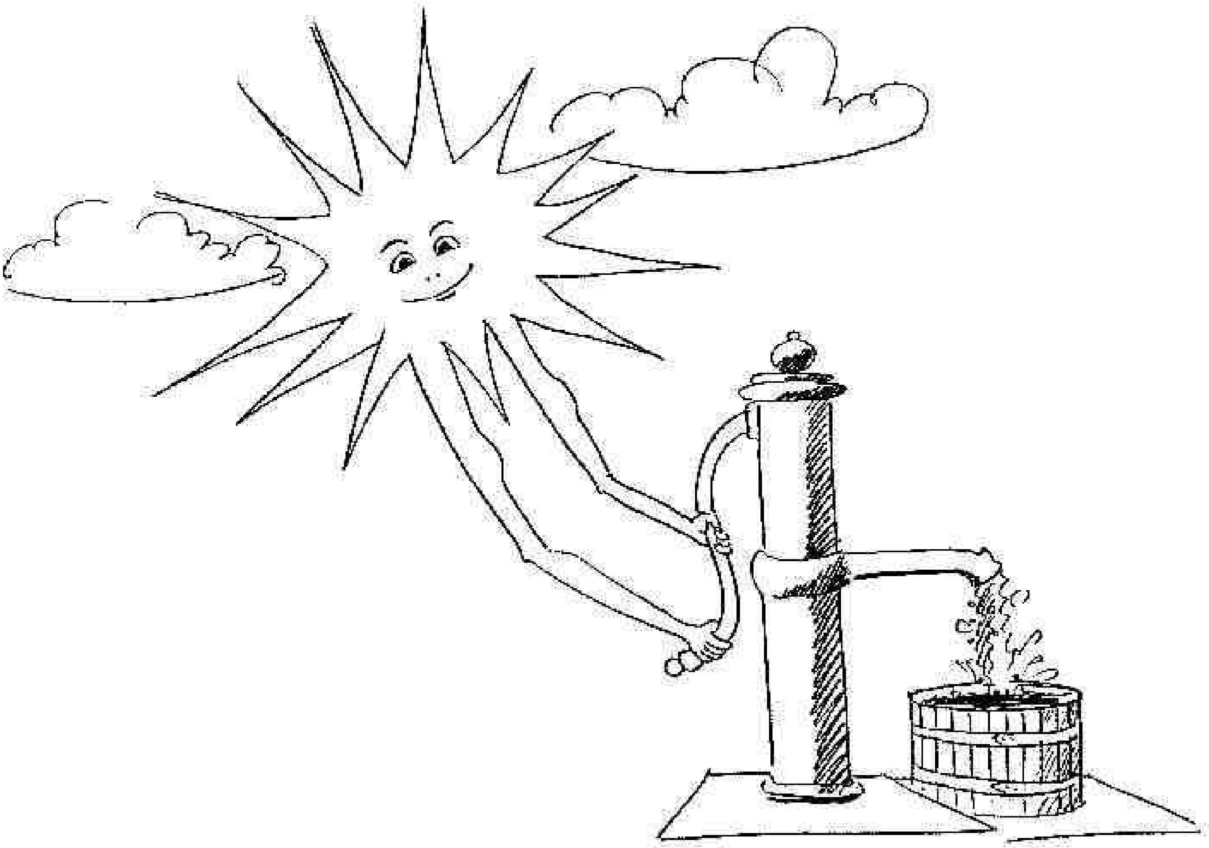
Photovoltaic Pumping Systems (PVPS)



Content

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1 Introduction

The need to cover the global demand for primary energy by other than the presently customary fossil and nuclear sources has become a topic of keen public interest. In view of the climatic effects of CO_2 emissions from fossil-fired power plants, the use of renewable sources of energy, in particular solar electricity, solar heat and wind energy, is becoming increasingly compelling.

The pursuit of affluence in emerging countries is legitimate. In general, though, it also involves an increasing demand for energy. That, in turn requires the creation of appropriate infrastructure. Poorer countries that lack the requisite capital often ask industrialized countries to provide them with – and pay for – adequate power plants and power engineering technology. Within that context, any interest group engaged in development cooperation must strive to introduce clean sources of energy to help avoid from the very start the kind of environmental problems that most industrialized countries already have, and to enable extensive independence from fuel imports.

Among the renewable energy options, one of the most prominent is electricity generated by photovoltaic means, i.e., by the direct conversion of solar radiation into d.c. current in solar cells. Electricity is a converted (refined) form of energy that is easy to convey (conduct) and can be used in practically any application. Photovoltaic systems have the advantage of requiring no moving parts, so they have inherently long service lives. Unlike windgenerators, solar cells are hardly suitable for manufacture in emerging countries, because those countries have neither the technical know-how nor the complex production equipment it takes to manufacture such high-tech products.

The first step towards economic progress in developing countries is to improve the people's living conditions. First of all, this means obtaining, providing and disposing of water as a vital prerequisite for human settlements (supply of drinking water), farming (irrigation) and grazing (stock watering points). In semi-arid regions, water resource management often is the decisive factor for regional development.

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2 The Energy- and Watersupply Situation in Developing Countries

The energy requirement for irrigation purposes in developing countries (/1/ Herrmann, 1989) is estimated at approximately 95,000 gigawatt hours per year (GWh/a). The size of an average farm ranges between 0.5 and 1 hectare. Each hectare requires somewhere between 20 m³ and 120m³ a day on such small farms (Table 1).

Drinking water		Water for animals		Water for irrigation	
Liters per person and day		Liters per head and day		Cubic meters per hectare and day	
Minimum	10	Horses	50	Rice	100
Normal rural living conditions	40	Dairy cattle	40	Cereal / grain	45
		Camels, donkeys	20	Sugar cane	66
		Pigs	20	Cotton	55
		Sheep	5		
		Goats	5		
		Poultry	1		

Table 1: Reference data for daily water requirements in tropical regions (from /1/ Herrmann, 1989)

Assuming that the average village has between 500 and 1,500 inhabitants, that village's daily water requirement would come to 20 – 60 m³. Below possibilities on how water is obtained are shown

2.1 Natural Artesian Wells

Pressurized water in an aquifer rises to the surface by virtue of the prevailing pressure head and needs only be captured;

2.2 Hand-Pump Systems

To the extent that no substantial lifting height (system head) has to be overcome, hand-operated reciprocating pumps (Fig. 1) or draw wells (Fig. 2) will suffice for obtaining water. Especially for women, who by tradition are responsible for obtaining household water in many developing countries, this means hard, time-consuming work.

Figure 1: Hand-operated reciprocal pumping system

Figure 2: Draw well in Chinguetti, Mauritania

2.3 Muscle-Powered Pumps

Muscle-powered pumps came into use long ago as an "automated" means of water delivery (Fig. 3). Usually powered by animals, such pumps are used for drawing irrigation water.

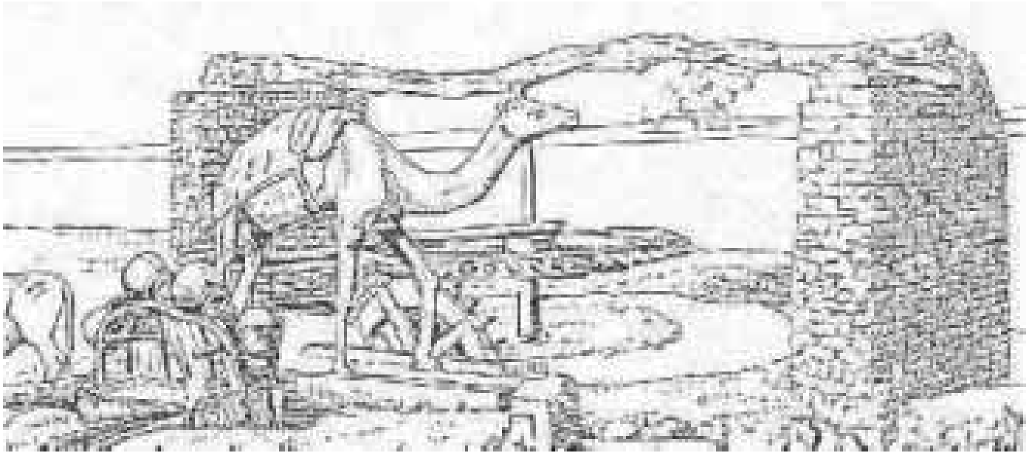

Figure 3: A typical animal-powered pump (Egyptian Sakieh, /2/ Mühlbauer, 1991)

Frequently, water has to be conveyed from its source to a more or less remote point of use. This involves certain hazards, though, particularly with regard to reliability and hygiene.

2.4 Diesel Pumps

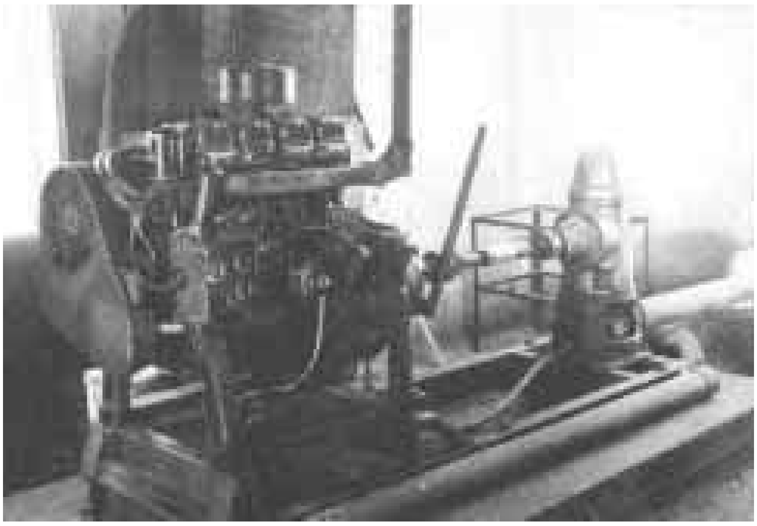

Figure 4: A diesel-powered pumping system

In developing countries, pumping systems powered by diesel engines are in widespread use for drawing water from deep wells (Fig. 4). Their range of application, however, is limited by several factors, including dependence on imported fuel, maintenance requirements, and such environmental impacts as potential pollution of the well water and/or groundwater with oil or other residues.

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2.5 Photovoltaic Pumping Systems (PVPS)

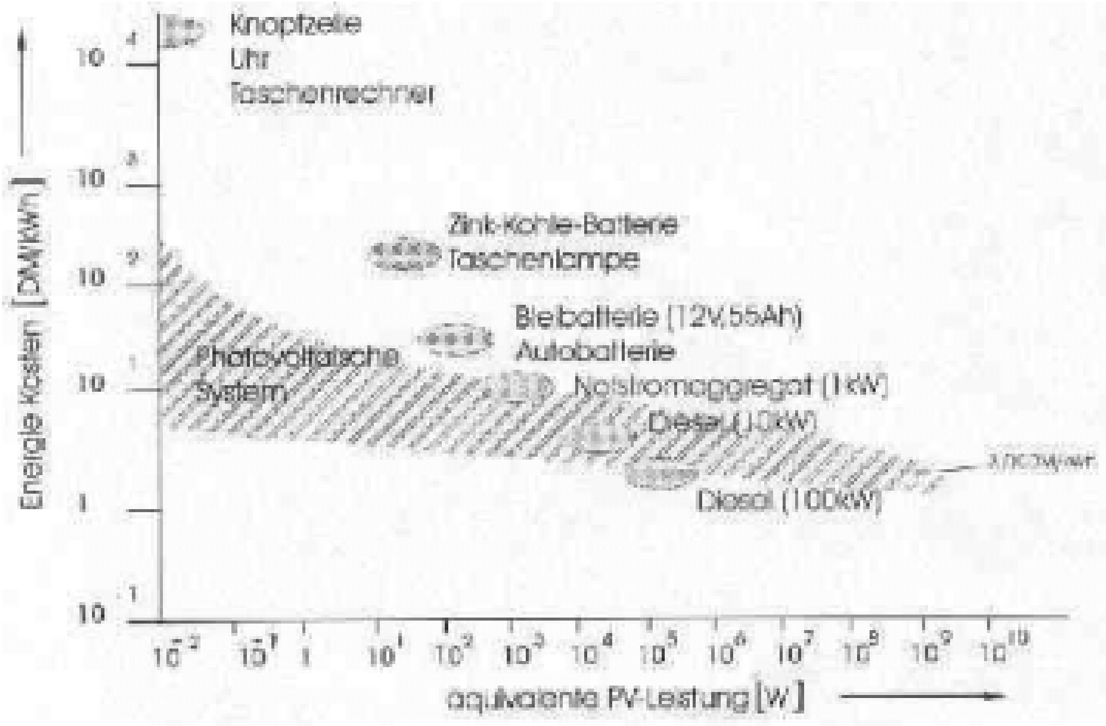
In recent years, numerous emerging countries have begun installing photovoltaic pumping systems (Fig. 5), which have an established reputation for reliability and long service life (/3/ GTZ, 1992).

Figure 5: Photovoltaic pumping system in Tunesia

2.6 Economy of PVPS

Most decisions for or against a particular type of pumping system are still being based primarily on economic factors, as opposed to ecological considerations and sociotechnical aspects. The process of introducing a new technical system, or replacing an existing system with a different one, always amounts to a certain disruption of traditional structures within the culture(s) in question. Nevertheless, most technical pumping systems are still being planned with too little consideration of their impacts on the recipient social system with regard to hygiene, education, family structure, division of labour, etc.

An attempt is therefore made below to estimate the range of areas in which the use of photovoltaic pumping systems is worthwhile.



Knopfzelle Uhr / Taschenrechner	=	Wristwatch battery / pocket calculator
Zink-Kohle-Batterie / Taschenlampe	=	Dry Cell / Flashlight battery
Blei- / Autobatterie	=	Lead battery / Motor vehicle battery
Notstromaggregat (1 kW)	=	Emergency power unit (1 kW)
Diesel (10 kW)	=	Diesel (10 kW)
Diesel (100 kW)	=	Diesel (100 kW)
Photovoltaik-Systeme	=	Photovoltaic systems
Energiekosten (DM/kWh)	=	Cost of energy [DM/kWh]
Äquivalente PV Leistung (W)	=	Equivalent PV power [W]

Figure 6: Cost of energy vs. equivalent PV power rating for various types of energy storage and power generating systems (Fraunhofer ISE, 1996)

Figure 6 shows the current cost of energy relevant to the equivalent photovoltaic output for various types of energy storage and various power generating systems. Up to an output of about 10 kW, photovoltaic power generation is more cost-effective than a diesel generator for general PV applications.

Regarding PVPS, GTZ has made an evaluation on their economy (/22/ GTZ, 1994; /23/ GTZ, 1995).

2.6.1 Objectives and Methodology of the Economy Investigation of PVPS

Besides technical maturity the economy of PVPS in comparison with competing systems is a decisive criterion for it's wider distribution.

The investigation concentrates on drinking water supply of villages without electricity supply and with approximately constant water demand. Drinking water supply for animals, as well as irrigation and dewatering are not taken into consideration. The seasonally varying demand in these cases of application requires special precautions on the consumers' side in order to achieve a high exploitation of the PVPS.

In case of low water demand the handpump generally is the most cost-effective technology. A typical human being can maintain a work output of about 70 W for hours at a time, while a draught animal can average around 300 W (/4/ GTZ, 1991). Assuming 65 % as the efficiency of the average pump, the effective hydraulic capacity figures to about 45 W for the human and 195 W for the animal. Since even human labour is generally much cheaper than high-tech equipment in developing countries - though there are exceptions - it takes a capacity requirement of more than 200 W to make the use of a photovoltaic pumping system (PVPS) economically justifiable.

However, for the examined village size of 500 to 1.000 inhabitants, predominantly Diesel pumps are used, which are in competition with PVPS. Basis for the investigation therefore is a comparison of costs of PVPS and small Diesel pumps. The investigation comprises PVPS with system sizes of 1, 2 or 4 kWp and covers the pumping station including riser pipe and water tank. Components determined by the location as the well or a distribution system, however, are not considered.

Criterion of comparison, are the specific water pumping costs (EURO / m^4), which in contrast to the net pumping costs (EURO / m^3) take into account the delivery head. This allows a more objective evaluation of the different pump technologies. The cost calculation was based on the dynamic annuity method.

The study is founded on market - investigations and cost evaluations in the project countries (Argentina, Brazil, Indonesia, Jordan, Philippines, Tunesia, Zimbabwe) which have been carried out during the last six months of 1993.

2.6.2 Cost Comparison of PVPS and Diesel Pumps

The medium investment costs of PVPS, investigated in seven countries (Argentina, Brazil, Indonesia, Jordan, Philippines, Tunesia, Zimbabwe) are shown in Table 2. The investment costs of PVPS compared to Diesel pumps with the same delivery output are indicated in Table 3. The cash-value of costs also takes into account the compensation investments for a period of 20 years. The investment costs for PVPS are always higher than for Diesel systems. PVPS, however, reveal advantages in terms of running costs (maintenance, repair, personnel expenditure).

