Chapter 1
Energy and Development

1.1 Introduction

Off-grid electrification refers to providing electricity to an unserved population by a means other than a connection to an existing centralized power grid. This book is concerned in particular with off-grid electrification in the context of so-called developing countries.[1]

Worldwide, 1.1 billion people—approximately one in seven—do not have access to electricity [12]. This form of energy poverty disproportionately afflicts those living in at-risk rural communities in Sub-Saharan Africa[2] (SSA) and South Asia, as shown in Fig. 1.1.

For many, the prime motivation for studying off-grid electrification stems from the idea that access to electricity improves people's lives. While the linkage between electricity access and quality of life surely exits, this perspective misses an important aspect of off-grid electrification: it need not be strictly a humanitarian effort. For-profit companies are increasingly active in this area. For example, over 130 million off-grid solar lighting units have been sold since 2010 with little or no subsidy, and the market for off-grid appliances—TVs, radios, refrigerators and the like designed to operate in off-grid conditions—exceeded US$500 million in 2015 [4, 7]. Even still, a substantial market remains. In 2015, people without electricity spent an estimated US$27 billion on candles, kerosene, and other stopgap fuels that could be replaced by off-grid solutions [10]. Off-grid electrification is a growing industry—over 100 companies are actively involved in electricity-access products and services—and there is a growing need for well-prepared engineers, technicians, managers, and entrepreneurs to support this effort [10].

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[1] See the Preface for a discussion on the definition and usage of this terminology.

[2] Sub-Saharan Africa refers to the 48 African countries south of the Sahara Dessert as defined by the World Bank.

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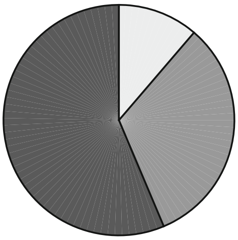

Fig. 1.1 The majority of the world's population without electricity access live in Sub-Saharan Africa (SSA) or South Asia (SA)[11, 15]

Fig. 1.2 A cluster of houses in rural Zambia (courtesy of the author)

Much of this book is dedicated to off-grid electrification in a rural setting like that shown in Fig. 1.2. Although over one hundred million people live in urban areas without electricity access, electrification rates are much lower in rural areas, as shown in Fig. 1.3. Off-grid electrification is associated with rural areas because it is usually economically unfavorable to connect remote, sparsely populated communities to the grid. This is true even in developed countries. While there is no strict definition of a rural community, they tend to exhibit these common characteristics [9]:

- decentralized population;
- geographic isolation;
- underserved in terms of health care, education, clean water, sanitation, and other infrastructure;
- unable to participate in regional and national markets.

Under certain conditions, rural communities can be better served by off-grid solutions, including solar lanterns, solar home systems, and mini-grids (see Fig. 1.4) rather than the national grid. Indeed, some projections estimate that as many as one-in-three people presently without a grid connection will one day be served by some form of off-grid solution.

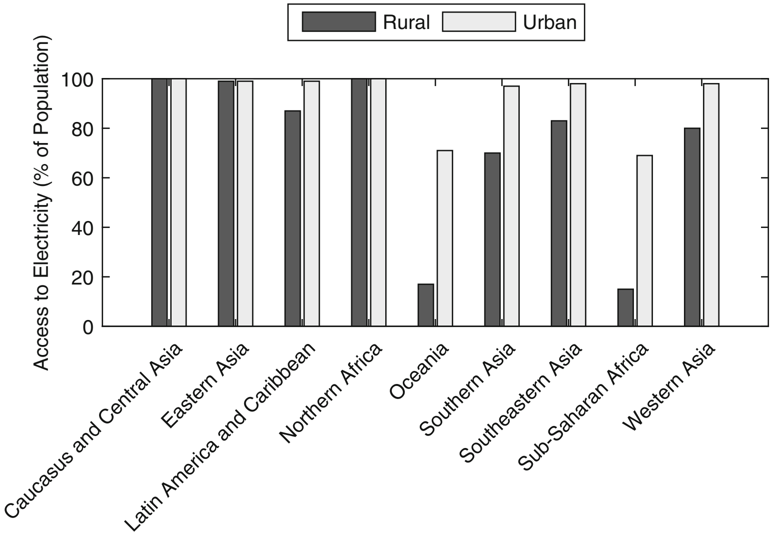

Fig. 1.3 People living in rural communities are less likely to have access to electricity than people in urban areas [11]

Fig. 1.4 Solar-powered mini-grid in Tanzania (courtesy of PowerGen)

This chapter discusses the important linkage between energy use and human development, with a focus on electrical energy. Basic descriptions of the various types of off-grid electrical systems—the primary focus of this book—are given. The chapter concludes with an overview of grid-connected power systems.

