Part I

Water and Energy – A Human Right

Clean water and basic energy are needed for a decent life. This is taken for granted by most people in the world. Yet still, in 2018, more than 650 million people lack clean water and around 1,000 million people do not have the electric power that could enable them to light their homes, cook their food and access clean water.

This book addresses this issue and claims that there are better opportunities than ever to satisfy the basic needs of clean water and energy for all.

The unique development of renewable energy over the last few years brings new hope for millions of people. Those living in remote areas, outside the national electric power grids, will now have a realistic opportunity to receive the benefits of clean energy. This in turn will open up possibilities of obtaining clean water and enable people to escape poverty, fight hunger, improve health and support education.

The United Nations has defined 17 Sustainable Development Goals (SDGs). Two of these relate to clean water and clean energy. However, without these two essentials it will hardly be possible to reach the other 15 goals.

Chapter 1

Water and energy – for all

"Before my mother got water every three days. Now she forces me to wash three times a day".
A six-year old boy in Phnom Penh, after water was delivered by piping.

Told by Ek Sonn Chan, General Director Phnom Penh Water Supply Authority, Cambodia.

The aim of this book is to describe how solar photovoltaic (PV) and wind energy have a huge potential to supply clean water for the developing world, in particular in areas with no electric power grid connection. Off-grid technologies can form a significant part of the solution, all the way from household level to village or community level. Small-scale off-grid systems can provide not only lighting but also energy for pumping to gain access to water and for treatment to purify and reuse water.

The cost development of renewable energy has been remarkable and will make electric power affordable even for the poorest. Since 2010, the cost of key energy devices has declined dramatically: LED lighting is 95% cheaper, solar PV 60% and battery storage 75% less expensive.

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Already today the cost of "new" renewable energy can compete with traditional electrical generation.

Clean water is a matter of life and death. Still, too many people lack this basic need. Lack of electric power for pumping and cleaning contaminated water is one of the missing prerequisites; one person out of seven has no electric power available. We wish to raise awareness of the fact that today there are great and realistic opportunities for those people living outside the electric power grid.

1.1 CLEAN WATER AND ENERGY FOR ALL

The World Economic Forum (WEF) presented its tenth global risk report in 2015 (http://reports.weforum.org/global-risks-2015). For the first time water crises took the top spot among the risks in the report, published by 900 leaders in politics, business and civic life about the world's most critical issues. In 2014 water had ranked third among the most serious threats to business and society. The risks for water crises in the 2015 report were deemed both highly likely and highly devastating. The top ranking of water reflects the growing recognition among world leaders that diminishing supplies of reliable, clean water will be a real threat to health and wealth for the poor, for the richest economies and for the largest cities.

One person out of seven has no electric power.

It is also notable that the WEF report reclassified water from an *environmental* risk to a *societal* risk. It has been recognised also by world leaders that nearly all human activity – food production, fishing, public health, industrial activities and power production – has water at its base.

Renewable energy technologies can make a major contribution to universal access to both energy and water in a sustainable way. In many regions with energy poverty there are abundant renewable energy sources. There is no lack of sunshine in sub-Saharan Africa or South Asia. In most regions of Africa there are more than 300 days of bright sunlight per year (Varadi *et al.*, 2018). Dry areas like the Sahara and the Sahel region can provide large areas with solar-powered electricity.

In rapidly growing peri-urban areas electric power grids may be available but need to be complemented with decentralised energy sources. Solar and wind can be part of new hybrid energy supplies. It is noted that there is a confluence of factors, such as greater urbanisation, population increase and economic development that will determine the energy mix. The United Nations (UN) Sustainable Development Goals of "clean water" and "energy for all" are strongly related and will depend to a large extent on solar PV and wind. This is further explained in Chapter 3.

World Economic Forum: lack of water is both an environmental risk and a societal risk.