Investment costs of PVPS (1000 EURO)	1 kWp	2 kWp	4 kWp
PV-generator, inverter, motor/pump	8.1	14.5	26.4
System, transport, assembly, tank, construction work, water-bearings	16.6	25.3	42.0

Table 2: Investment costs of PVPS (1000 EURO)

Comparison of investment costs PVPS / Diesel (reference: PVPS = 100%)	1 kWp PVPS / Diesel	2 kWp PVPS / Diesel	4 kWp PVPS / Diesel

Investment costs	100% / 54%	100% / 42%	100% / 32%
Cash-value of costs	114% / 82%	114% / 60%	110% / 48%

Table 3: Comparison of investment costs PVPS / Diesel (reference: PVPS = 100%)

The specific water pumping costs for PVPS on average of all examined scenarios are around 0.01 EURO / m^4 (Example: with a delivery head of 20 m the pumping costs amount to 0.01 EURO / $m^4 \bullet 20$ m = 0.20 EURO / m^3). The specific water pumping costs are reduced with increasing system size and growing energy demand. As this is valid for Diesel pumps even to a higher degree the benefits in cost of PVPS decrease with larger systems.

A comparison of the specific water pumping costs in Argentina and Indonesia has shown the strong influence of local and national preconditions. While in Argentina PVPS reveal advantages in all examined system sizes, in Indonesia Diesel pumps always represent the more cost-effective solution. Local and national preconditions may result in different custom fess, taxes, cost of personnel, etc.

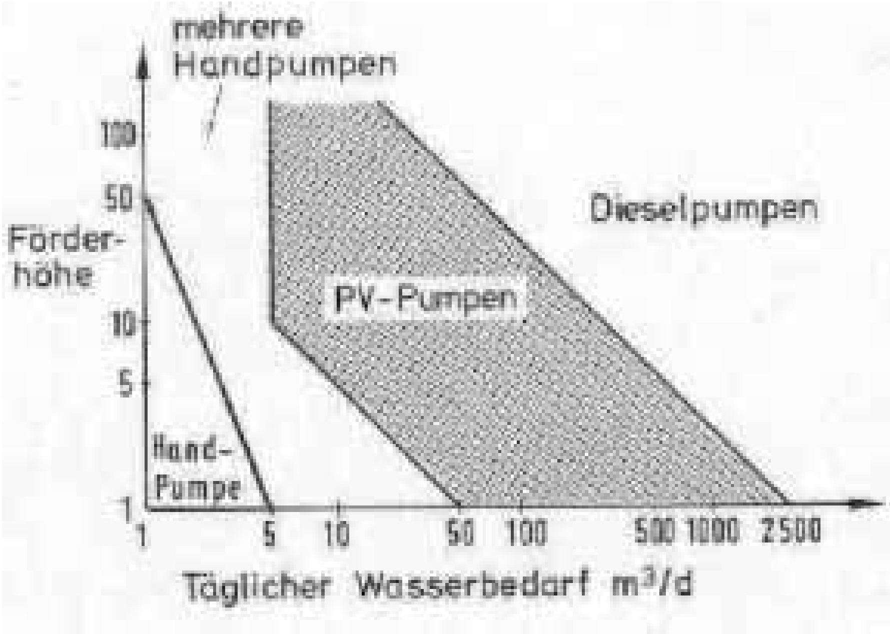
2.6.3 Cost Structure and Sensitivity

On average, the write-off only accounts for 40% of the specific water pumping costs. With public operators the running costs (essentially personal expenses) nearly account for the same share (36%).

The running costs of Diesel pumps, which come to 54%, are perceptibly higher, due to the high expenditure for maintenance and repair. The share of the fuel costs, on the other hand, only amounts to 7%. Consequently, the influence of the oil prices on the economy of PVPS is relativly insignificant. The construction expenses account for 11% - 36% of the specific water pumping costs but have a relatively low influence on the cost comparison of both systems. In countries with high labour costs the expenses and generally the rates of interest are sensitive parameters in the cost evaluation. Mainly special loans with good conditions are only available for certain investors.

2.6.4 General Usage Area of PVPS

With due allowance for the presented factors, Fig. 7 illustrates the economically expedient service range for photovoltaic pumping systems as a very general guideline (/4/ GTZ, 1991). The pump lift, or pumping head, typically ranges between 1 m and 100 m.



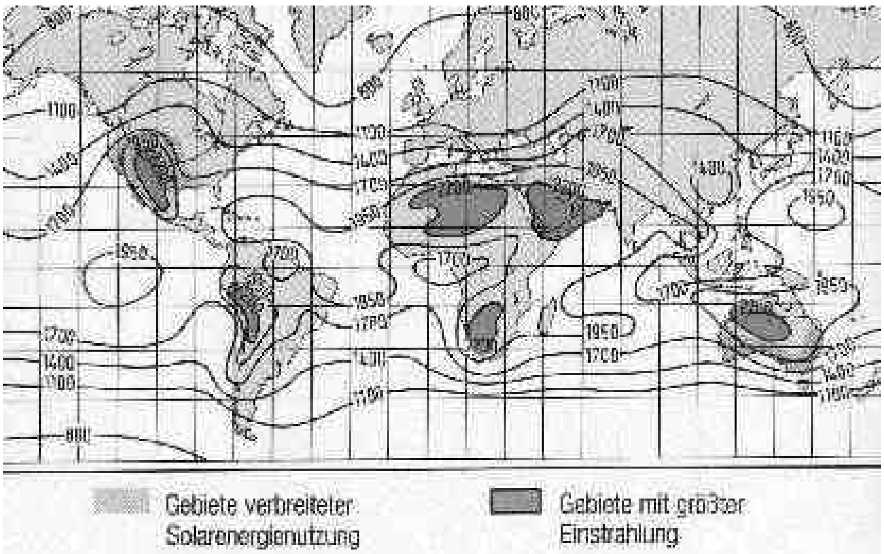
Förderhöhe	=	Water head
mehrere Handpumpen	=	Several hand pumps
Dieselpumpen	=	Diesel pumps
PV Pumpen	=	PV pumps
Handpumpen	=	Hand pumps
Täglicher Wasserbedarf	=	Daily water requirement [m³/d]

Figure 7: Duty limits for photovoltaic pumping systems (/4/ GTZ, 1991)

3 Technical Characteristics for PVPS

Both solar energy and wind energy have one crucial drawback in comparison with conventional energy management: they supply energy stochastically – unless they are diseconomically oversized – and their output therefore is not directly manageable. That is a decisive deviation from conventional power plant technology, in which the supply of energy can always be adjusted to match the momentary demand, and where most of the fuel can be saved during periods of low demand. In the case of solar power, however, the demand is dependent on the supply, i.e., some form of interim storage must be provided, because no power is generated in the absence of solar radiation – and that is the main challenge for anyone planning a solar plant.

Despite the substantial technical advances that have been made in the production of solar cells in recent years, the achievable efficiency in the conversion of solar radiation to electricity by solar cells is still relatively low in practice (9 % - 12 % under field conditions (/6/ Hummel, 1993). Since the requisite equipment is still very high-priced, this means that the use of photovoltaic systems is still accordingly expensive. Moreover, photovoltaic systems rarely achieve their optimal duty point, because – as already mentioned – the incoming supply of energy fluctuates. That is why PV systems have remained extensively confined to niche markets. PV pumps constitute one such niche, mainly because they can do without an electricity storage option. Most modern photovoltaic pumping systems extensively comprise off-the-shelf components from competent manufacturers, because series products are less expensive, and it would not yet be profitable for a manufacturer to produce customized components for specific photovoltaic systems. Thus, the components are designed for a fixed duty point (50 Hz a.c. systems).



Areas in which solar energy is being tapped

Areas with the highest insolation levels

Figure 8: Mean annual irradiance onto a horizontal plane [kWh/m²a] (/7/ RWE, 1990)

This extensive optimization for a narrow range of operation, or for a single duty point, detracts considerably from the system's part-load efficiency. Consequently, PVP systems face yet another problem when variable cloudiness imposes part-load operating conditions. Conversely, good system sites are characterized by stable insolation. As a rule, that coincides with those parts of the earth with the greatest need for water pumps. Figure 8 shows which parts of the world enjoy the highest insolation rates.

In connection with earlier PVPS projects, it became apparent that people in developing countries have a different relationship to technology than do people in industrialized countries. Thus, as complex as they are, the PVP systems must be made very robust and reliable, especially because qualified maintenance & repair personnel is normally very hard to find in the areas where such systems tend to be installed (/8/ Posorski, 1993).

Despite the limitations imposed on the application of photovoltaic pumping systems, the technology has a major future potential, thanks mainly to its environmental compatibility, reliability and lack of dependence on other sources of energy.

4 Description of PVP System Components and Actuating Variables

Photovoltaic pumping systems can be used in diverse configurations for drawing water (/9/ Bucher, 1993). Figure 9 sketches out two application options for photovoltaic pumping systems: deep-well and ground-level pumps. In deep-wells only submersile pumps can be installed, whereas in ground-level different pumps types are usable (chain pumps, screw pumps, etc.)

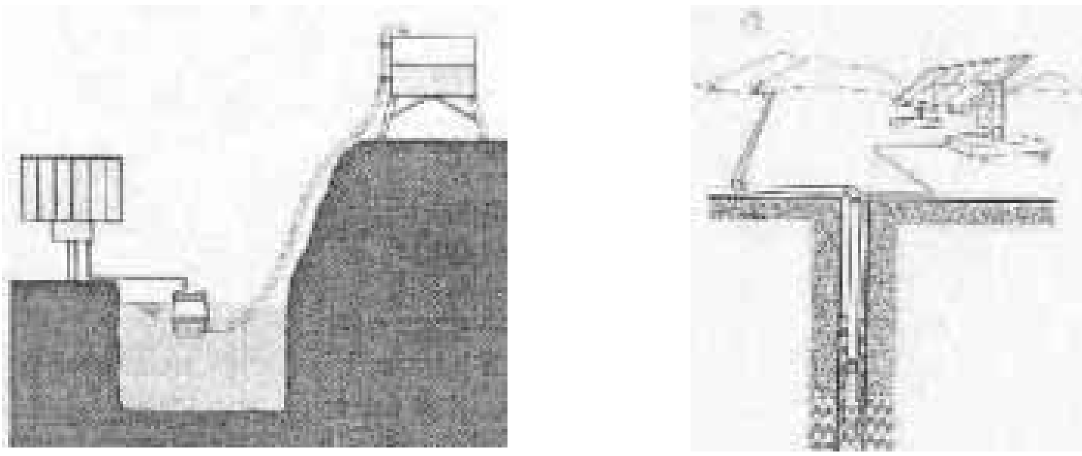


Figure 9: PV-powered pumping system: ground-level (left) and deep-well configurations

Photovoltaic pumping systems are made up of several independent components. All such systems, however, have the same basic configuration (Fig. 10).

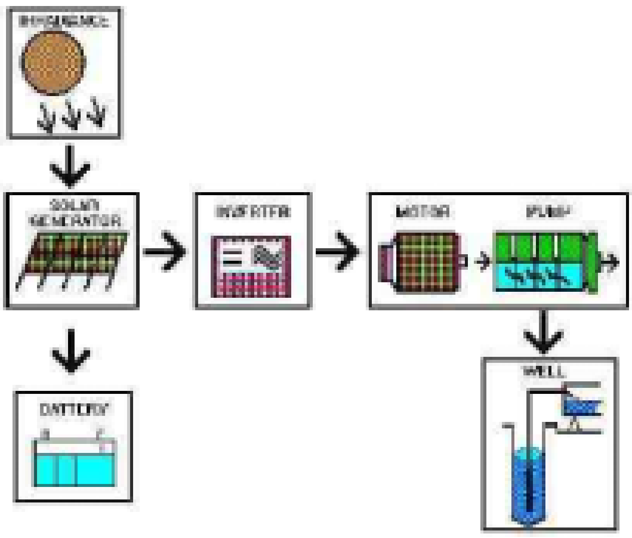
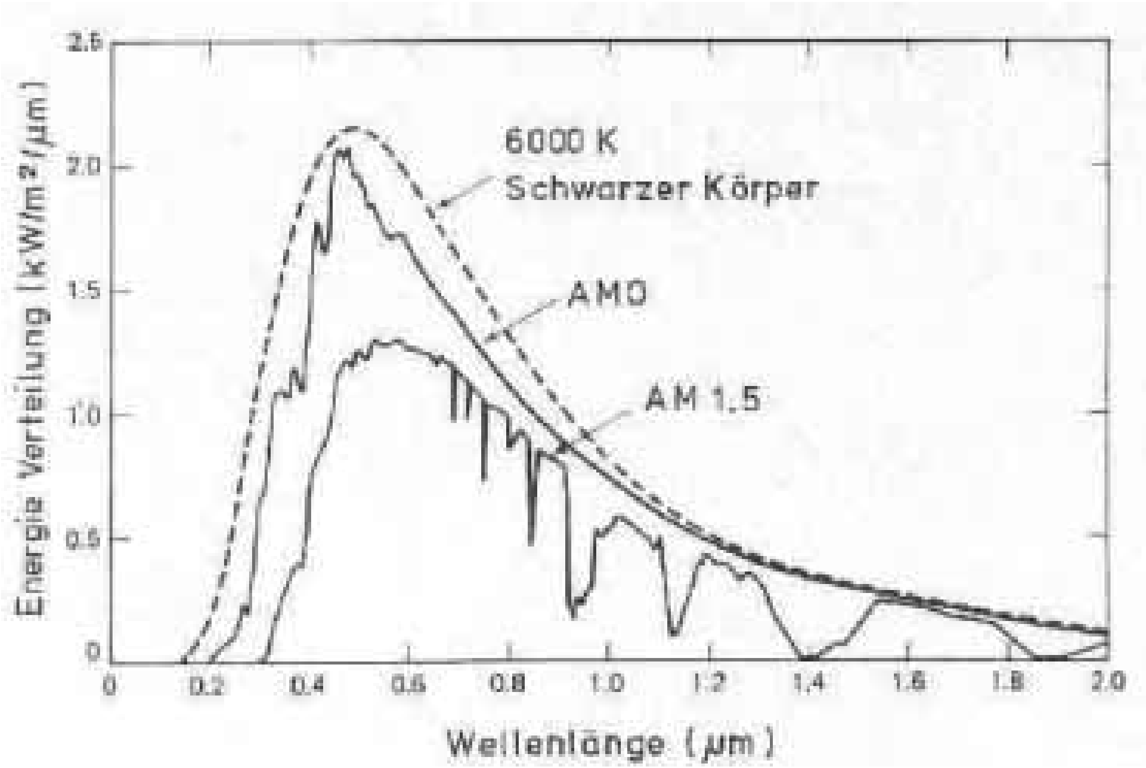


Figure 10: Block diagram of a photovoltaic pumping system

Basically, a photovoltaic pumping system comprises 6 main components: solar radiation, a solar generator, a generator/load matching module (power inverter), a drive element, a pump and a well (including all piping, of course). Depending on the case-by-base situation, such additional components as an energy store (battery) may also be included.

4.1 Insolation

Solar energy is radiant energy. The global solar irradiance, i.e., the amount of solar energy reaching the face of the earth each year, amounts to some 1.75 x 10^{18} kWh. Outside of the earth's atmosphere, the useful irradiance, i.e., that which can be collected by solar cells, amounts to S_{+} = 1353 W/m². The air mass (the sun-path mass of the earth's atmospheric layer) is a major criterion in the evaluation of radiation quality and of useful wavelength bands. Figure 11 shows the spectrum of solar radiation outside of the earth's atmosphere (AM 0) and how it can be measured from the earth (AM 1.5).



Energie Verteilung = Energy Distribution
Wellenlänge = Wavelenght

Figure 11: Spectrum of solar radiation outside of the earth's atmosphere (AM 0) and measured from the earth (AM 1.5)

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The sun's radiant energy cannot be stored directly, but first has to be converted into a different - storable - form of energy.

Solar energy can, however, be converted directly into electricity with the aid of a solar generator made up of several panels, each comprising a number of solar modules. The modules, in turn, consist of solar cells in which the electricity is actually generated (Fig. 12).

4.2 Solar Generator

The direct conversion of solar irradiance into electrical current is done by the solar generator. It consists of mounting units called panels which again consist of solar modules. Modules are made of solar cells in which the conversion is performed (Fig. 12).