1.2 Energy and Human Development

Energy in its many forms underwrites all human endeavors. Our most basic needs—growing and harvesting food, accessing potable water, and transporting goods and people—and our most complex undertakings, from robotics to space exploration, require access to inexpensive and abundant energy sources.

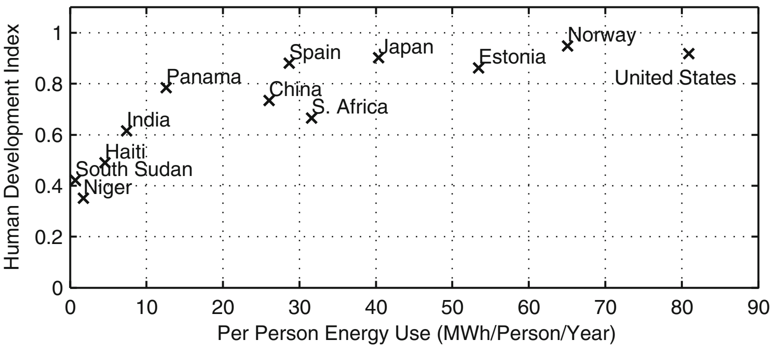

Fig. 1.5 Total primary energy use and the Human Development Index (2014) [15]

Access to energy, of which electricity is an important form, correlates closely with human development. Indeed, universal access to clean and affordable energy by the year 2030 is one of the United Nation's Sustainable Development Goals. This notion is succinctly captured by Fig. 1.5, which plots the Human Development Index (HDI) versus per person energy use[3] for various countries. The HDI is a commonly used metric that attempts to measure the development or well-being of a country, accounting for income, health, and education [13]. Higher HDI scores are associated with more developed countries. Countries with high HDI scores tend to use more energy per person than those with lower HDI scores [1]. However, a saturation effect is apparent: there is little sensitivity of HDI to variation in energy consumption for countries with high HDI scores, but for countries with HDI scores below approximately 0.7, modest increases in energy use are associated with sharp rises in HDI. A similar relationship can be shown for HDI and per person electricity consumption, suggesting that electricity is an enabling and critical infrastructure for high economic, health, and educational attainment.

Electricity provides lighting, which is important for work, study, socializing, and safety. It is supportive of improved health care at hospitals and clinics, and education at schools; it can reduce the toil of manual labor by powering pumps and motors for agriculture and milling; it can support income generation by allowing work to be done more efficiently and extending business hours[4]; and to many people, having electricity brings with it a newfound sense of dignity and modernity. In some countries, for example, Brazil and South Africa, access to electricity has been declared a fundamental right, in recognition of its importance to wellness and prosperity.

[3]Here "energy use" refers to primary energy before transformation to other end-use fuels. For example, it accounts for the energy used as input to a power plant, not just the electrical output of the power plant.

[4]It must be noted that evidence suggests that electricity alone does not necessarily increase productivity, but other factors, for example, access to machinery and education, are also required.

1.3 Units of Energy

It is more common to discuss energy use on an average annual basis rather than daily basis and to exclude the energy in the food people eat and the work animals they might use. The International System unit of energy is the joule (J). A joule is a derived unit, which is defined as

$$1\ \mathrm{J} = 1\ \mathrm{N\ m} = \mathrm{Pa\ m}^3 = 1\frac{\mathrm{kg\ m}^2}{\mathrm{s}} \tag{1.1}$$

where N is the unit for force (newton) and Pa is the unit for pressure (pascal). Energy can also be defined with respect to electrical quantities as

$$1\ \mathrm{J} = 1\ \mathrm{W\ s} \tag{1.2}$$

where W is the unit watt. It is not uncommon in popular media to confuse energy and power. The difference is extremely important in electrical systems. Power, expressed in watts, describes the rate in which energy is supplied or consumed. More generally

$$P = \frac{\mathrm{d}E}{\mathrm{d}t} \tag{1.3}$$

where P is power, E is energy, and t is time. The relationship between power and energy is analogous to the relationship between speed and distance.

