean availability of 99 % – a degree of reliability which other pump technologies hardly achieve.

In recent years, thousands of Solar Powered Irrigation Systems have been sold and manufacturers have gained extensive field experience to further improve their products. The field studies conducted in the framework of the present stocktaking and analysis exercise confirmed the high technical reliability of SPIS. Nevertheless, a precondition for safe operation and longevity is that all system components fulfil minimum quality requirements.

Solar Generator

Solar panels used in Solar Powered Irrigation Systems are usually standard components that have been used and tested for many years in residential, industrial and off-grid applications. Installed under the harsh environmental conditions of developing countries, the panels are constantly exposed to high temperatures and UV-irradiance, dust, humidity and rain. This puts a lot of stress on embedding materials and electrical connections. Therefore, it is important to select only high-quality products which at least meet the standards of the International Electrotechnical Commission (IEC).

Standard panels are usually certified to IEC 61215 (crystalline) and IEC 61646 (thin-film). These approval certificates have become generally accepted worldwide as one of the quality marks for solar panels. IEC 61215 standard testing, however, does not assess the durability of solar modules for 25 years. Therefore, additional testing of the solar modules is preferred. Some manufacturers even exceed IEC standards and simulate the aging of solar panels in climate chambers to ensure that modules satisfy the highest quality criteria upon leaving the production line. By changing the temperature and humidity in climate chambers, the aging of solar modules under extreme conditions can be simulated in a climate chamber.

A further important assessment criterion is the experience of the manufacturer and the given warranty period. Standard panels typically come with a 10 year product guarantee and a linear 25 year performance warranty which guarantees at least 80 % power output by the end of the 25th year.

Cabling

For the electrical installation of a photovoltaic system, only such wiring and cabling should be used that meet the requirements for this application. A distinction is made between panel or string cables, the DC main cable and the AC connection cable. The electrical connecting cables between the individual panels of a PV generator and the generator combiner box are generally used outdoors. In order to ensure earth fault and short-circuit proof cable laying, the positive and the negative poles may not be laid together in the same cable (DGS 2013).

Figure 5.7: Panel and string cables for outdoor applications such as SPIS

Source: GIZ / Robert Schultz, 2014

Single-wire cables with double insulation have proven to be a practicable solution and offer high reliability. Their main features are that they are UV and weather resistant and are suitable for a wide temperature range (e.g. 55°C to 125°C).

Some manufacturers even offer cables covered with metal mesh where the shielded cable not only provides protection against rodents but also improves protection against over-voltages. All cables should be laid in cable conduits and fixed with black UV-resistant cable ties.

PV Array Combiner Box

The individual strings of solar panels are connected together in the PV array combiner box. The PV array combiner box contains supply terminals and isolation points and, if required, string fuses and string diodes. Surge arresters are often installed in PV array combiner boxes to divert excess voltage to earth/ground. Due to the high operating voltages of solar-powered water pumps, proper earthing is essential, which must be done by a qualified electrician (DGS 2013).

The combiner box should be executed to Protection Class II and demonstrate a clear separation of the positive and negative sides within the box. If mounted externally, as in many SPIS installations, it should be protected to at least IP 54 (DGS 2013).

Mounting Structures

In most Solar Powered Irrigation Systems, PV panels are installed in the open field and therefore require a sturdy and weather-resistant mounting structure. Today's mounting systems are made of galvanised steel or aluminium profiles. The foundation of the mounting structure is mainly determined by the soil conditions at the installation site.

Metal supports that are pile-driven into the ground are generally recommended for larger systems. They make the utilisation of concrete foundations redundant and thus save both labour and material cost. However, in developing countries simple concrete foundations are state of the art for smaller installations and represent an appropriate solution if static requirements are met.

Figure 5.8: Example and string cables for outdoor applications such as SPIS
Source: GIZ / Robert Schultz, 2014

Figure 5.9: Example of an annually operated one-axis solar tracker mounted on concrete foundation in Rajasthan, India

Source: GIZ / Andreas Hahn, 2015

For fixing of PV panels and profiles, specially developed brackets, screws, washers and nuts are used. To avoid galvanic corrosion, it is important to select materials with similar corrosion potentials or to break the electrical connection by insulating the two metals from each other. If these basic rules are observed, fixed mounting systems will have a high reliability and a lifetime similar to the solar panels (+25 years).

In some SPIS applications it is recommended to use solar trackers (see section 2.1.2). Solar tracking systems are utilised to continually orient photovoltaic panels to the sun and help to increase the overall efficiency of the system. Nevertheless, the technical reliability of tracking systems is generally lower compared to fixed installations because moving parts and motors are included, which will require regular maintenance, repair work or replacement of damaged parts.

To enhance the reliability of tracked PV generators, manual tracking can also be an interesting alternative. In this case, the motor-less mounting system is movable but tracking is done by the farmer (e.g. manual tracking three times a day). Some manual tracking systems produced in India even allow for seasonal adjustment of the tilt angle.

Pump Controller/Inverter

The pump controller is the link between the PV generator and the motor pump and adjusts the output frequency in real time according to the prevailing irradiation levels. Modern controllers incorporate high-efficient power electronics and utilise Maximum Power Point Tracking (MPPT) technology to maximise power use from the PV generator (see section 2.1.3).

Additional features to increase system reliability should include over and under voltage protection as well as protection against reverse polarity, over load and over temperature.

As controllers/inverters are sensitive to overheating, they have to be installed in a place where faultless operation is guaranteed. Factors to be considered include the ambient temperature, the heat dissipation capability and the relative humidity.

For service and maintenance purposes, the controller should be easily accessible and it must also be provided with a circuit breaker between the PV generator and controller.

In recent years, innovations in DC/AC inverter technology have led to the development of specially designed pump inverters that can drive conventional AC motors. It is important to know that non-compatible inverter/motor combinations may reduce the expected lifetime of the conventional AC motor. Therefore, well matched and tested controller/motor combinations are the preferred option to increase system reliability.

In summary it can be stated that standardised quality controllers have proven to be very reliable. As a precondition, the controller and motor pump need to be well-matched and the installation must be done according to the manufacturer's specification.

Electric Motor

Electric motors of solar water pumps are generally powered by direct current (DC) sources, or by alternating current (AC) sources. DC motors are mainly used for small to medium size irrigation schemes, while AC motors gain importance in applications where higher output/head combinations are required.

Since DC motors tend to have overall higher efficiency levels than AC motors of a similar size, they are often the first choice of solar pump manufacturers. Especially water-filled brushless DC motors are gaining importance because they are maintenance-free and do not suffer from the frequent starts/stops typical in solar-powered systems.

Some solar pumps are still equipped with relatively cheap brushed DC motors. The main disadvantage of brushed motors is that brushes are subject to wear and tear and need to be replaced in regular intervals (approximately every 2 years). Therefore, in terms of system reliability, the use of brushed DC motors is not recommended because a regular maintenance in remote areas of developing countries cannot be assured.

Water Pump

Solar water pumps are generally constructed from non-corroding stainless steel and are designed to pump clean water without any solids and fibres. Under such optimal conditions, solar water pumps may easily reach a lifetime of +10 years. In real life this is usually not achieved.

In fact, the lifetime of a submersible motor pump strongly depends on the water and installation quality. In very poor wells and boreholes with high sediment content, the hydraulic part of the water pump may already have to be replaced after 2–3 years. Figure 5.10 shows an example of a dug well in Chile serving as water source for two solar pumps fixed with simple ropes.

Figure 5.10: Example of difficult conditions for solar water pumps installed in a dug well — Source: GIZ / Andreas Hahn, 2015

Besides the bad water quality in the dug well, the risk is high that the motor is surrounded by mud which may result in an overheating and finally burn-out of the motor. If the pump is not protected against dry-running, there is an additional risk that the pump will be destroyed. Fortunately, poor wells like this are an exceptional case. If the pump is installed in a drilled well with a proper well casing (and thus reduced sediment intrusion), submersible pumps may reach lifetimes of 7–10 years (Hahn, 2015).

Using control switches (such as float switches in water tanks and wells), submersible pumps can be operated in automatic mode. In contrast, surface-mounted pumps usually require the attendance of an operator who regularly checks the priming behaviour of the surface pump. Although the use of primary chambers and non-return valves can prevent loss of prime, in practice self-start and priming problems are experienced. Therefore, surface pumps are considered to be less reliable than submersible pumps.

5.2.2 Detected Failures and Trouble Shooting

For an appropriate maintenance, find an overview in the SPIS Toolbox Module MAINTAIN on Energypedia.

Due to the fact that the market for Solar Powered Irrigation Systems started booming around 2010, most installations do not have a long track record. The majority of all systems analyzed within the scope of this study were installed within the past nine years.

Furthermore, two brands dominate the case studies – Lorentz and Grundfos. One reason is that the site visits were organised and conducted with the assistance of international representatives of both companies. On the other hand, it emerged during the study that these two experienced companies currently dominate the SPIS markets in the selected target countries.

Taking the expected strong market growth into account, it is foreseeable that more manufacturers will enter the market and try to win market shares. Local manufacturers active in the selected target countries are described in detail in **section 7**.

As outlined above, a precondition for high technical reliability is that all system components fulfil minimum quality and safety requirements. Due to a lack of experience with SPIS technology and sometimes missing standards for system design and installation, system integrators and installers are often overtaxed by the task of planning and installing Solar Powered Irrigation Systems properly.

The analysis in the selected target countries generally confirmed the high technical reliability of individual system components. Nevertheless, the interplay of all system components must not be underestimated. The following examples clearly show the importance of using only high-quality products and that there is still need for technical training and component improvement.

Examples of Serious Component Failures

The most serious technical defect encountered was a burned-off solar panel of Chinese origin at Kaijado in Kenya.

The fire was probably caused by a hot spot effect. A hot spot situation arises when a solar cell within a panel generates less current than the string current of the panel or of the PV generator. This occurs when the cell is totally or partially shaded, damaged, or when cells are electrically mismatched (as typically found in low quality panels).

Figure 5.12: First signs of delamination due to humidity ingression
Source: GIZ / Andreas Hahn, 2015

In Chile, one solar panel started to show signs of delamination. Delamination is the detachment of layers due to humidity ingression. Bubbles appearing in the panel are a sign of delamination. If the white stains become larger, solar cells may corrode and loose efficiency.

Figure 5.11: Hot spot effect encountered on no-name panel (Chinese origin) in Kenya
Source: GIZ / Andreas Hahn, 2015

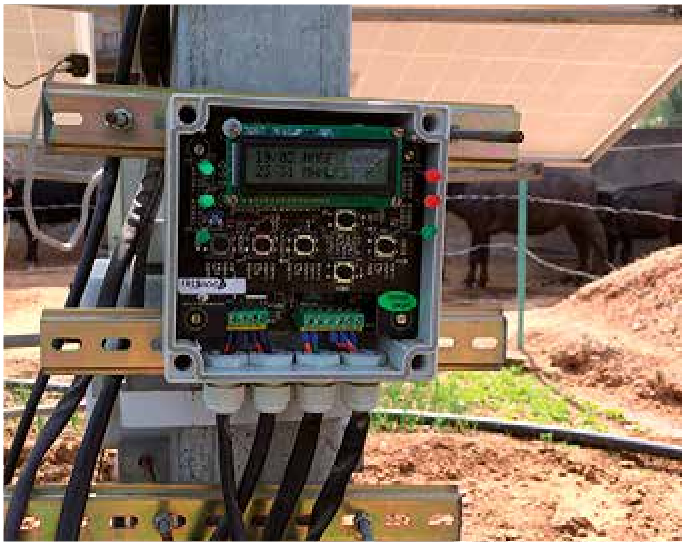


Figure 5.13: Defective tracker control unit in India
Source: GIZ / Andreas Hahn, 2015

Tracking systems are widely used in India. Nevertheless, some locally produced controls have not yet reached technical maturity. This was also confirmed by some farmers who were forced to manually operate the tracker motor.

In case of public tenders, the trackers come with a 5 year warrantee and some system integrators now tend to replace the automatic trackers with a manual solution.

Figure 5.15: Horizontal installation of panels limits self-cleaning of solar generator
Source: GIZ / Andreas Hahn, 2015

Examples of Faulty Planning/Design

In Emukutan in Kenya, a filtering system was installed because the water quality was not as good as expected by the donor organisation. The retrofitted filter consists of four chambers filled with sand through which the water is pumped. It is most likely that the filter causes a high pressure loss which was not considered in the initial design process. As a result, the solar pump already stops working at about 3 pm and does not meet the drinking and irrigation water demand of the Maasai village.

Figure 5.14: Retrofit filter system in Emukutan village, Kenya
Source: GIZ / Andreas Hahn, 2015

In another donor-sponsored system in Kaijado, Kenya, the solar panels are mounted on a fragile metal support structure at a height of about 6 m above ground level to protect against theft. The solar panels are not tilted at all so that dirt accumulates on the flat surface. Besides using a no-name Chinese panel manufacturer, this may also have caused the hot spot illustrated in Figure 5.11.

Although the PV generator at Holgojo Farm, Kenya is located close to the equator, there is a risk that the fence will shade the solar panels, especially in the early morning and late afternoon. Already in the planning phase such negative effects should be excluded.

Figure 5.16: Shadowing of solar panels by fence in Kenya
Source: GIZ / Andreas Hahn, 2015

Examples of Installation Mistakes

A problem that can be observed frequently in electrical installations is the poor sealing of electric casings. Ants and other small animals such as Geckos like to build their nests in junction boxes and may easily destroy electronic components (e.g. by formic acid). Therefore, proper sealing of all openings (e.g. with cable glands) is essential.

Figure 5.17: Unsealed junction box in Chile inhabited by ants   Source: GIZ / Andreas Hahn, 2015

Some electrical components used in Solar Powered Irrigation Systems (such as controllers and switches) are installed outdoors. Only such components should be used that meet the requirements for this application.

Figure 5.18: Non water-proof circuit breaker in India   Source: GIZ / Andreas Hahn, 2015

The circuit breaker shown in this figure is not the right choice for a safe disconnection of the PV generator and the motor pump. The example in Figure 5.19 shows an unprofessional and dangerous connection of the pump controller and water pump.

Figure 5.19: Example of a dangerous cable connection   Source: GIZ / Andreas Hahn, 2015

Although the installer used rubber tape to insulate the wires, the cable connection is still exposed on the ground. Electrical safety is questionable, particularly during irrigation or in the Monsoon season.

Figure 5.20: Galvanic corrosion of a manual tracking system in India   Source: GIZ / Andreas Hahn, 2015

Over time, metal objects are subject to rust and corrosion. Corrosion is normally associated with non-precious metals such as steel, zinc and aluminium. In the presence of air, water or salt, these metals will corrode rapidly and need to be covered with a protective sealant. This figure shows the bed-plate of an Indian tracking system. After one year of operation, the unprotected screws, washers and nuts used to fix the tracker to the bed-plate are heavily corroded.

Figure 5.21: Limited heat dissipation capability of corroded controller housing Source: GIZ / Andreas Hahn, 2015

The metal housing of the pump controller shown in this figure is also extensively corroded. Furthermore, the housing has no natural ventilation and after closing its front door, overheating of the controller is expected. Losses in DC cables could be reduced by simply cutting off the excess cable.

Examples of Inadequate Maintenance

Solar panels are generally self-cleaning, but in particularly dry areas or where panel tilt is minimal, dust and other substances such as bird droppings can build up over time and impact on the amount of electricity generated by a panel.

Given the nature of good quality solar panel glass, clean water and a little scrubbing with a cloth covered sponge or soft brush should remove the most stubborn grime, as the latter will reduce the power output of a panel.

Solar panels produce less power when they are shaded and should ideally be situated where there will never be any shadows on them. A shadow falling on a small part of a panel (e.g. a bunch of grass shown in Figure 5.23) can have a surprisingly large effect on output. This is because the cells within a panel are normally all wired in series, so that the shaded cells will affect the current flow of the whole panel.

Figure 5.22: Accumulated grime at the lower edge of a PV panel Source: GIZ / Andreas Hahn, 2015

Figure 5.23: Example of shadowing by uncontrolled ground vegetation Source: GIZ / Andreas Hahn, 2015

5.2.3 Availability of SPIS Components on Local Markets

Find some considerations to make to find a good SPIS supplier in the SPIS Toolbox Module DESIGN – Pre-select Potential Suppliers on Energypedia.

A prerequisite for sustainable dissemination of SPIS technology is the availability of all relevant system components in the local markets. Often driven by government-funded dissemination programmes, manufacturers of irrigation equipment and solar water pumps have started developing emerging markets and have established first local distribution and service structures.

Meanwhile, dependent on the size and maturity of these emerging markets, all components of SPIS can be purchased locally. Water-saving irrigation technologies were already introduced many years ago and are usually sold by agricultural service providers. However, many of these products still have to be imported from abroad (e.g. from Israel).

The market for solar water pumps for irrigation only started growing around 2010. Thus, individual system components can hardly be found in the portfolio of traditional agricultural service providers. Instead, pump manufacturers select specialised PV distributors and retailers to market their products in the target markets of Chile, India, Morocco and Kenya.

Today many well-known brands are still manufactured in Europe, the United States and China and have to be imported. The mid-term goal of development cooperation must be to enable developing countries with high market potential to install, operate and maintain SPIS with a minimum of imported components.

Local Production of System Components

Especially in public tenders, many governments give priority to locally manufactured components or systems to protect their home markets. From the manufacturer's point of view, local production of system components requires a critical market size to be economically viable.

Local manufacturing of PV modules is often the first fit, for it is the most visible, valuable and sophisticated component. While the production of silicon wafers and solar cells is high-tech, the encapsulation of panels is less complicated and thus can readily be implemented in emerging markets.

Nevertheless, a number of important considerations often make it more efficient to purchase PV panels on the international market:

- ➔ Beneficial local manufacturing of panels requires a relatively large local market (>50 MWp/yr);
- ➔ The technology is changing quickly. Only large companies can follow such changes and provide the necessary investment capital;
- ➔ The profitability of manufacturing PV panels is not as good as the demand for the product would suggest;
- ➔ Economies of scale are forcing manufacturers to expand production capacities to >1 GWp/yr to be competitive with today's world market prices.

The same probably holds true for high-quality DC pumps and controllers/inverters. Anyhow, if markets have reached a certain threshold size and maturity, local manufacturing makes a lot of sense and the decision to build-up local production lines should be left to the private sector.

5.2.4 Spare Parts and After Sales Service

A functioning spare part supply and an efficient after-sales service is one of the keys to project success. PV systems generally have a maintenance-free image but as described in **section 5.2.2**, regular care is required and a budget should be set aside for maintenance and possible replacements of system components (2–3 % of investment).

In case of failure, quick replacement of defective components is decisive. From the farmer's point of view, long reaction times of the system provider and delivery times of spare parts (e.g. from abroad) are not acceptable.

Figure 5.24: Storage room of Chilean PV distributor iEnergía

Source: iEnergía Group, 2015

To provide affordable and reliable services, it seems most effective to hook up with existing regional support infrastructure. These can be installers or agricultural service providers, who could also take care of stock keeping. However, it should be borne in mind that the average technician may not be conversant with PV installations and will need thorough training, adequate tools and spare parts.

It has been observed in the selected target countries that a conclusion of maintenance contracts between the farmer and the service provider is not common. As a consequence, the Indian government demands in public tenders that the whole system, including the submersible or surface pump, shall be serviced and warranted for 5 years.

Furthermore, an operation and maintenance manual (written in the local language) should be provided along with the solar pumping system. The manual should include information about solar energy in general, photovoltaic panels, DC/AC motor pump set, tracking system, mounting structures, electronics and switches.

It should also have clear instructions about the correct mounting of PV panels, DO's and DONT's and regular maintenance and troubleshooting of the pumping system. The name and address of the person or company to be contacted in case of failure or complaint should also be provided. A warranty card for the solar panels and the motor pump set should also be provided to the buyer.

5.2.5 Acceptance of SPIS

Find a short overview of this topic in the SPIS Toolbox Module SET UP – Acceptance Test on Energypedia.

For this purpose you can use the SET UP – PVP Acceptance Test

and the Workmanship Quality Checklist Tool.

Within the scope of the stocktaking and analysis phase, about 80 government officials, development workers, researchers, farmers and private sector representatives were interviewed. It emerged that the level of acceptance of photovoltaic technology in irrigated agriculture strongly depends on:

- Technical reliability and after-sales service;
- Financial support mechanisms;
- Farm size and structure;
- System configuration.

