Chapter 2
Energy Poverty

2.1 Introduction

Energy poverty is *the lack of access to modern fuels*. It is estimated that 2.9 billion people, approximately 40 % of the world's population, are energy-impoverished in some way [28]. Energy poverty is associated with economic poverty, and people living in rural areas are more likely to be energy-impoverished than those in urban areas.

The energy-impoverished rely on solid fuels such as fuel wood, animal dung, and crop residue, rather than more convenient fuel sources such as electricity, natural gas, or liquefied petroleum gas (LPG). The energy-impoverished tend to:

- consume low amounts of energy overall;
- rely on human and animal power for mechanical tasks;
- devote considerable time to procuring and processing fuel;
- spend a relatively large portion of their income on fuel.

Energy poverty detracts from income, educational attainment, and health, and so it impedes human development. Energy poverty is also seen as a gender issue. Women tend to disproportionately bear the burden of fuel collection and are more exposed to the health and safety risks associated with energy poverty. One approach to combating energy poverty is to implement local mini-grids that do not require connection to the national grid.

An off-grid electrical system that is successful and appropriate requires careful, holistic consideration of the energy resources and constraints of the community it serves. As such, it is important to understand how off-grid communities presently meet their energy needs: how much energy is used, from what sources, and what are the advantages and challenges of the status quo? This chapter presents this information, with particular attention to electricity use in energy-impoverished communities and how electricity access is quantified.

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2.2 Rural Community Energy Needs

Although this book focuses on off-grid electricity access, it is important to understand the complete energy needs and characteristics of off-grid communities. Since the majority of those without electricity access live in rural areas, we focus in particular on these communities.

The energy needs of a rural community can be divided into three categories [20]:

1. Energy for households
2. Energy for community services
3. Energy for productive uses

Each of these categories has different technical and economic requirements, and each provides different benefits.

2.2.1 Energy Use of Households

Household (domestic) consumption constitutes the majority of the energy used in rural areas. The energy is primarily used for cooking, water heating, and spacing heating, with the balance used for lighting and powering electronic devices and appliances such as mobile phones, radios, and in some cases fans and televisions. Rural households tend to rely on several fuel sources: fuel wood, charcoal, crop residue, animal dung, kerosene, candles, batteries, and in some cases small diesel- or petrol-powered generator sets and solar-powered systems. The per-person annual energy consumption for domestic purposes is often between 5 and 15 GJ per year [1, 3, 9, 15, 24]. However, consumption above this range does occur. For example, consumption of 50 GJ per person per year is not uncommon in colder climates. Even still, this is far below the global average of 80 GJ.

2.2.2 Energy Use of Community Services

Community services include schools (see Fig. 2.1), medical facilities (Fig. 2.2), churches, and community centers, among others. The typical energy uses in these facilities are lighting, ITC (Internet, telecommunications, computers), health-care equipment (refrigeration for medicine and vaccines, suction machines, diagnostic equipment), and clean and hot water. In addition, street or pathway lighting is desirable for protection against crime, wildlife, and tripping hazards. This can increase school attendance, especially for girls, as their commute to and from school is less dangerous [25].

Electricity is required for effective community services. In addition to direct benefits, electricity access helps health-care facilities and teachers attract and retain

Fig. 2.1 A government primary school in Zambia (courtesy of author)

Fig. 2.2 A rural health post in Malawi (courtesy of author)

qualified workers. The importance of this should not be overlooked [10]. Studies in Ghana, for example, have shown that 85% of teachers cited "lack of access to potable (drinkable) water and electricity" for the reason they turned down positions in rural areas [26].

2.2.2.1 Health-Care Facilities

Electricity access at health-care facilities is critical. Over 1 billion people do not have adequate access to health services due to energy poverty. The typical electricity requirements of health-care facilities are listed in Table 2.1. Health-care facilities have special electrical requirements. The electricity must be reliable, vaccines must

Table 2.1 Health facility energy use in rural areas [13]

Type	Energy (kWh/day)	Peak power (kW)
Hospital (>120 beds)	15–35	9
Health center (60–120 beds)	10–20	5
Health clinic (<60 beds)	4–10	2.4
Health post (intermittent use and storage)	0	0

be kept at tightly regulated temperatures, and of high quality—voltage spikes can damage sensitive medical equipment, which often cannot be easily or expeditiously repaired or replaced. As a result, medical clinics connected to the national grid often require backup generator sets or Uninterruptible Power Supplies (UPS). A UPS is a battery-based backup electricity source.

2.2.2.2 Education Facilities

Four out of five schools in Africa lack access to electricity [29]. Over 200 million children attend a school that has no electricity [26]. These schools are unable to make use of enhanced teaching technologies such as projectors, radios, computers, printers, digital cameras, and the Internet. Instruction times are limited to daylight hours. Electricity access in schools generally reduces absenteeism and increases enrollment, graduation rates, and test scores [17, 26]. However, these results are not universal. Some studies have found decreased educational performance when electricity is also available at home, as children watched television instead of completing homework and stayed awake later in the evening, decreasing their ability to concentrate in school [6, 26]. Others have noted that the increased economic opportunities in communities with electricity access may result in children joining the workforce at an early age.

The electricity requirements vary with the level of services provided and size of the school. This can range from less than 1 kWh per day for basic lighting of small schools to much more than 10 kWh per day if computer labs and other enhanced teaching technologies are used.