Example 1.1 A small generator linearly increases its power output from zero watts to 100 watts over a 10-min period. Compute the total energy output by the generator during this period.

Solution Equation (1.3) can be rearranged to solve for the energy output, noting that there are 600 s in 10 min:

$$E = \int P(t)\mathrm{d}t = \int \frac{100}{600} t\,\mathrm{d}t.$$

This yields

$$E = \int_0^{600} \frac{100}{600} t\,\mathrm{d}t = \frac{1}{6}\frac{t^2}{2}\bigg|_0^{600} = 30,000\ \mathrm{J}.$$

Depending on the context and scale considered, different units of energy are in common use. For example, electrical engineers often use units based on the watthour, whereas mechanical engineers might favor BTUs (British Thermal Unit) or joules. Economists or those describing energy characteristics of an entire country

Table 1.1 Conversion of energy units

Unit	Joules
Joule (J)	1
Calorie (cal)	4.1868
British Thermal Unit (BTU)	1055.87
Watthour (Wh)	3600
Kilocalorie (C, kcal)	4186.8
Kilowatthour (kWh)	3.6×10^6
Kilogram of oil equivalent (koe)	41.868×10^6
Megawatthour (MWh)	3.6×10^9
Tonne of oil equivalent (toe)	41.868×10^9
Quad (quad)	1055.87×10^{15}
Gigajoule (GJ)	1×10^9
Terawatthour (TWh)	3.6×10^{15}

might favor tonne[5] of oil equivalent (toe) or quad (quadrillion BTU). Several of these are defined with reference to the joule in Table 1.1. For context, the average house in the United States consumes 30 kWh (108 MJ) of electricity each day, an automotive battery can supply approximately 0.5 kWh (1.8 MJ), and a typical LED bulb consumes 0.009 kWh (0.0324 MJ) over the course of 1 h. We will most often use gigajoules to refer to energy in general and kilowatthours to refer to electrical energy in particular.

Example 1.2 The 2013 average annual per person energy consumption in Zambia was 26.6 GJ. Compute the average daily consumption in kilowatthours per day and kilocalories per day.

Solution Consumption of 26.6 GJ per year translates into $\frac{26.6\ \text{GJ/yr}}{365\ \text{days/yr}} = 72.87\ \text{MJ/day}$. Converting to kilowatthours:

$$\frac{72.87\ \text{MJ}}{1\ \text{day}} \times \frac{1\ \text{kWh}}{3.6\ \text{MJ}} = 20.24\ \text{kWh/day}$$

and to kilocalories

$$\frac{72.87\ \text{MJ}}{1\ \text{day}} \times \frac{1\ \text{kcal}}{4.1868 \times 10^{-3}\ \text{MJ}} = 17{,}406\ \text{kcal/day}$$

which is less than half of the world average.

[5] Here "tonne" refers to a metric ton, equal to 1000 kg.

1.4 World Energy System

The global energy system is a complex network of energy sources, bulk transportation, storage, distribution, and end use. The energy system is constantly evolving to meet growing demand and responding to economic, social, and environmental constraints. The existing world energy system does not adequately meet the needs of all people, nor is it sustainable in the long-term. Forty percent of the world lives in energy poverty. Greater innovation in technology, business models, and policy is needed by engineers, scientists, business managers, and government administrators across several decades to transform the energy system into one that provides sustainable energy for all.

1.4.1 Human Energy Use Throughout History

Human beings require approximately 2.8 kWh (2400 kcal) in the form of food each day to be able to function and do work. However, of this only about 500 Wh is available for motor function. The rest is used for resting metabolic function, including regulating our temperature, and digestion. A life restricted to this amount of energy was quite limiting and uncomfortable. It was the reality for humans until approximately 400,000 years ago when people began using fire [14].

