Part II

Water Technologies

Water operations need energy. The whole water cycle of water pumping and transport, treatment, consumption and collection and treatment of used water depends on energy. Therefore, the availability of local electrical energy is crucial in order to obtain clean water. Moreover, energy is essential to use water wisely and to reuse it whenever possible.

Pumping is part of many water operations and is the prerequisite for water transport. The energy aspects of pumping are discussed in Chapter 4. Different uses of surface water or groundwater require different water quality: water for irrigation can mostly be of lower quality than drinking water; grey water from washing can be reused for other purposes. Various water treatment methods are briefly described in Chapter 5. Electrical energy is not always required to obtain drinking water: solar still distillation is discussed in Chapter 6 and is a cheap and well-proven traditional method for obtaining fresh water. Used water must be treated and some traditional treatment technologies are described briefly in Chapter 7. The focus is on the energy requirement for the various technologies.

Chapter 4

Water supply

"Water is the driving force of all nature."

Leonardo da Vinci 1452–1519.

Too many people today still have to fetch water for their daily needs. Providing water via piping requires pumping capacity and electric power. Pumping is fundamental for all water supply and treatment as well as for irrigation. Some basic properties of pumping are examined in 4.1. It is important to consider many non-technical issues concerning pumping systems. In 4.2 a few of these are discussed in the context of developing regions. The parameters that characterise pumping are described in 4.3 and pump efficiency is defined in 4.4. Naturally there are several necessary components to a pumping system and some key parts are described in 4.5.

4.1 PUMPING

Pumping water – clean or contaminated – is a key operation in decentralised as well as centralised water operations. For the water supply the water must be moved from the source – a river or a lake – or drawn from underground to undergo treatment. In rural areas, water

The chapter is from the book *Clean Water Using Solar and Wind: Outside the Power Grid*, Gustaf Olsson (Author).
doi: 10.2166/9781780409443_0047

pumping for irrigation is most essential. Pumping, for water supply, reuse and treatment of used water, is typically the major use of electric power in rural areas. Energy consumption is generally the largest cost in the lifecycle costs of a pump system, where pumps often run for more than 2,000 hours per year. To provide electric energy for pumping in rural areas of developing countries is not trivial. However, interesting products based on solar energy are now available.

For a small-scale water supply the water distribution pressure can be obtained either by a pump or by an elevated storage where the potential energy can provide the water supply pressure. If contaminated water is treated by desalination, there is a significant need for pumping energy; see 5.3 and 8.5. Any used water treatment or water reuse will use pumping energy (Chapter 7). It is apparent that pumping technology is an essential component of any water system, and having efficient pumping is crucial for any operation.

Among the advantages of solar PV pumping there are four often emphasised: unattended operation, low maintenance cost, easy installation and a long life. Both technology and economic viability have been considered in comprehensive literature reviews of solar pumping technology (Chandel *et al*., 2017; Sontake & Kalamkar, 2016; Varadi *et al*., 2018, Chapter 5.2). The authors have identified factors affecting performance of solar PV pumping systems and the degradation of PV modules as well as efficiency-improving techniques. It has been verified that solar pumping systems are more economically viable than diesel-based systems for irrigation and water supplies in rural, remote and urban regions (IRENA, 2016e). The investment payback time for some solar PV water-pumping systems has been found to be four to six years. This depends of course on local conditions, as shown below.

The costs of the systems are significantly different depending on their scale, purpose and configuration. It may be more meaningful to calculate the cost of the energy services provided and compare that to the existing costs that the user will pay for energy services off-grid.

4.2 PUMPING IN DEVELOPING REGIONS

The electric energy required for pumping is dramatically illustrated by the situation in India, where nearly 20% of electricity generation capacity is used for agricultural water pumping (CEA, 2016). India has around 26 million agriculture pumps, including at least 12 million grid-based electric pumps and ten million diesel-operated irrigation pump sets (IRENA, 2015b). Farmers pay only an estimated 13% of the true cost of electricity (Casey, 2013). The national burden of electric power subsidies is becoming too heavy. The subsidies encourage inefficient water use and contribute to depletion of groundwater. As water levels drop, more power is needed to pump the water, thus increasing the energy requirement of water extraction.