Generally, the SPIS technology has a high level of acceptance in the selected target countries. Nevertheless, some exceptions have shown that the introduction of a relatively new technology must be handled with care.

Acceptance on Farm Level

The interviews conducted covered a broad spectrum of different farms. Farm sizes ranged from 0.4 ha (India, Kenya) up to 37 ha (Morocco). With the exception of two subsistence farms in Kenya, all farmers use the SPIS in a commercial way and sell their products on local markets.

Small-scale farmers usually live on their farm and are dependent on subsidies, whereas medium-scale farmers (e.g. in Morocco) often live in the city where they generate their main income. The mid-size farms mainly serve to generate additional income and are typically financed with own equity. Owners are usually experienced entrepreneurs and are used to act according to economic principles. On the other hand, they have only little agricultural experience and are often dependent on the knowledge of agricultural advisers and their farm workers.

Especially for the farm workers, the use of modern technology represents a significant expansion of their skills and strengthens their position in the social structure of the farm.

Figure 5.25: PV-experienced farm worker in Rajasthan, India — Source: GIZ / Andreas Hahn, 2015

It is important to mention that all farmers visited own their land. Landlords are usually not interested in investing in the modernisation of a farm occupied by farming tenants. Therefore, land ownership is also an important selection criterion found in public tenders in Chile and India.

In both countries, SPIS markets are mainly driven by government subsidies (see section 7). Reaching up to 90 % of the total investment, small-scale farmers highly appreciate the subsidies for the SPIS. In fact, the high financial contribution of the government encourages farmers to start something new and increases the level of acceptance.

In India, the government uses a combination of subsidy, credit and technical support to promote PV irrigation. An important conclusion is that technical and agronomic assistance should preferably be offered to farmers from one source (one institution) to facilitate the introduction of PV-powered drip irrigation systems and improved irrigation techniques.

Provided the system is well designed and services are readily available, farmers are generally highly satisfied with SPIS. High reliability, ease of operation and low operating costs are among the most appreciated benefits. The better the farmers are able to use the actually supplied quantities of water, which of course vary according to daily and seasonal fluctuations in insolation levels, the more accepted a PV water pump will be.

Unfortunately, insufficient evaluation of the water needs on site often lead to under-sized PV systems and thus to low user satisfaction. This frequently happens in subsidy-driven markets like India and Chile where the systems are standardised and size is fixed.

Several times during farm visits, the farmers/operators complained that the PV pumping system delivers too little water and that they miss the instant high pressure and water flow they are used to from electric and diesel pumps. This is especially noticeable at sites where water is injected directly into the irrigation system. Water tanks and reservoirs compensate daily fluctuations of solar radiation and thus minimise the effect of varying water flow.

Another social problem, especially encountered in Kenya, is the theft of solar modules and other system components. In rural areas, the use of solar panels for battery charging is quite common and accepted. As the theft of solar panels is a daily occurrence, systems need to be protected (e.g. by electric fencing as shown below).

Losing valuable system components such as PV panels poses an economic risk to the farmer and may be an obstacle to widespread distribution of PV technology in some developing countries.

Figure 5.26: Electric fencing on a farm in Kenya — Source: GIZ / Andreas Hahn, 2015

Acceptance on Government Level

Although prices for photovoltaic systems have decreased significantly in recent years, the relatively high initial investment is still the main barrier to the widespread application of PV pumps in rural agriculture. Especially small-scale farmers have little capital available. This increases the need for adequate financial support mechanisms.

Some governments and donors provide grants and subsidies for SPIS technology promotion and demonstration and thus have a strong influence on the competitiveness and acceptance of SPIS.

On government level, solar water pumps are regarded as a viable and economically competitive alternative to conventional water supply systems and enjoy a high level of acceptance. Ongoing support programmes and discussions with high-level government officials in Chile and India emphasise this very clearly.

A subsidised programme will produce a quick dissemination of PV pumps, but the risk is that potential consumers may form unrealistic expectations about obtaining systems at below-market rates. Farmers who were not considered in public tenders may stay in a 'sit-and-wait mode' and will wait for possibly up-coming subsidy programmes. This will definitely hamper a natural SPIS market development.

Furthermore, government policies subsidising SPIS have their limitations, because there is no guarantee that subsidies and grant money will continue indefinitely. Sustainable local business and industry development is not possible if companies have to rely on government-funded projects. The loss of jobs is highly likely if the government stops giving grants and subsidies.

Gender Related Aspects

Women make essential contributions to the rural economy of all developing country regions as farmers, workers and entrepreneurs. Their roles are diverse and changing rapidly, so generalisations should be made carefully. Yet one fact is strikingly consistent across countries and contexts: women have less access than men to agricultural assets, inputs and services and to rural employment opportunities (FAO 2011).

The World Farmers' Organisation reports that women comprise the largest percentage of the workforce in the African agricultural sector, but do not have access and control over all land and productive resources. The training of women is very important, especially with the adoption of modern agricultural techniques that are tailored to local conditions and that use natural resources in a sustainable manner with a view to achieving economic development without degrading the environment.

An SPIS pilot project in Kenya, coordinated by the Ministry of Agriculture and supported by the Swedish International Development Agency (SIDA), is undertaking efforts to improve the situation of women in the rural areas of Garissa County. Due to the arid climate, the population of Garissa County consists mainly of nomads who have specialised in camel breeding. Within the scope of the pilot project, nomads have the opportunity to settle and take up farming on communal land. With the goal to generate additional income, mainly women are trained by extension workers to plant and sell cash crops, such as banana, tomato and water melon.

Figure 5.27: Income generation by women through cash cropping Source: GIZ / Andreas Hahn, 2015

The project approach is well received by the target group and meanwhile 41 families joined the Holgojo farmers' association. The group of farmers jointly operates a 19 kWp Solar Powered Irrigation System which pumps the irrigation water directly from the nearby Tana River (see Figure 5.28).

The farmers' association collects monthly fees to pay for the water use and the salary of the (male) pump operator who takes care of the system. Since installation in October 2014, farmers enjoy the reliable and solar-powered water source and soon the first banana harvest is expected.

Figure 5.28: Floating solar water pump at Holgojo Farm, Kenya Source: GIZ / Andreas Hahn, 2015

5.3 Water Governance Issues

Find a short overview about this topic in the SPIS Toolbox Module SAFEGUARD WATER – Analyze Water Management and Regulation

and the chapter Explore Cooperative Water Governance on Energypedia.

Due to the favourable development of availability and financial viability of solar-powered irrigation options for all ranges of agricultural production, the technology is increasingly promoted as an economically interesting, reliable and sustainable alternative to conventional water extraction and pumping options. In many countries this promotion is largely based on private sector marketing on the one hand, and public subsidisation on the other. Furthermore, civil society organisations active in the development sector also promote the technology as an appropriate technological option for farming communities.

The underlying advantages of the technology have been outlined in the preceding sections. Section 8 discusses potential barriers and opportunities for the distribution of the technology. In summary, SPIS technology can not only contribute to increasing the efficiency and profitability of commercial farming, but can also open up the potential for food production and food security in rural areas with a low development potential.

The comparatively high initial investment requirements for the technology impose a limit on the accessibility of SPIS technology options to farm households or farming communities. In general, the investment needs exceed the financial capacity of most smallholder farm households and also that of subsistence or smallholder farm groups. Without the availability of suitable commercial financing products (long-term loans with non-land based collaterals), subsidisation from the public side or grant allocation from donors and development partners, the technology will not be accessible to the economically weaker sections of society. Even with a high degree of subsidisation, the required accompanying intensification of agricultural production is a significant barrier for many smallholder farm households.

In most contexts around the world, the technology tends to be available to farm households and enterprises with a higher commercial potential. In terms of utilising the often limited water resources, the SPIS technology may also create a bias and advantage for the productive use of surface or groundwater to those farm households with higher financial capacity. With regard to the creation of equal development opportunities to all sections of society, this causality will have to be taken into account by development planners.

High levels of water abstraction from surface and groundwater resources for agricultural and non-agricultural purposes are common around the globe – the increasing population requires increasing amounts of food, the expansion of agricultural production into dry lands or marginal lands, and the impacts of climate change require and cause a higher degree of water utilisation. Any farm household, no matter whether subsistence, smallholder or large commercial enterprise tends to strive to exploit the available water abstraction option to the point of non-feasibility, be it technical or financial. This is independent of the underlying technological option, hence not a particular characteristic of PV technology.

In view of the often articulated concern that the increased availability and affordability of PV technology for irrigation purposes may further increase pressure upon and an even higher degree of unsustainable use of water resources, it should be kept in mind that this risk basically exists for any water abstraction technology.

Without the formulation of water governance and water resource management principles and guidelines and without regulation and harmonisation of water abstraction and water utilisation, no sustainable water resource management is achievable. In Morocco, for example, the availability of subsidised household cooking gas (butane) at prices well below petrol/diesel and grid electricity has led to an increased use of butane engine driven pumps (refitted car engines) in smallholder irrigation. Both in India and in Morocco, the substantial subsidisation of large open farm water storage ponds has led to the widespread establishment of large water reserves on financially capable private farms that want to avoid water availability problems during the dry season (reduced water table). These reserves are supplied from groundwater resources without any restriction in most cases. In the drought prone areas of India like in Maharashtra this has led to significantly dropping groundwater tables, causing the wells of subsistence and smallholder farmers to fall dry.

The increased availability and promotion of water abstraction technologies for all categories of productive use requires the active promotion and implementation of key pillars for a sustainable and equitable exploitation of the limited water resources. This includes:

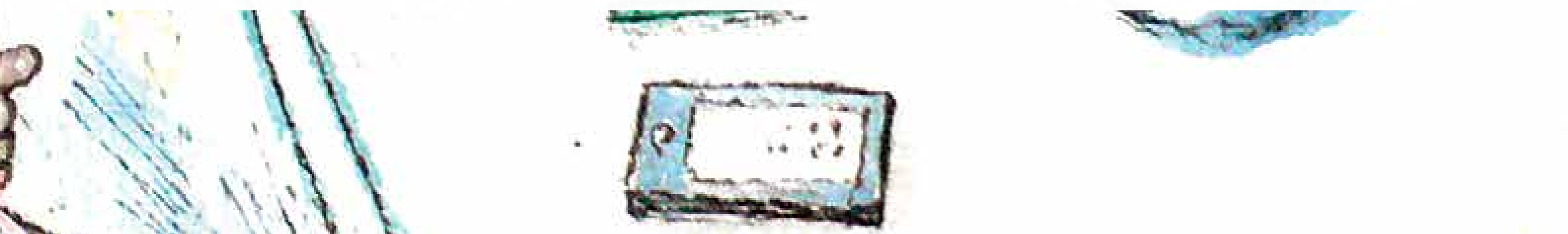
- Allocation of water rights and water abstraction concessions based on sustainable water resource management principles;
- Monitoring and regulation of water abstraction from surface and groundwater sources;
- Adherence to water rights and water availability in system design;
- Prescription and promotion of water-saving technologies in any productive water use (irrigation: modernisation towards closed, pressurised systems with drip irrigation, adoption of water-saving irrigation patterns and crop rotations, etc.).

In terms of planning and designing an SPIS (very much as any other irrigation system), the initial consideration should always be the requirement and the availability of water (water rights/concession, well/borehole yield). Subsequently, a system can be designed based on the water availability and the most suitable cropping pattern. Water abstraction and irrigation system components need to be adapted to each other in order to achieve the best result in terms of technical, financial and environmental viability. In practice, however, the common occurrence is that system components are planned and designed in a fragmented manner by different service providers without considering the above aspects. In all cases studied in the visited countries Chile, India, Kenya and Morocco, for example, not a single PV pump installation was designed based on actual water availability (unknown actual well/borehole yield) or sustainability considerations.

Further promotion of productive use of water in agriculture and beyond hence requires accompanying measures in pursuit of sustainable water resource management and water governance. This cannot be regulated by market principles but calls for the establishment of water resource management capacities, awareness creation and capacity development.

The availability of unconditional subsidies is counter-productive in this regard. As long as PV-based pumping solutions are subsidised to a large extent without demanding strict adherence to water availability and water utilisation monitoring, water-saving irrigation technologies and limitation of water storage, the risk of an unsustainable utilisation of the technology will prevail, giving credence to the widespread concern about ‘over-pumping’.

6 Tools for technical design and economic assessment



6 Tools for technical design and economic assessment

6.1 Design and Simulation Tools for PV Pumps

In this chapter, a selection of individual software tools will be presented. The information has been compiled from reliable documented and published references/resources as cited in the publication. Mention of any company, association or product in this chapter is for informational purposes only and does not constitute a recommendation of any sort by GIZ.

The SPIS Toolbox[4], developed by the Food and Agriculture Organisation of the United Nations (FAO) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH is accessible on Energypedia. It gives a broad overview about the stages and procedures required to establish or change to a solar powered irrigation system. The individual software tools introduced in the following will give further insights into SPIS planning.

4 Toolbox on Solar Powered Irrigation Systems (SPIS): https://energypedia.info/wiki/Toolbox_on_SPIS

Solar Pump Design Tool – COMPASS 3.1
COMPASS is a PV-based software tool for designing, planning and specifying LORENTZ solar pump systems. It incorporates meteorological data provided by NASA and uses precise algorithms to guarantee high performance and accuracy. Download is available to selected LORENTZ partners on partnerNET: https://www.lorentz.de/products-and-technology/pump-types/submersible-solar-pumps

The user simply selects a location and enters the required design data as described in section 2.3.1 Figure 6.1 shows the data input screen of COMPASS 3.1 for submersible pump design. Default settings enable the inexperienced user to start the design process.

The summary report includes the pump curve, the wiring diagram of the PV generator as well as drawings of the system layout. The printout can be adjusted and edited in many forms.

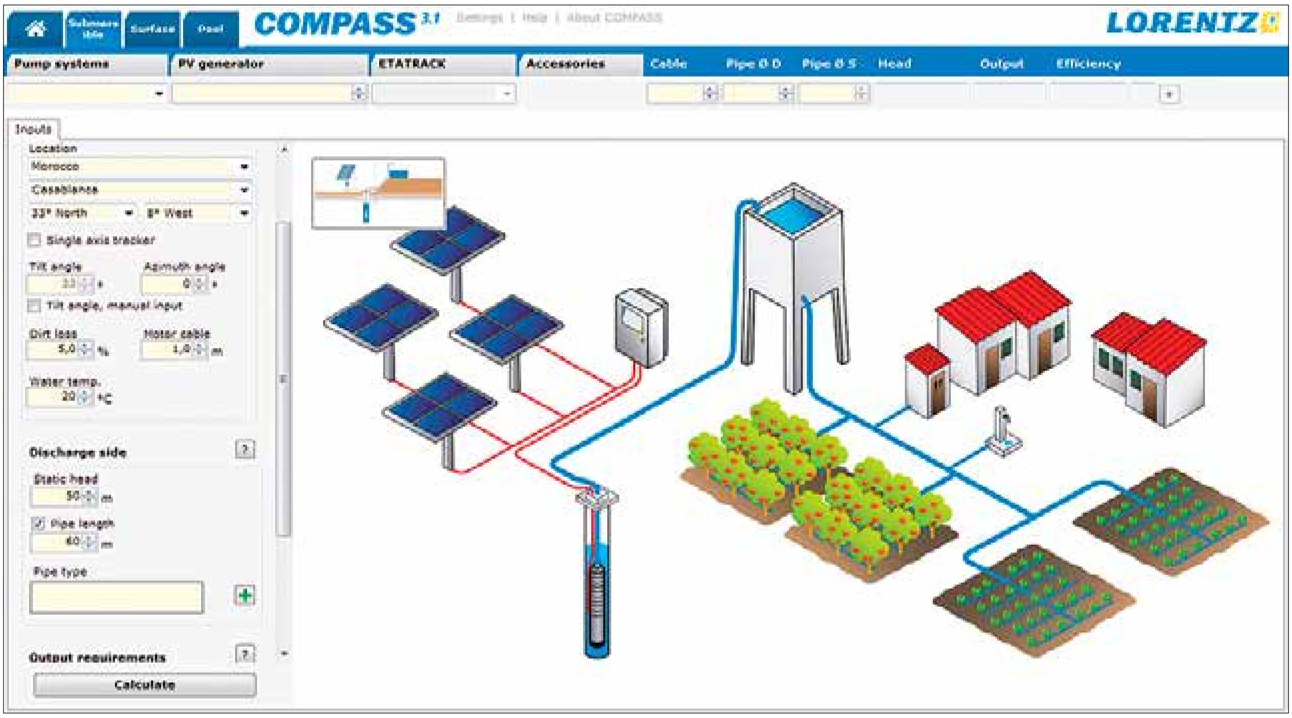


Figure 6.1: User interface of COMPASS 3.1 Source: LORENTZ, 2015

Grundfos Product Center
The Grundfos Product Center was developed by the Danish pump manufacturer Grundfos. It allows for the design and sizing of solar pumps for new installations, research of information for all pumps in the Grundfos catalogue, finding the right pump for replacement or selecting a pump according to the liquid to be pumped. The Product Center is freely available and can be downloaded on the manufacturer's website: https://product-selection.grundfos.com/front-page.html?qcid=755248968. After registration of the client, many additional functions are included for free.

The purpose of the Product Center is to offer a complete tool that contains an extensive catalogue of Grundfos products and a sizing programme to select the most suitable pump type.

Pump Design Tool – SOLARPAK SELECTOR
Long recognised as the world's largest manufacturer of submersible electric motors, Franklin Electric started some years ago the manufacturing of solar pumps. A simple and self-explaining online tool to pre-select the suitable Franklin Electric solar pumping system is available at http://tools.franklin-electric.com/solar/

Figure 6.2: Franklin Electric SolarPAK SELECTOR input screen

Source: Franklin Electric, 2020

The selected location shown above is Arica in Chile. Once the longitude and latitude of a specific location is entered, the graph produced is showing the average solar radiation per month appears. The main design data (total dynamic head and daily flow rate) are required as well. After selecting the proposed design options, the pump curves will be displayed and a flow rate chart and cable sizing chart can be selected and printed on demand.

Solar Pump Design Tool – DASTPVPS

The Design and Simulation Tool for PV Pumping Systems (DASTPVPS) is a manufacturer independent software package for detailed sizing, simulating and troubleshooting of photovoltaic pump systems. The program was developed at the Universität der Bundeswehr in Munich, Germany and includes an extensive library of irradiance data, solar panels and motor/pump units.

All individual components of a photovoltaic pumping system can be sized and later simulated using the program. The results are displayed in the form of graphs and tables:

Solar Pump Design Tool – PVsyst

Another software tool which is also manufacturer-independent is the professional design and simulation tool PVsyst. This tool is mainly intended for engineers in charge of solar pumping projects and has to be purchased at a price of around EUR 1,000.

PVsyst has a whole range of features, such as the ability to import system measurement data for directly comparing measured and simulated values, and a toolbox for solar geometry, meteorology and PV operational behaviour. PVsyst holds a meteorological database of around 1,200 sites, which are imported from the METEONORM database and allows for a three-dimensional shading analysis. Besides comprehensive layout of a PV pumping system, PVsyst also provides the possibility to start with a preliminary design as shown in Figure 6.3.