1.2 ACCESS TO CLEAN WATER

More than 650 million people lack clean water. Without safe water and sanitation people get caught in a vicious circle of poverty and sickness. In the poorest societies in the world, it is mostly women and children who lose precious time in their search for water and in the transportation thereof. Children die from diarrhoeal diseases that can be prevented. Open sewers running right through villages are far too common.

Water scarcity, poor water quality and inadequate sanitation have a significant impact on food security, educational prospects and other living conditions for poor families across the world. By 2050, the UN estimates that at least one in four people is likely to live in a country affected by chronic or recurring shortages of fresh water. The UN (www.un.org) summarises some of the huge challenges:

- 2.1 billion people lack access to safely managed drinking water services (WHO/UNICEF, 2017);
- 4.5 billion people lack safely managed sanitation services (WHO/UNICEF, 2017);
- 340,000 children under five die every year from diarrhoeal diseases (WHO/UNICEF, 2015);

- Water scarcity already affects four out of every ten people (WHO);
- 80% of wastewater flows back into the ecosystem without being treated or reused (UNESCO, 2017).

More than 650 million people lack clean water.

It is obvious that water supply and used water treatment need to be addressed simultaneously.

1.3 ACCESS TO ELECTRIC ENERGY

Today around 1,000 million people around the world lack electric power that could enable them to light their homes, cook their food or pump clean water (Jones & Olsson, 2017). Most of them live in rural areas of Africa and developing Asia. Another 1,000 million have unreliable electric power supplies (IEA, 2011). Furthermore, more than three billion rely on solid fuels and kerosene for access to cooking and heating (World Bank, 2017). The indoor and outdoor air pollution from burning wood and other biomass causes more than four million deaths each year.

Around 1,000 million people lack electric power. Another 1,000 million have unreliable electric power supply.

In sub-Saharan Africa alone, there are about 600 million people without access to electric power, around 57% of the population. Some 80% of these people live in rural areas. Less than 25% of the rural population have electric power. As a comparison 71% of urban residents in these countries have electricity (IEA, 2017b). Like lack of clean water, lack of electricity handcuffs poor families to poverty – especially women and girls, who must gather fuel and carry out the household chores. The good news, however, is that electrification efforts have accelerated so that electric power addition since 2014 is higher than the population growth.

The IEA (International Energy Agency) definition of access to electricity is at the household level and includes a minimum level of electricity consumption, ranging from 250 *kWh* per household per year in rural areas to 500 *kWh* in urban settings. The electricity supplied must be affordable and reliable. The initial level of electricity consumption should increase over time, in line with economic development and income levels, reflecting the use of additional energy services. (IEA/India, 2015).

It is well recognised that economic growth is closely related to access to energy. Electric energy consumption in Africa, particularly in sub-Saharan Africa, and in South Asia, is in disturbing contrast to the consumption in high-income countries. In sub-Saharan Africa the annual electric power production averaged 481 *kWh*/capita in 2012. This should be compared with the OECD average of 7,995 *kWh*/capita and the global average of 3,126 *kWh*/capita (Varadi *et al.*, 2018; World Bank, 2014). The contrast becomes even more upsetting when individual countries are compared, as in Figure 1.1. More details are found in Table 1.1 in Varadi *et al.* (2018), using data from the World Bank. sub-Saharan Africa (SSA) is the only region in the world where per capita access is falling (*ibid.*). Still it should be recognised that around 150 million sub-Saharan Africans have gained access to electricity since the year 2000 (IRENA (International Renewable Energy Agency), 2016d).