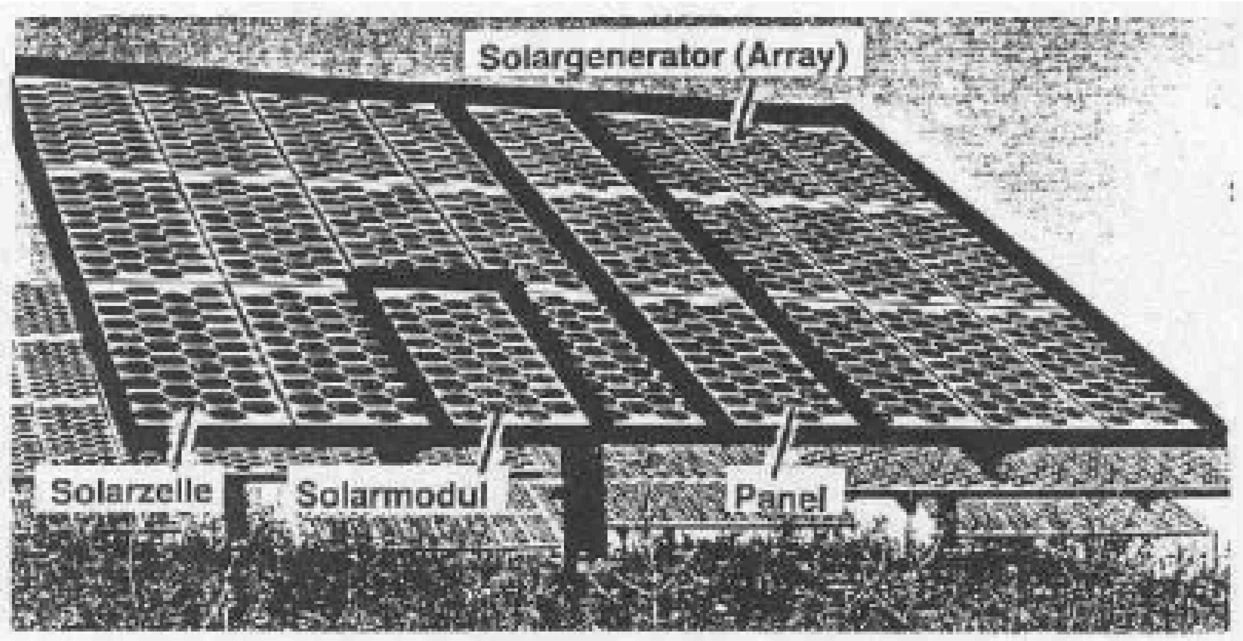
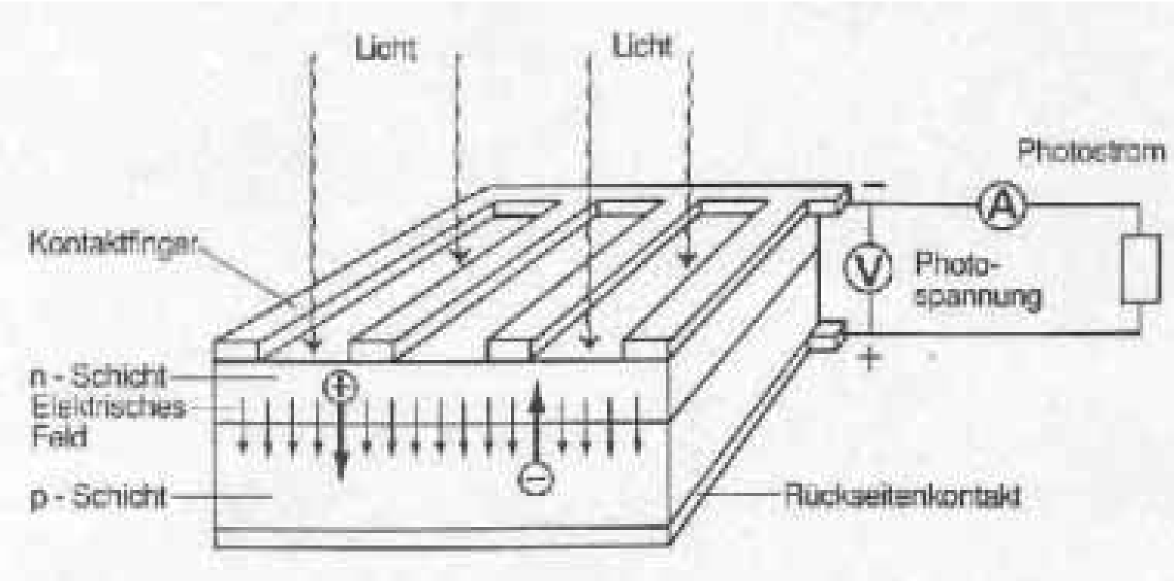


Figure 12: Modular construction of a solar generator (solarmodule area ≈ 0.5 m²)

4.2.1 Basic Function of Solar Cells

A.E. Becquerel discovered the photovoltaic effect in 1839, but its industrial exploitation had to wait until the appearance of suitable thin-film semiconductors made it possible to effectively separate the charge carriers.



Licht	=	Sunlight
Photostrom	=	Photovoltaic current
Photospannung	=	Photovoltaic voltage
Rückseitenkontakt	=	Rearwall contact
p-Schicht	=	p-type layer
Elektrisches Feld	=	Electric field
n-Schicht	=	n-type layer
Kontaktfinger	=	Contact finger

Figure 13: Schematic diagram of a solar cell

Most solar cells now on the market are silicon-based, and their function derives from an internal photoelectric effect. Solar radiation entering the solar cell alters the energy level of the material's atomic shells and, hence, liberates charged particles, i.e., charge carriers. This gives rise to the electron-hole pairs, or mutually opposite charge carriers of equal number. Within the silicon, an electric field is needed to serve as a material property that will keep the charge carriers from immediately recombining, and instead make them generate an outward flow of current. In a commercial-type solar cell, the electric field is generated by placing a pair of differently doped sheets of silicon (p-type layer and n-type layer) in juxtaposition. "Doped" means that chempure silicon has been alloyed with a very low concentration of heteroatoms. Thus, p-doping results from introduction of boron atoms into the silicon's atomic union, while n-doping involves phosphorus atoms instead of boron atoms. When these two discretely doped films are placed side by side, an electric field forms in the boundary layer (Fig. 13).

When sunlight impinges on a solar cell, the positive charge carriers (= the holes) and the negative charge carriers (= electrons) appear in pairs. If those pairs are able to reach the electric field before they recombine (meaning to reunite and, hence, to neutralize themselves), they are ultimately separated, with the electrons moving toward the frontwall (the n-type layer), where they collect on metallic contact fingers mounted above the surface and then return, by way of the external circuit, to the full-face, metal-coated backwall of the cell, where they ultimately recombine with the holes.

Solar-cell material	Efficiency under standard test conditions (η_{STC})	Price [Euro/W_p]

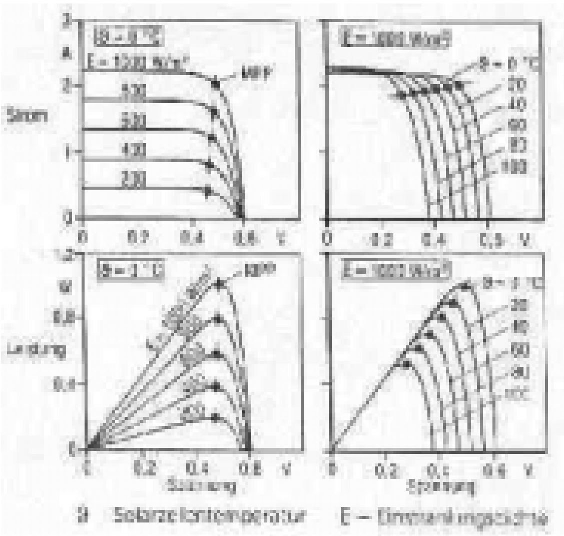
Monocrystalline silicon	15.1 %	6.50
Polycrystalline silicon	13.5 %	6.--
Amorphous silicon	7.4 %	5.--

Table 4: Efficiency and over-the-counter price of various types of solar cell

Practically all solar modules now available on the market rely on solar cells characterized by p-doped and n-doped layers. There are three basic types of solar modules on the market: those made of monocrystalline silicon, those made of polycrystalline silicon (a.k.a. multicrystalline silicon) and those made of amorphous silicon.

With hardly an exception, the solar modules produced to date for use in photovoltaic pumping systems have been made exclusively of crystalline silicon. This is because solar cells made of amorphous silicon tend to degrade rather rapidly, i.e., the longer they are in service, the less efficient they become. Table 4 lists the achievable efficiency levels for solar modules made of the different semiconductor materials.

Solar cells put out direct current with a voltage of about 0.5 V and a current density of roughly 20 mA/cm² (for an insolation level of 1000 W/m²). The voltage and/or current levels can be increased by grouping a number of cells into series-connected or parallel-connected modules. Panes of glass are placed over the modules to protect them from damage.



Strom	=	Current
Leistung	=	Power
Spannung	=	Voltage
Solarzellentemperatur	=	Solar cell temperature
Einstrahlungsdichte	=	Irradiance

Figure 14: Decoupled solar-cell performance characteristics

The characteristic curves of a solar cell describe the correlation between current and voltage. Figure 14 illustrates the irradiation- and temperature-dependence of a solar-cell characteristic. The curves at the left reflect various irradiance levels at a given ambient temperature, while those at the right are for a given irradiance level and different solar-cell temperatures.

In a real field configuration, both factors take effect simultaneously (Fig. 15), that is, there is a certain duty point at which the achievable power output reaches its maximum. Referred to as the maximum power point (MPP), it varies as a function of irradiance and temperature.

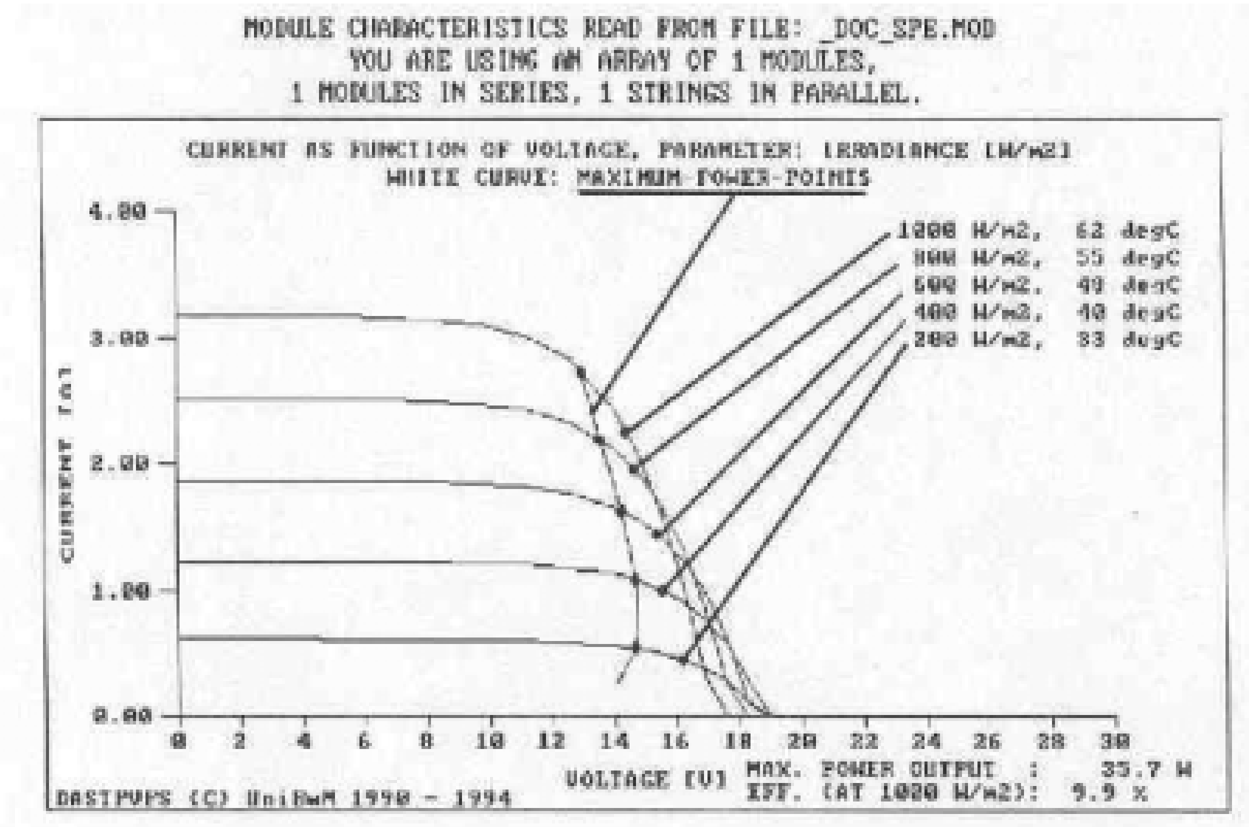


Figure 15: Operating characteristics of a real solar cell

4.2.2 Technical Makeup of a Solar Generator

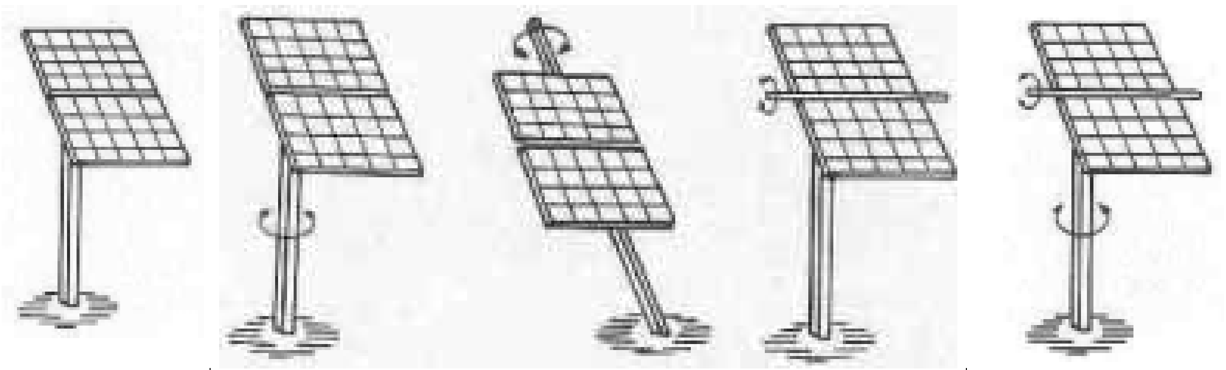
Most photovoltaic pumping systems have their solar modules installed in a stationary position. The north/south orientation (azimuth) and the optimal tilt for the generator depend on the local photovoltaic generating conditions. Assuming that the generator will be equipped for tracking, then the following cases can be differentiated (Fig. 16).

- Discrete tracking

- Continuous one-axis tracking
  - of the azimuth angle
  - of the tilt

- Continuous two-axis tracking

Tracking serves to maximize the energy gain. A one-axis arrangement in which only the angle of inclination (tilt) is kept "on track" can increase the energy yield by about 7 %, while azimuth tracking can improve a panel's energy uptake by some 22 % (William, 1983). Finally, two-axis tracking can add as much as 1/3 to a generator's output, as compared to that of a stationary, nontracking generator (Baltes, 1986).



Nontracking (stationary)	One-axis tracking Vertical axis or rotation, fixed angle of inclination Inclined axis of rotation axis of rotation in the solar-cell plan	Two-axis tracking

Figure 16: Tracking options for solar generators (Rouvel, 1990)

The advantages of tracking in terms of increased energy yield must be considered in the light of the systems' higher level of mechanical complexity and, hence, higher costs and reduced reliability. Thermohydraulic tracking systems constitute a possible alternative, because they can function without the normally necessary sensors, actuators and control devices. Such systems are presently under development (Knaupp, 1993).

For the sake of completeness, it should be mentioned that concentrating-type (focusing) photovoltaic systems are rarely used in photovoltaic pumping systems, because their concentrators demand precise tracking. Also, the technology of concentrating systems involves a number of specific problems, e.g., inhomogeneous illumination of the cells, thermal stress, long-term changes in optical properties, ...).

4.3 Generator / Load Matching

Depending on which type of motor is used for driving the pump (d.c. motor, a.c. motor, electronically commutated motor), a matching element must be included between the generator, which puts out d.c. current, and the load in order to enable proper system operation and, ideally, to optimize the performance of the pumping system. In the most simple of cases, the matching element may consist of merely a connecting cable (for connecting a d.c. motor directly to the generator). Depending on the chosen motor, a d.c./d.c. converter for MPP tracking or, alternatively, a d.c./a.c. inverter for a.c. motors may be necessary.

4.3.1 Basic Function of an Impedance Transformer

Impedance transformers can be used to achieve low-loss matching of load and generator. Figure 17 is a block diagram of a d.c./d.c. converter. An impedance transformer comprises a capacitor C_1, which serves as an energy store, a coil *L* as the power transfer element, a diode-capacitor network for smoothing the output voltage (*D*, C_2), and a controlled switch *S*.