2.2.3 Energy Use for Productivity

Productive uses of energy typically refer to income-generating activities. These are often related to agriculture in the rural context. Typical uses include land preparation and cultivation, irrigation pumping, harvesting, milling of grain and other

agricultural processing, brick and charcoal manufacturing, and small appliances such as shavers for barbershops and televisions for video halls. Solid and liquid (petroleum for generation sets) fuels and electricity are important in increasing or expanding productivity. The electricity requirements vary but often exceed those of households and social service facilities. The power of an irrigation pump depends on the pump type, the vertical distance pumped, and the flow rate. For example, a submersible pump lifting water 65 m and at a flow rate of 2.1 m^3/h requires approximately 1.2 kW. Solar pumping systems commonly range from less than 1 kilowatt peak to perhaps 10 kW. Hammer mills, used for processing maize, are rated from several kilowatts to perhaps 20 kW.

2.3 Fuel Choice

A variety of sources can be used to meet the needs of a rural community. The spectrum of fuels includes:

- Electricity
- Liquid Petroleum Gas (LPG)
- Kerosene
- Charcoal
- Fuel wood
- Animal dung and crop residue

This list can be further subdivided. Electricity can be provided from the national grid, mini-grid, energy kiosks, solar lanterns, solar home systems, and disposable batteries. LPG can be expanded to include natural gas (methane) in addition to propane and butane. We will focus our discussion of fuel choice to households, as energy use in households is better defined than in social institutions and industry.

2.3.1 Energy Content

The energy content by fuel source, in megajoules (1×10^6 J), is listed in Table 2.2. There is wide variability in the specific energy (energy per unit mass) of biomass fuels (wood, charcoal, dung, and straw) depending on moisture and ash content, so the values provided for these sources are not exact. Unprocessed biomass fuels such as green (freshly cut) wood tend to have low specific energy due to the added moisture.

Table 2.2 Energy content by fuel source [4]

Fuel	Unit	MJ/Unit
Charcoal	kg	30.8
Dung	kg	14.5
Electricity	kWh	3.6
Kerosene	liter	35.0
LPG (Gas)	kg	45.0
Wood (Dry)	kg	16.0
Straw	kg	13.5

Example 2.1 A household uses 100 GJ of fuel wood, 10 GJ of kerosene, and 10 GJ of LPG each year. Compute the quantity, in kilograms, of fuel wood and LPG, and the quantity, in liters, of kerosene required each year.

Solution Using the values in Table 2.2, the quantities of each fuel source are

$$\text{Fuel wood} = \frac{100\ \text{GJ}}{0.016\ \text{GJ/kg}} = 6250.00\ \text{kg}$$

$$\text{Kerosene} = \frac{10\ \text{GJ}}{0.035\ \text{GJ/liter}} = 285.71\ \text{liter}$$

$$\text{LPG} = \frac{10\ \text{GJ}}{0.045\ \text{GJ/kg}} = 222.22\ \text{kg}.$$

2.3.2 *Fuel Attributes*

Three attributes influence a household's decision to use a particular fuel [23]:

- Quality
- Convenience
- Cost

The desirable characteristics of these attributes are summarized in Table 2.3. Electricity is considered a desirable fuel source. It can be used in a variety of high-efficiency appliances. It is consistent, is easy to control, and has zero local emissions. It is therefore a high-quality energy source. If an electrical connection exists, electricity is extremely convenient, provided the connection is reliable. Electricity can be low cost, especially if it is subsidized; however, appliances must be purchased, which discourages its use. Note that a fuel that is desirable in one context might not be in another.

Table 2.3 Fuel source attributes

Attribute	Desirable characteristics
Quality	High efficiency, controllable output, consistent performance, low or zero emissions
Convenience	Delivered to home or locally-available, reliable supply, little or no processing, familiar/easy to use, versatile, safe, does not require storage
Cost	Low cost of fuel, low cost of equipment

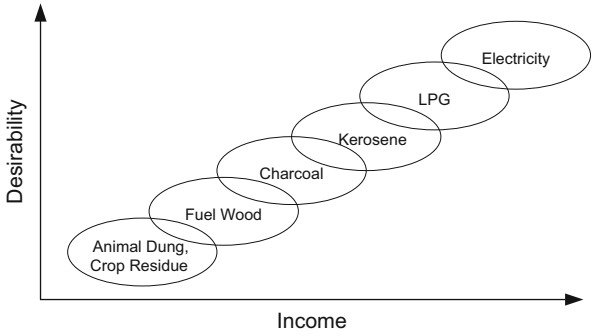


Fig. 2.3 The energy ladder shows the transition from fuel sources with low desirability to those with high desirability as income increases. The overlap represents the simultaneous use of multiple fuels

2.3.3 Energy Ladder

The different fuel sources can be arranged from least desirable to most desirable as seen in Fig. 2.3. Households tend to transition from least desirable fuels to more desirable fuels as their income increases. This concept was first articulated in the 1980s and is known as the "energy ladder"[19]. It remains an important starting point in understanding the dynamics of fuel transition.

The notion that a household "climbs the energy ladder," transitioning from one fuel source to the next as income increases, is somewhat simplistic. Many other factors, particularly local conditions, influence the transition. These include in particular access to the fuel, the cost of the equipment to use the fuel—such as burners and appliances—and the "lumpiness" of the fuel payments. A fuel with a lumpy payment is one whose minimum purchasable amount is relatively large, requiring a sizable up-front payment. LPG, whose minimum canister size might be 2 to 5 kg, is one example. Even if this bulk-buying behavior results in a substantial reduction in energy costs in the long-term, vulnerable households with variable income often prefer purchasing fuels available in smaller minimum quantities, such as fuel wood and kerosene. Other factors that tend to influence fuel transition are wealth, income, and educational attainment.