India has announced plans to replace many of its 26 million groundwater pumps for irrigation with solar pumps (Tweed, 2014). This will lead to large savings on installed electric power capacity and diesel and will hugely reduce CO_2 emissions. However, it is recognised that solar-based pumping poses a new risk for water resources: since the operational cost of solar PV pumps is negligible and the availability of energy is predictable, it could result in overdrawing of water. To combat that unintended consequence, the farmers who accept subsidies to purchase solar water pumps must switch to drip irrigation.

When “fuel” is free it is tempting to overuse water for irrigation. Therefore, Indian farmers who accept subsidies to purchase solar water pumps must switch to drip irrigation.

In sub-Saharan Africa around 40% of the population, more than 300 million people, have no access to an improved source of drinking water from the region (UN Water, 2014). An analysis of data from 35 countries in sub-Saharan Africa (representing 84% of the region’s population) shows significant differences between the poorest and richest fifths of the population in both rural and urban areas. More than 90% of the richest fifth in urban areas use improved water sources and over 60% have piped water on the premises. In rural areas, piped-in water is non-existent in the poorest 40% of households, and less than half of the population use any form of improved water source.

In the Sahel region solar-powered pumping stations have been in operation for almost two decades, providing better access to both electricity and water for two million people (IRENA, 2012). The region receives limited annual rainfall and the water table is at most 100 *m* down. The energy to extract groundwater has helped the people to cope with the prolonged drought conditions. The population in the Sahel region of West Africa without access to safe drinking water dropped by 16% during a ten-year period leading up to 2009.

In Kenya only 6% of the agricultural land is irrigated and the main reason for this is lack of energy for pumping. There are some 2.9 million farmers in Kenya. An ongoing project, supported by the Renewable Energy and Energy Efficiency Partnership (REEEP), seeks to implement solar-powered irrigation (IRENA, 2015b). A typical system can pump up to 20 m^3 per day and operate at depths up to 15 m. The capital cost for the system is around 400 USD. Taking into account the savings on fossil fuels the payback time is estimated at two years. The programme aims for 30,000 pumping systems by 2018. There are positive social consequences: for example, women and children are relieved from manual pumping and carrying water. As in India, there is an apparent risk of groundwater overdrawing due to the negligible operational cost of PV pumps.

As noted by Varadi *et al.* (2018), Chapter 5.2, there are more than 30 solar water pump manufacturers in the world. The pumps can be purchased on the Internet, but systems are available locally in most countries in Africa and developing Asia.

4.3 PUMPING CHARACTERISTICS

The most common pump type is the *centrifugal pump*, in which the pump principle is to convert mechanical energy from the motor to kinetic energy (i.e., energy related to the fluid speed or flow rate) in the pumped medium, the water. This will create a pressure difference in the media between the pump inlet and outlet. Here we will skip many details of pump characteristics; more details can be found in Olsson (2015), Chapter 16.

The *system characteristics* or the *load characteristics* describe the pressure that the pump must produce to drive the flow. The pressure consists of both *static* and *dynamic* pressures. The static pressure (also called the static head) appears at zero flow rate and depends on how much the water must be lifted by the pump. In other words, a deep well requires a large static pressure to lift the water compared to a shallow well.

The dynamic pressure depends on the speed of the water in the pipe, in other words on the flow rate. The higher the speed the higher the dynamic pressure. If the pipe is wide, then the friction losses in the pipe are small and the dynamic pressure increases only slowly as the flow rate increases. Conversely, if the pipe is narrow then the water speed increases much faster when the flow rate increases. Consequently, the dynamic pressure will increase faster with the flow rate.

Actually, the dynamic pressure and the friction losses depend on the square of the water velocity *v*, in other words on the square of the flow rate *Q*. So, if the flow rate is doubled, then the power to provide the dynamic pressure must increase by a factor of four. The static and dynamic pressures are illustrated in Figure 4.1.