Fire liberated energy stored in plant matter, and so its use increased our energy consumption. Along with this increased consumption came improvements in our lives: food could be cooked, broadening our diet and reducing spoilage, warmth was provided, evening lighting provided heat and some protection from predators, and basic tools could be made.

Agriculture was developed approximately 10,000 years ago and animal domestication began. The use of animal power for agricultural and travel increased our energy consumption further. Although small amounts of coal were used for heating during the middle ages, its consumption soared during the Industrial Revolution. The Industrial Revolution, ushered in part by the invention of the steam engine in the 1700s, began a rapid increase in mankind's energy consumption. By 1860, the average daily consumption of non-food and work animal energy was 2.4 kWh, nearly equal to the energy consumed in the form of food.

Electricity access, beginning in the late 1800s, provided an even more convenient form of energy which could be used for safe, high-quality lighting and to power motors which drove the industrial base. The automobile and airplane further spurred energy consumption. Nearly 20% of our energy is now devoted to transportation. By 1950, the average daily inanimate energy consumption was 20.9 kWh (18,000 kcal).

In more recent times, the daily energy consumption rose from 42.5 kWh (36,540 kcal) in 1971 to 61.4 kWh (52,790 kcal) in 2014. Whereas our ancestors consumed 2.8 kWh in food a day, we now average 22 times this amount in non-food energy consumption. The story of mankind's energy appetite is one of continued growth as our population increases and as we employ greater amounts of energy to improve our quality of life.

1.4.2 Total Energy Consumption

Figure 1.6 shows that the per person consumption of energy has been increasing over the last several decades. The trend, however, is not universal. Several countries with developed economies have seen a stabilization or even a decline of per person consumption. Germany, for example, uses the same annual per person energy (159 GJ) today as it did in 1970, as shown in Fig. 1.7. More astonishingly, the link between energy use and standard of living has been at least weakened as some countries are able grow their economies while using less energy. This is largely due to increases in efficiency associated with energy production, distribution, and end use.

However, these reductions in per person consumption are offset globally by rapidly increasing consumption, primarily in China, India, and developing countries. Another important factor is population growth, which compounds the increase in per person consumption. The global population grew by 1.5% per year from 1980 to 2014, increasing the population 66% from 4.4 billion to 7.3 billion. Over this same period, the total energy consumed each year increased 93%, from 282 quad to 545 quad.

Presently, over 80% of the worldwide energy is supplied by fossil fuels, which are depletable and whose carbon dioxide emissions contribute to global warming. Fossil-fuel resources tend to be concentrated in certain regions. Countries without

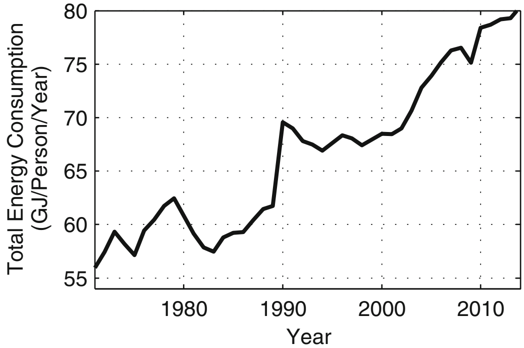

Fig. 1.6 Worldwide per person total energy consumption has increased rapidly since the 1970s [15]

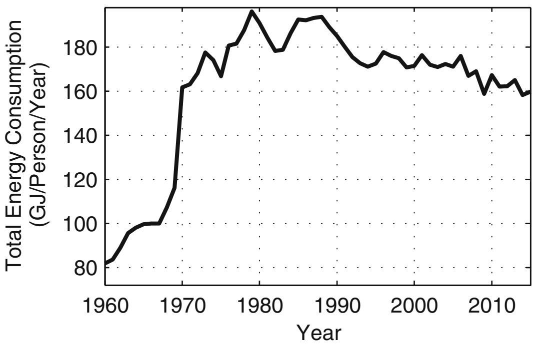

Fig. 1.7 Per person total energy consumption in Germany has started to decline [15]

natural supplies of fossil fuels must import energy. This can pose energy supply challenges in developing countries with weak currencies, poor credit, and without adequate infrastructure such as ports, pipelines, and railways.