Most often, lower-quality fuels are usually not completely abandoned as income increases [23]. Lower-quality fuels might be used for cultural reasons and to guard against price increases or shortages of other fuels. Thus, households might climb or descend the energy ladder and will simultaneously span more than one rung.

In general, as household income increases, so does total energy consumption. However, the increase is not proportional. For example, increasing income by a factor of ten might only increase the household energy consumption by 25%. This is in part due to smaller household sizes associated with higher income but also the greater efficiency that can be obtained from higher-quality fuels and appliances.

2.3.4 *Fuel Stacking*

The use of several fuels is referred to as "fuel stacking" and is an important characteristic of rural household energy use. Fuel stacking adds flexibility and robustness to the fuel supply, as households can switch between sources based on a fuel's availability and price. A household in an urban city on the other hand might be solely reliant on electricity. This adds vulnerability to their fuel supply should a blackout occur.

The annual household energy use by fuel source in several different locations is shown in Fig. 2.4. Different locations use different fuel stacks (also known as "energy matrices"), even within the same country. The types of fuel used and their quantity depend on the local conditions. The annual household consumption ranges between approximately 70 and 130 GJ per household per year for these locations. This generally agrees with an estimate of between 5 and 15 GJ per person per year, given that rural households tend to be large, for example, between 5 and 15 people.

2.3.5 *Fuel Expenditure*

The amount of money spent on each fuel source also varies within and across countries based on local fuel prices, climate, household size, and income. Figure 2.5 shows the average annual household fuel expenditure in several villages across

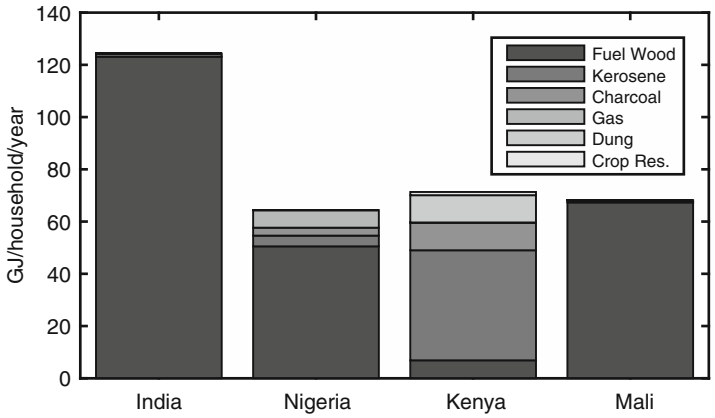


Fig. 2.4 Rural household energy use by fuel type, compiled from various sources [1, 3, 15, 24]

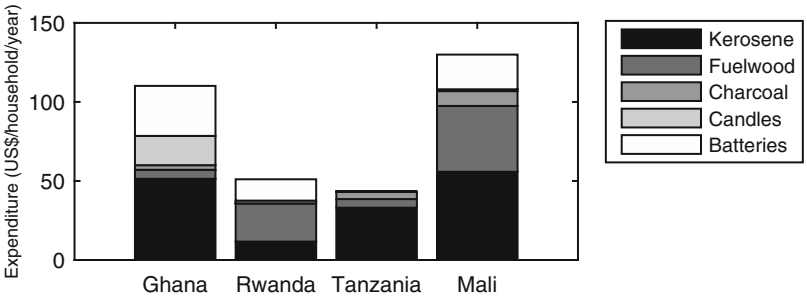


Fig. 2.5 Annual energy expenditure by fuel source for households in villages in Ghana, Rwanda, Tanzania and Mali. Adapted from [2]

Africa. Money spent on grid-connected electricity, which only a small number of households had access to, are omitted. There is a wide range in household expenditure, from approximately US$40 to US$140 per year, with some variation in the fuels used. A considerable portion of income is spent on fuels primarily used for lighting—kerosene and batteries.

The cost of fuel is a contributing factor to energy poverty. A desirable goal is that fuel expenses should be no more than 5 to 10% of a household's income [8, 12]. In some households, however, it exceeds 30%. This limits the resources available to purchase food, medicine, agriculture inputs and pay school tuition.

Example 2.2 Compute the annual fuel expenditure of the household in the previous example. Assume the cost of fuel wood is US$0.05 per kilogram, kerosene is US$1.10/liter, and LPG is US$1.60/kg. What must the household's annual income be so that no more than 10% of their income is spent on fuel?

Solution Using the values in Table 2.2, the expenditure on each fuel is:

$$\text{Fuel wood} = 6250 \times 0.05 = \text{US\$312.50}$$

$$\text{Kerosene} = 285.71 \times 1.10 = \text{US\$314.28}$$

$$\text{LPG} = 222.22 \times 1.60 = \text{US\$355.55}$$

for a total of US$982.33 per year. The household would need to earn more than US$9823.30 per year to spend no more than 10% of their income on fuel. This amount is much greater than the income of most rural households. Descending the energy ladder, by transitioning from LPG to fuel wood and reducing kerosene use, would reduce the energy expenditure.

2.4 Fuel Sources

We now consider the characteristics of the fuel sources commonly used in rural off-grid households. An off-grid system would be designed to supplement or replace some or all of these sources.