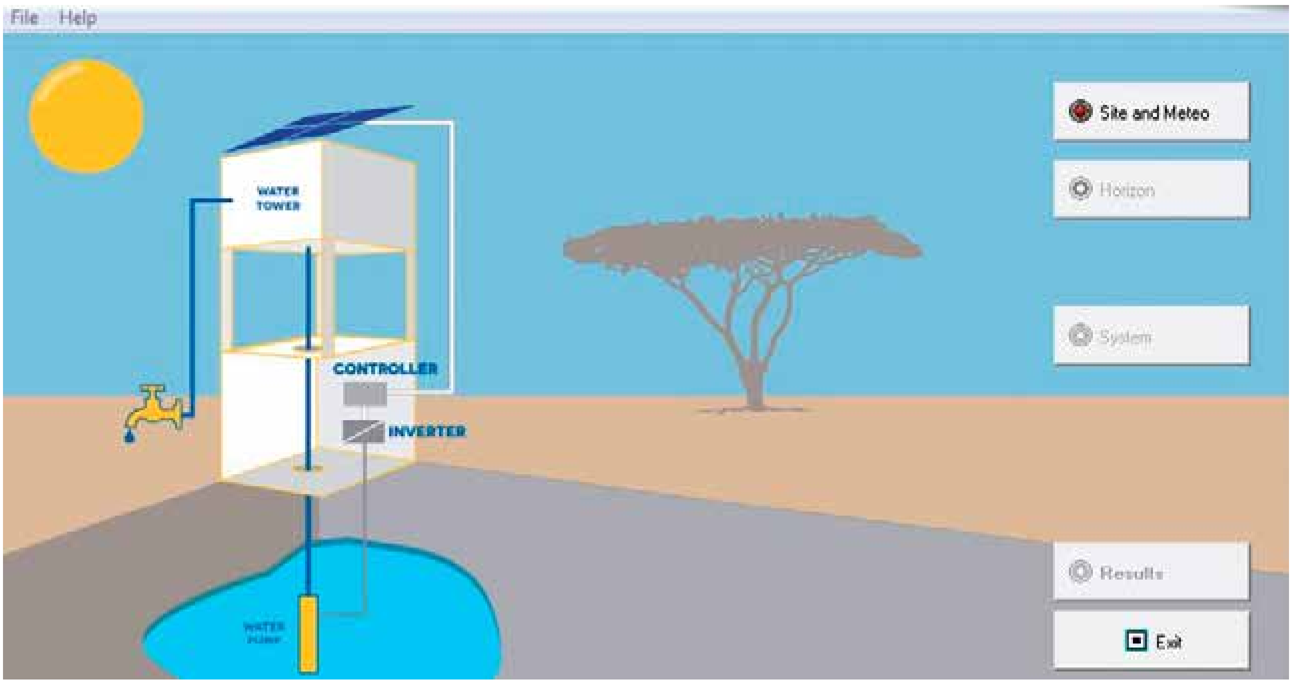


Figure 6.3: Simulation results of a PV pumping system using PVsyst Source: PVsyst, 2015

6.2 Design and Simulation Tools for Irrigation Systems

Irrigation System Design Tool – HydroCalc
The design software HydroCalc was developed by the Israeli company Netafim. It is freely available and easy to use, particularly for micro-irrigation systems: http://www.netafim.com/service/hydro-calc-pro

The software offers several options to calculate the drip line, sub line and main line. In general, it starts with the selection of the emitter followed by the drip line diameter, spacing, length and the pressure at the end of the line. Each emitter/dripper has its own characteristic (flow rate versus pressure) and as a result, the inlet pressure and flow rate per drip line are given. With these values, the total flow rate of a field can be calculated and the optimal diameter of the sub-main selected to keep the pressure drops in acceptable limits.

Figure 6.4: Input screen of HydroCalc irrigation software

Source: Netafim, 2015

Irrigation System Design Tool – GESTAR
GESTAR was developed by the Faculty of Fluid Mechanics at the University of Zaragoza and offers the most complete software package for engineering irrigation systems. It was designed for professional irrigation engineers with comprehensive knowledge of hydraulics and is a helpful tool for the sizing of medium to large scale irrigation schemes. GESTAR tools and modules are specifically designed for pressurised irrigation (such as sprinkler and drip irrigation), enabling optimum design, execution and management as well as integrating a wide range of resources.

Figure 6.5 shows an irrigation scheme in the design phase indicating water sources, flow rates and pressures in the different pipelines.

Within the scope of the GIZ pilot project entitled 'Resource-conserving Irrigation with Photovoltaic Pumping Systems', a module to simulate the characteristic of drip irrigation systems was developed.

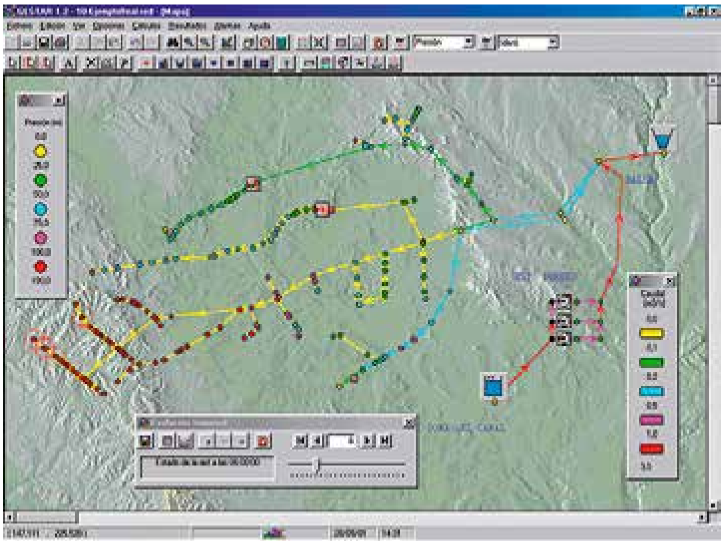


Figure 6.5: GESTAR display of an irrigation pipeline layout and sizing

Source: University of Zaragoza

6.3 Calculation Tools for Irrigation Requirements

You can find some more information on calculation of irrigation requirements in the SPIS Toolbox Module IRRIGATE – Calculate Water Requirements on Energypedia.

The Food and Agriculture Organization of the United Nations (FAO) has developed a specific decision support tool related to on-farm water requirements:

CROPWAT 8.0 for Windows

CROPWAT is a computer program (English, French, Spanish and Russian language modules) for the calculation of crop water requirements and irrigation requirements based on soil, climate and crop data. In addition, the program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying cropping patterns. CROPWAT 8.0 can also be used to evaluate farmers' irrigation practices and to estimate crop performance under both rain-fed and irrigated conditions.

The program includes standard crop and soil data but would require local data input to work accurately on farm level. The development of irrigation schedules in CROPWAT is based on a daily soil-water balance using various user-defined options for water supply and irrigation management conditions. Scheme water supply is calculated according to the cropping pattern defined by the user, which can include up to 20 crops.

Figure 6.6 illustrates the data entry interface in CROPWAT: ETo, rainfall data, crop details and soil characteristics are entered, or available reference tables are uploaded. In this example vegetable production in Kurnool, India, is projected:

The program then calculates crop water requirements and the irrigation schedule (see Figure 6.7).

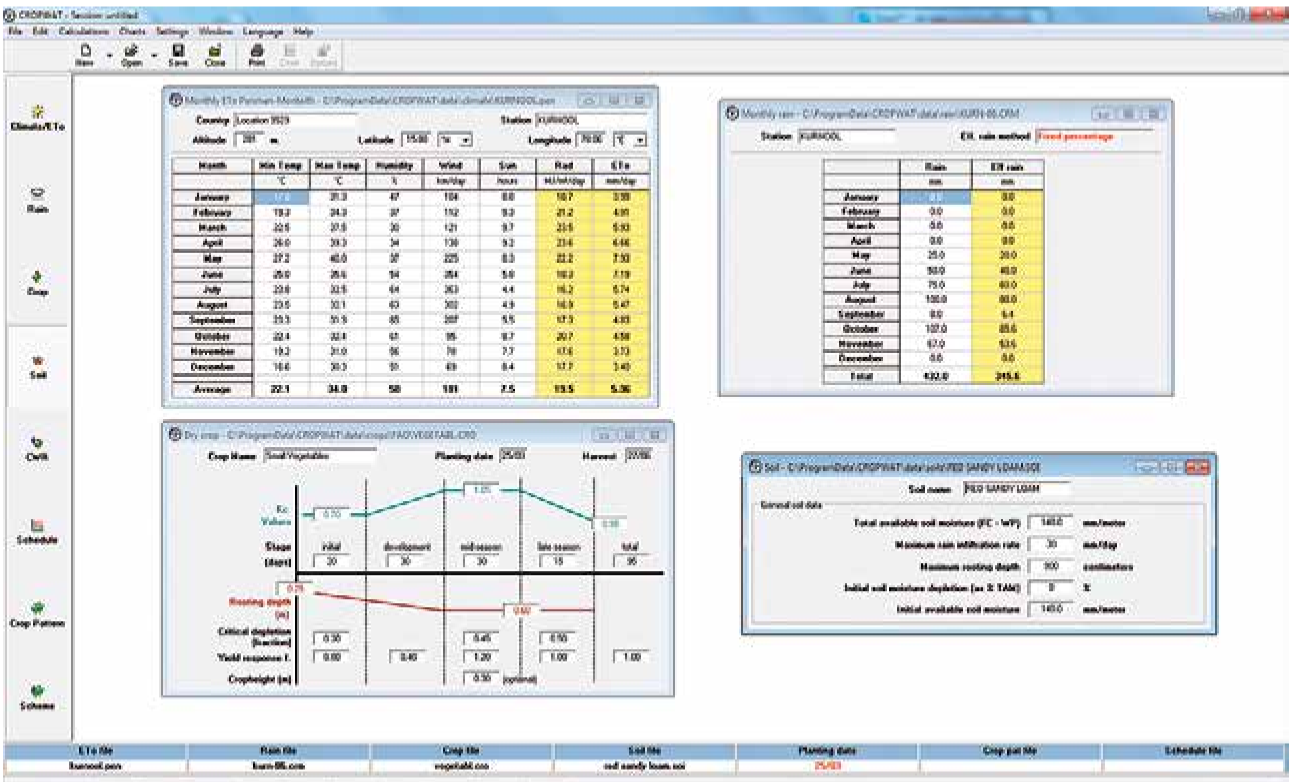


Figure 6.6: Data entry interface in CROPWAT 8.0 Source: FAO, 2015

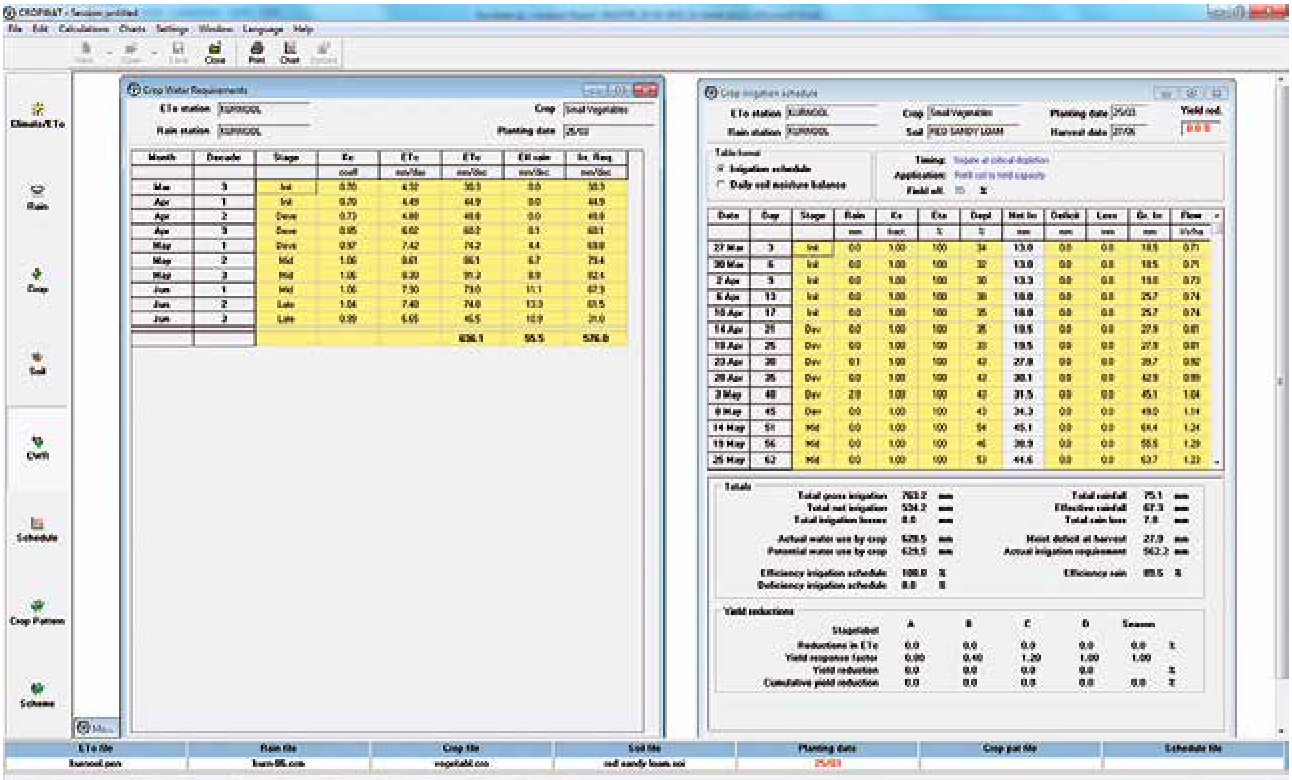


Figure 6.7: Calculation of CWR and irrigation schedule in CROPWAT 8.0 Source: FAO, 2015

Cropping patterns can be freely established and the related scheme water supply can be calculated as well. The program offers limited chart functions. It is by far the most useful tool for irrigation water calculation and scheduling for a worldwide application.

The program is available on the FAO website after registration, free of cost: `http://www.fao.org/land-water/databases-and-software/cropwat/en/`

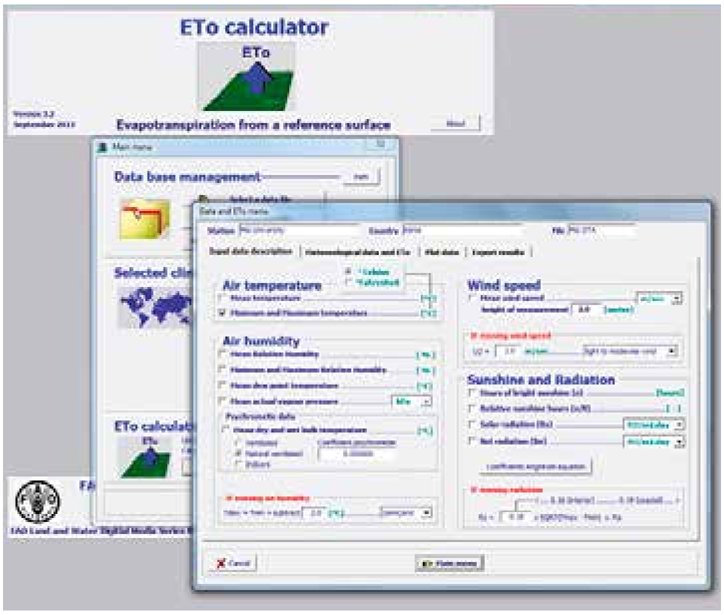


Figure 6.8: Calculation of reference data with ETo Calculator Source: FAO, 2016

ETo Calculator 3.1

Professional utilisation of CROPWAT requires input of local ETo data that may be available from agricultural or meteorological services. With the aid of FAO's ETo Calculator site, specific ETo datasets can be calculated that can then be used in CROPWAT (see Figure 6.8).

CLIMWAT 2.0 for CROPWAT

This program provides meteorological data for CROPWAT based on data from 5,000 stations worldwide.

7 Country case studies

7 Country case studies

Country case studies were carried out in Chile, India, Kenya and Morocco as part of the stock-taking and analysis exercise. The selection of countries was made to have a worldwide scope and provide an insight into different markets and market scopes:

- **Chile:** Widespread utilisation of PV pumping technology in irrigation, strong promotion of SPIS by government, main target group small to medium farms (2–5 ha), but also larger farms up to 30 ha under PV irrigation;
- **India:** High level of water abstraction with pumps, ambitious government programme to replace conventional pumps by PV technology, main target group small to medium farms (2–5 ha), local products/systems on the market;
- **Kenya:** Very high share of smallholders (< 2 ha) and high potential to develop dry lands by PV pumping from groundwater, local products on the market;
- **Morocco:** Main market for suppliers like Lorentz and Grundfos, medium (10–15 ha) and large size commercial farms utilising PV pumping.

Table 7.1 presents an overview of the visited schemes.

Table 7.1: SPIS visited during country case studies in Chile, India, Kenya and Morocco

SPIS-Location	PV Generator		Controller/ Inverter	Pump	Mounting System	Vd [m^3/d]	H [m]	Vd * H [m^4/d]	Farm size [ha]	Main Cash Crops
	Manufac-turer	Capacity [kWp]								
Chile										
San Pedro	SCHOTT Solar	1.5	Grundfos CU200	SQF 2.5	Self-Fixed	15	60	900	1.2	Tomato, Horse Bean, Coriander
La Tirana	Isofoton	1.0	Grundfos CU200	SQF 5A7	Hao-Electric-Tracker	28	33	924	1.2	Grenadine
Azap-Inia	CSG PVTECH	5.0	NEDAP, 5 kW, PR50SB-WalnutsBS/S24	Peggio	Self-Fixed	63	8	504	3.7	Flowers, Chili
Manso	Solar World	1.5	Grundfos CU200	SQF 5A7	Fixed	16	52	832	2.0	Walnuts
India										
Rajawas-2	JAIN Irrigation	6.6	2 x Lorentz PS4000	C-SJ-8-15	2 x Jain-Electric Tracker	160	50	8,000	6.0	Water Melon, Wheat, Mustard
Rajawas-1	Tata Power Solar	3.1	Lorentz PS4000	C-SJ-8-15	Tata-Manual Tracker	76	50	3,800	1.0	Water Melon, Wheat, Mustard
Najabas	Tata Power Solar	3.0	Lorentz PS4000	C-SJ-8-25	Tata-Electric Tracker	44	75	3,300	3.0	Tomato, Peas, Mustard, Wheat
Rundal	Tata Power Solar	3.0	Lorentz PS4000	C-SJ-8-25	Tata-Electric Tracker	50	70	3,500	2.0	Onion, Tomato
Baniya	PV Power tech	4.8	ABB-Inverter, 5.5 kVA	Shakti	Claro-Manual Tracker	165	21	3,465	8.1	Maize, Mustard
Lalpura	PV Power tech	4.8	ABB-Inverter, 5.5 kVA	Shakti	Claro-Fixed	165	21	3,465	16.2	Maize, Mustard

SPIS-Location	PV Generator		Controller/ Inverter	Pump	Mounting System	Vd [m³/d]	H [m]	Vd * H [m⁴/d]	Farm size [ha]	Main Cash Crops
	Manufac-turer	Capacity [kWp]								
Kenya										
Ongata-Rongai	Canadian Suntech	2.5	2 x Lorentz PS1800	CS-37-1 / CS-F12-2	Lorentz-Electric Tracker	200	12	2,400	1.5	Leaf Salads
Kaijado	No-Name Chinese	9.3	Lorentz PS9K AC	Dayliff DS 8/50	Self-Fixed	43	150	6,450	0.1	Cattle Watering, Vagetable Garden
Emukutan	Solar World	11.5	Lorentz PS9K AC	Dayliff DS 8/50	Davis Shirtliff-Fixed	72	146	10,512	0.1	Cattle Watering, Vagetable Garden
Holgojo	Canadian Solar	19.0	Lorentz PS21K AC	C-SG 150 17/4	Lorentz-Electric Tracker	2,035	10	20,350	16.6	Banana
Morroco										
Ain Louh	CNPV	56.4	Lorentz PS 21K AC / PS 25K2 AC	CSJ 42-10 / CSJ 42-12	AE-Photonics-Fixed	900	85	76,500	24.0	Apple
Alaoui	CSG PVTECH	29.4	Lorentz PS 9K / PS 15K	C SF42-20 / CSJ 30-12	AE-Photonics-Fixed	450	30	13,500	24.0	Grape
Boughleb	CNPV	42.2	2 x Lorentz PS 15K AC	CSJ 75-3 / CSJ 75-3	AE-Photonics-Fixed	1,600	23	36,800	37.0	Orange
Salek	Suntech	28.2	Lorentz PS 21K AC	CSJ 30-16	AE-Photonics-Fixed	269	120	32,280	5.0	Apricot

Source: Authors

The results of the country case studies were incorporated into the present report. Eight of the visited SPIS (two per country) were also the subject of an analysis of their financial viability (see section 4). In the following, the main information resulting from the country case studies is provided.

7.1 Chile

Figure 7.1: Water supply with a solar powered pump in Chile Source: iEnergía Group, 2015

Chile is one of the fastest growing economies in Latin America thanks to sound economic management and integration into the global economy. The continuous and strong economic growth in Chile is linked with a significant increase in energy demand. To meet this demand, Chile started the process of privatisation and liberalisation of its electricity sector in the 1980s. Today, the underlying principles of Chile's energy policy are characterised by private initiatives, competitive markets and the subsidiary role of the state.