1.4.3 Energy Inequality

Throughout history global per person consumption of energy has trended upward, with the world average annual energy consumption reaching approximately 80 GJ per person per year in 2014. However, there is vast inequality in energy consumption. Per person consumption is higher in developed countries, particularly in those whose climate necessitates use of space heating and air conditioning. The per person consumption in Canada, for example, is 318 GJ. On the other hand, the African continent—with a population of nearly 1 billion—consumed less than 4 % of the world's total energy in 2012. The average annual per person consumption in Sub-Saharan Africa is just 29 GJ.

Referring back to Fig. 1.5, it has been noted that no country with an HDI above 0.7—a reasonable target for a comfortable standard of living—has a per person consumption below 33.5 GJ (9.35 MWh). This suggests that, given the average consumption of 80 GJ per person, the present energy supply is sufficient to achieve a universal comfortable standard of living and that the problem is in the equitable distribution of energy.

1.4.4 Electricity Supply and End Use

Electricity is a convenient form of energy because it is easy to distribute with minimal losses. Electricity is versatile. It powers everything from motors, heaters, and chemical reactions to computers. The worldwide gross electricity production in 2014 was 23,815 TWh. Electricity is generated from power plants using a variety of input fuels, as summarized in Fig. 1.8.

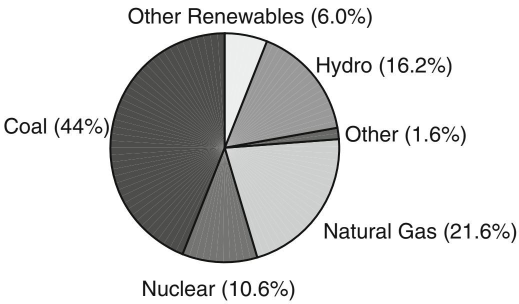

Fig. 1.8 Electricity generation by fuel source

The general reliance on fossil fuels in the electric power sector leads to a question of the environmental impact, namely, carbon dioxide emissions, of increasing electrification rates and consumption in developing countries. Under reasonable scenarios, the impact of increasing access to electricity on global carbon dioxide emissions is marginal, less than 1%, as shown in the following example:

Example 1.3 The global carbon dioxide emissions due to human activity in 2012 were 35 billion tonnes, approximately 40% of which were related to the electric power sector. The total electricity consumption in 2012 was 23,815 TWh. If the 1.1 billion people presently without electricity access were given a grid connection and each consumed a modest 100 kWh per year, what is the percent increase in global carbon dioxide emissions? Assume the electricity supplied produced the same amount of carbon dioxide per unit energy as the global average.

Solution Using the global average, the amount of carbon dioxide emitted for every terawatthour of consumption is

$$\frac{0.40 \times 35 \text{ billion tonnes}}{23,815 \text{ TWh}} = 587,865 \text{ tonnes/TWh}$$

The annual consumption of electricity would increase by

$$1.1 \text{ billion} \times 100 \text{ kWh} = 110 \text{ TWh}$$

so that the total carbon dioxide emissions rise by 64.7 million tonnes. This only represents a 0.18% increase in global carbon dioxide emissions. Note that this does not count the reduction in carbon dioxide emissions associated with the *reduction* of kerosene and biomass usually associated with access to electricity.

As with total energy, per person consumption of electricity has rapidly increased, as shown in Fig. 1.9. In countries like the United States, the more recent trend of per person electricity consumption has been stagnant—having peaked in 2005 with 2015 levels similar to 1995. Improvements in energy efficiency and the transition from energy-intensive industries such as manufacturing to information, finance, and service industries are likely causes. Keep in mind that some of this decrease is really a just a displacement to other regions. In other countries, notably China and India, the per person electricity consumption has gone up rapidly, increasing by a factor of seven since 1971, as shown in Fig. 1.10. Because these countries have large population bases—over 2.5 billion people total—their total consumption of electricity has dramatically increased.