2.4.1 Fuel Wood

Fuel wood is perhaps the most important fuel in rural areas and often supplies the majority of the energy consumed [21]. It is primarily used for heating spaces and water, as well as cooking as shown in Fig. 2.6.

Fuel wood can be purchased at a low cost or be gathered from trees for free throughout the year. Fuel wood is self-replenishing; however, there is some concern about overharvesting of fuel wood, in particular, to create charcoal. Depending on the household size and location, between 5 and 25 h per week are spent gathering fuel wood. Preparation of the fuel wood, if needed, can add a few additional hours each week. Fuel wood has low specific energy and low energy density, and so large quantities are needed. The typical fuel wood consumption for rural areas ranges from 1 to 5 kilograms per person each day [1, 9, 21]. In colder climates, it can exceed 10 kilograms per person each day. Seasonal variations also influence fuel wood consumption—less wood is consumed during summer months.

Over the course of a year, a typical household will collect several tonnes of fuel wood. Walking more than 5 km to collect wood is common. The burden generally falls upon women and girls, which is cited as one reason why energy poverty disproportionately affects women.

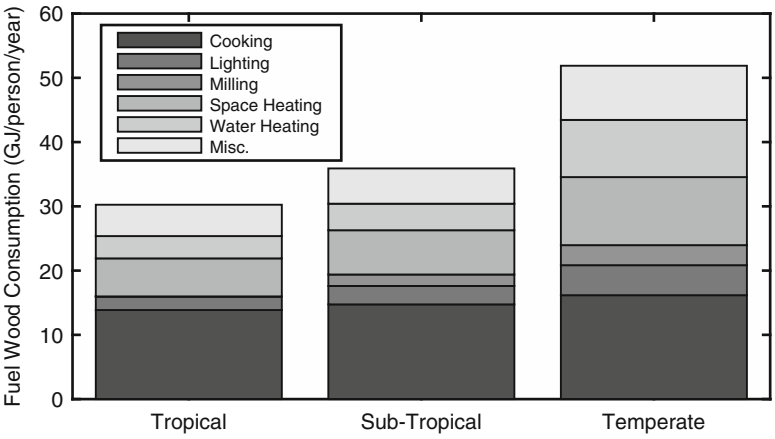


Fig. 2.6 Fuel wood use in rural communities in varying climates [9]

Fig. 2.7 Three-stone cook stoves are widely used in rural Sub-Saharan Africa (courtesy of author)

Table 2.4 Typical cook stove efficiencies [14]

Type	Efficiency (%)
Fuel wood	11
Charcoal	20
Kerosene	45
LPG	55
Electricity	75

The efficiency of cook stoves also influences the quantity of fuel wood consumed. In many communities, traditional three-stone cook stoves are used to heat water and to cook food (see Fig. 2.7). Traditional cook stoves have a low efficiency, around 11%. Improved designs can double the efficiency but, overall, they are less efficient than stoves designed for modern fuels like LPG and electricity, as shown in Table 2.4. Nonetheless, doubling the efficiency of the cook stove reduces the fuel wood demand by a factor of two. This saves both time and money.

2.4.2 Charcoal

Charcoal has about twice the specific energy of dry fuel wood and so is more convenient to transport, store, and use. It also lights easily and requires little if any preparation. Charcoal is often used in small stoves or braziers as shown in Fig. 2.8.

Charcoal is wood that has undergone a process called "pyrolysis." Pyrolysis is a thermal–chemical reaction in which wood is exposed to high temperatures—over 300°C—over many hours or days in the absence of oxygen. This prevents the wood from catching fire. At temperatures around 300°C, wood spontaneously breaks down resulting in water vapor, methanol, acetic acid, tars, and gases (primarily carbon dioxide, carbon monoxide, and methane). At these temperatures, the process

Fig. 2.8 Container of charcoal and cook stove ("jiko" in Kenya) (courtesy of the author)

becomes exothermic (energy is released) and continues until carbonized residue remains. The resulting charcoal is 75 to 85% carbon, with some remaining ash and volatile compounds. Because the volatile compounds have been reduced, charcoal tends to burn with little or no flame. A typical yield is 1 kilogram of charcoal for every 6 kilograms of input dry wood.

Creating charcoal is a labor- and energy-intensive process. It is not surprising then that charcoal costs more than fuel wood. This limits its use in poor households. Charcoal use among the urban and peri-urban (near urban), including those with access to electricity, is high. In many developing countries, charcoal production and distribution play a major role in the economy [16]. Over 36 million tonnes of charcoal, valued at over US$ 11 billion, were produced in Sub-Saharan Africa (SSA) in 2012 [14].

2.4.3 Animal and Crop Residue

Animal dung—from cows, horses, goats, llamas, yaks, camels, and even elephants—and crop residue are often abundant in rural settings, as many households are engaged in agriculture and animal husbandry. These fuels are free or extremely low cost, but are usually undesirable.

As shown in Table 2.2, the energy density of these sources is low, even after drying. The smoke from burning animal dung and crop residue is associated with negative health outcomes, including lung cancer and respiratory infections. When burned, cow dung releases more particulate matter and higher levels of microbial products than when fuel wood is burned or are emitted from diesel-powered generator sets [22].