The Chilean conventional and renewable energy sectors are fully privatised and do not receive any subsidies. Contrary to this, subsidising the agricultural sector is prevailing in order to support small and medium-size farmers in rural Chile. Many farmers using solar pumps for small-scale irrigation schemes rely on subsidies from governmental organisations.

Depending on the subsidy scheme provided by the different organisations and the farm size, farmers can receive subsidies of up to 90 % of the total investment. The high financial contribution of the government encourages farmers to adopt the technology and increases the level of acceptance. However, the risk is high that potential consumers may form unrealistic expectations about obtaining systems at below-market rates.

Farmers who were not considered in public tenders often refrain from financing their system on their own and wait for future up-coming subsidy programmes. The Chilean government has already announced that budgets for SPIS will be substantially increased and that subsidy programmes will be continued beyond 2015. The subsidy-driven market has so far prevented a market-oriented dissemination of SPIS.

Farmers using solar pumps for small-scale irrigation schemes can obtain subsidies from governmental organisations such as the **Instituto de Desarrollo Agropecuario (INDAP)**, **Comisión Nacional de Riego (CNR)** and **Instituto de Investigaciones Agropecuarias (INIA)**. Very often, farmers receive subsidies of up to 100 % of the total investment. Within the scope of the existing subsidy scheme, about 1,500 solar irrigation pumps (0.41.5 kWp) have been installed. The participating farmers and SPIS suppliers are selected via countrywide public tenders based on three standardised system layouts. The major solar pump manufacturers active in Chile, Grundfos and Lorentz, were selected to design and deliver the systems on an exclusive basis.

The standardised and limited system kits supported by the Chilean government subsidies only seldom meet the exact requirements of the target farms. In many cases, the system limitation led to serious acceptance problems among farmers. Farmers/operators complain that their solar pump delivers too little water and that they miss the instant high pressure and water flow they are used to from grid supplied electric and diesel engine driven pumps. This is especially noticeable at sites where water is injected directly into the irrigation system.

Water tanks and reservoirs compensate daily fluctuations of solar radiation and therefore minimise the effect of varying water flow. In Chile, irrigation water is often stored in open reservoirs. The main disadvantages of storing water in open reservoirs are the extremely high evaporation losses of water and the easy entry of debris, sediments and garbage. These effects can be significantly reduced by covering the tank. Covered water tanks, e.g. made of corrugated iron sheet, are currently being promoted and subsidised by INDAP.

In many cases, Chilean farms are already connected or very close to the public grid. In this case, an interesting alternative could be to install a standardised grid-connected PV system which supplies electricity for all electrical appliances on the farm, including the irrigation water pump.

Apart from a few exceptions, the government-driven market has prevented a market-oriented dissemination of SPIS. Furthermore, commercial financing of SPIS via banks does not exist. The aforementioned government bodies have already announced that budgets for SPIS will be substantially increased and that subsidy programmes will be continued.

Financing renewable energy projects in Chile is often difficult, as financing institutions are very reserved with regard to debt financing for small-scale projects in the agricultural sector. The knowledge and the capacity with regard to the assessment and risk management of these projects are low. Because of the high subsidy being offered by the government, the new segment of PV-based irrigation remains largely unattended by commercial banks.

Within the scope of the country case study for Chile, four different Solar Powered Irrigation Systems were visited and analyzed. The overall results of site visits were incorporated in the underlying stocktaking and analysis report. Two selected systems are presented in detail and are also the subject of the financial analysis presented in section 4.

Figure 7.2: Reservoir filled by PV powered groundwater pump in La Tirana, Chile — Source: iEnergía Group, 2015

SPIS La Tirana is located in the Pampa Tamarugal (latitude: 20°18'16" S / longitude: 69°37'50" W) at an altitude of 1,000 m. The location is remote and has no access to the public grid. The farmer used to work with a diesel generator set but replaced the conventional motor-pump by a PV solution in 2010 to reduce the cost of operation. Solar panels with a capacity of 1.0 kWp, mounted on a Hao tracking system, provide the energy for a Grundfos SQF/CU 200 pump/controller system.

Irrigation water is provided by two deep wells from which a covered elevated 200 m³ reservoir made of corrugated iron sheet is filled. The water quality is good but the groundwater level in the region is constantly decreasing. The sandy soil has a high salt content. Of about 50 ha of farmland 1.2 ha are currently cultivable and are under irrigation to produce pomegranate (5 different varieties).

Table 7.2: Agricultural production of La Tirana SPIS, Chile (Pampa Tamarugal)

Crop	Cultivated Area	Yield	Gross Margin
Pomegranate	1.20 ha	8,300 kg/ha	4,399 EUR/ha
Total cropped area: 1.20 ha Number of rotations/year: 1 (Pomegranate) Cropping intensity: 1.0			

Source: Authors

The daily mean water output of the pump amounts to 28 m³ at a pumping head of about 33 m. A basic monitoring system (e.g. water meter, pressure gauge) to check the main system parameters is connected. The drip irrigation system works with manually perforated tubes (1/2"), which cause a high water discharge of approx. 20–25 gph due to large boring. The irrigation water supply is effected by gravity flow from the elevated storage tank with a satisfactory uniformity of water distribution, but an apparent risk of over-irrigation and water losses. The farmer plans to extend pomegranate cultivation to 18 ha. The pilot project is supported by the University of Chile.

SPIS Azapa-INIA is located in the Azapa valley in Arica (latitude: 18°34'11" S / longitude: 70°6'2" W) at an altitude of 55 m. The farm is located in the main production area of Arica and was established in 1990. The site has a stable grid connection and is one of the first to have a grid-connected photovoltaic system with battery storage. The solar generator with a peak power of 5.0 kWp produces around 25 kWh of electricity during the day. The solar generator supplies energy to all electrical consumers, including the irrigation system which is composed of two conventional 220 Volt motor pumps of 1.5 kW each.

The generated electricity is preferably consumed on the farm. If the solar electricity is lower than the actual demand, the grid delivers the missing electricity. If the PV generator produces more energy than the actual demand on the farm, surplus energy is fed into the grid (net-metering scheme). Irrigation water is provided by a canal system, from which open reservoirs are filled on a regular basis. Previous irrigation was based on a surface (furrow) approach but today, water-conserving drip irrigation is applied. The water quality is good but poor soil conditions forced the farmer to buy structure topsoil from nearby sites. Of 5.1 ha of farm land, 3.5 ha are currently under irrigation to produce flowers and passion fruit as the main products. To protect the plants against diseases and insect attacks, production under net houses is typical for the region.

Figure 7.3: Flower production under drip irrigation in Chile (Azapa-INIA SPIS) Source: GIZ / Reinhold Schmidt, 2015

About 50 % of the photovoltaic energy produced is used for irrigation. The daily mean water output amounts to 63 m³/day at a pumping head of about 8 m. The drip irrigation system uses a 1/2" drip line with built-in turbulent flow emitters (discharge 0.6 gph). The system includes a central fertigation unit (electric booster pump to inject nutrient solution). The main products of the labour-intensive production are flowers and passion fruit; in addition, tomatoes and chili are cultivated. The flower stocks must be renewed every 3 years, the passion fruit stocks every 3–4 years.

Table 7.3: Agricultural production of Azapa-INIA SPIS, Chile (Arica)

Crop	Cultivated Area	Yield	Gross Margin
Flowers	2.50 ha	1,200 bunches/ha	842 EUR/ha
Passion Fruit	1.00 ha	10,500 kg/ha	1,306 EUR/ha
Tomato	2.00 ha	54,000 kg/ha	13,516 EUR/ha
Chili	1.00 ha	2,250 kg/ha	1,194 EUR/ha
Total cropped area: 6.50 ha			
Number of rotations/year: Flowers, Passion Fruit: 1; Tomato, Chili: 2			
Cropping Intensity: 1.9			

Source: Authors

Figure 7.4: Chili plantation with drip irrigation Source: GIZ / Reinhold Schmidt, 2015

7.2 India

Figure 7.5: Groundwater pump in India Source: GIZ / Andreas Hahn, 2015

India is experiencing an accelerated market growth and is reported to have a large PV market potential. Many SPIS system components are already manufactured in India. There are more than 12 million grid supplied electric and 9 million diesel irrigation pump sets in operation in the country to provide water for about 39 million ha of irrigated land. According to latest information from the Ministry of New and Renewable Energy (MNRE), about 50,000 solar powered pumping systems shall be installed in 2015.

The Indian government and international donors provide grants and subsidies for SPIS technology promotion and demonstration and thus have a strong influence on the competitiveness and acceptance of SPIS.

During the first period of SPIS promotion activities in the nineties, MNRE provided the financial support required for subsidising the capital and interest cost of the solar pumps. MNRE's funding was channelled by either the implementing agency – the Indian Renewable Energy Development Agency (IREDA) – or the State Nodal Agencies (SNA). IREDA also provided additional financing for the unsubsidised portion of the system costs from its own budget (GIZ, IGEN n.d.).

Capital subsidies, low-cost financing and 100 % depreciation in the first year were meant to provide incentives to farmers to purchase the PV pumping systems at a concessional rate, as low as 10 % of the actual equipment cost. However, with the Income Tax Department redefining the parameters for claiming accelerated depreciation, the financial incentives became redundant. The MNRE programme was unable to achieve its objective. As of March 2012, 7,771 solar PV water pumping systems as compared to the targeted 50,000 installations were achieved (GIZ, IGEN n.d.).

In 2010, solar water pumping became part of the off-grid and decentralised component of the Jawaharlal Nehru National Solar Mission (JNNSM). Several states such as Rajasthan, Gujarat, Chhattisgarh, Uttar Pradesh, Maharashtra, Tamil Nadu and Bihar have taken up initiatives to implement PV water pumping programmes using the financial assistance of JNNSM and funds available from the respective state governments (GIZ, IGEN n.d.).

The government uses a combination of subsidy, credit and technical support to promote PV irrigation. An important conclusion is that technical and agronomic assistance should preferably be offered to farmers from one source (one institution) to facilitate the introduction of PV-powered drip irrigation systems and improved irrigation techniques.

Besides the capital subsidies from MNRE (30 % subsidy) and state governments (30–40 %), there are no other specific financing schemes supporting farmers' acquisition of solar PV water pumping systems. With the financial support provided by the government, about 50,000 new installations are expected by the year 2015. This corresponds to 200–250 MWp/yr. Similar growth rates can only be expected in China and the United States, which have large areas under irrigation. According to MNRE, the subsidy programme for SPIS shall phase out by 2019 at the earliest but it is expected that the subsidy rates will be reduced stepwise until then (e.g. by 10 % per year).

Solar Powered Irrigation Systems supported by Indian government funds are generally limited in size. Typically, SPISs with a solar generator size between 3.0 and 5.0 kWp are specified in public tenders, regardless of whether the system solution meets the requirements (in terms of daily water flow and pumping head) of the individual farm after installation. It is important to note that in India, efficient and water-conserving irrigation technologies (such as drip) are known, but very often farmers also use the photovoltaic pump inefficiently in combination with standard type sprinkler systems, which operate at relatively high nominal pressures. The governmental subsidy scheme does not demand the adoption of drip irrigation for water savings – generally, the minimum requirement is to have 0.5 ha under sprinkler irrigation.

In recent years, the Indian private sector started offering SPIS components. Some manufacturers, such as Tata Power Solar and JAIN Irrigation Systems, diversified their portfolio and even provide farmers with turn-key solutions. This positive trend will definitely contribute to better overall system efficiency and performance of the technology. Meanwhile, all components required to build a Solar Powered Irrigation System are produced locally and new players appear on the market. Some well-known products manufactured in Europe, the United States and China are still imported. Individual SPIS components can hardly be found in the portfolio of traditional agricultural service providers. Instead, solar pump manufacturers select specialised PV distributors and retailers such as Claro Energy Pvt. Ltd. and Atom Solar Systems to market their products. International pump manufacturers such as the German company Lorentz and the Danish company Grundfos have also set up own branch offices to sell their products to distributors and installers in India.

Within the scope of the country case study for India, six different Solar Powered Irrigation Systems were visited and analyzed. The overall results of site visits were incorporated in the underlying stocktaking and analysis report. Two selected systems are presented in detail and were also the subject of the financial analysis presented in section 4.

SPIS Rajawas-1 is located in the region of Jaipur in the state of Rajasthan (latitude: 24°4'17" N / longitude: 75°44'10" E) at an altitude of 430 m. The location is quite remote but has access to the public grid. The grid is characterised by regular voltage fluctuation and frequent load-shedding. Therefore, electricity for irrigation purposes is only available for up to six hour per day/night. Farmers in the region typically pay a flat rate for grid electricity of 1,000 INR/month.

The solar pump is connected directly to the irrigation system. Thus the solar water flow and the irrigation water flow are the same. Solar panels with a capacity of 3.1 kWp, mounted on a Tata Power Solar manual tracking system, provide the energy for a PS4000 Lorentz pump/controller system. The solar pump mainly serves to bridge periods of lacking grid electricity. The irrigation water, pumped from a drilled deep well, is free of charge. The water quality is good but the groundwater level in the region is constantly falling. The PV generator and motor/pump unit are not well matched. Due to the comparatively small solar generator, pump capacity is not fully exploited. The daily mean

Table 7.4: Agricultural production of Rajawas-1 SPIS, India (Rajasthan)

Crop	Cultivated Area	Yield	Gross Margin
Wheat	0.50 ha	1,750 kg/ha	319 EUR/ha
Mustard	0.25 ha	210 kg/ha	5 EUR/ha
Green Peas	0.25 ha	745 kg/ha	52 EUR/ha
Water Melon	0.50 ha	39,560 kg/ha	3,104 EUR/ha
Vegetables	0.50 ha	9,500 kg/ha	424 EUR/ha
Total cropped area: 2.00 ha Number of rotations/year: Wheat, Mustard, Green Peas, Water Melon, Vegetables: 1 Cropping Intensity: 1.6			

Source: Authors

water output amounts to 76 m³/day at a pumping head of about 50 m.

The 1.2 ha smallholder farm cultivates wheat, mustard, water melon, green pea and vegetables. A drip irrigation system is used for vegetable production and a conventional impact sprinkler system for wheat and mustard irrigation. There is no systematic irrigation layout; sprinklers/drip lines are moved frequently. Cereal and oilseed cultivation are irrigated with impact sprinklers (2 bars nominal pressure, discharge 2.72 gph, 11.5 m radius); vegetable production on 0.25 ha is irrigated by a 1/2" drip tube with built-in emitters (turbulent flow, discharge 0.2 gph).

Table 7.5: Agricultural production of Lalpura SPIS, India (Bihar)

Crop	Cultivated Area	Yield	Gross Margin
Maize	6.00 ha	2,430 kg/ha	369 EUR/ha
Mustard	6.00 ha	205 kg/ha	15 EUR/ha
Green Peas	1.50 ha	685 kg/ha	270 EUR/ha
Water Melon	3.00 ha	34,680 kg/ha	2,714 EUR/ha
Vegetables	1,50 ha	9,300 kg/ha	424 EUR/ha
Paddy	12.00 ha	2,150 kg/ha	331 EUR/ha
Total cropped area: 30.00 ha Number of rotations/year: Wheat, Mustard, Green Peas, Water Melon, Vegetables, Paddy: 1 Cropping Intensity: 1.9			

Source: Authors

SPIS Lalpura is located in the region of Vaishali in the state of Bihar (latitude: 25°45'0" N / longitude: 85°25'0" E) at an altitude of 58 m. Although the public grid is in the vicinity of the SPIS site, the location is not connected to the mains supply. Before the installation of the SPIS, irrigation water was supplied by an old diesel engine, which still serves as back-up in case of extraordinary water demand. The SPIS is owned and managed by the Vaishali Area Small Farmers' Association (VASFA). In close cooperation with the Indo-German Energy Programme (IGEN), VASFA developed an innovative project concept. GIZ provided the technical and financial support to install the Solar Powered Irrigation System, which now serves as a pilot and demonstration site for the region. 49 farmers jointly operate the system and collect fees for PV pump utilisation. The amount collected by the group is sufficient to pay the salary of the pump operator and shall serve to replace more diesel-driven pump sets in the coming years. The system can be considered a successful pilot project demonstrating a group management approach for a PV pumping solution.

The solar pump is connected directly to the irrigation system. The irrigation water is pumped from a drilled deep well and is directed into an open canal system. Thus, the solar water flow and the irrigation water flow are the same. Solar panels with a capacity of 4.8 kWp, installed on a fixed mounting structure, provide the energy for a locally manufactured Shakti submersible AC pump with ABB inverter. The daily mean water output amounts to 165 m³/day at a pumping head of about 21 m. A monitoring system (e.g. water meter, pressure gauge) to check the main system parameters such as daily water flow and pumping head is not connected. Currently, a traditional surface (basin) irrigation system is in place. Primary water distribution is effected in a lined open canal, secondary and tertiary water distribution by earthen makeshift field canals. The soil and water quality are good and the groundwater level in the region is shallow and stable.

Agricultural production is based on cereals, oil seed and cash crops on 16.2 ha. The individual farm sizes of the group's households differ. No change in cropping patterns or intensification of production was associated with the introduction of the PV pumping system.

7.3 Kenya

Figure 7.6: Aquaponics farming system supplied with solar pumped groundwater, SPIS Ongata-Rongai

Source: GIZ / Andreas Hahn, 2015

Kenya used to be an important market for solar energy for many years. The use of solar water pumps for irrigation, however, is a comparatively new application. Within the scope of the Rural Electrification Master Plan (REMP), remote public buildings are equipped with solar PV systems (e.g. SHS for schools and rural clinics). REMP also includes the installation of diesel / diesel-hybrid mini-grids but there is no specific support programme for solar-powered irrigation so far. Recently, first private companies started developing the Kenyan market and installed a few hundred SPIS. The main purpose of solar water pumps installed in rural areas is to secure drinking and livestock water supply. These systems are often sponsored by international donors (e.g. World Vision, SIDA).

For private investment in SPIS, commercial financing schemes are usually required. A number of flower farms and tea plantations are willing to invest in solar solutions to bridge grid power failures and to reduce their monthly electricity bill. For these business cases, regular customer loans are provided by local banks which usually feature high down payments (to minimise defaults) and short maturities. As interest rates up to 18 % on agricultural credits are quite common, some farmers/ companies also tend to buy the SPIS straight from distributors, thereby using private savings.

Although the advantages of solar technology are evident, purchase decisions in Kenya are often taken in favour of the competing conventional energy systems. The comparatively high initial investment costs of solar options are critical in this context as they impose high financial burdens on farmers who opt for photovoltaic irrigation. The perception persists that PV is prohibitively expensive and from today's point of view, this is the main barrier to a widespread dissemination of solar pumps in Kenyan irrigated agriculture. Other key hurdles that stand in the way of SPIS dissemination include:

- Lack of awareness among farmers, financial institutions and government stakeholders;
- Lack of flexible payment schemes for farms with irregular income streams;
- Lack of quality assurance and service.

Solar pumps could play an important role in the development of greenfield agricultural production in remote and arid regions of Kenya (such as the Turkana and Marsabit counties in the North). As the majority of farm households are smallholders, group operation of PV pumps for cash crop production could be a prospective model for SPIS.

Kenya has a comparatively stable market for small-scale off-grid solar systems. Turn-key solutions (partly of low quality) are sold by a large number of resellers. The size of this competitive market segment is estimated to be about 2–3 MWp/yr. The Ubbink company (Naivasha) manufactures about 2 MWp of solar panels per year. The panels are mainly sold on the local market, but also distributed to neighbouring countries. No other manufacturers of SPIS components are known. It is thought that several small-scale manufacturers are active in the off-grid segment, focusing on the production of BOS components, such as mounting systems. Other SPIS components (solar pump, controller, drip irrigation systems) have to be imported.

Only a few Kenyan distributors have included SPIS in their portfolio. The main companies who have established contacts to international SPIS manufacturers are Davis & Shirtliff Pvt. Ltd. (Lorentz and Grundfos pumps), Centre for Alternative Technologies Ltd. and SunCulture Ltd. Most distributors of SIPS components have specialised over time and focus on the production and sale of the individual system components. Complete system solutions, which include the photovoltaic pump and the irrigation system, are rare on the Kenyan market.