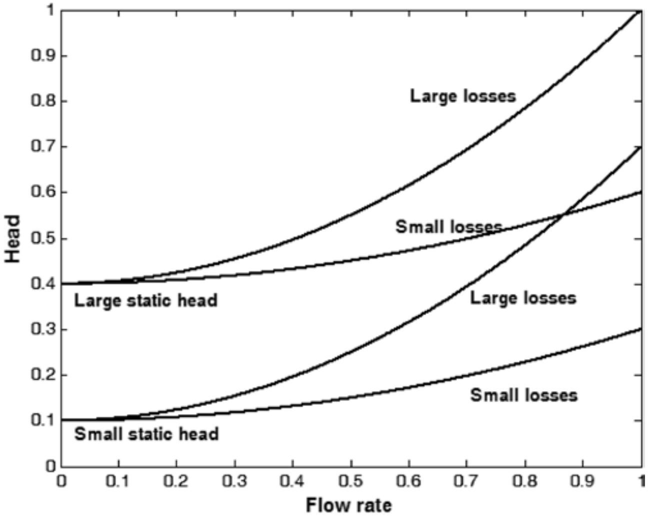

Figure 4.1 Different system curves that represent the load to the pump. If the water is lifted only a small height then the static head is small, and vice versa. If the pipe is narrow, then the losses are relatively high and the required dynamic pressure increases rapidly with the flow rate.

The pump curve, called the QH curve, describes the pressure that a pump can produce as a function of the flow rate, Figure 4.2. This is called the *pump characteristics*. The static and dynamic pressures are expressed as the *head*. Head is measured in metre liquid column and is proportional to the pressure that is created by the pump. Expressed differently: the head tells how high the pump can lift the water, given a certain pressure. The higher the flow rate the lower the head that can be produced by the pump.

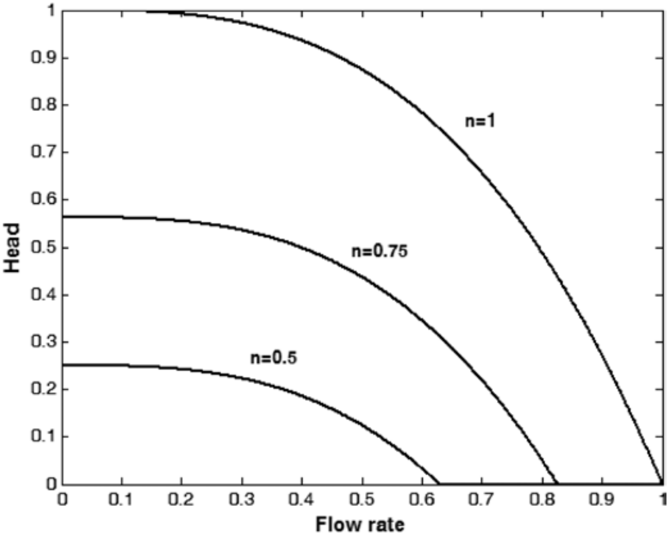

Figure 4.2 Typical pump characteristics or QH curves at different pump speeds (n). Q denotes the flow rate while *H* is the pressure, expressed in metres head.

The relation between the head (H, expressed in m) and the pressure (p, expressed in $Pa = N/m^2$) is

$$H = \frac{p}{\rho \cdot g} \tag{4.1}$$

Where ρ is the liquid density (kg/m^3), and g the acceleration of gravity (m/s^2). The formula indicates that pumping at a pressure of 1 *bar* (=10^5 *Pa*) corresponds to a water column ($\rho = 1000\ kg/m^3$) of 10.2 *m*.

If the rotational speed (*n*) of the pump is changed, then the QH curve is changed according to Figure 4.2. A lower speed means that the pump produces a lower head at a given flow rate, or produces a lower flow rate, given the head. If the pump is aimed to work at only one given head and flow rate, then the slope of the QH curve has no importance.