Fig. 2.9 A kerosene lamp made from an up-cycled tomato paste can (courtesy of author)

2.4.4 Kerosene

Kerosene, sometimes locally known as "paraffin," is a transparent petroleum-based liquid. It has high specific energy but also high cost. Kerosene is used to start fires and for lighting. It may also be used for cooking by higher-income families. Kerosene lamps are widely used in SSA, and it is common to see the lamps constructed using upcycled materials, as shown in Fig. 2.9. Kerosene can often be purchased from petrol stations, even in remote areas. Kerosene is often purchased in small quantities, perhaps 1 liter or less. Repurposed plastic water or soda bottles are used to transport it home.

The consumption of kerosene by a lamp varies considerably depending on the physical characteristics of the lamp. It typically ranges between 5 and 50 liters per year based on 3.5 h of evening use per lamp. Most lamps use a simple flat wick which is low-cost and can be manufactured locally.

Kerosene lamps pose safety and health risks. They are used indoors, where they might leak, be knocked over, or come in contact with flammable materials. Combustion of kerosene releases emissions including particulate matter, carbon monoxide, formaldehyde, polycyclic aromatic hydrocarbons, sulfur dioxide, and nitrogen oxides [30]. These are harmful to human health. Research has found an increased risk of cancer, respiratory infection, asthma, tuberculosis, and cataracts related to kerosene use. Kerosene is transparent and is often stored in reused beverage bottles, increasing the risk of accidental ingestion by children.

Although energy from kerosene often contributes to less than 10 % of the total energy of a household, it can comprise about half of total energy expenditure. Kerosene use is affected by government subsidies and its availability in rural areas. In some regions such as Zambia, candles or disposable battery flashlights ("torches") are preferred to kerosene [18]. The high cost coupled with the low quality and efficacy of kerosene lamps presents an opportunity to greatly reduce fuel expenditure by replacing kerosene with LED lighting.

2.4.5 *Batteries*

Some households are transiting to electric lighting solutions. Although solar lanterns are becoming more common, disposable dry cell battery flashlights (torches) and lamps using highly efficient LED bulbs are common in some areas [7].

A challenge with the proliferation of flashlights in rural areas is the disposal of the dry cell batteries. Professionally managed disposal or recycling facilities are uncommon. The batteries are depleted relatively quickly—a rural household uses between 4 and 15 per month. The batteries, which contain hazardous materials, are commonly discarded in nature or in latrines [7]. Batteries discarded in latrines can concentrate the hazardous chemicals from the batteries, which could possibly cause greater harm then if discarded in nature.

2.5 Household Electricity Needs

Electricity can replace or complement existing fuels used in rural households. Complete replacement is not likely unless a subsidized grid connection is available due to the high cost of high-quality electricity service, appliances, and electrical energy, as explored in the following examples.

Example 2.3 Consider a household whose consumption is 60 GJ (16,667 kWh) per year using fuel wood and kerosene. Of this, 36 GJ from fuel wood is used for cooking and water heating on a cook stove with an efficiency of 12%, and 20 GJ from fuel wood is used for space heating. Kerosene is used for lighting, with an annual consumption of 4 GJ. Compute the annual energy required, in kilowatthours, to replace the fuel with electricity from the national grid. Assume the electric cook stove is 75% efficient and the electric lamps consume 45 kWh per year.

Solution The use of an electric cook stove reduces the consumption from water heating and cooking to:

$$36 \times 0.12/0.75 = 5.76 \text{ GJ}.$$

The electrical energy consumption excluding lighting is

$$(60 - 36 - 4) + 5.76 = 25.76 \text{ GJ}.$$

Converting to kilowatthours and adding the energy from the electric lights:

$$25.76 \times 10^9 \times \frac{1}{3.6 \times 10^6} + 45 = 7201 \text{ kWh}.$$

The transition to electricity reduced the energy consumption by 57%.

Example 2.4 Consider the energy consumption described in the previous example. Assume that each liter of kerosene costs US$1.10, and that 75% of the fuel wood is gathered for free, and the rest is purchased at US$0.05 per kilogram. Compute the annual energy expenditure of the household and compare it to the annual expenditure if electricity is used, assuming the electricity price is unsubsidized at US$0.15/kWh.

Solution Consulting Table 2.2, the household consumes

$$\frac{36\text{ GJ} + 20\text{ GJ}}{0.016\text{ GJ/kg}} = 3500\text{ kg of fuel wood}$$

$$\frac{4\text{ GJ}}{0.035\text{ GJ/liter}} = 114.3\text{ liters of kerosene.}$$

The total annual expenditure is

$$3500\text{ kg} \times (1 - 0.75) \times 0.05\text{ US\$/kg} + 114.3\text{ liter}$$
$$\times 1.10\text{ US\$/liter} = \text{US\$}169.48.$$

If electricity replaces kerosene and fuel wood, the annual expenditure becomes

$$7201\text{ kWh} \times 0.15\text{ US\$/kWh} = \text{US\$}1080.15$$

which is likely cost-prohibitive for this household.

Example 2.4 showed that switching entirely to electricity is not likely to be economically viable. Instead of complete replacement, electricity can be used to complement the existing fuel sources by being used for services that traditional fuels cannot provide. For example, fuel wood cannot be used to power fans and televisions. Although traditional fuels can be used for lighting, it is inferior in quality to electric light. The electricity needs of a household therefore is a continuum, based upon the electrical services required.

There are seven broad categories of household electricity services, as shown in Table 2.5. We can estimate the electrical energy required for these services, or a combination of these services, based on the duration of use and electrical characteristics of the appliances. For example, we can estimate the energy requirement of providing 6 h of single-room electric lighting and 2 h of television per day. Using typical appliance ratings of 9 W per LED light bulb and 30 W for a television, the daily requirement is $(6 \times 9 + 2 \times 30) = 0.114$ kWh per household per day. This is far less than if the entire energy needs were replaced by electricity.