The Kenyan company SunCulture offers an exemplary product called AgroSolar Irrigation Kit. The kit combines cost-effective solar pumping technology with a high-efficiency drip irrigation system to make it cheaper and easier for users to start farming.

The promotion of water-saving modern irrigation technologies is not yet very prominent in Kenya. In smallholder schemes, photovoltaic water pumps are often combined with traditional surface irrigation systems. In commercial farming (e.g. flower farms), the use of water-conserving drip irrigation systems is quite common and even sophisticated hydroponic irrigation technologies have been introduced by individual farmers.

Within the scope of the country case study for Kenya, four different Solar Powered Irrigation Systems were visited and analyzed. The overall results of site visits were incorporated in the underlying stocktaking and analysis report. Two selected systems are presented in detail and were also the subject of the financial analysis presented in section 4.

SPIS Ongata-Rongai is located in Nairobi County (latitude: 1°24'5" S / longitude: 36°48'58" E) at an altitude of 1,731 m. The location is quite remote but has access to the public grid. The grid is characterised by regular voltage fluctuation, frequent load-shedding and black-outs. Electricity for irrigation purposes is only available for a few hours per day/night. For the production of lettuce, the farmer installed a sophisticated hydroponic irrigation system, which requires a constant water supply (24/7).

Using a conventional electric pump, fresh water is pumped from a drilled deep well to fill two subsurface tanks with a capacity of 10 m³ each. Because of high sodium content, the groundwater needs to be treated by a reverse osmosis filter with about 4,000 l daily treatment capacity. The nutrient solution is prepared and circulated within two hydroponic irrigation circuits by two independent solar surface pumps. Solar panels with a capacity of 2.5 kWp, mounted on a Lorentz tracking system, provide the energy for two PS1800 Lorentz pump/controller systems. Two gravity tanks serve to buffer supply during periods of varying cloud cover and to blend the nutrient solution with fresh water. The daily mean water agitation amounts to 200 m³/day at a pumping head of about 12 m.

1.5 ha of the 5.0 ha farmland are under hydroponic irrigation in net houses. Additionally, maize and fodder is produced on about 2 ha of farmland. Under the local conditions, crisp lettuce is a suitable cash crop for hydroponic irrigation due to its tolerance of plant diseases and short periods of non-irrigation. Five to six crop rotations per year allow for a very profitable business. The chosen system concept is interesting for intensive farming with limited landholding and in poor soil conditions.

SPIS Holgojo Farm is located in the region of Garissa in Garissa County (latitude: 0°27'25" N / longitude: 39°39'30" E) at an altitude of 151 m. The Swedish International Development Agency (SIDA), in cooperation with the University of Nairobi and supported by the Ministry of Agriculture, Livestock and Fisheries (MALF), developed an innovative group irrigation project concept. Holgojo Farm is a new site development (2014) and is not connected to the public grid. It also serves as a pilot and demonstration site for the region.

The population of Garissa County consists mainly of pastoralists and agro-pastoralists. Camel breeding is quite common and livestock-based livelihoods prevail. Within the scope of the pilot project, nomads have the opportunity to settle and take up farming on communal land. With the goal to generate additional income, mainly women are trained by extension workers to plant and sell cash crops, such as banana, tomato and water melon. 41 families joined the Holgojo farmers' association. The group of farmers jointly operates the Solar Powered Irrigation System, which pumps the irrigation water directly from the nearby Tana River into an open canal system. The water quality is good and there is no seasonal shortage of irrigation water. The farmer group finances operational expenses (incl. pump operator) and the fixed annual water tax.

Table 7.6: Agricultural production of Ongata Rongai SPIS, Kenya (Nairobi)

Crop	Cultivated Area	Yield	Gross Margin
Lettuce	6.00 ha	15,000 kg/ha	4,085 EUR/ha
Total cropped area: 6.0 ha			
Number of rotations/year: Crisp Lettuce: 4			
Cropping Intensity: 4.0			

Source: Authors

Figure 7.7: Drinking and irrigation water supply for Maasai village Emukutan in Kenya

Source: GIZ / Andreas Hahn, 2015

Table 7.7: Agricultural production of Holgojo SPIS, Kenya (Garissa)

Crop	Cultivated Area	Yield	Gross Margin
Banana	8.00 ha	12,000 bunches/ha	3,053 EUR/ha
Melon	4.50 ha	11,500 kg/ha	1,649 EUR/ha
Tomato	4.50 ha	25,000 kg/ha	6,267 EUR/ha
Total cropped area: 17.00 ha Number of rotations/year: Banana, Melons, Tomatoes: 1 Cropping Intensity: 1.0			

Source: Authors

The solar pump is connected directly to the irrigation system, thus the solar water flow and the irrigation water flow are the same. Solar panels with a capacity of 19 kWp, installed on a Lorentz tracking system, provide the energy for a PS21k AC Lorentz pump/controller. The daily mean water output amounts to 2,035 m^3/day at a pumping head of about 10 m. A monitoring system (e.g. water meter, pressure gauge) to check the main system parameters such as daily water flow and pumping head is not integrated.

Banana was selected by agricultural extension workers as main product, because it is easy to handle and allows for parallel camel-breeding. In addition water melon and tomato crops are cultivated. The production on the available 16.4 ha is based on traditional surface irrigation (basin and furrow) and low-input practices. No fertilisation takes place despite a prevailing sensitive demand of banana crop in N and P fertiliser and pH-management of the soil (problem of insufficient agricultural extension).

Figure 7.8: Optimal growth of water melon seedlings in an SPIS scheme

Source: GIZ / Andreas Hahn, 2015

7.4 Morocco

Figure 7.9: Drip irrigation on a vineyard at SPIS Alaoui

Source: GIZ / Andreas Hahn, 2015

Since 2010, solar pumps for irrigation are gaining importance in Moroccan agriculture. The German solar pump manufacturer Lorentz is leading the local SPIS market and sells about 2,000 pump/controller units per year, mainly to private investors. The International Finance Corporation (IFC) conducted a market assessment in Morocco and identified a solar pump market poised for rapid growth in the medium term with a potential market size between around USD 800 million and 1.3 billion by 2020 (IFC 2015).

The Moroccan SPIS market is mainly driven by small to medium-size private farmers who produce cash crops for the local market and for export. Compared to other markets, the systems are comparatively large and can provide sufficient irrigation water for larger plantations (up to 40 ha). The use of efficient irrigation technologies (drip irrigation) is supported by the government through a subsidisation programme (Plan Maroc Vert). Only tax incentives promote the use of solar pumps. This is why commercial financing schemes are usually required.

Private investors often live in the city where they generate their main income. The mid-size farms mainly serve to generate additional income and are typically financed with own equity. The owners are usually experienced entrepreneurs and are used to act according to economic principles. They mainly invest in SPIS technology to reduce the monthly electricity bill. In some areas of Morocco, grid electricity for irrigation is already more expensive than solar power. Therefore, many Moroccan farmers tend to disconnect their electric pumps and go for the solar option. This fact is currently driving the Moroccan solar pump market, although the electrification rate is > 95 %.

In coming years, one key market driver for solar pumping will be the implementation of a USD 180 million grant programme that was expected to launch in early 2015. Within the scope of the Moroccan Green Plan, subsidies will be targeted to smaller farmers and are expected to reduce investment costs by up to 50 %. The commencement of the announced government subsidy is expected to spur dramatic and immediate demand for solar equipment, solar compatible pumps and solar knowledge and expertise, providing a unique opportunity for rapid growth for well-positioned and knowledgeable private sector players. The target is the installation of 100,000 pumps until 2020. The grant programme is expected to be coupled with an existing successful programme on drip irrigation. The mechanism for grant distribution, including inspection, certification and disbursement, is already operational through the existing drip irrigation subsidy structure operated by Credit Agricole (Morocco).

The availability of stolen PV panels (sometimes called 'second-hand panels') is a unique feature of the Moroccan SPIS market. These second-hand PV panels mainly come from Italy. They are imported by questionable distributors and sold at around 0.3 EUR/Wp without any warranty. Due to the questionable quality of the panels, farmers' perception of reliability may be spoiled, contributing to a bad image of solar technology in the country.

Within the scope of the Moroccan Green Plan, water-saving drip irrigation technology has been successfully introduced to the market. Therefore, it is quite common to use solar water pumps in combination with highly automated drip irrigation systems. As irrigation water consumption is usually quite high (e.g. > 1,000 m³/day), systems with capacities ranging from 30 to 60 kWp are no rare occurrence.

Table 7.8: Agricultural production of Alaoui SPIS, Morocco (Rabat)

Crop	Cultivated Area	Yield	Gross Margin
Grape	24.00 ha	5,800 kg/ha	3,261 EUR/ha
Total cropped area: 24.00 ha			
Number of rotations/year: Table Grape: 1			
Cropping Intensity: 1.0			

Source: Authors

Subsides being provided for LPG use in rural households are a barrier to SPIS dissemination. Originally intended to reduce the high cost of LPG for cooking purposes, the subsidy now serves to promote LPG-driven generators for large-scale irrigation on Moroccan farms. Despite this trend, about 10,000 SPIS have been installed in recent years. In some regions of Morocco, groundwater is often used as the only irrigation water source. If groundwater abstraction exceeds the natural groundwater recharge for extensive areas and long times, overexploitation or persistent groundwater depletion occurs.

Within the scope of the country case study for Morocco, four different Solar Powered Irrigation Systems were visited and analyzed. The overall results of site visits were incorporated in the underlying stocktaking and analysis report. Two selected systems are presented in detail and were also the subject of the financial analysis presented in section 4.

SPIS Alaoui is located close to Rabat (latitude: 33°47'28" N / longitude: 6°50'30" W) at an altitude of 46 m. The location is quite remote but has access to the public grid. Mainly due to the high cost of electricity, electric pumps have been replaced by solar pumps. The local water level is stable and there are no significant seasonal changes. The risk of regional groundwater depletion is relatively low. The groundwater quality is good – the well also serves for drinking water supply. The farm house is also equipped with an off-grid PV system, which was designed and supplied by AE Photonics (Morocco).

Two individual subsystems are installed:

- The first subsystem pumps irrigation water from a deep well into an open reservoir;
- The second subsystem is installed close to the open reservoir. From there, a surface pump delivers the water straight to the drip irrigation system.

Solar panels with a capacity of 2 x 14.7 kWp, mounted on a locally manufactured fixed mounting system, provide the energy for two PS9k/PS15k Lorentz pump/controller systems. The daily mean water output amounts to 450 m³/day at a pumping head of about 30 m (subsystem 2). The conventional electric pump is still installed in the well and serves as back-up. Subsystem 2 provides a comparatively high pressure of 3 bars at the inlet of the drip irrigation system. It is assumed that the irrigation scheme would also work properly at lower operating pressures. Therefore, the PV generator of subsystem 2 with a total capacity of 14.7 kWp is oversized.

A drip irrigation system (in total 34,000 drippers) is used for table grape production. The water is conveyed by a ½" high-quality drip tube with mounted pressure compensated diaphragm emitters (discharge: 0.2–0.3 gph). The system includes a large capacity filter installation and a fertigation unit, including two nutrient solution injection tanks.

Out of a total farm size of 35 ha, currently 24 ha are under irrigation (March – September). Five- to nine-year old grape-vines produce about 580–620 metric tonnes of table grapes per year.

SPIS Boughleb is located close to Casablanca (latitude: 31°40'57" N / longitude: 8°12'1" W) at an altitude of 57 m. The farm is located in a peri-urban area and has access to the public grid. The grid is stable and the PV system mainly serves to reduce the electricity bill. Irrigation water is provided by three deep wells and pumped with conventional electric pumps into an open reservoir. There is also the possibility to fill the reservoir by gravity from a nearby dam (only in winter, extra charges apply). The groundwater level is fairly shallow, with some wells falling dry after about 6 hours of operation. Therefore, the risk of regional groundwater depletion is relatively high.

Table 7.9: Agricultural production of Bougleb SPIS, Morocco (Casablanca)

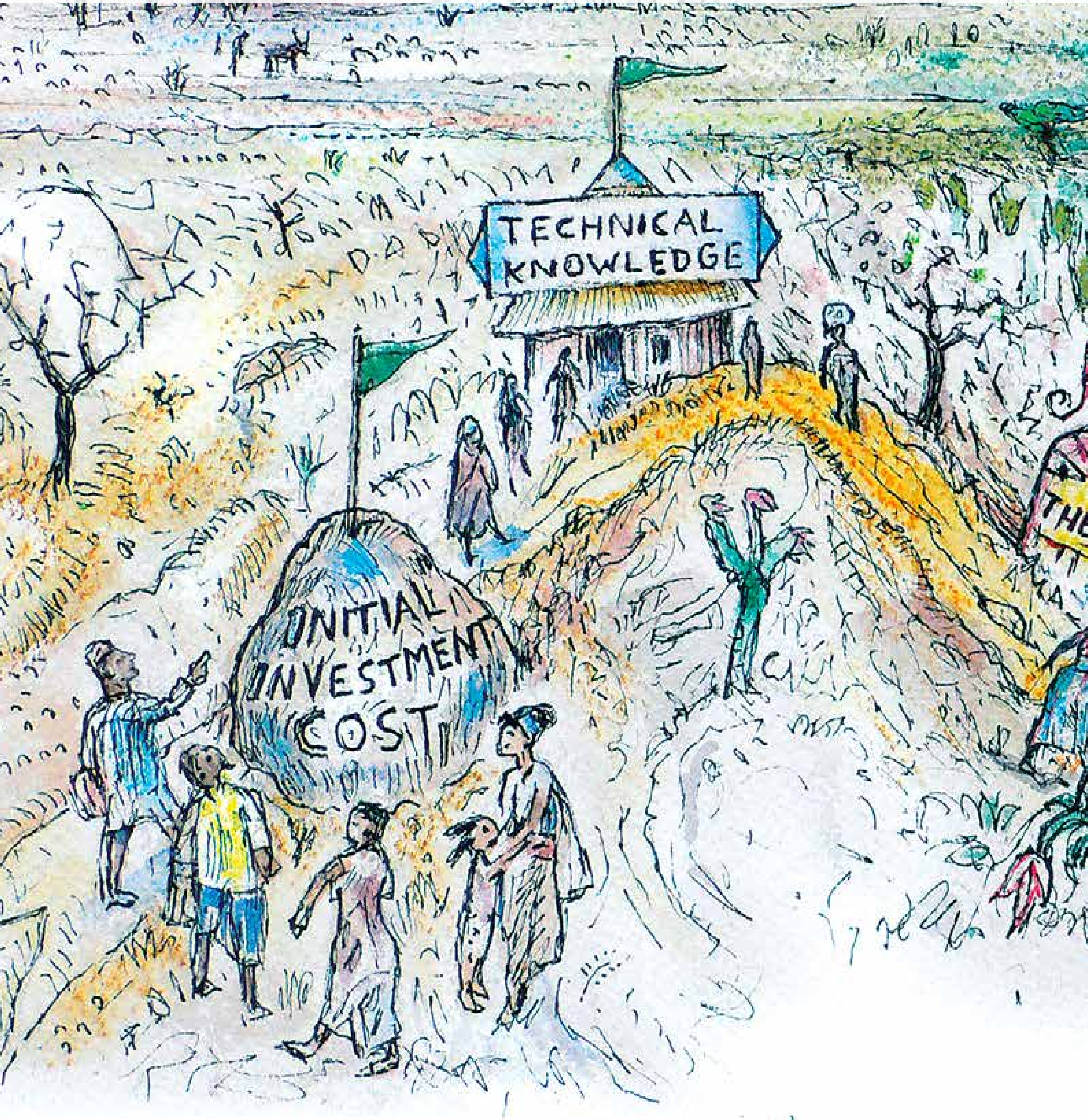
Crop	Cultivated Area	Yield	Gross Margin
Orange	28.00 ha	42,000 kg/ha	2,944 EUR/ha
Lemon	5.00 ha	30,000 kg/ha	5,044 EUR/ha
Pomegranate	4.00 ha	12,000 kg/ha	1,054 EUR/ha
Total cropped area: 37.00 ha Number of rotations/year: Navel Orange, Lemon, Pomegranate: 1 Cropping Intensity: 1.0			

Source: Authors

Two submersible pumps are installed in an open reservoir and pump the irrigation water directly into the irrigation system. Solar panels with a capacity of 2 x 21.1 kWp, mounted on a locally manufactured fixed mounting system, provide the energy for two PS15k AC Lorentz pump/controller systems. The daily mean water output amounts to 1,600 m³/day at a pumping head of about 23 m.

Out of a total farm size of 56 ha, currently 37 ha are under irrigation. A drip irrigation system is used for orange, lemon and pomegranate production. The water is conveyed by two parallel ½" drip tube lines with built-in emitters (turbulent flow, 0.4 gph discharge). Irrigation management is based on sectors of 1–1.4 ha. To check the pressure loss in the filter system, several pressure gauges are installed. The system includes a large capacity filter installation and a fertigation unit, including four nutrient solution injection tanks.

8 Potential and barriers for SPIS distribution



A GREEN OASIS
SCHOOL
GOOD MAIN TE N ANCE
SERVICE
REPAIR
NEGLI (GENCE)

8 Potential and barriers for SPIS distribution

8.1 Opportunity Assessment

8.1.1 Global PV Market Growth

Read about the advantages in the SPIS Toolbox Module GET INFORMED – The Solar Alternative on Energypedia.

Even during a difficult period of industry consolidation and economic crisis, the global photovoltaic market is developing well. According to the European Photovoltaic Industry Association (EPIA), at least 38.4 GWp of newly-installed PV capacity had been added around the globe by the end of 2013. For the first time, a global cumulative installed capacity of almost 140 GWp of solar PV was reached, an amount capable of producing at least 160 terawatt-hours (TWh) of electricity every year. This energy volume is sufficient to cover the annual demand of over 45 million European households (EPIA, 2014).

In all the different growth scenarios developed by EPIA, the global PV market is expected to grow steadily until 2020 (see Figure 8.1).

China was the top market in 2013 with 11.8 GWp of newly-added capacity out of which 500 MWp represent off-grid systems. The fastest PV growth in the coming years is expected to continue in China and South-East Asia, with India, Latin America and the MENA countries following (EPIA, 2014).