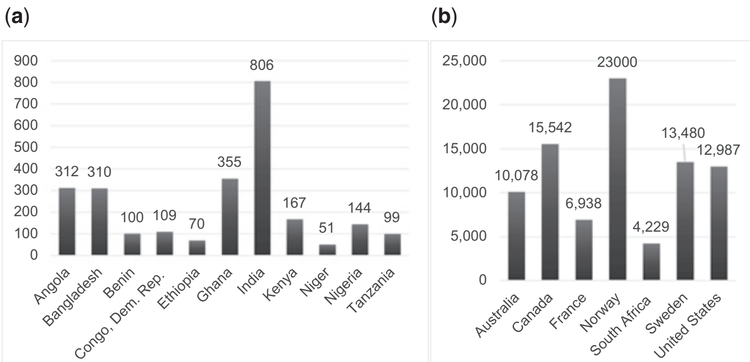

Figure 1.1 The annual electricity consumption (*kWh*/capita/year) in some countries. Low-income countries (a) are compared with high-income countries (b). Observe that the scaling to the left is more than an order of magnitude smaller than that on the right. *Note* the differences between Sweden, Norway, US and Canada. In the US and in Canada more natural gas and fossil fuels are used for energy production, while electric power is more widely used in Scandinavia. Data from World Bank (2014).

> The annual electric power production in sub-Saharan Africa is more than six times lower than the global average and almost 17 times lower than the OECD average.

The message from World Bank (2017) is clear: "In many countries with low levels of electrification access, both grid and off-grid solutions are vital for achieving universal electricity access – but they must be supported by an enabling environment with the right policies, institutions, strategic planning, regulations, and incentives."

Access to electric power is extremely important for access to clean water. For people living in remote and rural areas or in rapidly expanding peri-urban areas in poor regions of the world, power grids are out of reach. They cannot wait for conventional electric networks to be completed to solve their water supply or sanitary challenges.

1.4 DECOUPLING WATER FROM ENERGY WITH RENEWABLES

The close dependency between water, energy and food, the water-energy-food nexus, has been recognised for a long time. In my previous book (Olsson, 2015) the couplings and their consequences are described in detail. This book will show how renewable energy in combination with decentralised water operations can decouple many of these dependencies and meet challenges caused by climate change, population increase, water scarcity and poor water quality.

1.4.1 Renewable energy water footprint

Renewable energy can improve energy and water security. The energy sector relies heavily on water for energy extraction and production, accounting for 15% of water withdrawals globally. In a water-constrained world, conflicts with other end uses, such as agriculture, are intensifying and further impacted by climate change. With access to water increasingly recognised as a risk for energy security, it is becoming necessary to decouple energy sector expansion from water use.

Water is needed for fossil fuel extraction, transport and processing. Conventional thermal power plants, like nuclear, natural gas or coal, use huge amounts of water for cooling (Olsson, 2015, Chapter 13). Both water withdrawal and water consumption are significant.

The beauty of renewables is that they dramatically reduce not only the carbon footprint but also the water footprint. Solar PV and wind consume up to 200 times less water than conventional options (IRENA, 2015b). Substantial water savings are already being realised. Solar PV has a very low water footprint since water is not used for electricity generation. The water requirement, estimated at 118 litres/MWh, comes from the manufacturing of the PV cells and maintenance of modules (WEC, 2016, Chapter 8). Wind energy is certainly a low-carbon source, and the turbines have no water requirement during operation.

Solar PV and wind energy have a very low water footprint.

1.4.2 Small-scale renewables

We will address the key issues – clean water and energy for all – and show the enormous potential of renewable energy, made possible by the technical developments of recent years. Around the world, low-carbon renewable energy is emerging as the go-to-green growth and poverty reduction strategy. The development of inexpensive solar and wind technology is considered a potential alternative, providing an electricity infrastructure consisting of a network of local-grid clusters with distributed electricity generation. This makes it possible to become independent of long-distance, centralised power-delivery systems. The emphasis in this book is to demonstrate how decentralised power from renewable sources and decentralised water supply and used water treatment offer new possibilities and hope for the un-privileged people left outside the advanced systems of today.