Estimates of the electricity need range from about 20 to 100 kWh per person per year, depending on the services provided. Some organizations target 365 kWh per

Table 2.5 Household services and power requirements [8]

Service	Very-low power	Low-power	Medium-power	High-power	Very high-power
1. Lighting	Task	General	–	–	–
2. Communication & entertainment	Phone charging, radio	TV, computer, printer	–	–	–
3. Space cooling & heating	–	Fan	Air cooler	–	Air conditioner, heater
4. Refrigeration	–	–	Refrigerator, freezer	–	–
5. Mechanical loads	–	–	Water pump, food processor	Washing machine	Vacuum cleaner
6. Product heating	–	–	–	Iron, hair dryer	Water heater
7. Cooking	–	–	Rice cooker	Toaster, microwave	Electric range (cooker)

Table 2.6 Electricity consumption of various services [11]

Services	Consumption (kWh/person/year)
Task lighting	1
Light or TV or radio	2
Light, phone, radio, small TV	22
Light, phone, radio, TV, fan, productive uses	220

year (1 kWh per day) per household [8], which is 20 to 30 times less than consumed in most households in developed countries. Always be careful to distinguish between energy use per person and per household. The assumption of appliance type also strongly influences the required energy; for example, an LED light can be up to twice as efficacious as a compact florescent light. Table 2.6 is an example of per person annual energy requirements.

2.6 Electricity Access

Electricity access of a region or country is quantified by the *electrification rate*—the percent of the population with access at home to the electricity from the national grid. The simplicity of this definition makes it easy to interpret but, as discussed later, has shortcomings as well. The 2012 global electrification rate is 85% and has generally been increasing over the last several decades as shown in Fig. 2.10. An 85% electrification rate seems high, but it means that 1.1 billion people do not have access to electricity.

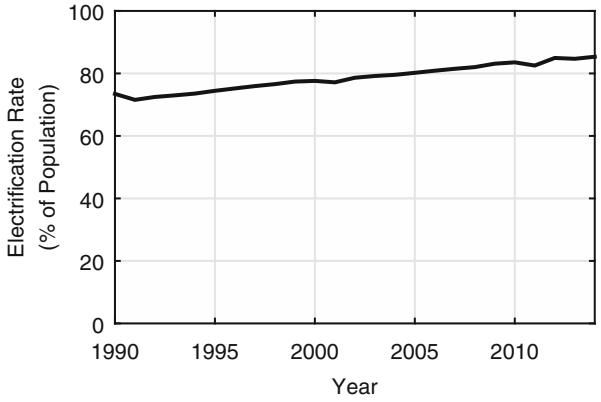
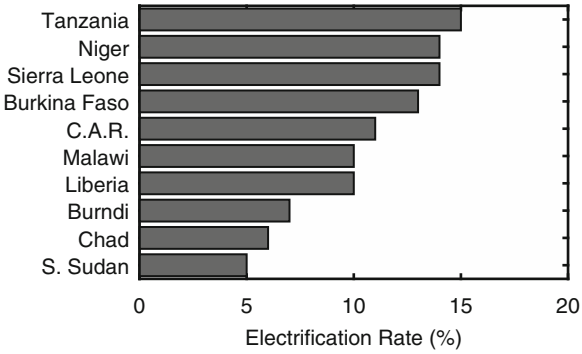


Fig. 2.10 World electrification rate

Fig. 2.11 Countries with the lowest electrification rate [28]



Approximately 80% of those lacking electricity access live in just 20 countries in Sub-Saharan Africa and South Asia. People without access tend to live in rural areas. The global electrification rate in urban areas is 96% but just 72% in rural areas [28]. This "rural penalty" is evident in Sub-Saharan Africa, where the urban and rural rates stand at 69% and 15%, respectively. The countries with the lowest electrification rates are all found in SSA, as shown in Fig. 2.11 [28]. In terms of total population without access, India is the unfortunate leader, with over 250 million people without electricity, as shown in Fig. 2.12.

Achieving universal electrification—a state in which the electrification rate globally is 100%—will be expensive and take time. Although challenging to estimate with high accuracy, the cost of universal access will be between US$0.5–0.9 trillion, approximately US$45 billion per year through 2030. Present investment levels are far under this target, at approximately US$10 billion per year [28].

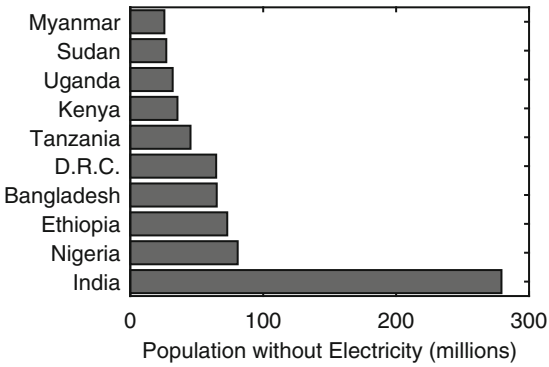


Fig. 2.12 Countries with the largest number of people without access to electricity [28]