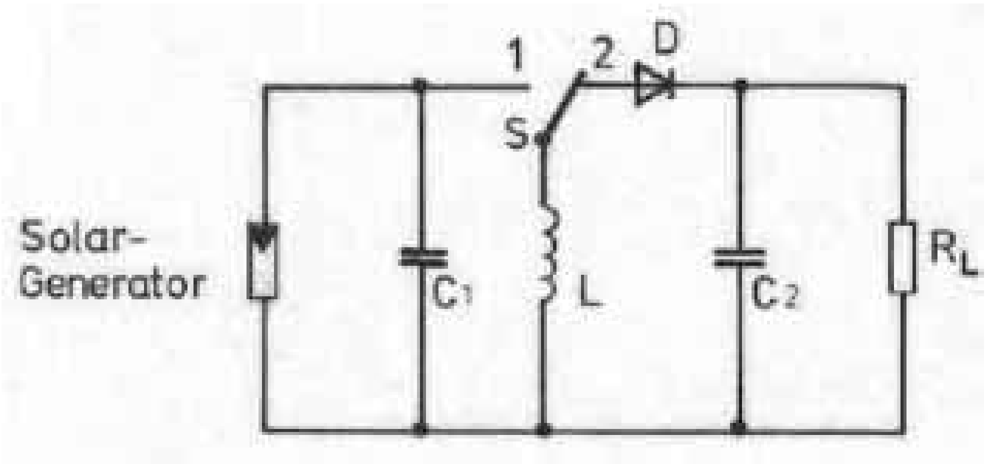


Figure 17: Block diagram of d.c./d.c. converter

An impedance transformer functions as follows: First, with the switch *S* set to position 1, the coil *L* picks up the electrical energy from the solar generator and from the capacitor C_1. Then, with switch *S* in position 2, the stored energy flows forward to the load resistor R_L, while the generator is recharging C_1. The diode *D* precludes return losses (reverse power), and the capacitor C_2 smoothes the flow of energy and ensures a practically continuous flow of current through the load resistor R_L.

The input resistance of the on/off controller (non-dissipative transfer of power P_E presumed) figures to:

$R_E = U_E^2 / P_E$

The voltage ratio U_E / U_L is determined by the retention time t_1 of switch *S* in position 1, in comparison with its retention time t_2 in position 2 ($T = t_1 + t_2$):

$U_1 = (T/t_1 - 1)\ U_2$

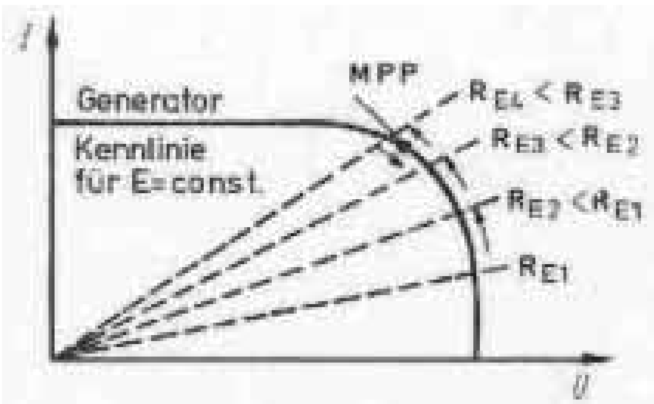
Thus, it follows:

$R_E = R\ [(1-a)^2 / a^2]$

where $a = t_1 / T$ (duty factor)

4.3.2 Control of an Impedance Transformer

R_E can be made to match the cell resistance by altering the duty factor. The optimal input resistance R_{Eopt} is defined by the respective current-voltage characteristic of the generator and can be adjusted by varying the variable 'a'. Due to the fact that the characteristic of the solar cell is a function of the insolation level and of the ambient temperature, the input resistance of the impedance transformer must adjust automatically by way of a control arrangement. Figure 18 illustrates the control principle: R_E begins at a high value (R = U / I) and is gradually varied toward smaller values. Meanwhile, the output end of the transformer is monitored to see whether the available electrical output increases or decreases. Variation of R_E continues in the same direction, as long as the output keeps increasing. As soon as the output begins to subside, R_E has to be altered in the other direction until just past the maximum possible output (maximum power point = MPP). Thus, the output swings back and forth around (= tracks) the maximum power point.



Characteristic for irradiance (E) = constant

Figure 18: Control strategy for an MPP tracker

4.3.3 D.C./A.C. Inverters

A special impedance transformer in the form of a d.c./a.c. inverter is needed for operating three-phase machines. Such inverters are long-since tried & proven for industrial applications, e.g., CNC machinery, multiple-machine printing and textile-processing systems. For PVPS applications, though, the standardized industrial components require customization (Fig. 19). Among the various potential choices, inverters with an intermediate d.c. circuit have emerged as the best-suited alternative (/10/ Klemt, 1993). The solar generator can be connected directly to the intermediate d.c. circuit, but a supplementary controller has to be included for the MPP tracking function.

Figure 19: A typical d.c./a.c. inverter (Grundfos) for PVPS applications

Figure 20 is a block diagram of a d.c./a.c. inverter (/11/ Yechcuron, 1990). Its input circuit, which essentially consists of a capacitor for smoothing the input voltage, is connected directly to the power pack. The power pack comprises three half-bridges. The load (in this case a motor) connects up to the power pack's half-bridges.

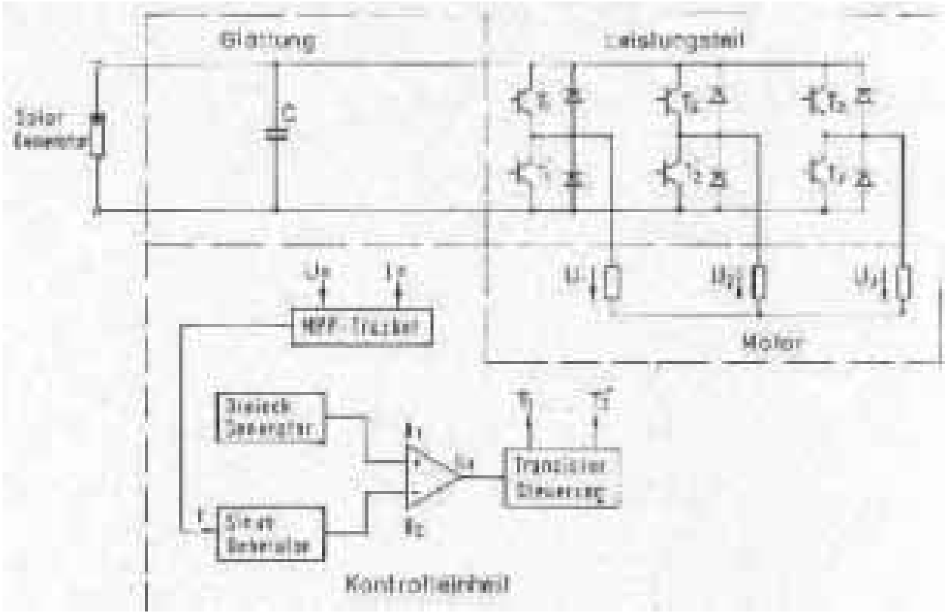


Figure 20: Block diagram of a d.c./a.c. inverter

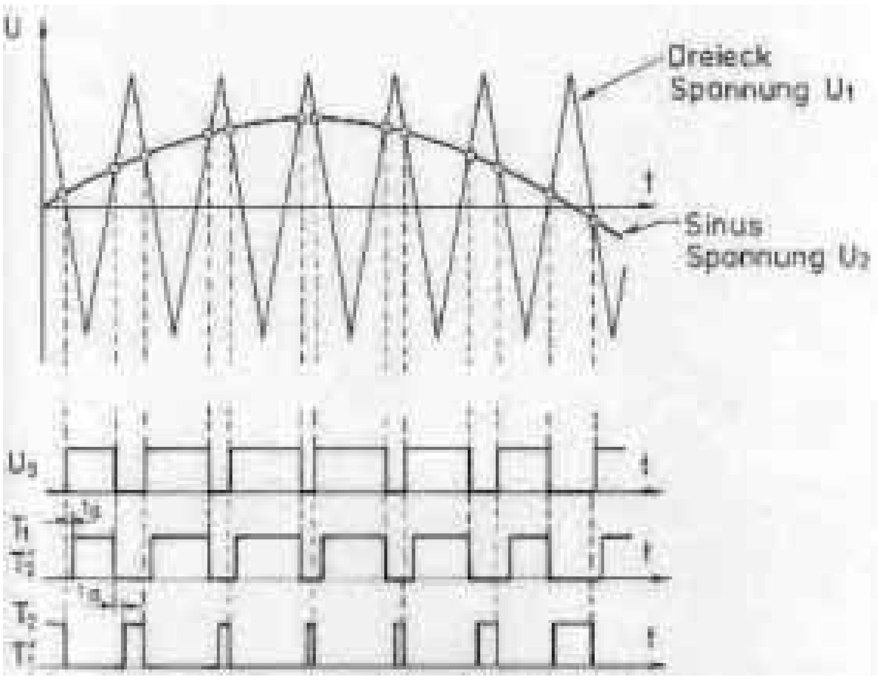


Figure 21: Conceptual diagram of control signal generation for the power transistors in a single-phase d.c./a.c. inverter (with t_a as the transistors' ON/OFF lag time in preclusion of short circuits)

The control unit generates three 120°-phase-angle nominal sine signals for driving the power transistors (T1-T3). The frequency of the signals depends on the available output from the solar generator. A comparator modulates the nominal sine signals with a high-frequency triangle signal (Fig. 21), so the power transistors receive a pulse-width-modulated (PWM) square wave signal.

The motor itself receives a pulse-width-modulated power signal with a voltage that fluctuates between $+U_{solar}$ and $-U_{solar}$ and impresses a current that has been smoothed by the inductive reactance of the motor windings. The character of the current is that of a triangle voltage that oscillates around the ideal sine curve within the limits of a tolerance band (Fig. 22). This gives the current its fundamental wave and a harmonic content. The sinusoidal fundamental wave serves to generate the torque, while the harmonics content is converted into heat – and lost – in the motor.

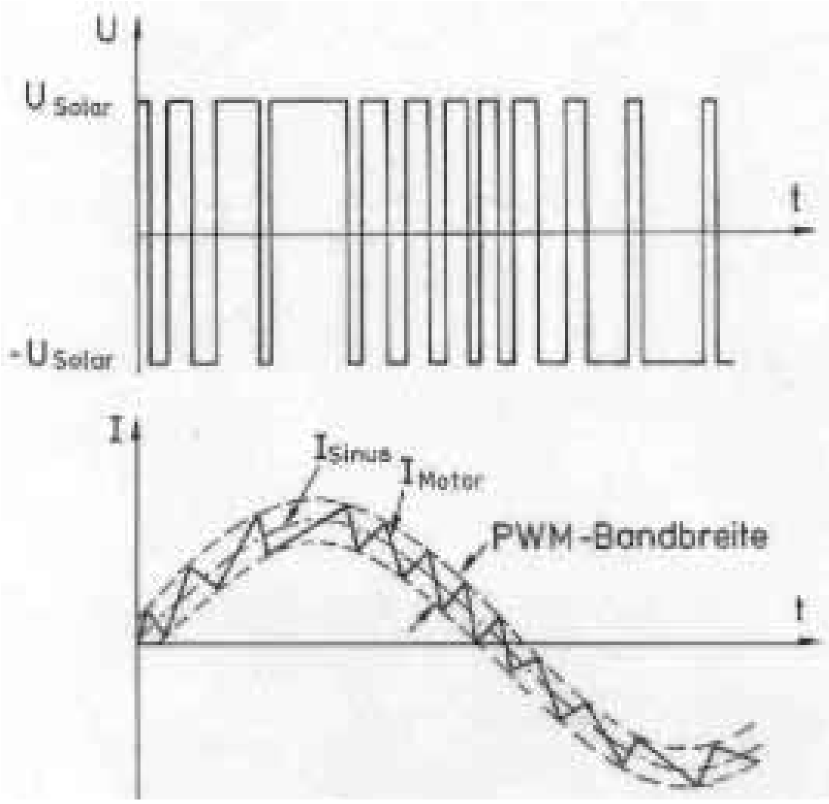


Figure 22: Motor-winding current

4.4 Drive Motors

The drive unit converts electrical energy into mechanical energy, and since rotational motion is preferable for use in operating pumps, electric motors are inherently well-suited for the task. For driving the pumps in a photovoltaic system, d.c. motors are the logical choice. Those populating the power range around 1.5 kW are characterized by relatively high efficiency (ca. 85 %). Unfortunately, however, most d.c. motors on the market use brushes for commutation. That means that they require periodical maintenance, because the brushes only last about 1,000 hours under normal operating conditions. In case of installation in a deep-well this means a scheduled dismounting of the pipe in order to reach the motor.

Figure 23: Floating pump with brushless d.c. motor

One alternative solution is to use commutatorless d.c. motors, i.e., units with electronic commutation. Such motors are inverter-fed and wired for synchronous operation. The technology calls for real-time monitoring of the rotor's angular position. Thus, if this kind of motor is installed as part of a borehole pumping system, either the sensor signals would have to be transmitted in parallel with the power conductors over a long distance to the electronic control unit, or the latter would have to be integrated, together with the motor, into a waterproof capsule. Both alternatives are problematic: if the motor and the electronics are separated, line induction can cause interference, and a waterproof capsule would hardly enable maintenance of the electronic components. Consequently, such motors have not yet entered the wholesale manufacturing stage for high-powered underwater applications. They are, however, very well suited for inclusion in ground-level pumping systems and small compressor units, as long as the motor and control system remain easily accessible. A floating pump with an electronically commutated d.c. motor is shown in Fig. 23.

Figure 24: Standard asynchronous motor for borehole pumps

Many photovoltaic pumping systems instead rely on asynchronous motors, some of which are available as well-proven, off-the-shelf products. Since the driving torque is generated by a rotary field, no sensors or other connections (excepting the power connections) are necessary. Hence, the asynchronous motor is maintenance-free, but it still has the drawback of having to be driven via an inverter. Fig. 24 shows a standard-type submersible asynchronous motor for driving a borehole pump.

4.5 Pumps

The pump converts rotary motion into hydraulic output. Practice-proven centrifugal pumps are the most popular option, though displacement pumps are also suitable. Due to their low-efficiency, however, systems incorporating friction, jet or upthrust pumps must be ruled out (/12/ Herrmann, 1989).

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4.5.1 Centrifugal Pumps

Centrifugal pumps, as kind as fluid-flow pumps, (Fig. 25) have some major advantages to offer:

- affordable prices (large-scale production)
- easy starting
- simplicity of design (modular / one design application for multiple stages)
- broad range of head- and delivery-specific applications

Essentially, a centrifugal pump is a fluid flow machine. Each pumping stage comprises a casing and an impeller. The pumped medium flows axially in toward the impeller, and the rotating impeller accelerates the water radially outward (by centrifugal force), thus building up discharge pressure. The pump's ultimate delivery pressure can be arbitrarily increased by adding as many stages in series as desired. A multiple-stage arrangement does produce a corresponding increase in mechanical friction, however, so small-capacity pumps, usually of correspondingly small diameter, should have pumping heads of about maximum 100 m.

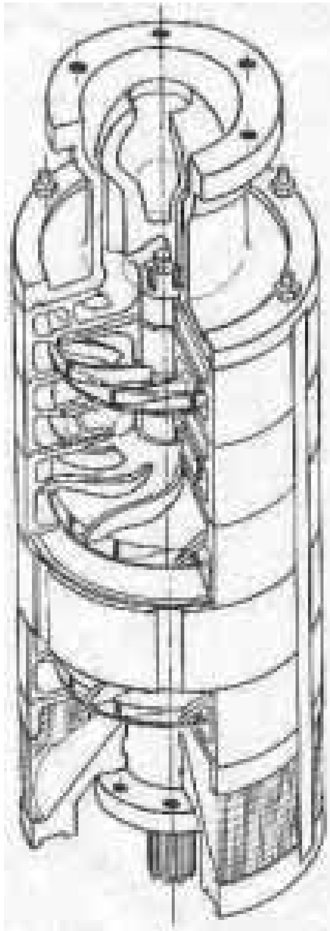
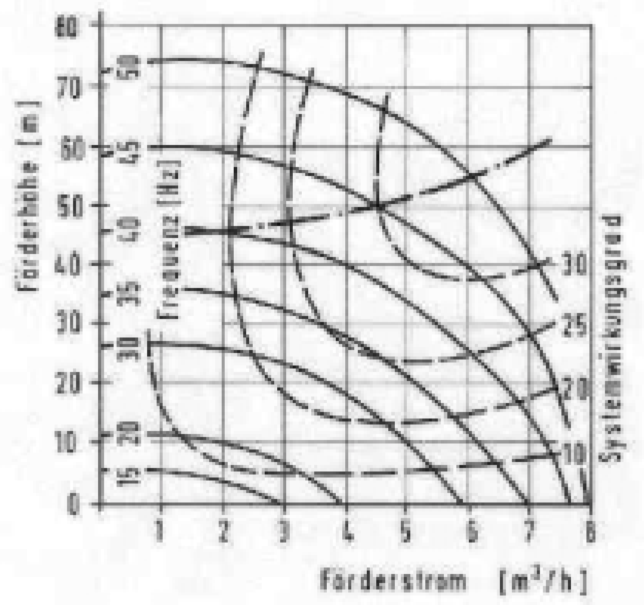


Figure 25: Centrifugal pump

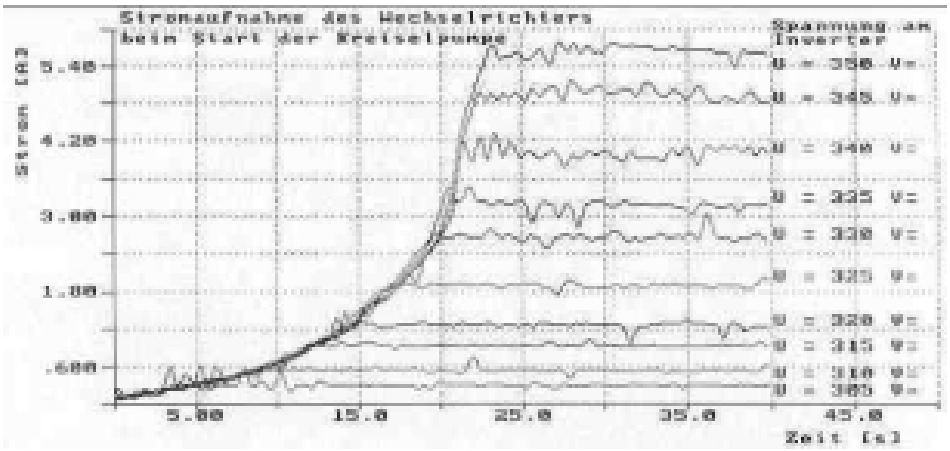
Since the pressure buildup is a function of centrifugal force, the pump's discharge pressure is a quadratic function of speed. Figure 26 shows a typical centrifugal pump performance curve.