Renewables offer viable, affordable and scalable solutions. They are at the core of any strategy to meet climate goals while supporting economic growth, welfare, domestic value creation and employment generation. The potential of renewables is there for every country to harness. A major advantage of solar PV is that there isn't any minimal or maximal project size; it can be scaled to match the user load size and type. Solar PV can be used to power systems from the very small in size up to residential systems and utility-scale projects, ranging from a few *kW* to several hundred *MW*. Solar PV is at this moment probably the most attractive option for mini-grids (see also 3.2) for small villages (REN21, 2017a).

Renewable energy delivered by solar photovoltaic (PV) or wind will have a profound impact on water delivery and water treatment over the next decades. Any domestic user will require two kinds of energy: electric energy for illumination, machines, pumps, water treatment units and other equipment and thermal uses of solar energy for (1) process heat (including cooking), (2) ambient comfort, depending on the actual location.

We will describe how three kinds of renewables can satisfy these needs: solar photovoltaic (PV), wind power and solar heating. It should be noted that the direct use of solar energy for cooling via thermal processes has been tested in several situations, but so far it does not work satisfactorily.

Biogas is an important and environmentally friendly source of energy, and many rural areas depend on it. In this book we refer to biogas as a by-product of used water treatment but will not specifically consider the production of biogas as an energy source. We purposefully exclude some energy technologies, like geothermal energy, concentrating solar thermal energy and large-scale wind energy. In fact, the growth of bioenergy, concentrating solar energy and geothermal energy represented only 4% of renewable energy capacity growth in 2016 (IEA, 2017b).

We will show the potential of small-scale solutions that realistically can be used by individual households as well as small villages or a subdivisions of a city. Naturally, small-scale hydro can be considered an alternative energy source. This is already practised in regions with water resources but is not available in water-scarce areas. Regions with water scarcity or insufficient sanitation are certainly not areas where hydropower is an alternative. For the ongoing discussion we will exclude hydropower since our focus will be towards regions with water scarcity.

1.4.3 Providing water using renewables

Water is the critical element for a decent life and sustainable growth. Once the very basic needs connected to electric power are met, such as lighting and low-load production, new avenues open up. Renewable energy technology is already used to meet energy demand in many parts of the water cycle. Solar pumps can provide water for drinking, crop irrigation, increase access to piped water and reduce vulnerability to erratic rainfall patterns, thus increasing yields and incomes.

Renewable energy can also meet energy needs across the water supply chain, including various kinds of treatment such as desalination, water reuse and treatment, thus directly contributing towards access to both water and energy.

An important aspect is that the solar PV system has free "fuel" from the sun, while conventional fuels represent a major share of the operating cost. In many regions in rural Africa and developing Asia there are abundant solar resources. Even taking into account that the energy cost of desalination is relatively high, it is already acknowledged that solar-powered reverse osmosis desalination can produce water at a lower cost than fossil fuels. Likewise, wind power has free "fuel" from the wind. In each individual case it will be determined if wind is a viable complement or replacement for solar PV.

With free "fuel" as much energy as possible should be extracted for good use.

When fuel is free the concept of energy-saving will get another meaning. Having free "fuel" means that as much energy as possible should be extracted for good use. The constraint is the power that will limit the number of appliances, water supply or water cleaning capacity.

1.4.4 Renewables versus nuclear and fossil energy

The interesting aspect of solar PV and wind power is that they are *technologies* and not *fuels*. They are unlimited, and the price will decrease as deployment increases. For fossil fuels it is the opposite: the more they are used, the more expensive they become (Wesoff & Lacey, 2017). Of course it should be remembered that fossil fuels have enabled our economy to develop. The message of today is that now there are realistic alternatives for producing energy.

The International Atomic Energy Agency (IAEA) has released the 2017 edition of its *International Status and Prospects for Nuclear Power* report series (IAEA, 2017). It states that the share of nuclear power in total global electricity generation has decreased for ten years in a row, to 10.5% in 2015, yet "this still corresponds to nearly a third of the world's low carbon electricity production." This means that renewables (including hydro, solar and wind) generate more than twice as much electricity (24.5%) as nuclear power and the gap is growing rapidly.