The operating point (or *duty point*) of a pump is determined by the intersection of the pump (QH curve) and system characteristics, as shown in Figure 4.3. The QH curve defines what the pump can produce, while the system curve (the load) defines which pressure is needed.

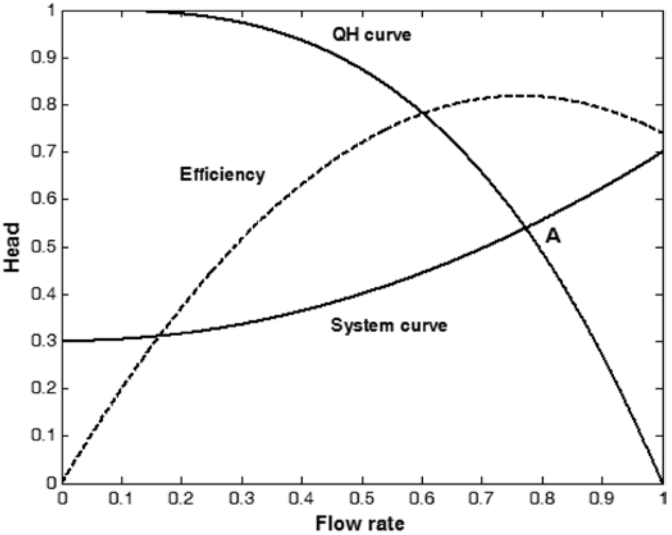

Figure 4.3 The duty point A of a pump is determined by the intersection of the QH curve and the system curve. The efficiency for a typical centrifugal pump is also shown. This indicates that the pump should be designed so that the maximum efficiency appears at the duty point. Expressed differently, the efficiency should be close to its maximum at the most common flow rates.

4.4 PUMP EFFICIENCY

The pumping efficiency depends on the flow rate as well as on the design of the pump.

- The electric power delivered to the electric motor connected to the pump is called the *incoming power*.
- The power transferred to the pump shaft is the *mechanical power* (the *shaft power*) and is slightly smaller than the incoming power and depends on power losses in the motor. The rated power of a motor is the mechanical power at the normal operating point and is slightly smaller than the consumed electric power. Typically, the motor efficiency is higher than 90%.
- The mechanical power is transferred to the *hydraulic power* P_{hydr} – the power that the pump transfers to the liquid in the shape of flow. This efficiency depends on the flow rate and is illustrated in Figure 4.3. The figure illustrates that the pump should be designed so that it has a maximum efficiency at the most common flow rates.

For the most common pump types, the term *power rating* normally refers to the *shaft* power and is measured in *W* or *kW*.

The efficiency of a large-scale pump may be around 89%. High-performance, small-scale pumps can reach an efficiency of 85%, but the performance of less expensive small pumps may be significantly lower.

The hydraulic *power* to lift water *H* metres is derived from:

$$P_{\text{hydr}} = Q \cdot H \cdot \rho \cdot g \tag{4.2}$$

where the hydraulic power is expressed in watts (*W*). Q = flow rate (m^3/s), H = head (*m*), ρ = liquid density (kg/m^3), and g = acceleration of gravity (m/s^2). Obviously, the required electric power must be higher than the hydraulic power. Naturally the total pump efficiencies depend on the actual equipment, and here we assume a typical value of 80%.

Example 4.1: *Power to Pump Groundwater*

Assume that the groundwater source is located 10 *m* below ground ($H = 10$). We need to supply 1 m^3 per hour ($Q = 1/3600\ m^3/s$). The water density is 1,000 kg/m^3 and $g = 9.81\ m/s^2$.

The required hydraulic power is:

$$P_{\text{hydr}} = \frac{1}{3600} \cdot 10 \cdot 1000 \cdot 9.81 = 27\,W$$

It is necessary to take some head loss in the piping system into consideration. We can assume this to be 10%. The required electric power, given an 80% motor/pump efficiency and a 10% head loss, then becomes

$$P_{\text{el}} = \frac{27}{0.8 \cdot 0.9} = 37.5 \approx 38\,W$$

The power is proportional to the head (depth) so a 20 *m* lift would need twice as much hydraulic power (54 *W*) and 76 *W* of electric power.