Photovoltaically driven centrifugal pumps start easily, because no "breakaway torque" is needed. A number of startup power consumption curves for a centrifugal pump are shown in Fig. 27. The speed of the pump adjusts to the available power.



Förderhöhe	=	Pumping head
Förderstrom	=	Flow rate
Systemwirkungsgrad	=	System efficiency (inverter/motor/pump)
Frequenz	=	Frequency (motor rounds per second)

Figure 26: Performance chart of a centrifugal pump



Strom	=	Current
Zeit	=	Time
Spannung am Inverter	=	Voltage at inverter

Figure 27: Power consumption curves of a centrifugal pump

In a solar-powered system, pronounced speed dependence is a disadvantage. The higher the head, the higher the minimum operating speed of the pump. When the incident radiation level is low (cloud cover, generator out of line with the sun, ...), the system's power output is also low, so the pump runs at low speed and is unable to develop the necessary discharge pressure. In other words, the generator's output cannot be converted into delivery capacity. Thus, the sunshine duration outstrips the time in which water actually can be pumped. This drawback can be substantially ameliorated by opting for positive displacement pumps instead.

4.5.2 Positive Displacement Pumps

Unlike centrifugal pumps, positive displacement pumps can work at relatively low speeds and, hence, are able to pump water at low insolation levels. On the other hand, to get started, most positive displacement pumps need a certain "breakaway torque", i.e., a brief burst of power to overcome their standstill friction.

Basically, there are two types of positive displacement pump:

- rotary displacers, e.g., rotary piston pumps, vane cell pumps and progressive cavity pumps (screw pumps)
- reciprocating displacers, e.g., reciprocating piston pumps and diaphragm pumps

4.5.2.1 Progressive Cavity Pumps (Screw Pumps)

Progressive cavity pumps (Fig. 28) act on the principle of volumetric displacement. With each turn of the pump, a certain volume of medium is moved to the discharge side. The pump is made up of a stator in the form of a hollow elastomer body, and a steel rotor (impeller) in an interference-fit configuration. In comparison with that of a centrifugal pump, the performance curve of a progressive cavity pump is much steeper (Fig. 29). This gives the advantage of higher efficiency in combination with better resistance to abrasive material entrained in the pumped medium (/13/ Zängerl, 1993).

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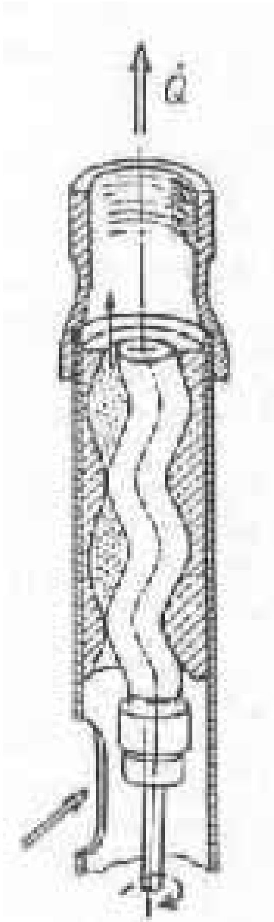
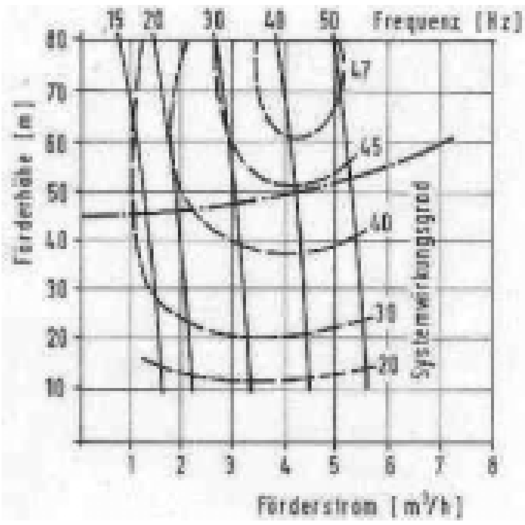


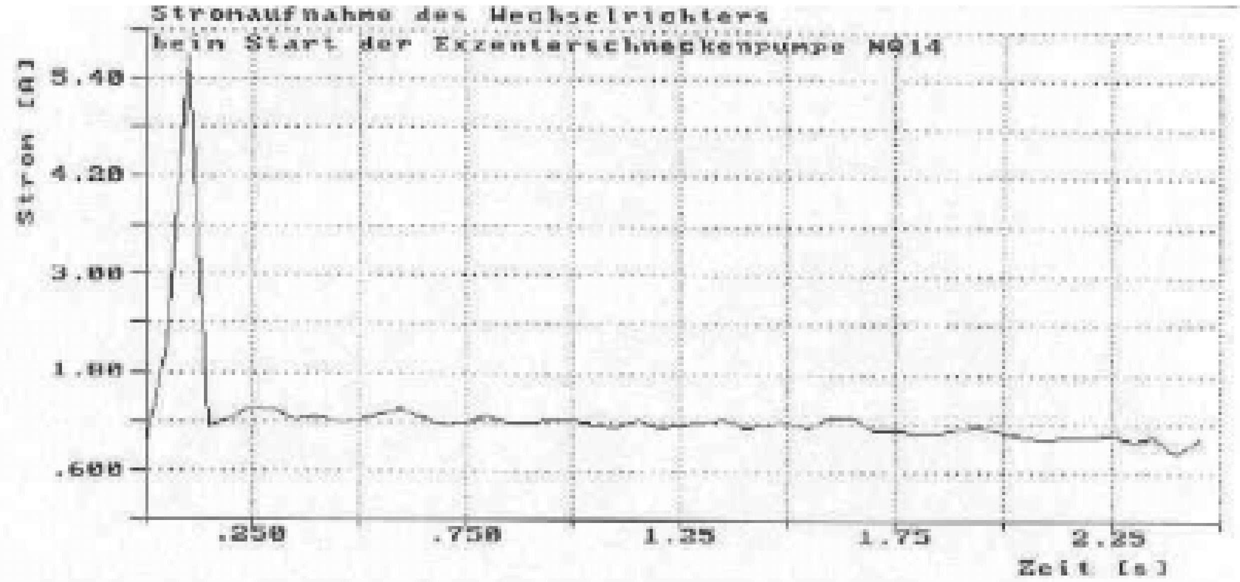
Figure 28: Progressive cavity pump



Förderhöhe	=	Pumping head
Förderstrom	=	Flow rate
Systemwirkungsgrad	=	System efficiency (inverter/motor/pump)
Frequenz	=	Frequency (motor rounds per second)

Figure 29: Performance chart of a progressive cavity pump

The interference, i.e., the tightness of fit between stator and impeller, is the decisive factor for the part-load efficiency, because it more or less precludes medium backflow, but it is also what necessitates the "breakaway torque". Figure 30 shows the pump's startup current consumption curve. At first, a short surge of power (power impulse) is needed for overcoming the static friction. But photovoltaic generating systems are not readily able to provide such an impulse. Consequently, appropriate measures must be taken to counter that effect.

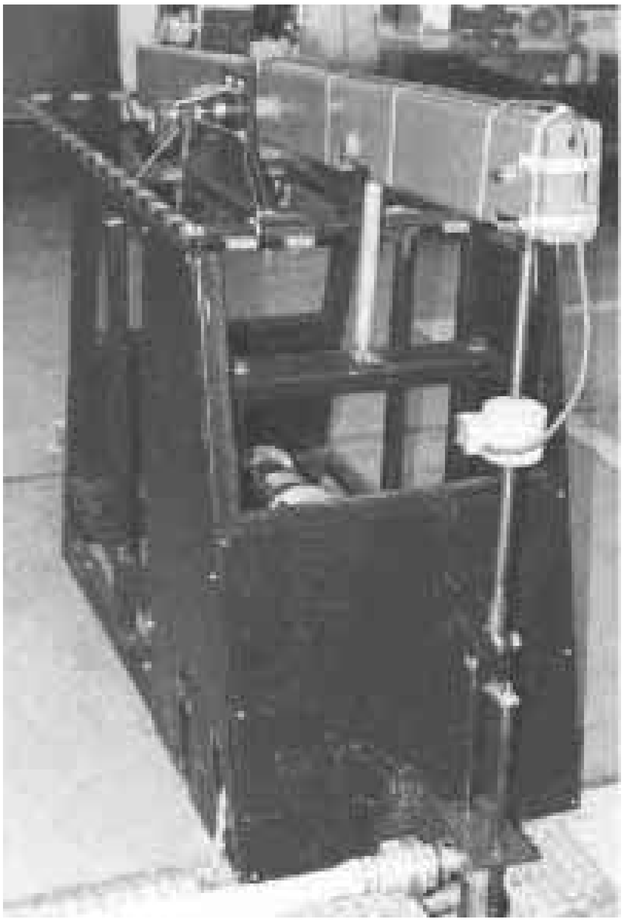


Strom	=	Current
Zeit	=	Time
Spannung am Inverter	=	Voltage at inverter

Figure 30: Power consumption curve of a progressive cavity pump

4.5.2.2 Piston Pumps

Piston pumps also make an interesting water-lifting option, especially when great depths are involved (Fig. 31). Their pumping head is almost completely independent of their driven speed. The number of strokes per minute is what determines the delivery rate. Such pumps have no bottom operating limit, so water can still be delivered at relatively low insolation levels. Like progressive cavity pumps, positive-displacement-type reciprocating piston pumps have the drawback of requiring a certain "breakaway torque". In addition, the pump's torque fluctuates in the course of a full rotation. Figure 32 shows charcteristic of a piston pumps, Fig. 33 the time-dependent power consumption of a piston pump's d.c. drive motor during three cycles of operation.



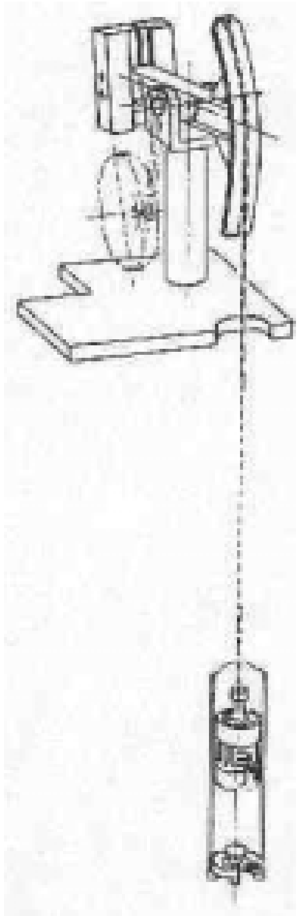
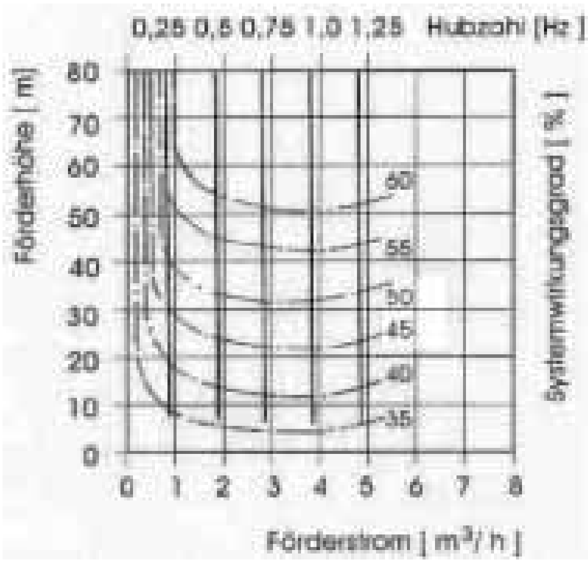


Figure 31: Piston pump with d.c. drive motor



Förderhöhe	=	Pumping head
Förderstrom	=	Flow rate
Systemwirkungsgrad	=	System efficiency (inverter/motor/pump)
Frequenz	=	Frequency (motor rounds per second)

Figure 32: Performance chart of a piston pump

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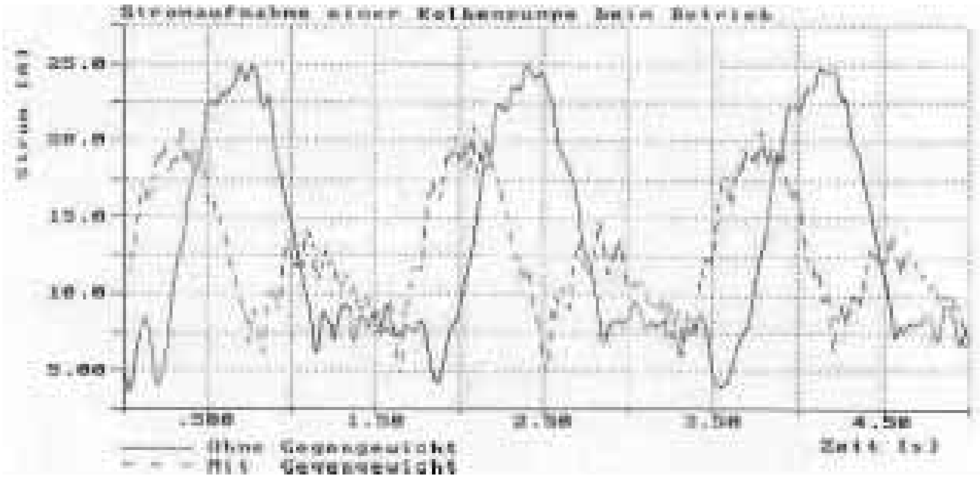

Strom	=	Current
Zeit	=	Time
Spannung am Inverter	=	Voltage at inverter

Figure 33: Current consumption curves of a piston pump over three full cycles of operation

With a view to reducing the pump's starting torque requirement and torsional variation, certain design modifications can be effected, e.g., tuning in the form of compensating weights, tailoring of the leverage, and incorporation of mechanical energy stores/buffers. In any concrete case, this will require optimization for photovoltaic deployment.

4.5.2.3 Diaphragma Pumps

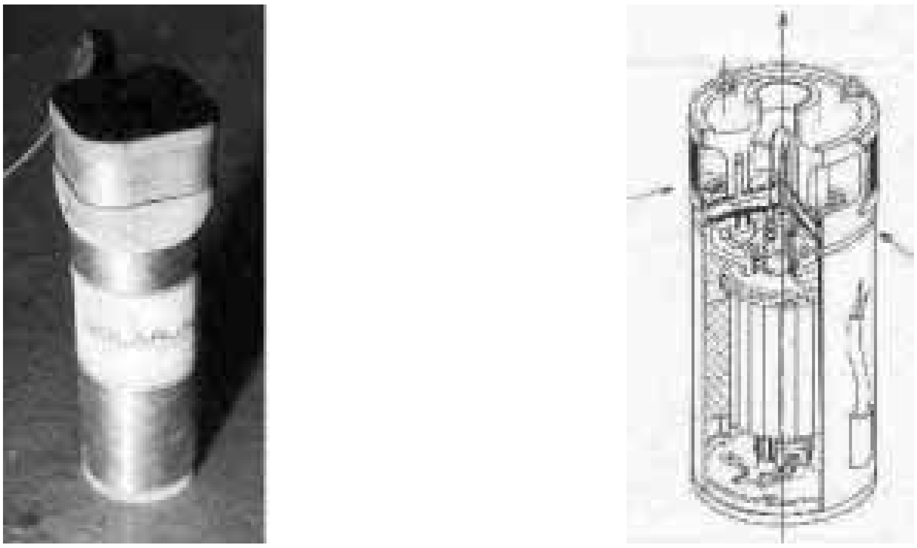

Figure 34: Diaphragm pump and cutaway view of a diaphragm pump

Diaphragm pumps are a special kind of piston pump. For PVPS applications, they are preferentially employed in d.c. systems with ratings up to about 100 W. In this type of

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pump, a rubber diaphragm driven by a nutating disk (swash plate) takes the place of the piston. The "stroke" is relatively short and the flow rate accordingly modest. That is why diaphragm pumps tend to be installed in duplex, triplex or quadruplex arrangements. The nutating-disk drive also does away with most startup problems.