It is predicted that by 2022 renewables will be generating three times as much electricity as nuclear reactors. The International Energy Agency (IEA – not to be confused with the IAEA) in 2017 released a five-year global forecast for renewables, predicting capacity growth of 43% (920 *GW*) by 2022. The latest forecast is a "significant upwards revision" from last year's forecast, largely driven by expected solar power growth in China and India (IEA, 2017b). Non-hydro renewable electricity generation has grown eightfold over the past decade and will probably surpass nuclear by 2022, or shortly thereafter.

Globally, investments in fossil fuels will decrease to less than half of today's around $3.4 \cdot 10^{12}$ USD/year to $1.5 \cdot 10^{12}$ USD/year in 2050, while non-fossil energy expenditures show the reverse trend, increasing fivefold from around $0.5 \cdot 10^{12}$ USD/year today to $2.7 \cdot 10^{12}$ USD/year in 2050 (DNV GL, 2017).

Shifting investments to renewables, where the investment is up-front capital expenditures (capex), implies a shift from an energy system with a 60/40 split between operating expenditures (opex) and capex to one with the inverse split of 40% opex and 60% capex. In dollar terms, global opex will decline from about $2 \cdot 10^{12}$ USD/year in 2015 to $1.5 \cdot 10^{12}$ USD/year in 2050. Conversely, capital expenditure will increase almost 50% from $1.8 \cdot 10^{12}$ USD/year in 2015 to $2.6 \cdot 10^{12}$ USD/year in 2050. These figures do not include the cost of grids and energy efficiency investments (*ibid*.)

Eliminating the use of oil and gas will cut about 13% from the world's energy budget because mining, transporting and refining those fuels are all energy-intensive activities (Solutions Project, a US-based non-profit organisation). The greater efficiency of electric motors versus internal combustion engines could reduce global energy demand by another 23%.

1.4.5 Electric power cost development

Some recent reports emphasise that the energy field has undergone a massive change in less than a decade. Obviously we need tools to evaluate and compare costs for both conventional and renewable sources of energy, otherwise this could easily become an exercise in comparing apples and oranges.

An economic instrument is the levelised cost of energy (LCOE), which is defined as a way to express the lifetime costs divided by energy production and can be expressed in cost/*kWh*. The LCOE shows both capital costs in form of annual amortisations and variable costs. The LCOE is a step forward in the definition of a metric for the real costs of energy, though it also has its limits. The LCOE depends on the selected amortisation period and the reference interest rate. This is further examined in Chapter 12.1.

In addition, the LCOE doesn't say anything about the demand for power. A solar *kWh* in bright sun during summer has a different value from the same *kWh* in a cold region in winter, the same as a litre of fresh water has a different value in a hot desert from on the shore of a Nordic lake. It represents, however, a step forward in the comparison of quantities that by their nature are difficult to relate to each other.

A key observation from Lazard's latest levelised cost of energy (LCOE) analysis (Lazard, 2017) published in November 2017 is: "as LCOE values for alternative energy technologies continue to decline, in some scenarios the full-lifecycle costs of building and operating renewables-based projects have dropped below the operating costs alone of conventional generation technologies such as coal or nuclear. This is expected to lead to ongoing and significant deployment of alternative energy capacity." The report further notes that the global costs of renewable energy generation continue to decline. The LCOE for both large-scale solar PV and onshore wind technologies declined around 6% in 2017.

> The energy field has undergone a massive change in less than a decade. Solar PV and wind are now the electric energy sources with the lowest cost.

It is also observed that the gap between the costs of alternative energy technologies like large-scale solar PV and onshore wind energy compared to conventional generation technologies continues to widen. For example, the cost development for coal generation remains flat, while for nuclear power it is increasing. The LCOE for nuclear generation has climbed around 35% compared to previous estimates. The reason is the increased capital costs at various nuclear facilities in development. In 2017 new nuclear capacity of 3.3 *GW* was outweighed by lost capacity of 4.6 *GW* (Green, 2018).