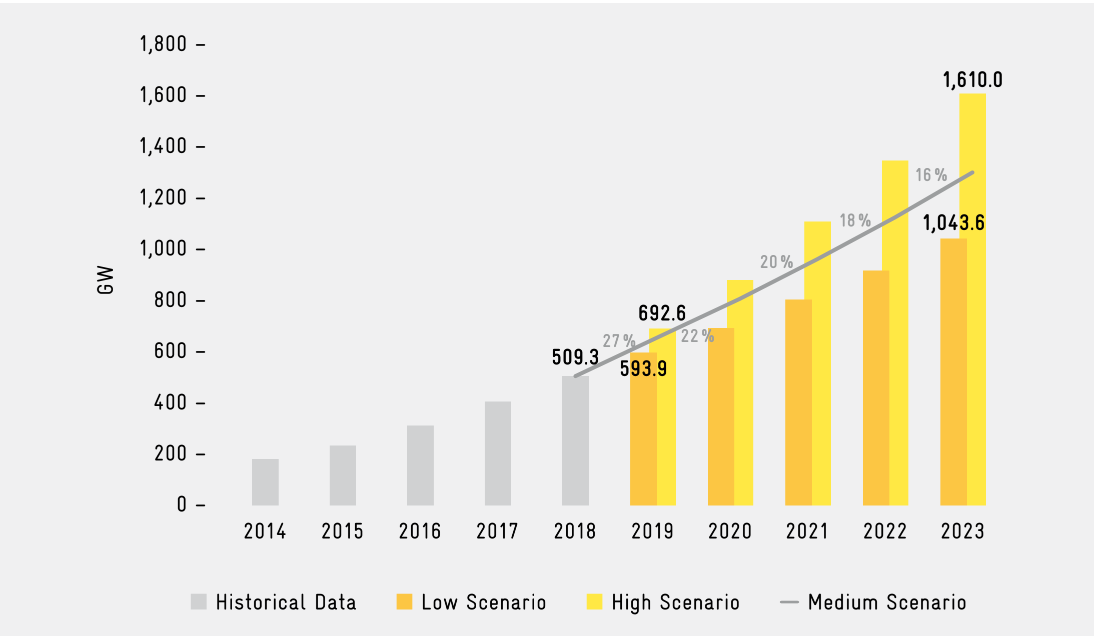


Figure 8.1: Global PV cumulative scenario until 2023 Adapted from SolarPower Europe, 2019

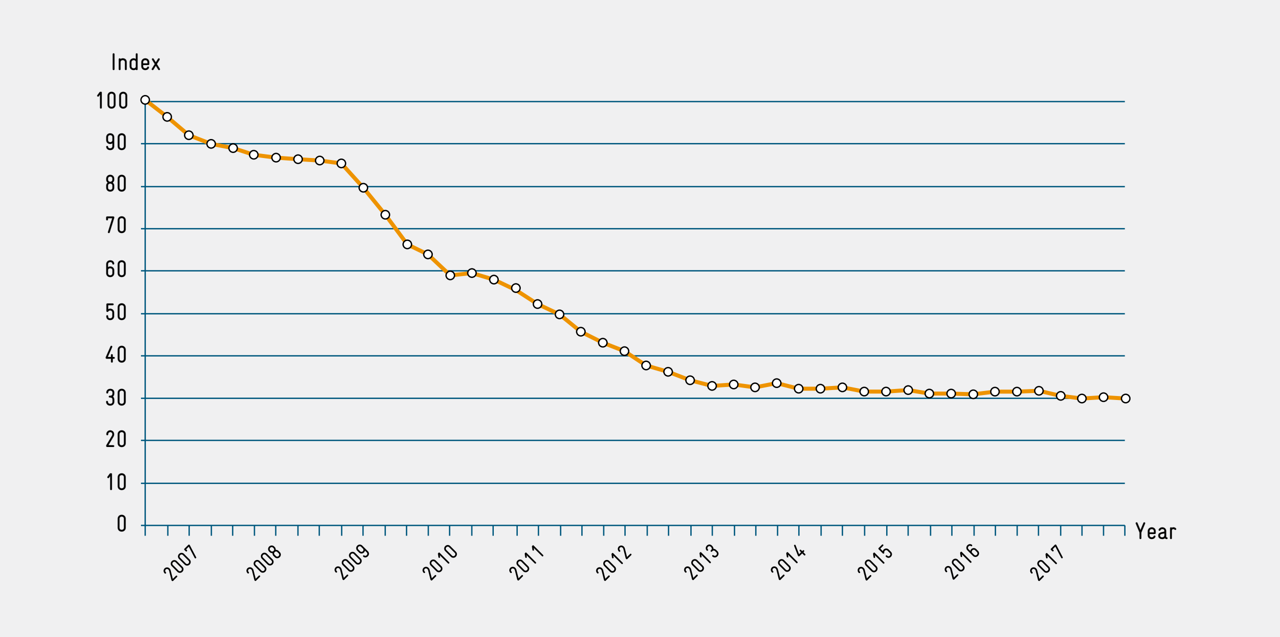


Figure 8.2: BSW-Solar PV Price Index. Average end-costumer prices (system prices, index) for installed roof-mounted systems of up to 10 kilowatt peak per kilowatt peak without tax. Adapted from BSW-Solar, 2018

According to EPIA, the PV potential of the 'sunbelt countries'[5]12, where PV can already compete with diesel generators without financial support, could range from 60 to 250 GWp by 2020 and from 260 to 1,100 GWp in 2030. Although PV markets in sunbelt countries have clearly started developing, their high solar potential remains largely untapped as yet.

In many cases, the perception prevails that PV is an expensive technology option, and that it is still not competitive with conventional energy sources.

The statistical data provided by the German Solar Industry Association (BSW-Solar) clearly show how drastically the prices of photovoltaic systems have decreased over the last years.

5 The term 'sunbelt countries' refers to 66 countries that are based within 35° of the Equator.

8.1.2 Diesel Generator Replacement

In non-electrified parts of the world, solar energy helps to provide access to an environmentally sound and reliable energy supply. Especially in developing countries, the prospect of grid extension and establishment of a reliable, uninterrupted electricity supply in rural areas is a distant vision. Rural electrification in economically weak rural areas of Africa, Asia and Latin America will be largely based on investment in local off-grid solutions.

In regions with high solar insolation levels, photovoltaic water pumps are always an alternative worth considering when the objective is to pump irrigation water to crops at locations with no or only limited access to grid power. The customary means of pumping irrigation water in rural areas are diesel-, gas- or petrol-driven pumps. Such conventional pumps, however, have the double drawback of requiring much and expensive maintenance and depending on a regular supply of fuel. Unattended operation is thus not possible. Often, particularly in remote areas of developing countries with inadequate spare parts and maintenance structures, conventional pumps can repeatedly suffer outages of several days' duration. The resultant lack of water can cause such serious damage to crops that yields drop noticeably. For the farmer, the use of conventional pumping systems thus amounts to an economic risk. This is why photovoltaic water pumps have found their way into numerous horticultural and agricultural areas of application. The replacement of diesel pumps is therefore the main market segment for PV pumps.

First steps towards a wider use of photovoltaic water pumps for drinking water supply and irrigation started in the early nineties. Several multi-year field tests were conducted by various research institutions, government and non-governmental organisations.

Figure 8.3: Old diesel pump as example of main market target for PV pumps

Source: GIZ / Andreas Hahn, 2015

Figure 8.4: Livestock water supply as an example of additional market target for PV pumps

Source: GIZ / Andreas Hahn, 2015

The main goal was to adapt the different components of a PV pump set to the harsh environmental conditions usually found in developing countries, and to demonstrate their technical reliability and economic competitiveness. In the first phase of market introduction, PV pumps were mainly used for drinking and livestock water supply. In recent years, thousands of photovoltaic water pumps have been sold and manufacturers gained extensive field experience to further improve their products.

Since 2010, solar pumps for irrigation are gaining importance and even dominate the portfolio of some suppliers. This market segment is expected to continue its growth path over the coming years.

Accelerated market growth is reported from India. Several studies came to the conclusion that the Indian market potential is huge. There are reportedly more than 12 million electric and 9 million diesel irrigation pump sets in operation to provide water for about 39 million ha of irrigated land. If only 50 % of these diesel pumps were replaced with solar PV pump sets, diesel consumption could be reduced to about 225 billion l/yr (Raghavan et al. 2010).

In 2011, KPMG estimated the potential for solar-powered pumps in India to be about 16 GWp by 2017–2022 (KPMG 2012). According to latest information from the Indian Ministry of New and Renewable Energy, about 50,000 solar powered pumping systems shall be installed in the year 2015. This corresponds to 200–250 MWp/yr (GIZ, IGEN n.d.). Similar growth rates can only be expected in China and the United States, which also have large areas under irrigation.

8.1.3 Greenfield Development

Many parts of developing countries have major agricultural potential; however, this potential often remains largely untapped. The reasons why there is still too little investment in greenfield agriculture are manifold.

New commercial farming ventures typically suffer from:

- Difficult access to financing;
- High one-off start-up costs such as land clearing;
- Lacking infrastructure such as bad road conditions;
- No or limited irrigation water and grid electricity supply;
- Expensive agricultural inputs (e.g. fertiliser);
- Inexperienced farm workers and managers;
- Lack of agricultural advisory services;
- Difficult market access;
- High transportation costs;
- Low prices of agricultural produce.

It is obvious that providing an economically viable and reliable source of energy (such as solar) will only solve a few problems of greenfield agriculture. Nevertheless, it may help to overcome the first barriers to entry into commercial agriculture if the task is to pump irrigation water from deep wells or open reservoirs.

A good example is the Turkana region in Northern Kenya. Turkana is one of the hottest, driest and poorest parts of Kenya and is frequently hit by devastating droughts. Many of the region's inhabitants are nomadic herders, who are especially vulnerable to a lack of rain. Recently, a huge water source has been discovered in Turkana region which could help secure the water supply of the country for about 70 years.

Tapping the new reserves in Turkana with the help of solar pumps could create vast new zones of farmland in landscapes where today even the hardiest plants struggle to survive.

8.1.4 Technology Access to Smallholders

Find more information about the difficulties for smallholders finding financing options and the role of the governments in the SPIS Toolbox Module PROMOTE & INITIATE – Analyze Access to Finance on Energypedia.

Although prices for photovoltaic technology have decreased significantly in recent years, many smallholders are not in the position to purchase a Solar Powered Irrigation System. Government grants and subsidies definitely help to support this target group but clearly hamper market-oriented dissemination approaches.

The foundation of multi-user groups and cooperatives could be a promising business model to provide smallholders with access to SPIS technology without government support.

The concept behind this approach is that a group of farmers shares a photovoltaic irrigation system and uses its financial resources to finance, operate and maintain the system. The main advantage is that an organised multi-user group or farmers' cooperative has much better access to commercial financing schemes, and usually gets better conditions because of the lower non-payment risk for the financing institution.

The most difficult point in the implementation of multi-user systems is to combine the interests of the potential users. For successful implementation, it is important that all users are satisfied with the solution found and they all support the PV irrigation system. Depending on specific socio-cultural framework conditions and the personality of individual farmers, this model may not always work.

Positive examples can be reported from India and Kenya where the foundation of user groups and cooperatives is quite common and generally accepted in rural areas (see section 7).

In India, GIZ supports the Vaishali Area Small Farmers' Association (VASFA) and installed two pilot facilities for cash crop irrigation. About 70 farmers jointly operate the systems and collect fees for PV pump utilisation. The amount collected by the group is sufficient to pay the salary of the pump operator and serves to replace more diesel-driven pump sets in the coming years.

The project clearly demonstrates the cash flow potential of farmers and thereby influences rural banks to customise loan products that are flexible with convenient repayment mechanisms to ensure end user financing.

Figure 8.5: On-site exposure visit of loan officers of financial institutions in Bihar, India

Source: GIZ / Andreas Hahn, 2015

8.1.5 Bridging Grid Power Failures

Even if a remote farm is connected to the public grid, constant availability of electric power is not guaranteed. In some rural areas of developing countries load-shedding is quite common and outages of several hours are frequently experienced by farmers.

Photovoltaic pumps can bridge power failures and substantially reduce the monthly electricity bill. In Morocco, grid electricity for irrigation is even more expensive than solar power. Therefore, many Moroccan farmers tend to disconnect their electric pumps and opt for solar. This fact is currently driving the Moroccan market, although the electrification rate is >95 %.

Figure 8.6: Example of an unreliable grid connection in Rajasthan, India Source: GIZ / Andreas Hahn, 2015

8.1.6 Job Creation and Local Production

Read the SPIS Toolbox Module SET UP – Select Suitable Installer to find out what are the services you will need for installation on Energypedia.

It is expected that with the widespread introduction of SPIS in developing countries, new employment opportunities will be created. Many SPIS components are still manufactured in industrialised countries. Nevertheless, the growing global SPIS market allows international manufacturers to expand their production capacity and thus employ more people.

As soon as individual target markets in developing countries have reached a critical mass, local manufacturing of system components will increase (see also section 5.2.3).

India, currently the biggest market for solar water pumping, sets a good example. Meanwhile, all components required to build a Solar Powered Irrigation System are produced locally and every day new players appear on the market, trying to win market shares. Besides job creation in manufacturing, qualified jobs will evolve along the value chain.

Distributors will establish necessary sales channels and sell their products to system integrators who are responsible for the user-specific design of the plants. Qualified installers are required for proper plant installation, and regional agricultural extension workers and operators take care of sustainable plant operation.

Having access to an inexpensive and reliable water supply, farmers are expected to expand their production and create new jobs for farm workers and facility managers, in both greenfield and brownfield irrigation schemes.

8.1.7 Innovation Potential

You can read about the feasibility of SPIS and the risks involved in the SPIS Toolbox Module INVEST – Credit Policy – Analyze Potential on Energypedia.

While the technical aspects of solar irrigation are generally regarded as adequately developed, a closer look reveals that there is still room for innovations, component improvement and field research.

East/west Orientation of Solar Generator
Solar trackers are utilised to continually orient PV panels to the sun. Especially in Solar Powered Irrigation Systems with direct feed-in, solar trackers are gaining popularity. The main disadvantage of trackers being used in remote areas of developing countries is the need for regular upkeep because of moving parts and electronic controls (see sections 2.1.2 / 5.2.1). The fixed east/west orientation of a solar generator is regarded as a simple and appropriate technical solution to improve the performance and reliability of a PV pumping system.

East/west mounting systems are already well-known for installing PV panels on large industrial roofs, as shown in Figure 8.7.

Figure 8.7: East/west orientation of PV panels on industrial rooftop
Source: photovoltaikbuero Ternus & Diehl GbR, 2011

Design Software Improvement
The promising east/west mounting technique has not yet found its way into several design programmes mentioned in section 2.3.3. More important is the fact that there is currently no commercially available software solution on the market which integrates design features for photovoltaic pumps and irrigation systems. Here, an urgent need for research and development exists.

Solar-Powered Centre Pivots

Centre pivot systems have the advantage that they can cover a wide range of applications. Sloping terrain, different soils and crops can be irrigated efficiently and the investment cost per ha is one of the lowest.

Because of the relatively high pressure needs and daily water demands of centre pivots, they would generally not be powered by solar photovoltaic. Nevertheless, due to the increasing fuel prices in recent years and unreliable grid supply in remote areas of developing countries, some companies have started developing partly or even fully PV-driven devices.

Figure 8.8 shows the principle of a solar-powered centre pivot irrigation system suitable to irrigate 50 ha. A first pilot plant, optimised for solar operation, has been installed in Sudan for Alfalfa production and field results are promising.

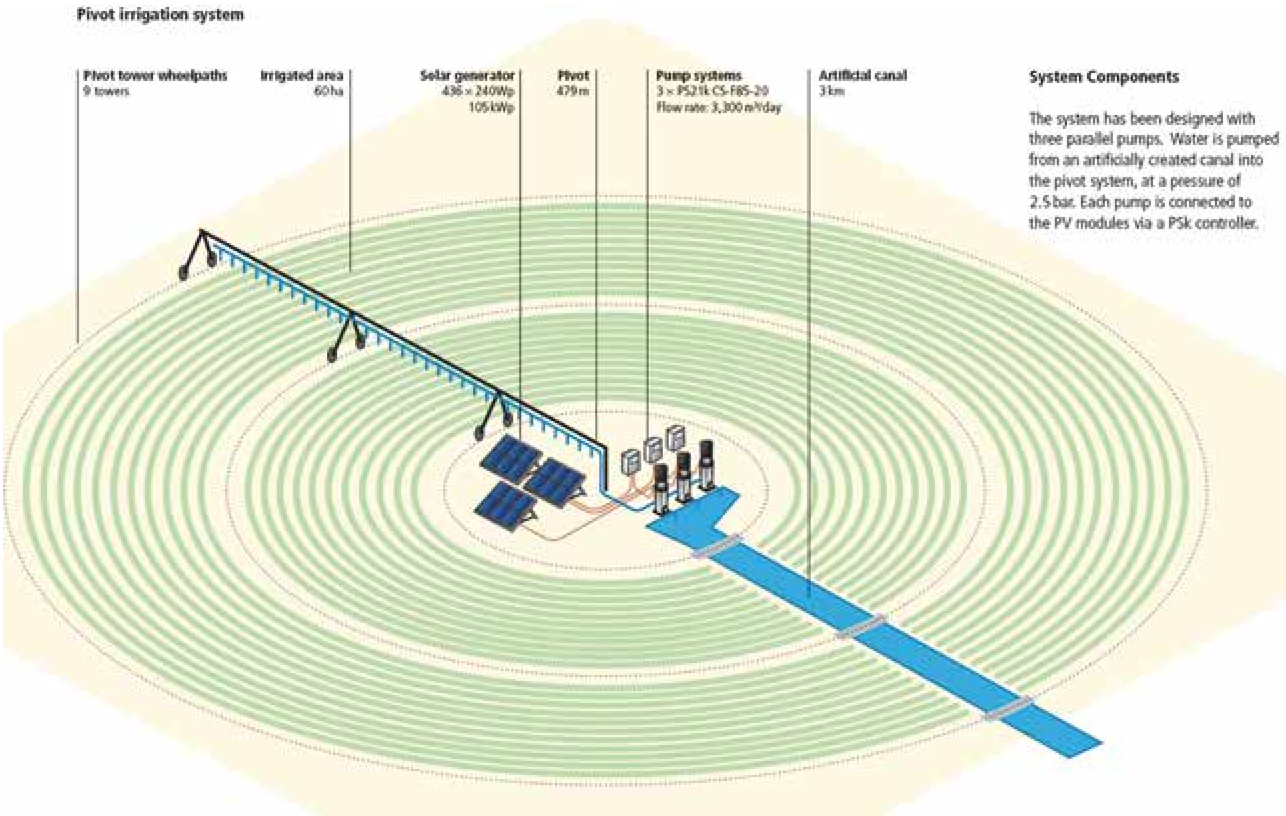


Figure 8.8: Design concept of a solar-powered centre pivot irrigation system Source: Lorentz GmbH & Co. KG, 2014

Pump Solutions for Very Small and Marginal Farmers

In India, a number of technology developers are currently testing portable solar pump solutions that are designed to cater for the needs of very small to marginal farm households. The pumps have a performance of 1 HP and below and operate up to 10 m head with a significant throughput of up to 10,000 l/hour. The power generator comprises 12 solar panels of 100 W.

Smaller PV-driven centre pivots for field sizes of about 25 ha are also under development in India, USA and China. Centre pivot technology may be the door opener for photovoltaic to enter the large-scale irrigation segment.

Turn-Key Solutions

Most suppliers of SIPS components have specialised over time and focus on the production and sale of individual system components. Integrated solutions which include the photovoltaic pump and the irrigation system can only rarely be found on the market, although it is useful to have a concerted system configuration.

The Kenyan company SunCulture offers an exemplary product called AgroSolar Irrigation Kit. The kit combines cost-effective solar pumping technology with a high-efficiency drip irrigation system to make it cheaper and easier for users to start farming. Several standardised solar and irrigation kits are available, which can be adjusted easily to the individual field size and type of cash crop.

Indian manufacturers such as Tata Power Solar and JAIN Irrigation Systems have also diversified their portfolio and have become one-stop-shops for farmers. This positive trend will definitely contribute to better overall system efficiency and performance of SPIS.