Most diaphragm pumps are purchased as complete sets, i.e., with motor and pump joined together as an inseparable unit (Fig. 34). Most of their motors are of the d.c. brush type. Considering the familiar characteristics of d.c. motors, it is advisable to include a booster for accommodating the generator's characteristic to that of the motor.

4.6 Wells and Hydraulic Systems

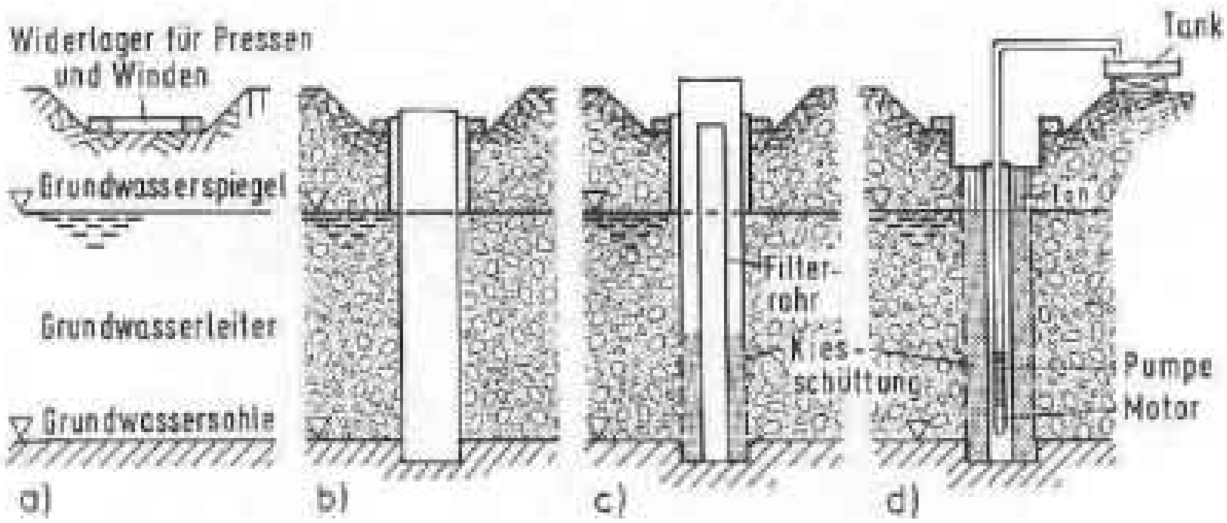
The well and the hydraulic system are the fluid-dynamic components that complement the system upstream and downstream of the pump.

4.6.1 Wells

Most wells in developing countries are either drilled or dug (/14/ Thöle, 1988). Drilled wells with diameters ranging from 20 to 80 cm are best suited for tapping into deep-laying groundwater tables. They tend to be equipped with motor-driven pumps. Dug wells, with diameters ranging from 100 to 200 cm, are more suitable for shallower depths (2 – 20 m) and are still being sunk as dig-down wells from which water can be drawn in buckets or leather/rubber bags if the pumping system breaks down or is in need of maintenance. The main disadvantage of such open wells is the danger of contamination.

Basically, both kinds of wells are sunk in the same manner. Figure 35 illustrates the main phases of well construction.

The first step is to drill the well (Fig. 35b) according to a suitable method, e.g., standard or hydraulic percussion method.



Abutment for presses and winches
Groundwater table
Aquifer
Groundwater bed
Groundwater bed

Filter pipe
Gravel fill

Pump
Motor

Figure 35: Main phases of well construction

The standard (dry) percussion method is primarily employed in loose rock. The impact or rotational effect of the drill action is what dislodges the material. The bit works its way in a certain length, and then the casing is pressed down by the same increment (Fig. 36). When the friction on the casing as increased to the point of impeding the pipe’s progress, another pipe is inserted into the first (telescoping), thus reducing the likelyhood of pipe breakage.

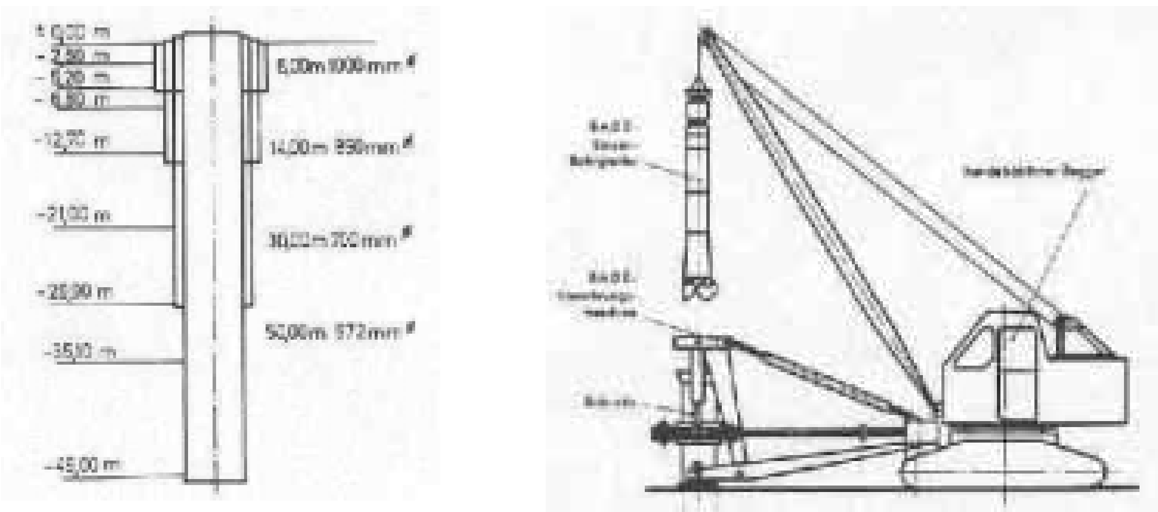


Figure 36: Pictorial schematic of the standard percussion method with telescopic casing (/15/ Bischhofsberger, 1982)

The most widely employed jetting-down methods are rotary drilling, reverse rotary drilling (mud flush drilling) and airlift drilling. Common to all three methods is that the soil is kept stable by flushing instead of tubing. The entire borehole is filled with flushing medium. A pump draws the flush water out of the drilling pond and forces it down through the boring rods to the bottom of the hole, in turn forcing the dislodged material up and out of the borehole and into the drilling pond (Fig. 37).

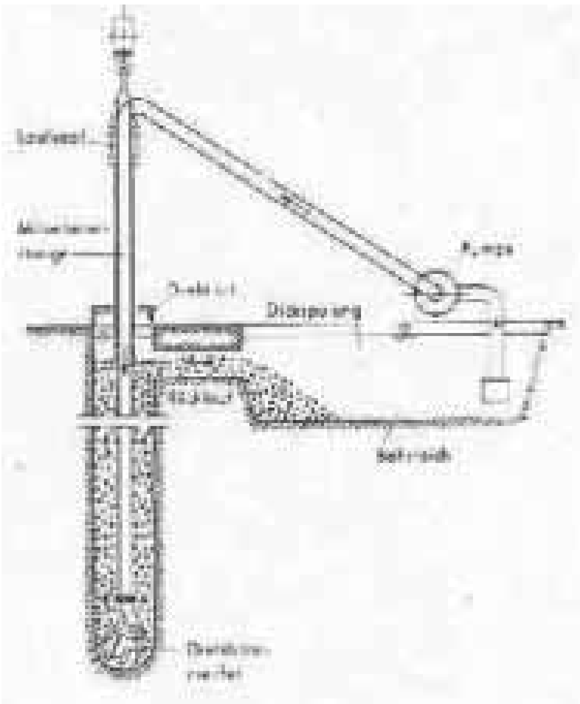


Figure 37: Pictorial schematic of the reverse rotary drilling method (/15/ Bischhofsberger, 1982)

Upon completion of the drilling phase, a filter pipe is lowered into the well (Fig. 29c). Then, the space between the filter pipe and the surrounding soil is filled with gravel, after which the casing pipe / drilling fluid is removed.

Finally, the top of the filter pipe, i.e., the well head, has to be sealed off with a clay packing (Fig. 35d) and the pump has to be installed (Fig. 36)

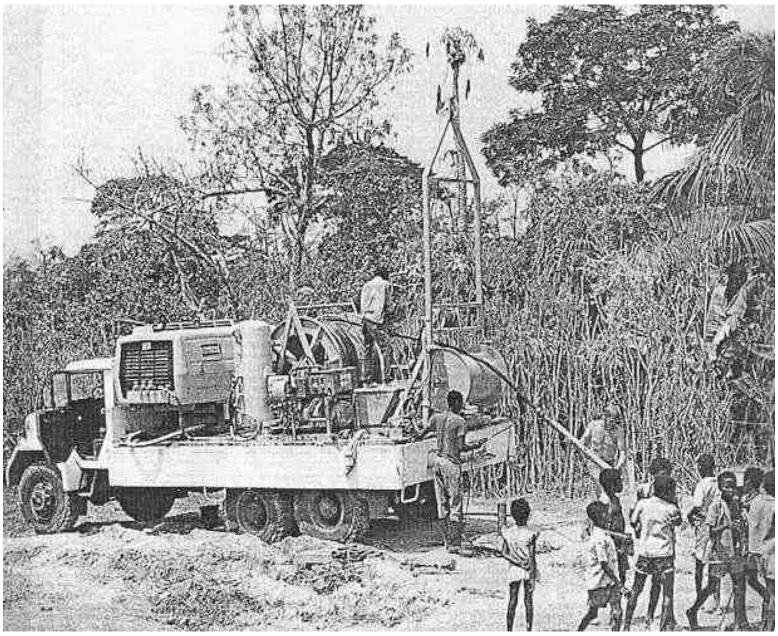


Figure 38: Installation of a pump in a well in Ghana (/16/ Sandomeer, 1985)

4.6.2 Hydraulic System

The pump delivers the water to the storage tank by way of the hydraulic system. The latter comprises the connecting pipework, valves and fittings between the pump and the tank. In most cases, standard metal pipes (inch-system sizes) with bell-and-spigot joints are used, because they are reasonably priced and relatively easy to come by on local markets. Their main drawback is that they have to be dismantled and reassembled afterwards when the pump is pulled for maintenance or repair. This makes it difficult to maintain and monitor leaktightness of the spigot ends.

Flexible well tubing presents itself as an alternative solution that allows in-well installation of the pump without need of rigid piping.

The valving of a typical photovoltaic pumping system comprises a water meter and at least one shutoff valve. Since solar power is so expensive, PVP systems must be designed for minimal losses. One frequently overlooked factor in that connection is that the pipes, bends, meters, valves and sundry fittings all cause hydraulic losses.

4.6.2.1 Flow Losses in the Pipes (Continuous Losses)

As water flows through a pipe, wall friction imposes a resistance to flow that can be interpreted as an additional head loss that has to be overcome. To determine the value of the continuous losses due to wall friction, the planner must calculate the coefficient of flow resistance, k, for each pipe of the system and then use it to find the pipe friction-induced energy loss (head), H_{cl}:

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$$H_{cl} = \lambda \frac{l_p 8Q^2}{d^5 g\pi^2}$$

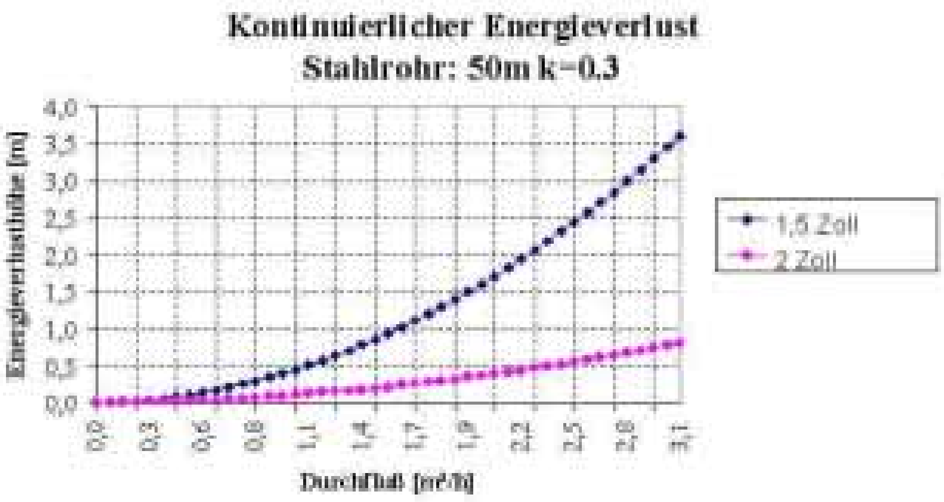
where:	H_{cl}	=	head loss due to continuous friction [m]
	λ	=	coefficient of friction [-]
	l_p	=	length of pipe [m]
	d	=	inside diameter of pipe [m]
	Q	=	flow rate [m³/s]

The coefficient of friction, λ, is generally calculated according to the Prandtl-Colebrook-White formula, though it can only be accurately calculated by way of iteration. Zanke's method provides a simpler means of calculating the coefficient of friction without need of iteration and with enough accuracy for practical applications:

$$\lambda = \frac{64}{Re}(1-\alpha) + \alpha[-0.868 * ln\{\frac{ln(Re)^{1.2}}{Re} + \frac{k}{3.71d}\}]^{-2}$$

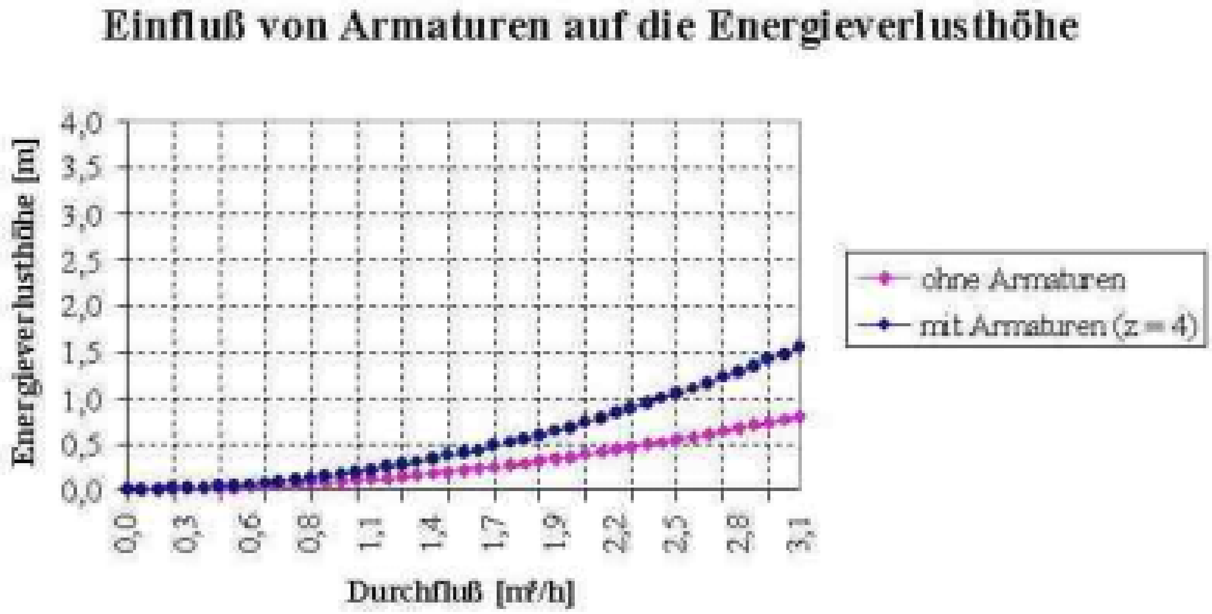
where:	λ	=	coefficient of friction [-]
	Re	=	Reynolds number (water: 4Q/πdν) [-]
			(Q = flow; d = pipe diameter; ν = kinetic viscosity)
	α	=	laminar / turbulent transition factor [-]
			(= exp-[exp-(0.0033Re –8.75)], Zanke, 1991)
	k	≈	effective peak-to-valley height (steel pipe: k = 0.3) [m]

With the aid of the above equations, the continuous head loss attributable to pipe friction (which also has to be overcome by the pump) can be calculated as a function of the flow rate (pipe characteristic, Fig. 39).



Energieverlusthöhe	=	Head loss
Durchfluß	=	Flow rate

Figure 39: Continuous head losses in a 50-m length of steel pipe (1.5" and 2" diameter)



Armaturen	=	Fittings and bends
Energieverlusthöhe	=	Head loss
Durchfluß	=	Flow rate

Figure 40: Effects of 4 bends on the head loss

4.6.2.2 Losses caused by Valves & Fittings, e.g., Bends, Meters and Slide Valves (Equivalent Resistances)

The valves & fittings installed in the piping cause local energy (= pressure) losses that are referred to as equivalent resistances. The resultant head loss can be calculated as follows:

$$H_{ll} = \frac{8Q^2}{d^4 g \pi^2} \zeta$$

where: H_{ll} = local head loss [m]
ζ = equivalent resistance (Bechteler, 1992) [-]

The local pressure losses for each and every valve & fitting must be calculated separately. The sum total of local pressure losses then figures from the sum of the individual pressure losses. Figure 40 shows the effect of local pressure losses on a hydraulic system.