Doubling the flow rate also means doubling the required power. Thus, to lift 10 m^3 per hour from a depth of 100 *m* will require a hydraulic power of

$$P_{\text{hydr}} = \frac{10}{3600} \cdot 100 \cdot 1000 \cdot 9.81 = 2725\,W \approx 2.7\,kW$$

and around $2.7/(0.9 \cdot 0.8) \approx 3.8\,kW$ of electric power.

To get the *energy* (in joules) the *Q* is replaced by the total volume *V* (m^3) in the calculations.

Example 4.2: *Energy to Pump Groundwater*

Let us calculate the energy to lift 1 m^3 of water from a depth of 10 *m*. This will require:

$$E_{\text{hydr}} = 1 \cdot 10 \cdot 1000 \cdot 9.81 = 9.8 \cdot 10^4\,J$$

where *J* is the energy measured in joules. With 10% pipe loss and 80% motor/pump efficiency taken into consideration the required electric energy input is around $13.6 \cdot 10^4\,J$. Translating *J* (=*Ws* or watt seconds) to *kWh* as a more commonly used unit for electric energy:

$$\begin{aligned} 1\,kWh &= 1000\,(W) \cdot 3600\,(\text{seconds}) = 3.6 \cdot 10^6\,Ws \\ &= 3.6 \cdot 10^6\,J = 3.6\,MJ \end{aligned}$$

so, the electric energy of $13.6 \cdot 10^4\,J$ corresponds to $3.8 \cdot 10^{-2}\,kWh$. Another way to calculate the energy is to simply multiply the power (38 *W*) by time:

$$E_{el} = 38 \cdot 3600\,Ws = \frac{38}{1000}\frac{3600}{3600} = 0.038\,kWh$$

Again, the required energy is proportional to the head and to the volume of water. So, instead of lifting the water 10 *m* we now calculate for the head of 100 *m* and lift 10 m^3 instead of 1 m^3. This will require 100 times more (hydraulic) energy or $0.027 \cdot 100 = 2.7$ *kWh*; in other words, it demands the hydraulic power of 2.7 *kW* for one hour. The required electric energy for a pump system with 80% efficiency and pipe loss of 10% is 3.8 *kWh*.

If the pump is running during daylight solar hours (assuming eight hours) then the required energy is produced for eight hours (only 1/8 m^3 of water is pumped every hour), which will require the power $3.8/8 = 0.48$ *kW* from the solar PV system. This is 1/8 of the power calculated in Example 4.1.

In a solar PV pumping system, typically two types of system configurations are prevalent. In the first one a submersible pump lifts groundwater into an overhead tank that serves as an energy store and supplies the pressure needed for the pressurised irrigation system. In the second configuration there is no storage system and the water is pumped directly into the irrigation network.

Example 4.3: *Experiences from Solar-Powered Pumping*

Solar PV water-pumping systems are used for irrigation and drinking water in India (Roul, 2007). Most of the more than one million pumps in operation have the motor power 2.0–3.7 *kW*. Typically, a 1.8 kW_p (*kW* peak power, see also Chapter 8.2) solar PV array is used for irrigation purposes. Such a system can deliver around 140 m^3 of water per day from a total head of 10 *m*.

Let us compare this energy need with the theoretical hydraulic power (4.2). Assuming that the pump is working eight hours per day and only 60% of the peak solar power can be used:

$$P_{\text{hydr}} = \frac{140 \cdot 0.6}{8 \cdot 3600} \cdot 10 \cdot 1000 \cdot 9.81\,W = 286\,W$$

Apparently, the PV/motor/pump systems are quite inefficient, or the solar array is designed with a large safety margin.