It should be emphasised that the conclusions consider the global average. The actual cost will vary significantly from country to country depending on the cost of coal, gas, the cost of capital and the nature of the wind and solar resources.

Lazard (2017) emphasises the dramatic fall in the cost of large-scale solar PV from an average cost of 359 USD/*MWh* in 2009 to 50 USD/*MWh* in 2017, an 86% decline. This is half the cost of coal generation (102 USD/*MWh*). The cost of solar PV is far cheaper in some solar-rich countries. Contracts have been written at around 21 USD/*MWh* in Chile and 30 USD/*MWh* in Abu Dhabi (IEA, 2017a).

In the same period the global average LCOE for wind energy has fallen from 135 USD/*MWh* to 45 USD/*MWh*, a drop of 67%. On a global scale wind energy is today the cheapest electric energy. The global average LCOE (November 2017) for the most common energy sources is displayed in Figure 1.2.

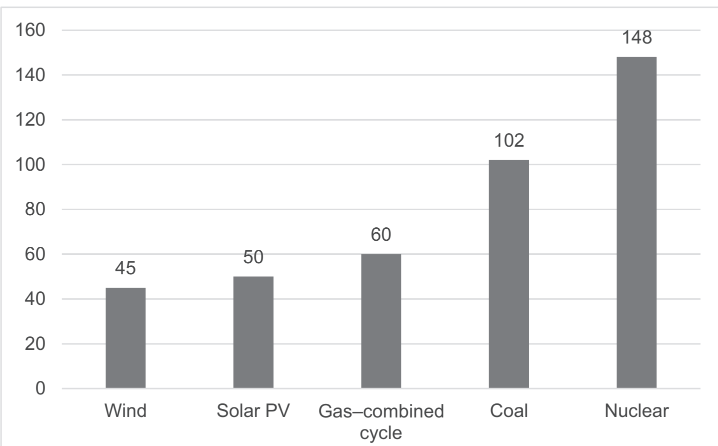

Figure 1.2 Global average of LCOE (USD/*MWh*) values in late 2017. Data source: Lazard (2017).

1.5 CLIMATE CHANGE CONSEQUENCES

A major and critical contribution of renewable energy is its impact on climate change, which is also one of the United Nations Sustainable Development Goals (see Chapter 2). The present global energy system contributes about 60% of all anthropogenic greenhouse gas emissions (IEA, 2017a). In particular, generation of electric power contributes over 40% of combustion-related CO_2 emissions. The carbon footprint varies vastly between different technologies and depends on power plant type, components, fuel types and waste intensity.

The combination of improved energy efficiency and renewable energy can give the world a realistic chance of limiting global warming to 2°C. At the same time, it will reduce air pollution, both locally and globally. This will have profound health effects from the public-health to the individual-household level.

> Replacing fossil fuels with solar PV generation and wind turbines will reduce global CO_2 emissions.

Solar PV generation and wind turbines reduce global CO_2 emissions compared to fossil fuel energy production. The estimates of total global warming emissions depend on several factors. For solar PV it depends on the total solar irradiation and the number of sunshine hours. For wind turbines it depends on the wind speed and percentage of time the wind is blowing. The material composition of the solar cells or the wind turbines also contributes to carbon emissions.

According to NREL (National Renewable Energy Laboratory) (2012a), solar PV will generate around 40 g CO_{2eq}/kWh. Most estimates of wind turbine lifecycle global warming emissions are in the range 9–18 g CO_{2eq}/kWh. As a comparison, estimates of lifecycle global warming emissions for natural-gas-generated electricity are between 270 and 900 g CO_{2eq}/kWh and estimates for coal-generated electricity are 600–1,600 g CO_{2eq}/kWh (IPCC (Intergovernmental Panel on Climate Change), 2011).