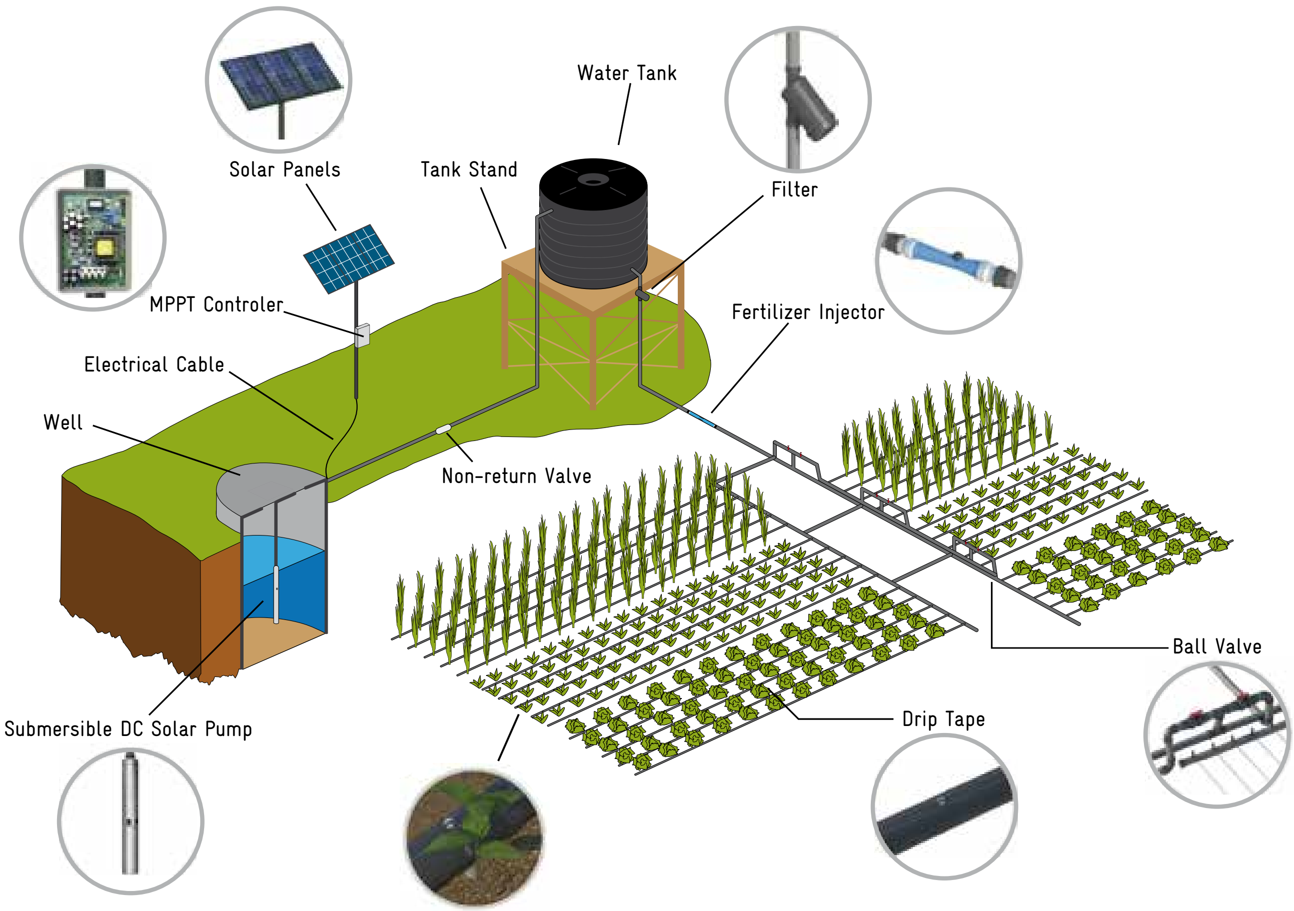


Figure 8.9: Concept of the AgroSolar Irrigation Kit from Kenya

Adapted from SunCulture, 2014

8.2 Assessment of Barriers and Risks

You can find a Review of Potential Risks and Impacts in the SPIS Toolbox Module SAFEGUARD WATER, and Analyze Opportunities & Risks in the Module PROMOTE & INITIATE on Energypedia.

Several barriers need to be overcome in developing countries to tap their huge PV potential. This chapter gives a brief overview of key hurdles that stand in the way of SPIS dissemination.

8.2.1 High Initial Investment Cost

You can find a short overview of financial advantages and risks and other agri-lending tools in the SPIS Toolbox Module INVEST – Credit Policy: Risk Analysis on Energypedia.

As explained above, the cost of PV systems has been constantly decreasing over the last 30 years. Mainly smart incentive programmes, technology improvements and economies of scale have spurred steady production cost reduction. It is expected that this trend will continue in coming years as the PV industry progresses and the global market continues to grow.

Although the advantages of solar technology are evident, purchase decisions in rural areas of developing countries are often taken in favour of the competing conventional energy systems. Ready-to-run PV pumping systems cost approximately twice as much as diesel pumps of comparable performance.

The comparatively high initial investment costs of the solar option are critical here because they impose high financial burdens on farmers who opt for photovoltaic irrigation. However, it is frequently overlooked that after installation of the solar system, only a fraction of the operating cost of a diesel pump is incurred.

Consequently, it does not make economic sense to compare different technologies solely on the basis of their investment costs. However, the perception persists that PV is prohibitively expensive and from today's point of view, this is the main barrier to a widespread dissemination of solar pumps in irrigated agriculture.

8.2.2 Lack of Market-Oriented Financing

To overcome the first cost barrier, affordable and accessible financing mechanisms are required. Commercial financing schemes are given preference as compared to subsidies and grants. However, regular consumer loans which usually feature high down payments (to minimise defaults) and short maturities limit SPIS purchases to high-income farmers.

For a small farmer, getting a loan is sometimes difficult. Particularly rural banks may remain reluctant to finance 'exotic' technologies such as solar pumping. Investing in a proven diesel pump is both cheaper and easier in terms of finance – rural banks know the technology and have been lending for this for decades.

Even if farmers are able to secure a big enough loan, they usually have to pay high interest rates and put up collateral, which is mostly their land. In Kenya, for example, farmers have to pay up to 18 % interest on an agricultural credit. If the pump fails to perform as promised and a poor harvest results, it can mean defaulting on the loan and, in the worst case, losing their farms.

The inability of borrowers to offer adequate security is therefore a major constraint to offering term credit. Some approaches to overcome this problem include using the PV system as part-security, seed capital funds, loan guarantees, supplier credits, and equity investments or debt financing assistance from the government. Furthermore, flexible payment schemes are needed for farms with irregular income streams (Cabraal et al. 1996).

If such affordable and accessible financing mechanisms cannot be provided, the risk is high that conventional pumps will continue to dominate the market.

8.2.3 Oil Price Development

Oil prices fell sharply in the second half of 2014 as US shale oil production increased and Europe's and China's demand for oil decreased. In December 2014, the price of crude oil reached its lowest level since 2009, bringing an end to a four-year period of high and stable prices.

Whereas average crude oil prices in the first half of 2015 recovered a bit, in the second half of the year they dropped again to the lowest level since end of 2003. In 2016 oil prices recovered to levels between USD 45–55 per barrel (see Figure 8.10).

Figure 8.10: Crude oil price development from 2012 to 2018 Source: World Bank, 2018

World Bank in April 2017 was holding steady its crude oil price forecast for 2017 at USD 55 per barrel, increasing to an average of USD 60 per barrel in 2018 and USD 61.5 in 2019. Rising oil prices, supported by production cutbacks by Organization of the Petroleum Exporting Countries (OPEC) and non-OPEC states, will allow markets to gradually rebalance. These oil price forecasts are subject to downside risks should the rebound in the US shale oil industry be greater than expected (World Bank 2017).

In recent years, market development of solar pumps was mainly driven by the constantly rising diesel price. Stabilisation or even a further decline of the diesel price could have a negative impact on future market growth.

On the other hand, the competitiveness of solar pumping systems is not only dependent on the selling price of diesel. In remote areas of developing countries, bringing the diesel fuel to the remote farm-site is sometimes the most important cost factor. Therefore, it is assumed that the impact of the low diesel price on SPIS market development is rather short-term, at a relatively low risk.

8.2.4 Lack of Market-Oriented Policies

A judicious use of grants and subsidies can help smallholders gain access to SPIS technology. However, the use of grants and subsidies could undermine the long-term sustainability of SPIS dissemination.

In Chile and India, for example, the strong government promotion of SPIS technology via subsidies has limited the initiative of private sector actors to develop the market themselves and to serve customers' needs. In both countries, 99 % of SPIS business is driven by government-supported programmes.

This makes it all the more important that subsidies are paid out on time (e.g. immediately after system installation and acceptance). In India companies reported that they frequently have to pre-finance SPIS – in some cases for more than two years. It is logical that necessary financing costs will be added to the system price and artificially increase the system costs.

Furthermore, the system kits offered in Chile and India are standardised and limited in size and only seldom meet the exact water requirements of the farms. In numerous cases, this system limitation led to serious acceptance problems among farmers (see also section 5.2.5).

Tendering of public support programmes is common and sometimes only locally produced products are accepted. This promotes local manufacturing but may compromise system reliability if low-quality or immature components are used.

On the other hand, imported SPIS components are often subject to import taxes and customs duties. It is recommended that governments adjust duty and tax structures if these discriminate against SPIS market development. Relatively high import duties and other taxes (particularly on PV modules) may limit the potential for commercially viable, market-driven SPIS programmes. In India for example, importers must pay 14.5 % taxes and duties just on the motor/pump and controller unit (Cabraal et al. 1996).

Duties and taxes on PV system components clearly raise the financial costs of SPIS. At the same time, subsidies for rural grid service or for conventional fuel often lower the cost of competing energy options to well below their economic value (Cabraal et al. 1996). A good example is the subsidy of LPG for rural households in Morocco. Originally intended to reduce the high cost of LPG for cooking purposes, the subsidy now serves to promote LPG-driven generators for large-scale irrigation on Moroccan farms.

Examples show that policies of many authorities subsidising SPIS are constrained because they do not stimulate market-oriented dissemination. If the wrong promotion strategy is chosen, the risk is high that such programmes will fail.

8.2.5 Lack of Awareness and Impact Monitoring

Find a brief description about monitoring in the SPIS Toolbox Module MAINTAIN – Documentation & Monitoring on Energypedia.

Solar Powered Irrigation Systems provide new possibilities for pumping irrigation water. As long as only few countries already promote the technology, SPIS constitutes a rather unknown technical option, especially in the agricultural sector of many developing countries.

In fact, low awareness of SPIS technology and its potential is often the main reason for limited demand among farmers and low willingness of banks to finance the systems. It usually takes another big step to incorporate the use of SPIS into agricultural policies and regulations. As already outlined in section 8.2.4, some governments are subsidising the use of SPIS. However, limited understanding of rural markets and poor knowledge of farmers' needs has resulted in a lack of customisation of the technology.

What is usually missing in government- and donor-driven initiatives is the existence of monitoring programmes to measure project success or failure. Often, the main goal of programmes is just to achieve the set quantities of solar-pumping systems, without taking into account the actual benefit gained or the requirements of end-users.

Technical acceptance tests by the financing institution are not common either. Mostly, it is even impossible to check the basic functions of the systems because of missing water meters and other helpful measuring devices (see section 2.1.6).

Knowledge networks and web-based information platforms could help to improve information exchange among the different stakeholders but these are usually lacking.

Knowledge is power – therefore, the provision of reliable information and the exchange of field experience will have a strong influence on the further dissemination of SPIS technology.

Figure 8.11: Water metering device – an essential but rare component of SPIS Source: GIZ / Andreas Hahn, 2015

8.2.6 Lack of Quality Assurance and Service

Use the SPIS Toolbox MAINTAIN – Water Application Uniformity Field Guide Tool for a quality check of the SPIS on Energypedia.

As already outlined in section 5.2, the long-term sustainability of SPIS dissemination programmes depends on well-designed products and the quality of installation. Only field-tested system components should be used that fulfil minimum quality requirements. If low-quality SPIS are introduced to the market and fail, the credibility of solar photovoltaic as a reliable energy source for rural electrification can be seriously undermined.

Taking the harsh environmental conditions of many developing countries into account, costs should never be reduced by compromising on system quality or support services.

The development and use of already existing technical specifications and standards can support government authorities in the preparation of tender documents and help manufacturers to work towards common goals. When widely accepted, technical standards contribute to lower production costs, reduce installation time and facilitate repair. Standards also foster fair and transparent competition as all actors in the market must play by the same rules. Government-funded programmes should also include the quality control of end customer installations. This task is usually left to system integrators and manufacturers who should also take care of adequate installer training. As field experience has shown, this is a weak point in most developing countries and a threat to the successful implementation of dissemination programmes.

8.2.7 Natural Disasters and Theft

The risk of theft and frequently occurring natural disasters, such as cyclones and earthquakes, are often cited as reasons for farmers being reluctant to invest in the relatively expensive PV technology.

This is sometimes justified, as showed for example a farm site in the Atacama Desert of Chile, where a well collapsed because of a strong earthquake. Besides losing the well, the farmer lost the valuable solar pump, cabling and riser pipe.

Statistically, the risk of losing a system by natural disasters is relatively small. It is more likely that high-value system components, such as the PV panels, will be stolen. The awareness and popularity of solar systems have risen and so has the number of thefts of solar panels. Since the price of the panel amounts to up to 50 % of the investment cost of a PV system, it is most lucrative to steal this part of the installation.

Several techniques have proven effective in mitigating the likelihood of system theft, including anti-theft mounting systems and marking the underside of the panels with the farm name and contact details in non-removable paint. Mounting panels on high poles is another common solution, often found in rural Africa. For SPIS, the most effective anti-theft measure is probably installation close to the farm house.

No matter what strategies to protect SPIS against theft and natural impacts are taken, the risk of losing equipment remains and will probably influence the investment decision of the farmer.

8.3 Summary of Opportunities and Risks

You can do your own SWOT Analysis using the PROMOTE & INITIATE – SPIS Rapid Assessment Tool on Energypedia.

The main opportunities related to solar powered irrigation include:

- Despite rapid growth of the PV market, most of its potential remains untapped;
- Despite a drastic reduction in PV prices, the perception of PV panels being expensive persists. This hinders higher market penetration levels in the near future;
- Rural electrification in developing countries continues and PV water pumps present a good off-grid alternative (possibly involving feed-in tariffs for surplus energy);
- High potential of the local markets – example of India: If 50 % of the country's diesel pumps were replaced with PV pumps, diesel consumption could be reduced to about 225 billion l/yr;
- SPIS opens up opportunities with respect to agricultural productivity;
- Collective use of SPIS (group or cooperative schemes) may help overcome the current financing hurdles;
- PV systems can reduce electricity costs and problems of unreliable power supply;
- As the PV market develops locally, it will create employment opportunities;
- There is scope for innovation and improvement.

The main risks for the promotion of SPIS include:

- PV systems are falsely perceived as being too expensive and are hence not considered as a technical option;
- No affordable financing services for PV systems are available yet;
- Fluctuating oil prices may create a favourable environment for conventional pumping systems;
- The use of grants and subsidies could undermine the long-term sustainability of SPIS dissemination;
- A low awareness of technological SPIS options prevails, particularly in the agricultural sector in developing countries;
- Low quality and false use of SPIS can undermine its reputation regarding technical reliability and credibility;
- Risks such as theft can negatively influence the decision-making of the farmer.

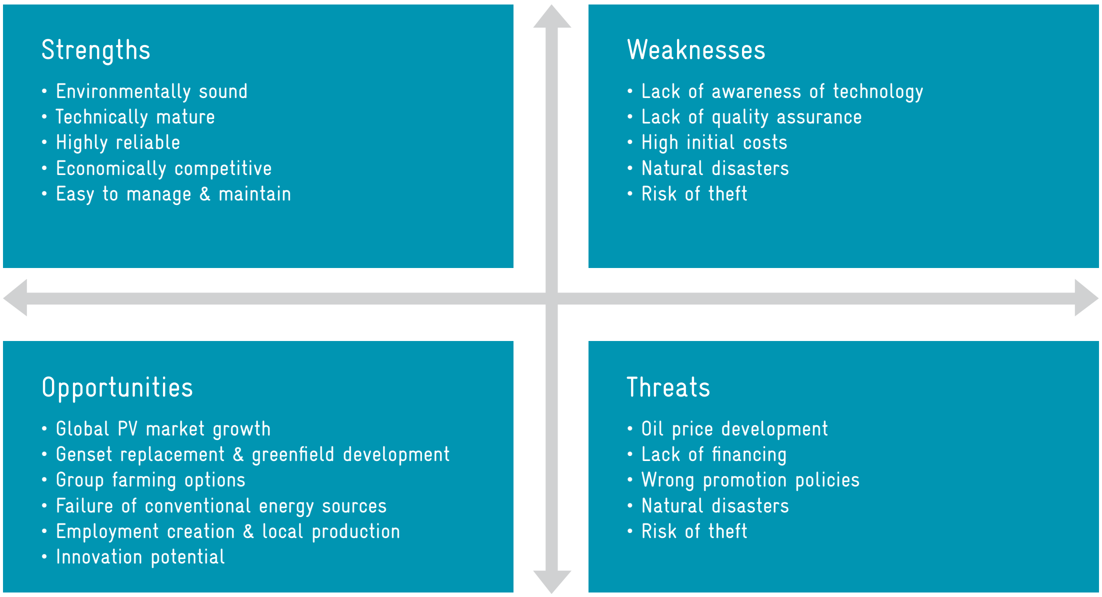


Figure 8.12: SWOT analysis for SPIS promotion

Source: Authors

9 Conclusions and recommendations

9 Conclusions and recommendations

Find some recommendations about how to Define a Promotion Strategy,

Plan & Implement Promotion Activities in the SPIS Toolbox Module PROMOTE & INITIATE on Energypedia.

Worldwide, the need for energy, the availability of renewable resources, and the falling cost of renewable energy technologies create multiple opportunities for PV technology. The employment of photovoltaic solutions for on-grid and off-grid electrification has become quite common. Solar energy based water pumping is already widely used in drinking and livestock water supply as a low-maintenance option for rural areas. In the irrigation sector, however, the exploitation of PV-based water abstraction and conveyance technology options is still relatively rare.

Most water pumps utilised for irrigation purposes worldwide are powered by engines running on fossil fuels (diesel, petrol, gas) or on electricity supplied from the grid (and thus produced by fossil fuel based generators). Fossil energy sources are limited in availability and the emissions from their use have severe impacts on the global climate.
At the same time, electricity supply especially in developing countries tends to be insufficient and unreliable, if not largely absent in rural areas. This context presents a significant potential to introduce PV technology in irrigated agriculture to a much larger extent. For India alone it is estimated that farms operate 26 million diesel and electric pumps. Rising fuel prices and energy tariffs have a financial impact on the gross margins generated from agricultural production.

The analysis in this report underlines that PV-powered irrigation is a technically mature option, even though it is not yet very widespread. Solar-powered water pumping can be integrated into irrigation systems in different ways. The case studies from different countries give an insight into the wide range of application of the technology. From a technical point of view, photovoltaic water pumping can be integrated into most irrigation concepts. Water abstraction from ground or surface water sources is technically feasible even where large pumping heads and large conveyance quantities must be handled. PV pumps can also be employed to pressurise closed irrigation systems including centre pivots. On the side of the pump manufacturers, technology development is far advanced and the market can hence provide a suitable pumping solution for almost any requirement and condition. This includes the integration of PV pumps into hybrid systems.

Limits upon meaningful and feasible application of PV technology result mainly from aspects of agronomic and financial viability. In contrast to public water supply, water pumping for irrigation has to follow an economic rationale – a farmer is an entrepreneur, no matter how small his landholding may be. The main considerations of a farm household are always production (food) security and the generation of income, hence maximisation of production and minimisation of fixed and variable production costs.

The information and analysis brought together in this report show that agronomic and financial feasibility requirements limit the range of application of PV technology in irrigation. The promotion of the technology will have to take these limits into account and must proceed from an understanding that the utilisation of PV technology requires high initial capital investment and technological know-how for system design and development.

Photovoltaic water pumping in irrigation is largely promoted by subsidising the technology in order to be an attractive alternative for the farmer. Subsidisation, however, should not result in non-adherence to principles of economic feasibility – for example, solar-powered water lifting from a deep borehole should not be employed to irrigate low-yielding oilseeds in traditional basins, as can be observed in India. Here, the costs and benefits are in no meaningful relation, yet the equation is neglected due to the subsidisation involved.

Based on the analysis presented in this report, photovoltaic water pumping in irrigation can be best utilised in the following contexts:

- **Surface irrigation:** Water abstraction from surface water resources (rivers, lakes) or shallow groundwater resources and injection into primary canals for onward water distribution;
- **Drip irrigation:** Water abstraction from surface or groundwater resources and (i) injection into storage facilities, (ii) direct injection into a pressurised system or (iii) injection from a storage facility into a pressurised system.

Water pumping with PV pumps from deep groundwater resources (or lifting from surface water resources up-hill with a large head) for water-intensive surface irrigation is not a feasible option due to the required dimensions of the PV generator and pump. Likewise, water pumping from groundwater or surface water resources for pressure-demanding sprinkler irrigation is not a viable option.

As outlined in the present report, PV pumps have the comparative disadvantage that their performance is correlated to the level of radiation or rather the yield in solar energy that can be supplied to the pump. A PV pump is hence always sized larger than alternative diesel or grid-fed electric pumps, as it must achieve an adequate performance related to irrigation needs even in the low-radiation periods of the day (morning/afternoon). This need for larger sizing results in over-capacity in the high-radiation periods of the day (noon).