Example 4.4: *Rule of Thumb for Solar Water Pumping*

A common rule of thumb is that a 1000 W_p (1 kW_p) solar water pump can draw and pump around 40 m^3 of water per day from a source that is up to 10 m deep. Again using (4.2), we find that the hydraulic energy is:

$$Q_{\text{hydr}} = 40 \cdot 10 \cdot 1000 \cdot 9.81\,\text{J} \approx 4\,MJ \approx 1.1\,kWh$$

Assuming eight hours of sunshine, 80% motor-pump efficiency and 10% pipe loss the required electric power would be 0.19 *kW*. In other words, a large safety margin is assumed.

Typically, 40 m^3 of water per day is sufficient to irrigate up to one hectare of land planted with regular crops.

4.5 COMPONENTS IN A SOLAR PV PUMPING SYSTEM

The solar panels make up most of the cost in a solar PV pumping system, while the pump usually only represents a marginal cost. Of course, the size of the energy supply depends on the required flow rate (m^3/hour), and the solar irradiance.

4.5.1 Solar panels

One of the major advantages of solar flat panels is that they can produce economically interesting quantities of energy without the need to track the sun's position. The reduced demand for maintenance due to the lack of moving parts is reflected in a better overall economic result.

Typically, for most solar panels it is guaranteed that the module will produce 90% of its rated output for the first ten years and 80% of its rated output for up to 25 years. This is an outstanding operational life, longer than that for most other equipment. The limited complexity of mounting and operating a solar PV system (compare Chapter 8) and the safety of the solar cells in combination with the manufacturing costs are all factors in the success of the expansion of solar PV. Of course, if the equipment is in a remote area the commercial value of the guarantee may be quite limited. However, the fact that such a guarantee is still given is an indication of the reliability of the system.

4.5.2 Inverters and pump controllers

Solar panels deliver a direct current (DC) and the pump can be either a DC or an AC type. For an AC pump the DC from the solar panels must be converted from DC to AC. This is performed in an inverter, a power electronics device. A DC pump, however, does not need an inverter. DC pumps are more common for small-scale applications, typically less than 3 *kW*. This is adequate for a single household or for a small irrigation systems.

DC motors tend to have higher efficiency than corresponding AC motors. Traditionally it has been simpler to control the speed of a DC motor. Today, however, it is more economical to install an AC motor with an electronic variable speed controller. Furthermore, DC motors have many moving parts that are expensive to replace. They are supplied with brushes and commutators that have a limited operational life and must be replaced regularly. An AC motor with power electronics controller is both more reliable and more economical. It has no brushes and has a rugged design.

Inverters represent a proven technology over a very wide range of power levels and usually have very high efficiency: 98% or higher. Inverters for solar PV systems are often subject to harsh conditions, exemplified by operation during many sun hours combined with temperatures higher than 40°C. Dust is another challenge. When a small inverter is coupled directly to a PV module and mounted on the rear side the conditions may be severe. The temperature may reach up to 80°C. Under these conditions the electronics must be ready to operate for a period comparable with the lifetime of the PV modules, at least 20 years. Therefore, it is important to have a design margin that will ensure long-term reliability. The individual components must meet the harsh conditions. Given an adequate design the useful life of an inverter will exceed 20 years.

There is an internationally accepted standardisation of test procedures for PV system components. The standard IEC1215 defines the electrical and thermal properties of the components and can give an indication of the expected lifetime.

The pump also needs a controller that can adapt the power directed to the pump with the power delivered from the energy source. Generally, a controller should be provided with a voltage protection capability that will shut down the pump if the supplied voltage is too low or too high. In Chapter 11 we analyse more details concerning the control equipment.

4.6 FURTHER READING

Many pump manufacturers provide information about pumping principles and equipment. Grundfos Pump Handbook presents an excellent description of pumping principles (www.grundfos.com). The full link to their – now classic – work about pumps is http://machining.grundfos.com/media/16620/the_centrifugal_pump.pdf.

Solar array-based pumping technology is now commercially available. One example is the Lifelink concept from Grundfos (www.grundfos.com/market-areas/water/lifelink.html).

Another large pump manufacturer Xylem (https://www.xylem.com) has a web-based pump selection tool, Xylect, to guide the customer to find a suitable pump.

There is a lot of practical information on www.youtube.com. Search for “solar pumping systems”.