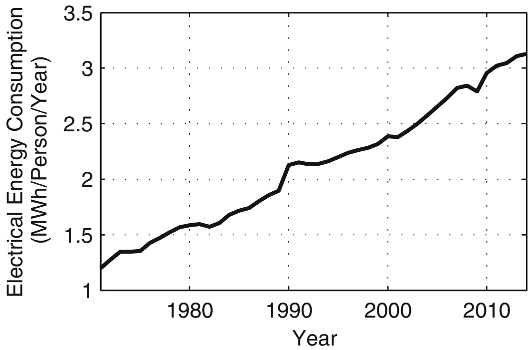

Fig. 1.9 Trend in worldwide per person electricity use. Note the dip in 2008, corresponding to an economic downturn, highlighting the linkage between electricity use and economic activity

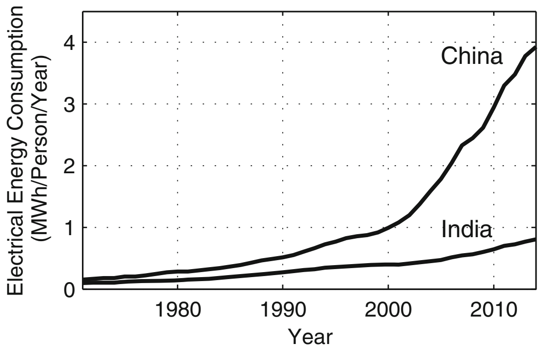

Fig. 1.10 Trend in per person electricity use in China and India [15]

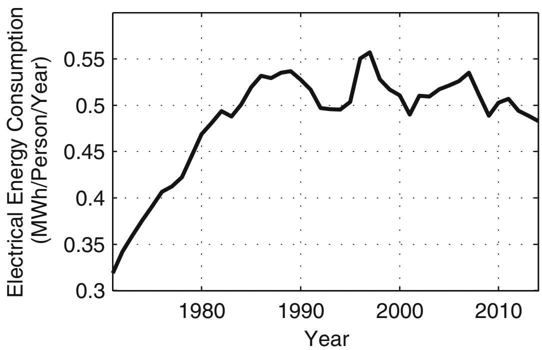

Fig. 1.11 Trend in per person electricity use in Sub-Saharan Africa [15]

In Sub-Saharan Africa, the story is different. Incredibly, in Sub-Saharan Africa as a whole, a region of 1 billion people, the per person consumption has recently regressed to its level in the 1980s, as shown in Fig. 1.11. This is largely attributed to a rapidly expanding population base without a similar expansion of electrical infrastructure. Consumption per person, therefore, went down.

1.5 Electrification Approaches

One significant factor affecting per person energy consumption is access to electricity. There are two general approaches to providing access to electricity: on-grid and off-grid. On-grid electrification refers to the provision of electricity through a connection to a large centralized grid. In most countries, there is a single interconnected grid, which is also referred to as the "national grid."

In rural areas, connection to the national grid usually requires the construction of infrastructure such as power lines, transformers, and substations; in urban areas, it might only require establishing a low-voltage connection and modest infrastructure enhancements.

Off-grid electricity access to can be provided in several ways [8]. The terminology used in practice is not strict, and in some cases the characteristics are not sharply defined. The following is a basic description of the off-grid approaches to electricity access.

1.5.1 Solar Lanterns

Solar lanterns (see Fig. 1.12), also known as "pico solar," are designed to provide lighting and perhaps USB charging of devices such as mobile phones. They rely on photovoltaic (PV) cells to generate electricity. Solar lanterns have peak PV capacity of less than 10 W—with many solar lanterns sized at less than 1 W. They typically contain a battery using lithium-ion or lead-acid chemistry. In most solar lanterns, the PV cells and battery are integrated into the lantern, rather than being separate components. Solar lanterns are designed to be portable and low-cost, typically US$5 to US$20. They provide very minimal but still quite useful electrical power to a home or someone in a remote location.

Fig. 1.12 A solar lantern includes a small solar panel and LED light (courtesy of d.Light)

Fig. 1.13 Solar home systems are often capable of powering several LED lights and small appliances (courtesy of BBOXX Ltd.)

Fig. 1.14 A solar-powered energy kiosk in Zambia (courtesy of KiloWatts for Humanity)

1.5.2 Solar Home Systems

Solar home systems (see Fig. 1.13) refers to products with PV modules rated between 10 to 350 W. The battery is in a ruggedized case, often supporting several LED lights and USB ports. Some can power televisions and fans. These are not portable devices. They are installed in a semipermanent fashion.