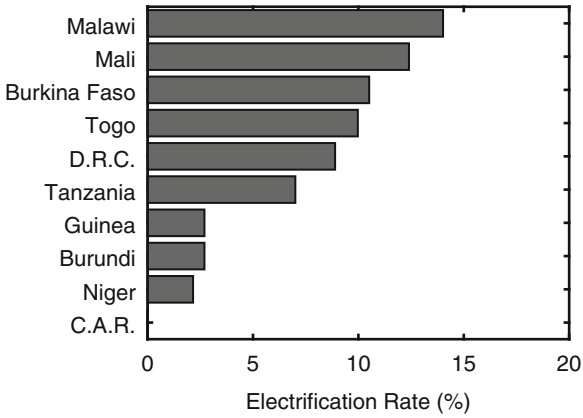


Fig. 2.13 Public primary school electrification rates (various years) [27]

2.6.1 Electricity Access of Community Service Institutions

As discussed in Sect. 2.2.2, social institutions, schools, health-care facilities, and government offices require electricity to effectively provide their services. The electrification rate of schools and medical clinics in various countries are provided in Figs. 2.13 and 2.14. Social institutions are often given high priority by governments for electrification because they support improved education, health care, and other development outcomes.

2.6.2 Annual Growth Rate of Electricity Access

The (AGR) of electricity access is used to quantify the change in electricity access over a period of time. The use of the AGR is preferred over reporting the change in the electrification rate or the change in the absolute number of people with or without access. These indicators alone without accounting for population dynamics can be misleading.

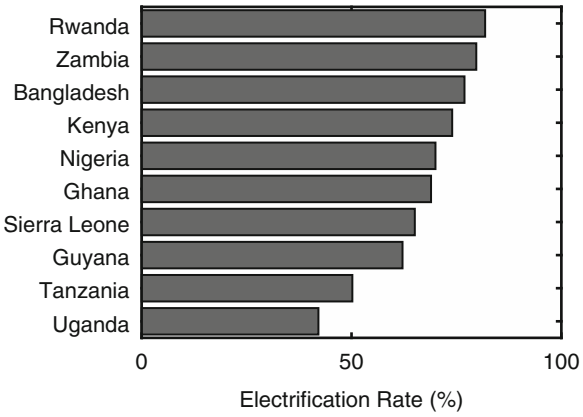


Fig. 2.14 Health clinic electrification rates (various years) [27]

Consider the following. A government points to an increasing electrification rate within the country as a sign of progress. At the same time, the opposition party claims that the total number of people without access to electricity in the country has increased. Both the government and the opposition can be correct. How is it possible for the electrification rate to increase, yet there is also an increase in the number of people without electricity?

Consider a brief case study of Malawi, a country in southern Africa. The population of Malawi in 2010 was 14.8 million; by 2012 it had grown to 15.7 million. The electrification rate during the same period increased from 9% to 10%—a small sign of progress. Based on the 2010 population, the number of people without access to electricity can be calculated as $14.8 \times (1.00 - 0.09) = 13.47$ million people. Repeating the calculation using the 2012 data shows that 14.13 million people do not have access to electricity, an increase of 660,000 people—a step backward.

The cause of these seemingly incompatible results is that Malawi's population increased faster than the number of people that gained access. The number of people with access increased but so did the number of people without access, because the population as a whole increased.

Sub-Saharan Africa as a whole is another example of a region where electrification rates are increasing but so is the number of people without access to electricity. Here, the electrification rate increased from 32 to 35% from 2010 to 2012, but the population grew from 874 million to 923 million over the same period, leading to an additional 5 million people without electricity. Whether or not this represents progress depends on one's perspective.

The AGR captures the effects of changes in the electrification rate and population dynamics. The AGR considers the changes in number of people with access $A[y]$, in a given year y, and the population, $P[y]$, over a period of years t. The AGR is the change in the number of people with access between the years considered, minus the change in population during the same span, divided by the population. It is divided by the number of years considered to determine the annual rate.

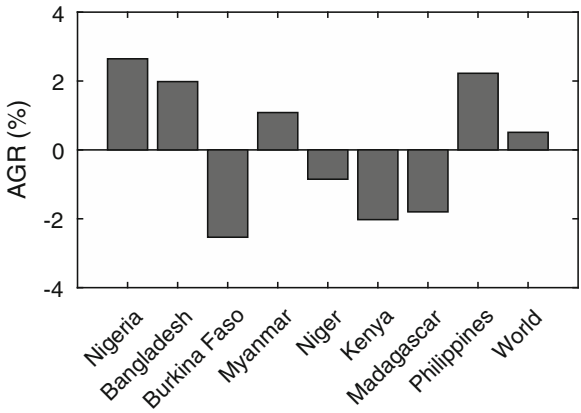


Fig. 2.15 Annual Growth Rate of electrification in various countries

$$AGR = \frac{(A[y] - A[y-t]) - (P[y] - P[y-t])}{P[y]} \times \frac{1}{t} \tag{2.1}$$

The AGR is often expressed as a percentage, in which case (2.1) is multiplied by 100.

The AGR is positive if the number of people with access increased faster than the population grew over the same period. A country's AGR is typically between $\pm 3\%$. Some countries have obtained much greater AGRs, for example, Cambodia at 7% and Afghanistan at 10%. Encouragingly, the worldwide AGR is positive. Progress is attributed to a few countries with both a high AGR of electricity access and a large population. India, Nigeria, and Bangladesh are examples of this. The AGR for select countries between 2010 and 2012 are shown in Fig. 2.15.

Example 2.5 Compute the AGR of electricity access for Malawi between 2010 and 2012.