1.6 THE NEED FOR COOPERATION

To make clean water accessible it is necessary but not sufficient to engage electrical engineering professionals to supply the electricity.

Water professionals, key customers, financial institutions, health service providers and educators need to be involved and engaged in a collaborative effort.

A system for clean water is built up of many components that must work together and operate reliably. The customer should not need to be an expert in operation or maintenance but should be able to make the basic actions and manoeuvres to run the system. Chapters 4–14 aim to explain processes and systems that can produce clean water and renewable energy so that water professionals and power engineers will understand each other better. Financing is a key condition for success, so we will illustrate some financing approaches in Chapter 12.

1.7 OVERVIEW OF THE BOOK

It is illustrated in Chapter 2 that the development of renewable energy is a key contribution to achieving climate goals. This development can also improve public health in poor regions. Clean water is a key factor, but also air pollution-related health hazards can be limited when solid fuels and kerosene are replaced by solar PV and wind. The UN Sustainable Development Goals (SDGs) all closely depend on access to energy and to water.

The development of renewable energy is nothing less than a revolution and gives for the first time a realistic opportunity to make electricity accessible to all. The main obstacle is not technology but political will, financing and education, as described in Chapter 3.

In Part II (Chapters 4–7) we describe various water treatment technologies for small-scale operations. Pumping, discussed in Chapter 4, is a key operation in almost all water supply and treatment processes. Desalination and membrane technologies are expanding exceptionally fast and present new and realistic possibilities to clean contaminated groundwater or surface water, as illustrated in Chapter 5. In coastal areas seawater can be desalinated at a realistic cost. Most of the developing rural areas lacking electricity today are warm and rich in sunshine. This makes it possible to produce clean water with simple thermal technologies, using no electricity. This option is discussed in Chapter 6 and should be remembered as a complement to the processes supplied by electric power. Treatment of used water can be accomplished with many technologies, and a brief overview is given in Chapter 7.

Part III (Chapters 8–11) describes renewable energy systems. Solar PV has the potential to be the dominating technology in warm and sunny countries, as described in Chapter 8. Wind energy can be an interesting complement to solar PV in many regions, discussed in Chapter 9. Solar cells of course only produce energy during the daytime, but wind and solar together can provide a more reliable source of energy. Still, both solar and wind are intermittent sources of energy; therefore, some storage of energy is needed in order to produce energy when there is no sunlight or wind. This storage challenge is the topic of Chapter 10. Finally, all components in a system producing clean water using renewable energy requires a system that can manage all the units and coordinate the energy flow in the system. This is described in Chapter 11.

Part IV of the book "Applying renewable energy to water operations" (Chapters 12–14) concentrates on "soft" issues. Financing renewables in low-income areas is a crucial issue and may be the biggest obstacle to making clean energy and clean water accessible to all. This is illustrated in Chapter 12. Any electric power system needs a land area and this aspect is described in Chapter 13. A number of cases of water supply and treatment powered by renewable energy are described in Chapter 14.

Part V looks at the future; in Chapter 15 we dare to predict the unpredictable, with a look forward to the year 2030. If you read it in a few years' time it may look amusing.

1.8 FURTHER READING

There is a lot of official material about the water and energy situation in the world. The UN reports UN Water (2014) and UN WWDR (2014) describe the water situation in the world and Olsson (2015) explains the many connections between water and energy.

Access to electric power is described in World Bank (2017) and in IEA (2017a, 2017c). The two reports REN21 (2017a, 2017b) reveal a lot of information about renewable energy. The situation in Africa is particularly emphasised in IRENA (2016b, 2016d).

The books Varadi (2017) and Varadi *et al.* (2018) present excellent information for the non-specialist. The former book tells the story of the remarkable development of solar power systems and the latter shows in detail the consequences of the solar power revolution for countries in Africa and the Middle East.