1.5.3 Energy Kiosks

Energy kiosks (see Fig. 1.14) provide centralized access to electricity to a community [6]. They use a "walk-up" retail model of electricity access, rather than direct wired connections to households. Community members can have batteries

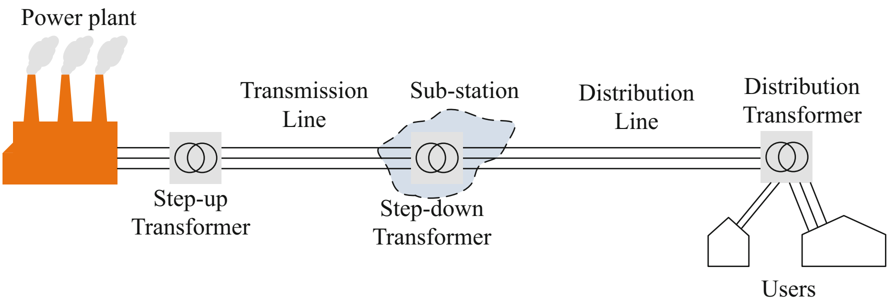

Fig. 1.15 Traditional flow of power in a national grid

recharged at the kiosk, and some kiosks provide services for higher-powered appliances such as refrigeration. Energy kiosks typically have higher power output capacities than solar home systems. The electrical system is often housed in a small building and requires on-site staff to interact with customers.

1.5.4 Micro-Grids and Mini-Grids

Micro- and mini-grids generally refer to stand-alone electrical systems that serve multiple customers through wired connections. They can be powered by multiple sources such as PV modules, fossil-fueled generators, and wind turbines. There is no strict distinction between a "micro-grid" and a "mini-grid." However, a micro-grid has the connotation that it is smaller in peak power rating than a mini-grid. Hereafter, we shall use the term "mini-grid" for the sake of clarity. We shall consider mini-grids whose peak power rating is less than 1 MW. While this serves as an upper limit, most mini-grid systems are in the 1 to 10 kW range.

1.5.5 National Grid Electrification

Although this book focuses on off-grid systems, we will briefly discuss how larger national grids are configured. This will equip us with the background needed to understand the role of off-grid solutions in the larger electrification context.

Providing access to electricity is more complex than simply running a wire to a house or factory. The interconnected electric power system is one of the most complex creations ever engineered by mankind. Figure 1.15 shows the traditional flow of power in a national grid.

Electric power systems can be separated into three subsystems: generation, transmission, and distribution. Electricity is generated by power plants fueled by sources such as coal, nuclear, natural gas, hydro, wind, and solar. The bulk of the energy generated occurs at large power plants often with capacities exceeding 1000 MW. More recently, distributed generation—small-scale power plants that are located near or in cities and neighborhoods—has become popular and may supplement generation from large power plants. Rooftop solar power is one example of distributed generation. In order to reliably supply power, it is necessary for a country to have enough generation capacity to serve the maximum anticipated simultaneous load. Otherwise, the country will be forced to import power, often at high prices, in order to avoid a complete or partial blackout. In many developing countries, there routinely is insufficient generation capacity to meet the demand, and short- or long-term blackouts are common.

Most power plants produce electricity using three-phase generators at a frequency of either 50 Hz or 60 Hz, depending on national standards. The voltage at which the generators output the electricity, typically 10 kV to 30 kV, is too low for efficient transmission across long distances. Transformers are used to increase the voltage and thus decrease the losses for long-distance transmission.

Transmission voltages typically range between 110 kV and 750 kV. Transmission lines often run hundreds of kilometers atop metal lattice or guyed wooden or composite poles. Reliable national grids have meshed networks, meaning there are several parallel transmission paths between the power plants and the load. They are also interconnected, allowing neighboring countries or regions to share generation resources.

Once the transmission lines reach their destination—typically an industrial or population center—the voltages are reduced at a substation. Transformers step down the voltage to the local distribution lines. Typical distribution voltage levels are 11 kV, 22 kV, and 33 kV. These lower voltages are safer and require less clearance than transmission lines and so are more suitable to populated areas. Transformers located near customers again step the voltage down to levels that are safe for consumption, typically 120 or 230 V. Due to losses, the power can only be transmitted a short distance at this low-voltage level.