4.6.2.3 Conversion of Local Head Losses to continuous Losses

The local head loss, H_{ll}, can be converted into a continuous head loss by calculating an equivalent length of pipe to replace the valves & fittings. The question is, how much equivalent pipe length must be added to the hydraulic system to produce the same overall loss of head as in the system with the valves and fittings.

By equating H_{cl} with H_{ll}, we obtain the equivalent pipe length, l', representing the valves & fittings:

$$l' = \zeta \frac{d}{\lambda}$$

where: l' = equivalent pipe length [m]
ζ = equivalent resistance of the respective valve or fitting [-]

Finally, the total loss of head, H_v (continuous + local) is calculated, except that l_p needs to be replaced by l ($l = l_p + l'$):

$$H_v = \lambda \frac{l\, 8Q^2}{d^5 g \pi^2}$$

where: H_v = total head loss [m]

Thus, the pipe system pressure losses are calculable.

In any PVPS, the depth of the well and such local circumstances as the position of the water tank normally dictate the overall length of pipe and how many valves & fittings of which kind will have to be installed. The size of the pipe is the crucial parameter by way of which the flow losses can be reduced, though this does have its limits in the form of material availability, local prices (i.e., in the developing country) and the like.

4.6.2.4 Losses attributable to non-return Valves

Commercial-type pumps come with non-return valves, since they are usually installed as part of direct-solar-power systems. However, the advantages of including non-return valves in a PVP system (pipe stays full at night, feed point can be situated at the bottom of the tank to minimize the system head, etc.) need to be weighed against the disadvantage of making the pump constantly contend with the extra flow losses.

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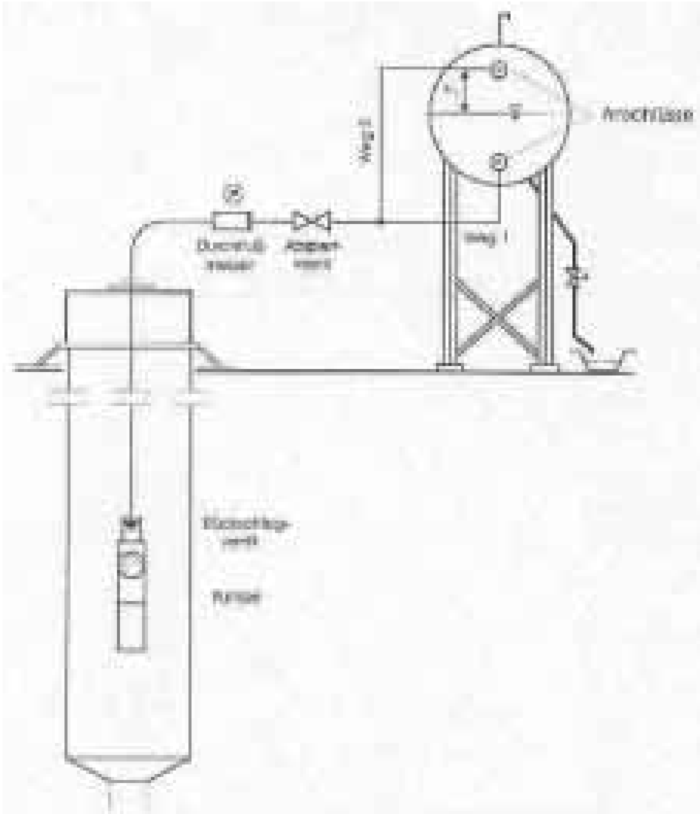
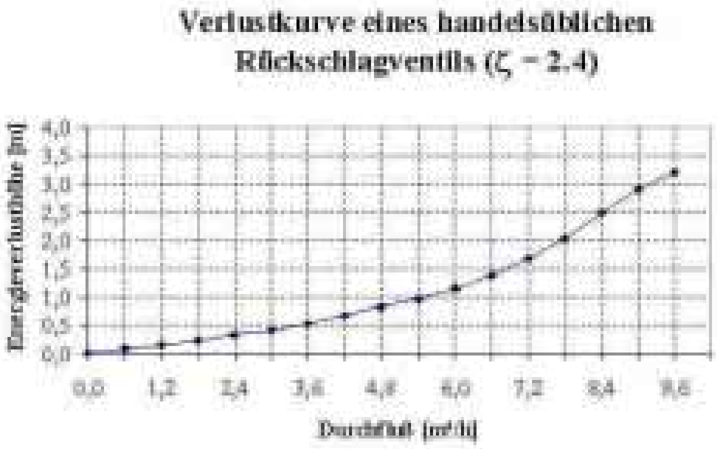


Anschlüsse	=	Connections
Weg 1	=	Path 1
Weg 2	=	Path 2
Absperrventil	=	Valve
Durchflußmesser	=	Flow rate measurement
Rückschlagventil	=	Non-return valve
Pumpe	=	Pump

Figure 41: Schematic representation of a PVPS hydraulic system

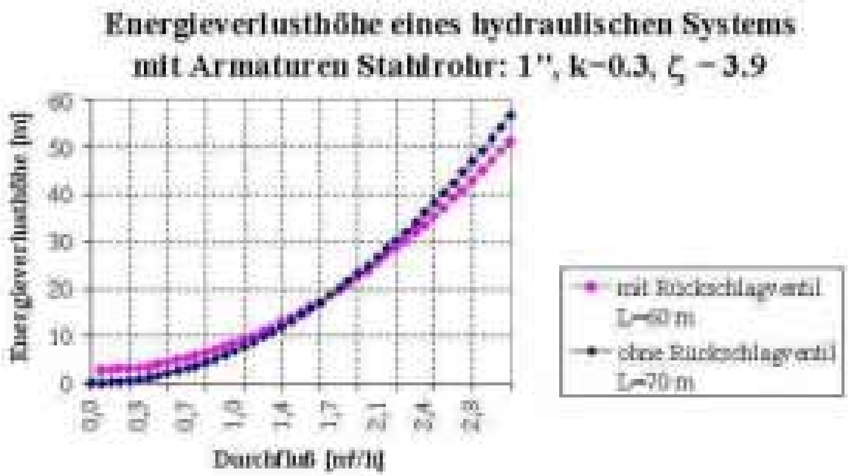
Figure 41 is a schematic representation of a typical PVPS hydraulic system. If a non-return valve is included, the piping can be connected to the tank below the water level (path 1), thus reducing the system head. Especially for a well with a shallow water level of only one or two meters, the savings can have a substantial effect (10 m overall head less hl = 1 m means 10% less losses). In addition, path 1 (Weg 1) is shorter than path 2 (Weg 2), which also reduces the continuous losses.



Energieverlusthöhe	=	Head loss
Durchfluß	=	Flow rate

Figure 42: Head loss curve of a commercial-type non-return valve (KSB-pump)

On the other hand, the non-return valve constitutes an equivalent resistance, the value of which depends on the flow rate. Figure 42 shows a typical flow-loss curve for a normal non-return valve. To facilitate decisions about whether or not a non-return valve should be included in the system, a software program was designed for use in identifying (calculating) the better version as a function of diverse parameters (system head, flow rate, size of pipe, equivalent resistances of valves and fittings, equivalent pipe lengths, difference between geodetic altitudes of top and bottom inlets,..., Figure 43).



Energieverlusthöhe	=	Head loss
Durchfluß	=	Flow rate
Rückschlagventil	=	Non-return valve

Figure 43: Head losses with and without non-return valve and the corresponding different pipe lenght (L = 60m and L = 70m)

Should the decision fall in favour of incorporating a non-return valve and connecting the feed pipe to the bottom of the tank, then consideration should be given to the fact that, if the valve springs a leak, the tank can run dry, in which case there would be no water supply, and the pump might have to be pulled to enable repairs.

4.7 Energy Storage

The momentary demand for water rarely coincides with the time of its delivery. Consequently, photovoltaic pumping systems must include some form of energy store that will warrant a uniform supply of water. There are two basic options to choose from:

- storage of hydraulic energy in a tank or basin
- storage of solar-generated electricity in a battery

All PVP systems include a reservoir for catching and collecting the pumped water in order to have a reserve supply for periods in which the pump is not running (maintenance, repair, malfunction, ...)
Electrochemical accumulators are only included in exceptional cases. The most widely employed form of accumulator is the lead battery. Using accumulators has the advantage of being able to run the PVP system at a fixed duty point. Moreover, accumulators are able to collect and store low levels of energy (during periods of scant insolation) that could not be directly utilized by the PVP system. There are, however, some disadvantages, i.e., the maintenance expenditures, initial investment and operating costs are all higher (batteries having to be replaced every four or five years), and the batteries themselves take up additional space (Fig. 44).

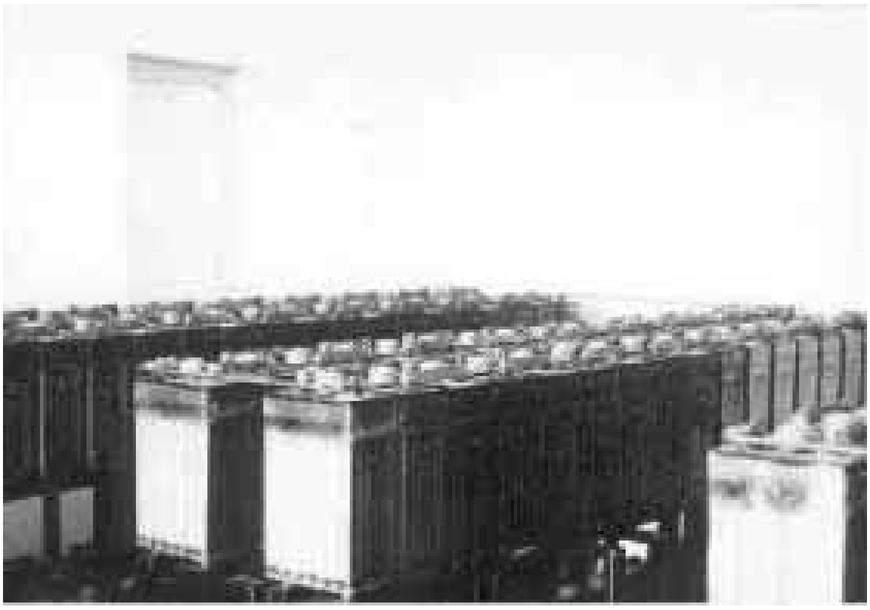


Figure 44: Battery room of a photovoltaic pumping system

Capacitors and flywheels can also serve as energy stores, though only to cover brief periods of peak demand, e.g., for starting up a progressive cavity pump or the like.

4.8 System Configurations

Depending on how they are put together, the equipment components discussed above will yield a broad variety of different pumping systems, the most widely disseminated of which are dealt with here:

- Submerged systems with in-well motor and pump

This system is opted for most frequently of all. It covers the 10 m – 100 m discharge head range, with capacities extending up to about 200 m^3/d. The motor, usually an asynchronous model, connects directly up to the centrifugal pump (Figure 45) to form a close-coupled unit that can be suspended from the delivery pipe in the well. A d.c./a.c. inverter is required here to serve as a matching circuit. An added advantage of this variant for applications in developing countries is that the motor is "water-cooled" and causes no overheating problems, even in a tropical climate.

- Submerged pump with ground-level motor

In this configuration, the pump is situated in the well and connected to its ground-level motor by a rod assembly (Figure 45). The obvious advantage of this arrangement is the motor's easy accessibility, meaning that d.c. motors can be used. Its drawback is that the torque has to be imparted by way of the long shaft. This gives rise, in particular, to suspension and lubrication problems as well as to potential resonance phenomena.

- Floating pump with d.c. motor

In this case, the centrifugal pump and its motor are mounted on a float. Such setups are used for irrigating crops with water from rivers, ponds or canals when the system head does not exceed approximately 10 m. The easy accessibility of pump and motor greatly facilitates maintenance operations. D.c. motors are frequently chosen for such applications (Figure 45).

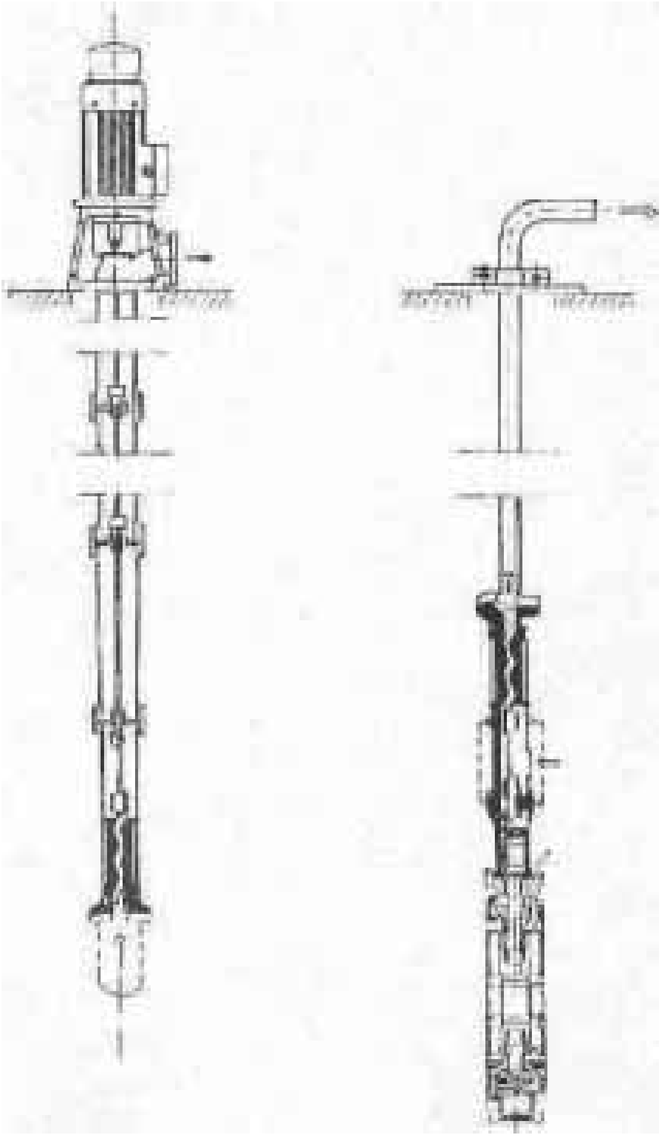


Figure 45: Pump connected to a ground-level motor by a rod assembly — Close-coupled in-well pump set (pump + motor)

All of these configurations can be implemented with or without power storage batteries.

5 Desing and simulation procedures for PVPS

As a rule, designing a photovoltaic pumping system is a demanding, laborious job – mainly because PVP systems cannot be designed for one or more certain, fixed duty points, but only for a quite broad duty range, unless storage batteries are included. Added difficulty derives from the fact that the time history of the duty point is dependent on the insolation level, i.e., on the weather, and is therefore unpredictable.

There are three main methods for designing photovoltaic pumping systems:
- calculation based on synthetic data
- layout based on nomograms
- computerized simulation

5.1 Calculation based on synthetic data

5.1.1 Calculation of water output for a given solar generator

This is the simplest approach to system design and the easiest way to obtain points of reference for PVPS configuration. It is based on empirical data from the operation of existing PVP systems.

The hydraulic output of a pump can be calculated according to the following equation:

$$E_{hyd} = \rho\, g\, Q\, H$$

where:	E_{hyd}	= Hydraulic output	[kW]
	g	= Gravitation constant	[m/s²]
	ρ	= Density (for water, ρ can be assumed as 1000 kg/m³)	[kg/m³]
	Q	= Flow rate	[m³/s]
	H	= Head	[m]

The amount of electrical energy needed for generating the hydraulic output can be estimated by way of the system efficiency (SE).

Target values range between 30 % < η_{SE} < 55 % with the system operating under its rated conditions. With allowance for the fact that the insolation level fluctuates in the course of a day, so that the operating point changes accordingly, and that there are times in which the supply of energy is too low to keep the pump in operation, it is necessary to replace the system efficiency, η_{SE}, with an "energetic yield factor, η_{PV}". With deference to the imposed part-load operating conditions, η_{PV} is, of course, lower than η_{SE} under normal operating conditions. In a typical case, the thusly corrected efficiency will amount to 15 % < η_{PV} < 35 %. Referred to the incoming solar energy, this amounts to an overall energy conversion efficiency level of 1.5 % - 3.5 %.

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For a PVPS with a solar generator rated at 1 kWp (southern Mediterranean location), a well with a depth of 30 m, and an irradiation level of 1000 W/m², the estimated pumpage would come to:

1 kW * 25% / 9,81 m/s² / 30 m = 0.85 l/s = 3.06 m³/h -> 3 m³/h (peak value!)