Cost-efficient and viable operation of PV pumps in irrigation can be achieved if a number of principles are observed:

- Water-saving irrigation methods should be employed in order to reduce water pumping requirements – the most appropriate irrigation method in this sense is drip irrigation in low-pressure systems < 4 bars;
- Intermediate water storage tanks/basins (covered storage is to be preferred to avoid evaporation losses) should be integrated into the design of an SPIS (in particular in areas with deep aquifers) to create a low-head water source and create water autonomy for periods with low radiation – elevated storage tanks/basins that can provide onward gravity flow into the (low-pressure) network are ideal;
- Direct injection drip irrigation system designs should only be considered for smallholdings under the condition that the entire irrigated area can be irrigated at least once a day on any given day during the vegetation period;
- Irrigation systems with PV water abstraction and conveyance should be sub-divided into irrigation blocks adapted to the specific pumping performance to enable irrigation rotation between blocks (to avoid excessive over-sizing of the pumping system);
- PV water pumping should only be considered for high-value crops with excellent market prospects in order to cover the high initial investment;
- PV water pumps should not be used as back-up system to conventional pumping solutions, as their financial viability depends on a high utilisation rate with as little as possible additional operational expenses – if a decision is made to employ a PV pumping system, the PV pump(s) should become the primary pumping component;
- System design should incorporate flow and pressure requirements for filter and fertigation system components, even if their integration is not immediately planned;
- Every water pumping installation should be equipped with a monitoring device (at least a water flow meter, ideally also pressure gauge).

PV-based water abstraction and conveyance have a number of positive ecological effects, notably due to the low carbon footprint of the technology, the avoidance of emissions and the reduction of groundwater contamination risks. With regard to the sustainable utilisation of water resources, PV-based pumping solutions can have a widespread positive effect if planned in a meaningful way. The daily operational window of a solar-powered pump is up to 60 % narrower than that of a pump driven by conventional energy sources, which suggests introducing modern, water-saving micro-irrigation approaches to counter this limitation. This, combined with the fact that over-sizing of PV pumps and the establishment of large water storage capacities result in financial non-viability in almost all cases (except for greenfield development), presents a barrier to broad-scale deployment of the technology.

Experience with the design of SPIS shows that almost no systems – not even existing turn-key solutions – are planned in such a way that system capacity is oriented towards the specific farmer's requirement and based on the availability of water resources. Furthermore, most SPIS are designed and planned in a fragmented way: water source, PV generator/pump and irrigation system, and subsequently also cropping patterns and irrigation management are seldom harmonised and often do not match. In many cases this creates system inefficiencies that may influence production and/or gross margins negatively. In some cases this may result in system failures and/or inherent financial non-viability, in particular when the PV generator/pump is significantly over- or undersized or when network design does not allow for appropriate irrigation management. In particularly severe cases this may also result in unsustainable exploitation of water resources – none of the representative SPIS visited during the underlying case studies was designed by considering actual water availability and groundwater recharge. Even worse, none of the visited farmers and responsible system developers had knowledge of the specific water resource's capacities.

The strong recommendation emanating from this report is naturally an adherence to water governance and integrated planning when designing and developing an SPIS, no matter what size. The envisaged development of a promotion and planning manual and tools for Solar Powered Irrigation Systems should take the above aspects into account. Planning an SPIS is a complex exercise that requires a significant level of knowledge and skills. These requirements often exceed the capacity and possibilities of an individual farmer and an individual extension worker or advisor. Yet, it must be assured that all components are adjusted to each other to the maximum possible extent. Here again, a promotion and planning manual is needed to provide practical orientation.

Further promotion of productive use of water in agriculture and beyond hence requires accompanying measures in support of sustainable water resource management and water governance. This cannot be regulated by market principles. It rather requires the establishment of water resource management capacities, awareness creation and capacity development.

A counterproductive instrument in this regard is the availability of unconditional subsidies. As long as PV-based pumping solutions are subsidised to a large extent without demanding strict adherence to water availability and water utilisation monitoring, water-saving irrigation technologies and limitation of water storage, the risk of unsustainable utilisation of the technology will prevail in view of widespread concerns about over-pumping.

Key barriers to a larger degree of SPIS development today include up-front investment costs and the technical know-how for site-adapted design and development. Professional services for installation and maintenance are available to a rapidly growing extent. The operational skills that SPIS demand from the end users (farmers) are manageable as long as system developers document the systems in an appropriate way and provide training to their clients. Key to an individual system's sustainability and success is the adaptation of the agricultural production process. Here, agricultural extension and information services need to develop their capacities in line with the demands arising from SPIS.

The absence of suitable financing products catering for the specific needs of SPIS development (high initial capital needs, no additional collateral options, long repayment period) is an obstacle to the dissemination of the technology. Good examples like in India and Morocco show that corresponding loan financing is an option, even though it may require a particular risk management. The proposed concept for the SPIS promotion and planning manual takes this into account and should therefore also integrate the information needs of staff of financing institutions that deal with financing products for the agricultural sector.

Subsidies are widely used to promote PV water pumping in irrigation, often in combination with water-saving micro-irrigation concepts. These subsidies create a growing demand for the SPIS technology in the short run, but they also hinder the development of a professional private sector market that provides services catering for the needs of farmers in the long run. This problematic context should be taken up in policy dialogues and sector strategy development exercises, which are often supported by donors.

10 Bibliography

Aaberg, D. (2007): Generator set noise solutions: Controlling unwanted noise from on-site power systems, Power topic no. 7015: Technical information from Cummins Power Generation Inc. Available online at www.power.cummins.com.

Abrol, I., Yaday, J. & Massoud, F. (1988): Salt-Affected Soils and their Management, FAO Soils Bulletin 39, published by Food and Agricultural Organization of the United Nations. Available online at http://www.fao.org/docrep/x5871e/x5871e00.htm#-Contents.

Allen, R., Pereira, L., Raes, D. & Smith, M. (1998): FAO Irrigation and Drainage Paper No. 56: Crop evapotranspiration – Guidelines for computing crop water requirements, published by Food and Agricultural Organization of the United Nations. Available online at https://appgeodb.nancy.inra.fr/biljou/pdf/Allen_FAO1998.pdf.

American Cancer Society (2015): Diesel exhaust and cancer. Available online at https://www.cancer.org/cancer/cancer-causes/diesel-exhaust-and-cancer.html.

Awulachew, S., Lemperiere, P. & Tulu, T. (2009): Training manual on agricultural water management, Module 4: Pumps for small-scale irrigation, published by International Water Management Institute. Available online at https://www.doc-developpement-durable.org/file/eau/pompes/pompes-a-pedales/Module%20 4%20Pumps%20for%20small-scale%20 irrigation.pdf.

Badr, A. & Abuarab, M. (2013): Soil moisture distribution patterns under surface and subsurface drip irrigation systems in sandy soil using neutron scattering technique, Irrigation Science, May 2013, Volume 31, Issue 3, pp 317-332. Available online at https://scholar.cu.edu.eg/?q=m12s1978/files/lnskh_lnhyy.pdf.

Bevacqua, Robert F.; Phillips, Richard (2001): Drip irrigation for row crops. New Mexico State University. Las Cruces. Available online at https://aces.nmsu.edu/pubs/_circulars/CR573/welcome.html.

Brouwer, C. & Heibloem, M. (1986): Irrigation Water Management: Irrigation Water Needs, Training Manual No. 3, published by Food and agricultural Organization of the United Nations. Available online at http://www.fao.org/docrep/s2022e/s2022e00.htm.

Brouwer, C., Prins, K. & Heibloem, M. (1989a): Irrigation Water Management: Irrigation Scheduling, Training Manual No. 4, published by Food and agricultural Organization of the United Nations. Available online at http://www.fao.org/docrep/t7202e/t7202e00.htm.

Brouwer, C., Prins, K., Kay, M. & Heibloem, M. (1989b): Irrigation Water Management: Irrigation Methods, Training Manual No. 5, published by Food and Agricultural Organization of the United Nations. Available online at http://www.fao.org/docrep/s8684e/s8684e00.htm.

Cabraal, Anil; Cosgrove-Davies, Mac; Schaeffer, Loretta (1996): Best practices for photovoltaic household electrification programs. Lessons from experiences in selected countries. Washington, D.C: World Bank (no. 324). Available online at http://documents.worldbank.org/curated/en/502521468777286393/Best-practices-for-photovoltaic-household-electrification-programs-lessons-from-experiences-in-selected-countries.

Deutsche Gesellschaft für Sonnenenergie (DGS) (2013): Planning and installing photovoltaic systems. A guide for installers, architects and engineers. 3rd edition. Abingdon, Oxon: Routledge. Available online at http://www.worldcat.org/oclc/940845413.

De Wild-Scholten, M. & Cassagne, V. (2013): Environmental footprint of photovoltaics, EU PVSEC 28, Paris, France, 3 October 2013, Available online at http://smartgreenscans.nl/publications/deWild-Scholten-Cassagne-2013-Environmental-footprint-of-photovoltaics.pdf.

Dosatron (2019.): Water powered dosing technology. Available online at http://dosatron-sales.com.au/dosing-dispensing-technology/.

DripWorks (n.d.): Sand media filters. Available online at https://www.dripworks.com/sand-media-filters.
European Photovoltaics Industry Association (EPIA) (2011): Sustainability Working Group Fact Sheet – Sustainability of Photovoltaic systems. The Energy Payback Time. Available online at http://www.zonne-energie-wageningen.nl/wp-content/uploads/2012/08/EPIA-2011-Fact_Sheet_on_the_Energy_Pay_Back_Time.pdf
European Photovoltaics Industry Association (EPIA) / GREENPEACE (2011): Solar Generation 6 - Solar Photovoltaic Electricity Empowering the World. Available online at http://www.greenpeace.org/international/Global/international/publications/climate/2011/Final%20SolarGeneration%20VI%20full%20report%20lr.pdf.
European Photovoltaics Industry Association (EPIA) (2014): Global Market Outlook for Photovoltaics 2014 – 2018. Available online at https://resources.solarbusinesshub.com/solar-industry-reports/item/global-market-outlook-for-photovoltaics-2014-2018.
Everfilt (n.d.): Sand filters and multi media water filters. Available online at http://everfilt.com/sand-filters-multi-media-filters/.
eXtension (2015): Introduction to energy efficient irrigation. Available online at http://articles.extension.org/pages/27775/introduction-to-energy-efficient-irrigation.
Food and Agriculture Organization of the United Nations (FAO) (2011): Women in agriculture. Closing the gender gap for development. Rome: FAO (The state of food and agriculture, 2010-11). Available online at http://www.fao.org/docrep/013/i2050e/i2050e00.htm.
Food and Agriculture Organization of the United Nations (FAO), AQUASTAT (FAO's global water information system) (2014): Area equipped for irrigation. Available online at http://www.fao.org/3/I9253EN/i9253en.pdf.
Fraunhofer Institute for Solar Energy Systems (ISE) (2014): Photovoltaics Report 2014. Available online at https://de.slideshare.net/ashishverma061/photovoltaics-39887778.
Frenken, Karen (1997): Irrigation potential in Africa. A basin approach. FAO Land and Water Bulletin 4. Rome: FAO. Available online at http://www.fao.org/docrep/W4347E/W4347E00.htm.
Fritsche, U. & Lenz, V. (2000): Kurzstudie: Ökobilanz zu PV- und Dieselbetriebenen Bewässerungspumpenanlagen in Entwicklungsländern, published by Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. Available online at http://iinas.org/tl_files/iinas/downloads/GEMIS/2000_PV_Pumpen-GTZ.pdf.
Fthenakis, V., Kim, H., Frischknecht, R., Raugei, M., Sinha, P. & Stucki, M. (2011): Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, published by International Energy Agency (IEA) PVPS Task 12, Report T12-02:2011. Available online at http://www.seas.columbia.edu/clca/Task12_LCI_LCA_10_21_Final_Report.pdf.
Goldstein, Hannah (2019): What is the Carbon Footprint of Solar PV from Electricity Generation?, Available online at https://sites.lafayette.edu/egrs352-sp15-pv/global-climate-change/solar-pv-vs-renewable-technologies-on-carbon-footprints/
GIZ; IGEN (n.d.): Solar water pumping for irrigation. Opportunities in Bihar, India. Available online at https://tuewas-asia.org/wp-content/uploads/2017/05/30-Solar-Water-Pumping-for-Irrigation-Opportunities-in-Bihar-India.pdf.
Goodwin, Ian (2010): Minisprinkler microspray irrigation for orchards. The State of Victoria, Department of Environment and Primary Industries. Melbourne. Available online at http://agriculture.vic.gov.au/agriculture/horticulture/fruit-and-nuts/orchard-management/minisprinkler-microspray-irrigation-for-orchards.
Grundfos (n.d.): The centrifugal pump. Available online at http://machining.grundfos.com/media/16620/the_centrifugal_pump.pdf.
Hall, Mark (n.d.): Renewable energy - irrigation. Available online at http://farmenergy.blogspot.com/p/irrigation.html.

Hillel, Daniel (1997): Small-scale irrigation for arid zones. Principles and options. Rome: FAO. Available online at http://www.fao.org/docrep/w3094e/w3094e00.htm.

Huld T., Müller R., Gambardella A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. Solar Energy, 86, 1803-1815.

ICID (n.d.): Sources of irrigation. Available online at http://www.icid.org/res_irri_source.html.

International Finance Corporation (IFC) (2015): Market Assessments for Solar-Powered Irrigation Pumps in Morocco, South Africa and Yemen. Available online at http://docplayer.net/21236588-Market-assessments-for-solar-powered-irrigation-pumps-in-morocco-south-africa-and-yemen.html.

KPMG (2012): The Rising Sun – Grid parity gets closer: A point of view on the solar energy sector in India. Available online at http://www.indiasmartgrid.org/reports/Rising-Sun-2%20%20KPMG%20Report%20 2012.pdf.

Kulkarni, S., Reinders, F. & Ligetvari, F. (2006): Global scenario of sprinkler and micro irrigated areas, 7th International Micro Irrigation congress in Kuala Lumpur, Malaysia 13 – 15 September 2006.

Larsen, K. (2009): End-of-life PV: then what? - Recycling solar PV panels. Feature available online at http://www.renewableenergyfocus.com/view/3005/end-of-life-pv-then-what-recycling-solar-pv-panels/.

Mining & Hydraulic Supplies (n.d.): Helical rotor pumps. Available online at http://miningandhydraulics.com.au/pumps/2-products/43-helical-ro-tor-pumps.

National Renewable Energy Laboratory (NREL) (2012): Life Cycle Greenhouse Gas Emissions from Solar Photovoltaics, published by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. Available online at https://www.nrel.gov/docs/fy13osti/56487.pdf.

Netafim (n.d.): Low pressure automatic disc-kleen filters. Available online at https://www.environmental-expert.com/products/netafim-model-2-compact-low-pressure-automatic-disc-kleen-filters-374950.

New South Wales Farmers Association (2013): Saving energy in irrigation. Available online at https://www.aginnovators.org.au/sites/default/files/Energy%20%20Irrigation%20-%20Saving%20energy%20in%20irrigation.pdf.

Pachepsky, Y., Shelton, D., McLain, J., Patel, J. & Mandrell, R. (2011): Irrigation Waters as a Source of Pathogenic Microorganisms in Produce: A Review. In Advances in Agronomy, Vol. 113. Available online at https://pubag.nal.usda.gov/download/55092/PDF

Pond, W., Nichols, B. & Brown, D. (2009): Adequate food for all – Culture, Science, and Technology of Food in the 21st Century (CRC Press).

ProMinent GmbH (n.d.): Solenoid driven metering pumps. Available online at https://www.prominent.com/en/Products/Products/Metering-Pumps/Solenoid-Driven-Metering-Pumps/pg-solenoid-driven-metering-pumps.html.

Raghavan, S., Bharadwaj, A., Tatte, A., Harsih, S., Iychettira, K., Perumal, R. & Nayak, G. (2010): Harnessing Solar Energy: Options for India, published by the Center for Study of Science, Technology and Policy (CSTEP). Bangalore. Available online at https://shaktifoundation.in/wp-content/uploads/2014/02/cstep-harnessing%20solar%20energy%20-%20final%20report.pdf.

RAP (2006): Proceedings of the international forum on water resources management and irrigation modernization on Shanxi province, China. FAO. Taiyuan and Yuncheng, Shanxi (RAP Publication, Regional Office for Asia and the Pacific (RAP)). Available online at http://www.fao.org/3/ah995e/ah995e00.htm.

Raschid-Sally, L.; Faruqui, N.I.; Scott, C.A. (2004): Wastewater use in irrigated agriculture. Confronting the livelihood and environmental realities. Oxfordshire, Colombo, Ottawa: CABI; International Water Management Institute; International Development research Centre. Available online at http://www.ais.unwater.org/ais/pluginfile.php/225/mod_label/intro/iwmi_4.pdf.

Renner, J. (2012): Global irrigated area at record levels, but expansion slowing, published by the Worldwatch Institute.

Robillard, Tracy (2019): Example of a linear irrigation project, Keudell Farm, Marion County, licensed under CC BY-ND 2.0, published via flickr.com (https://www.flickr.com/photos/nrcs_oregon/40768797393/in/photolist-257AJmM-257AKCV-TzWxmm-257ALdn-2fDwCso-257AK6T-2fJdHXM-257AJGB-2f... DwzL1-RXHx96-RXHs72-2fDww65-2fJdMtK-RXHrWH-2fJdKp4-257AHYn-RXHsjX-2fJdKPT-2fDwz7f-RXHrw4-2fJdGvPTzWquL-257AVhe-2fJdLQa-257AUoFw6So54-2fDwwNh-TzWrBA-2fJdJU6-2fJdJn4-w6SjUX-x1qiX3-x1qgjh-w6HtAdwLfh38-x4hhVX-w6Hkt1-wLfcFc-x3JRbMx3JSDB).

Schmidt, R. (2012): Aplicaciones de Energía Solar Fotovoltaica. Diseño, Implementacion, Experiencias.

Sela, Guy (n.d.): Irrigation Water Quality. SMART! Fertilizer Management. Available online at http://www.smart-fertilizer.com/articles/irrigation-water-quality.

South African Irrigation Institute, SABI (2014): Norms for the design of irrigation systems. Available online at https://sabi.co.za/0-pdf/SABI%20Norms%2012%20March%202014.pdf.

Stauffer, B. & Spuhler, D. (2019): Surface Irrigation. Sustainable Sanitation and Water Management Toolbox - SSWM.info, published by seecon international GmbH. Available online at https://sswm.info/sswm-university-course/module-4-sustainable-water-supply/further-resources-water-use/surface-irrigation.

Stauffer, B. & Spuhler, D. (2019a): Sprinkler irrigation. Available online at http://www.sswm.info/content/sprinkler-irrigation-0.

Stryker, Jess (1997): Irrigation tutorials. Drip irrigation emitters. Available online at https://www.irrigationtutorials.com/drip-irrigation-emitters/.

Stryker, Jess (2003): Jess Stryker's Landscape Sprinkler Design Tutorial. Irrigation Pumping Systems. Available online at http://www.watertraining.ca/courses/wt/204i/pump.html.

The Republic of Uganda Ministry of Water and Environment (2013): Water Supply Design Manual Second Edition. Available online at https://www.mwe.go.ug/sites/default/files/library/Water%20Supply%20Design%20Manual%20v.v1.1.pdf.

Thurston, Charles W. (2012): From land to water. PV Magazine (Issue 04-2012). Available online at https://www.pv-magazine.com/magazine-archive/from-land-to-water_10006317/

UN Water (2015): Wastwater Management – A UN-Water Analyical Brief. Available online at https://www.unwater.org/publications/wastewater-management-un-water-analytical-brief/.

USGS (2016): Irrigation: How farmers irrigate fields. Some irrigation methods. Available online at https://water.usgs.gov/edu/irquicklook.html.

Wada, Y., Van Beek, L., Van Kempen, C., Reckman, J., Vasak, S. & Bierkens, M. (2010): Global depletion of groundwater resources. In: Geophysical Research Letters, Vol. 37 (20). DOI: 10.1029/2010GL044571. Available online at: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010GL044571

Walker, W. (1989): Guidelines for Designing and Evaluating Surface Irrigation Systems. FAO Irrigation and Drainage Paper No. 45. Rome: FAO. Available online at http://www.fao.org/3/t0231e/t0231e00.htm.

Woods Institute for the Environment (n.d.): Solar-powered drip irrigation. Stanford University.

World Bank (2017): Commodity market outlook. Quarterly report. Available online at http://pubdocs.worldbank.org/en/174381493046968144/CMO-April-2017-Full-Report.pdf.

World Bank (2018): Commodity Price Data (The Pink Sheet), Available online at http://pubdocs.worldbank.org/en/561011486076393416/CMO-Historical-Data-Monthly.xlsx.

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