Increasing electrification rates often requires investment not only in power lines and connections but also power plants and other equipment that keep the grid operating. In the context of rural electrification, the following must be kept in mind:

- higher voltages are required for efficient transmission;
- transmission and distribution lines are expensive to construct;
- energy supplied by the grid is nearly always less expensive than from mini- or micro-grids.

Additional information on power systems design and analysis can be found in the numerous textbooks on the subject [2, 3, 5]. Finally, we note that even in countries with expansive national grids, there may be some portions of the population without access, even in the United States, as shown in Fig. 1.16.

Fig. 1.16 An off-grid system in the Navajo Reservation in the United States (courtesy D. Terry, Navajo Tribal Utility Authority)

1.6 Summary

This chapter established the motivation for the study of off-grid electrification. Access to electricity is a widely recognized humanitarian challenge; more recently, it is being viewed as an emerging market for commercial enterprise. Energy consumption is closely tied to human development and has increased on a per person and absolute basis. Worldwide average energy consumption stands at 80 GJ per person per year, but there is wide variation between countries. Developing countries use substantially less total energy and electrical energy than developed countries. Electricity access can be increased through connection to the national grid, or by off-grid solutions, including solar lanterns, solar home systems, energy kiosks, and mini-grids.

Problems

1.1 Place the following quantities of energy in order from highest energy content to lowest: 1 Calorie, 1 BTU, 1 MWh, 100 kWh, 5000 J, 10,000 calories, 1 toe.

1.2 A hamburger at a popular fast-food restaurant contains 600 kcal. How many of these hamburgers are needed to equal the energy consumption by the average Canadian each day, assuming their average consumption is 318 GJ per year?

1.3 One liter of gasoline contains 34.2 MJ of energy. If humans could drink gasoline to satisfy our daily caloric need of 2400 kcal, how many days could a human survive on one liter of gasoline? Assume the cost of gasoline is US$1 per liter. What is the daily cost of such a diet?

1.4 Assume that a kilowatthour from an outlet costs US$0.15. If humans could consume electricity to satisfy our daily caloric need of 2400 kcal, what would be the cost of such a diet?

1.5 Research three companies that manufacture or distribute either solar lanterns or solar home systems. Select a product from each company and describe its features and rating of the PV module (in watts) and battery (in amp-hours or watthours).

1.6 The power produced by a PV module with a 200 W rating on a certain day is described by the equation:

$$P(t) = \begin{cases} P_{\text{PV}} \frac{900}{1000} \cos\left(\frac{t\pi}{12} - \pi\right) & : 6 < t < 18 \\ 0 & : \text{else} \end{cases}$$

where P_{PV} is the rating of the module and t is in hours. Compute the energy produced by the PV module, in kilowatthours, on this day.

1.7 A certain off-grid system is supplied by a diesel generator set. The generator produces a constant 1 kW of power. How many 200 W PV panels are needed to replace the energy supplied by the generator, if the power output by each panel is described by the equation in the previous problem?

1.8 Compute and compare the total electricity consumption of Sub-Saharan Africa to the United States in 2012. The population of Sub-Saharan Africa was 926 million, and the United States was 314 million. The per person consumption in the United States in 2012 was 12.96 MWh per year. Consult Fig. 1.11 for the per person consumption in Sub-Saharan Africa.

1.9 A proposed mathematical model estimating HDI based on per person energy consumption is

$$H\hat{D}I = 0.1185 + 0.1412 \ln(E)$$

where E is the total primary energy demand per person measured in gigajoules. Plot this function and compute the percent error for the following countries: United States (HDI: 0.912, Energy: 289 GJ/person), Gabon (HDI: 0.697, Energy: 60.1 GJ/person), Niger (HDI: 0.380, Energy: 6.36 GJ/person), Thailand (0.743 Energy: 83.0 GJ/person).

1.10 Compute and plot the derivative of the HDI model presented in the previous problem, and describe what it suggests in terms of the relationship between HDI and per person energy consumption.

1.11 In 2015, the United Nations set 17 Sustainable Development Goals to be achieved by the year 2030. Research and select three of these goals (other than Number 7), and describe the role of electricity access in achieving them.

References

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