On a "good" day in the Mediterranean area, i.e., one with an insolation rate of some 5000 Wh/m²/d, the pump can be expected to run for about 6 hours, and the system would therefore yield about 18 m³ of water.

5.1.2 Calculation of solar generator peak power for a given daily water volume

Another way of estimating a PV system is to calculate on basis of a required water volume to be pumped per day the required peek power of the solar generator. The corresponding, following formular has been developed by GTZ on basis of many PVPS programs perfomed in the past (GTZ, 1998)

$$P_{SG} = 11,6\,\frac{H \cdot Q}{\overline{G}_d}$$

where:	P_{SG}	= Peak power of the solar generator	[kWp]
	Q	= Required flow rate	[m³/day]
	H	= Head	[m]
	G_d	= Mean global irradiance	[kWh/m²/day]

In case hydraulic data are given (water head 40 m, water output per day: 20 m³, global irradiance = 6 kWh/m²/d) the needed solar generator can be estimated to:

$$P_{SG} = 11,6\,\frac{40 \cdot 20}{6} \approx 1.5\,kWp$$

5.2 Nomograms

Nomograms are graphic representations of the pumping system's pumping performance under consideration of some decisive parameters. Equipment manufacturers draw up such diagrams on the basis of calculated and / or measured data. The typical input parameters of a given system can be used to arrive at the desired standard data. Nomograms exist as design / simulation tolls undependend of specific components. These kind of graphes are used to define basic system data. Other nomograms are founded on component data and thus system specific. These kind of graphes define the pumping system itself.

The example above shows a component specific nomogram. For a 1 kWp solar generator and a well head of 30 m, the nomogram shown a daily yield of 17 m³/d.

Nomograms or originally given as paper diagrams but nowadays, with the PC being available, nomograms are being put into computer programs (e.g. CASS).

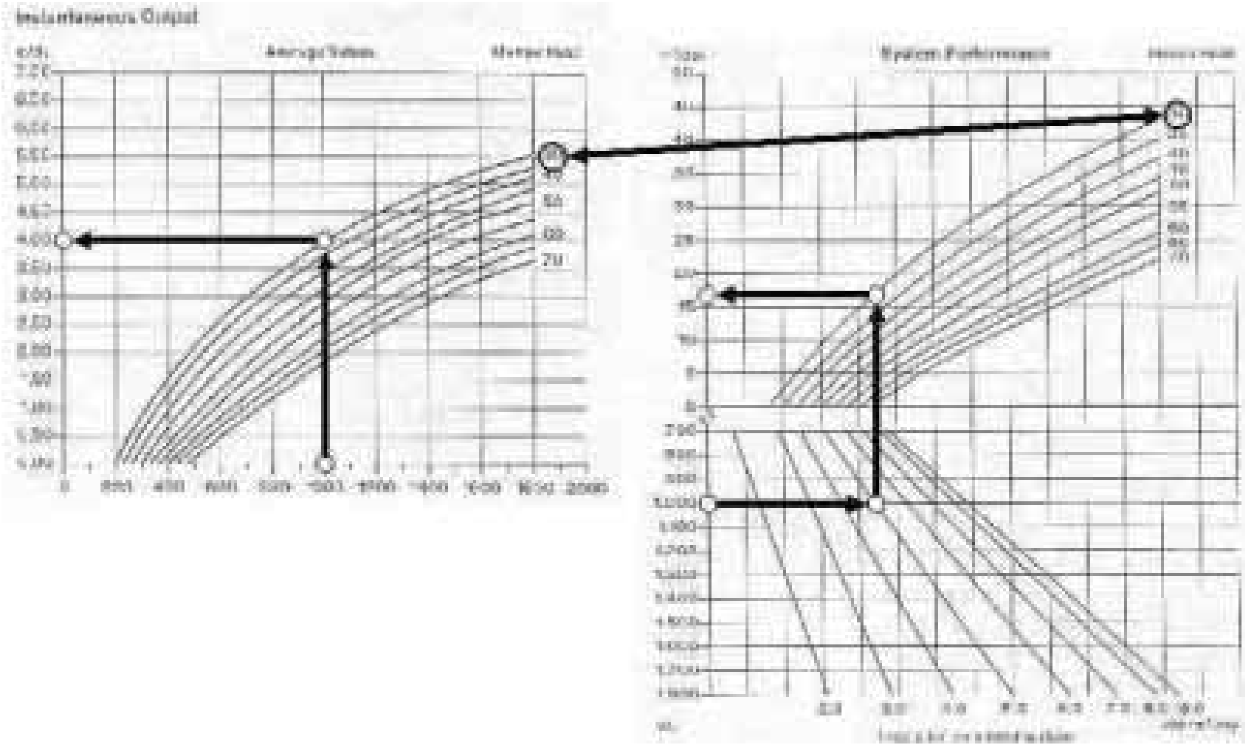

Figure 46: Nomogram for Grundfos System

5.3 Simulation programs

The most accurate – and laborious – approach to the design of a PVPS is to compute the system's configuration-dependent yield with the aid of a simulation program. There are two basic kinds of simulation programs:

- block diagram-oriented programs
- system-oriented programs

Block diagram-oriented programs treat the system's various components as modules (black boxes) with input and output connections. System assembly consists of interconnecting the modules and simulating their operation. The main advantage of such programs is the flexibility they derive from the freely designed modules. Hence, they can be used for designing not only pumping systems, but also solar-thermal systems, physical models, etc. (e.g., ITE-BOSS; Insel). The drawback in this case is that it takes lots of training, familiarization and experience to work with them effectively.

As a rule, system-oriented programs are easier to learn and use, but that is because they are only able to simulate the kind of system that has been implemented in their program (e.g., DASTPVPS).

Most simulation programs offer a broad range of data and parametric variables. This allows quick ascertainment of how a PVPS would react to different irradiance (total solar energy) curves and different solar generator configurations. The results shown for the example discussed above are given in the following figure 47. The PVPS is seen to yield an accumulated water output of 16.6 m³/d.

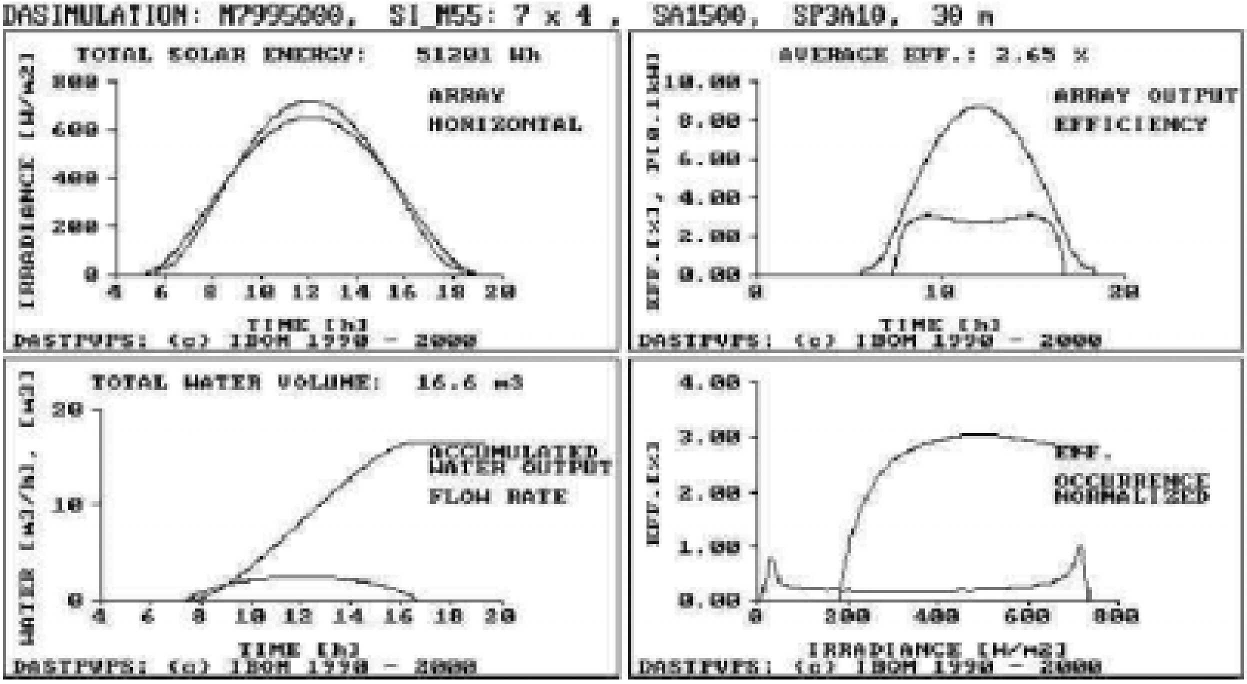

Figure 47: System simulation with DASTPVPS

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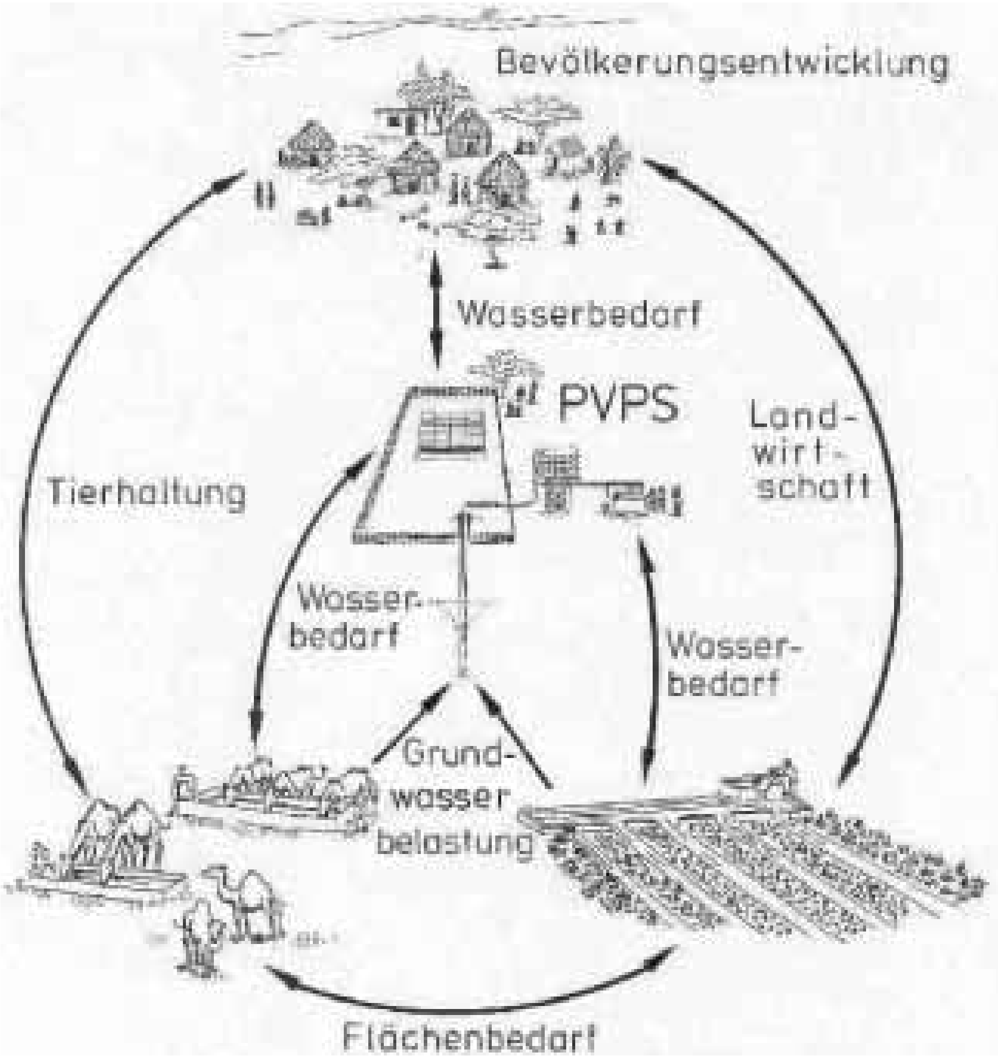
6 Sample Applications for Photovoltaic Pumping Systems

PVP systems can be used to obtain potable water for people, drinking water for domestic animals, and irrigation water for field crops. In planning such a system, one must keep in mind the fact that the pumping system is only part of a higher-order system with diverse control mechanisms. Figure 48 illustrates some of the causalities that become apparent upon closer scrutiny of the overall system.



Bevölkerungsentwicklung	=	Population development
Wasserbedarf	=	Water requirement
PVPS	=	Photovoltaic Pumping System
Tierhaltung	=	Animal husbandry
Landwirtschaft	=	Agriculture
Grundwasserbelastung	=	Groundwater pollution
Flächenbedarf	=	Land-area requirement

Figure 48: Higher-order cross-linkage and interdependencies surrounding photovoltaic pumping systems

To ensure that their photovoltaic pumping systems will have sustainably positive effects, responsible planners give due consideration both to these interdependencies

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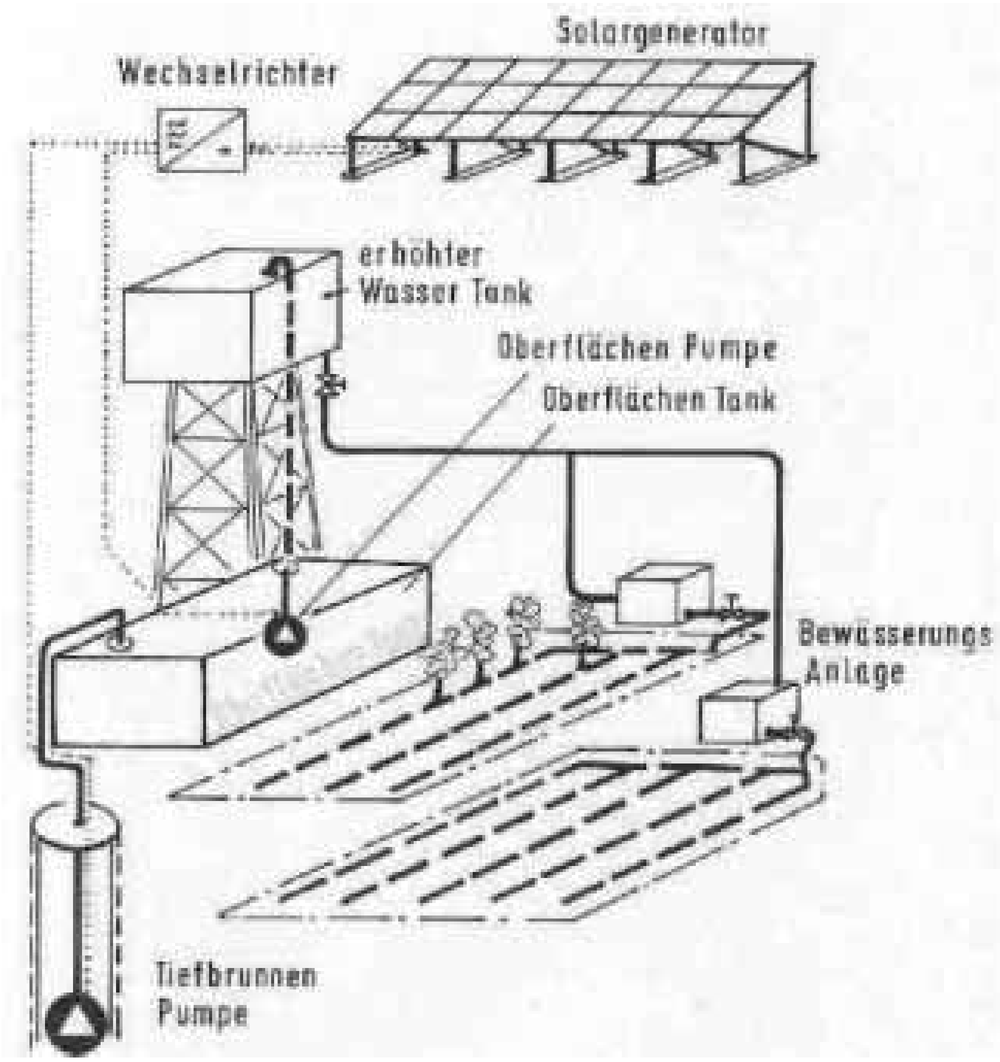
and to pertinent ecological, hydrological and sociological relationships. In closing, the following photos (Figures 49 through 54) are intended to convey an impression of the PVPS situation in various developing countries.



Solargenerator	=	Solar generator
Wechselrichter	=	Inverter
Wasser Tank	=	Water tower
Oberflächen Pumpe	=	Ground-level pump
Oberflächen Tank	=	Ground-level storage tank
Bewässerungsanlage	=	Irrigating system
Tiefbrunnen Pumpe	=	Deep-well pump

Figure 49: Schematic representation of a dual-pump system for field-crop irrigation

Figure 50: Photovoltaic drinking-water pumping system in the Philippines

Figure 51: Watering trough in Mauritania

Figure 52: PVPS with water tanks in Brazil

Figure 53: PVPS for irrigation in Egypt

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