Solution The AGR is found by applying (2.1) to the data for 2010 and 2012 presented in the text. The population with access is found by subtracting the population without access from the total population each year:

$$14.8 - 13.47 = 1.33 \text{ million people with access (2010)}$$

$$15.7 - 14.13 = 1.57 \text{ million people with access (2012).}$$

The AGR is therefore:

$$AGR = \frac{(1.57 - 1.33) - (15.7 - 14.8)}{15.7} \times \frac{1}{2} = -0.0211.$$

The AGR is negative indicating that the number of people gaining access is outpaced by the increase in population.

Example 2.6 Compute the AGR for the world between 2010 and 2012. The population of the world was 6.92 billion in 2010 and 7.09 billion in 2012. The electrification rates were 83% and 85% for 2010 and 2012, respectively.

Solution The population with access is found by multiplying the population by the electrification rate for each year

$$6.92 \times 0.83 = 5.744 \text{ billion people with access (2010)}$$

$$7.09 \times 0.85 = 6.027 \text{ billion people with access (2012).}$$

Applying (2.1), the AGR is computed as:

$$AGR = \frac{(6.027 - 5.744) - (7.09 - 6.92)}{7.09} \times \frac{1}{2} = 0.0080.$$

From the above example, we see that the world AGR is positive so that the electrification rate is increasing and the number of people without access is decreasing. The AGR, however, is very small and below what is needed to achieve universal access by the United Nations' target year of 2030.

2.7 Multi-Tier Electricity Access Framework

The electrification rate by itself suffers from several criticisms:

- it ignores the quality of the electricity supply;
- it treats all electricity supplies the same;
- it ignores the reliability and availability of the electricity supply.

For example, a household with a connection that can supply at most 1 kVA of apparent power—not enough for cooking—is only available a few hours a day and at a tariff[1] that prohibits regular use is treated the same as a 20 kVA connection, available 24 h a day at an affordable tariff. The method also ignores the modest electricity supplied by solar lanterns, solar home systems, and low-capacity mini-grids. These criticisms have led to the development of several alternative measures [5, 8]. In general, these approaches consider the *quality* of the electricity supply in defining electricity access. We will consider the *Multi-Tier Framework* (MTF) developed by ESMAP [8].

[1]The term "tariff" refers to the pricing structure for electricity. It typically consists of a fixed monthly "connection" fee and a variable "energy" fee.

The MTF is part of a comprehensive approach to assessing energy access in general. It considers energy access for household uses (electricity, cooking, and heating), for productive uses, and for community uses (street lighting, health and education facilities, and community and public buildings). We will focus on household electricity use.

There are three different MTFs for assessing household electricity access based upon attributes of the supply, the services such as lighting and cooking made possible by the supply, and the consumption level. These MTFs provide a more holistic accounting of a household's access to electricity than the electrification rate. The MTFs are also technology neutral. They can equally be applied to on- and off-grid electricity supplies. However, more time and resources are required to collect the data needed to apply the MTFs than to determine the electrification rate.

2.7.1 Supply Multi-Tier Framework

The Supply Multi-Tier Framework assigns a household's electricity access to one of the six tiers based on *attributes* of the electrical supply. A household with higher-tier access is served by a higher-quality electricity supply. There are seven attributes considered:

1. Capacity
2. Availability
3. Reliability
4. Affordability
5. Legality
6. Health and Safety
7. Quality of Voltage and Frequency

The seven attributes are separately evaluated according to a predefined scale and each assigned a tier. The tier of the supply is the minimum tier achieved when all attributes are considered.

2.7.1.1 Capacity Attribute

The capacity attribute of an electricity supply is assessed using one of two scales. The first scale is well-suited for grid or mini-grid connections. It is based on two indicators: the peak power capacity and the daily total energy that can be provided by the supply. This scale is provided in Table 2.7. The minimum peak power and daily energy escalate with the tier level and are related to the type of appliances that could likely be operated at each tier. Although peak power and daily energy are often related, their tiers can be different. The overall tier of the capacity attribute is set to the lower of the peak power tier or daily energy tier. For example, if a supply is capable of providing 9000 Wh (Tier 5) of energy per day, but the peak capacity

Table 2.7 Capacity attribute scale: peak and daily energy

Indicators	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Power capacity rating	–	≥3W	≥50W	≥200W	≥800W	≥2000W
Daily energy potential	–	≥12Wh	≥200Wh	≥1000Wh	≥3400Wh	≥8200Wh

Table 2.8 Capacity attribute scale: service

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Service	–	≥ 1,000 lm/hr of lighting/day	Lighting, air circulation, television, and phone charging possible	–	–	–

rating is only 1000 W (Tier 4), then the capacity attribute of the supply is Tier 4. Note that the supply is evaluated based on its potential capability, not whether or not a particular amount of peak power or daily energy is actually consumed by the household.

The second scale is based on the services that can be supported by the supply, according to the scale in Table 2.8. Tier 2 is the maximum tier that can be achieved using this scale. This scale can more readily be applied to households that do not have a grid or mini-grid connection but rather are served by solar lanterns or solar home systems. The quantity of lighting required for Tier 2 service capacity is 1000 lumen-hours (lm hr) per day. A lumen is a unit of luminous flux, which can be thought of as the light output of a lamp. Note that either the scale in Table 2.7 or Table 2.8 can be applied, but not both.

2.7.1.2 Availability Attribute

The availability attribute is based on the length of time that the supply is available each day. Supply availability can be limited when countries face electricity shortages and must intentionally disconnect customers; in off-grid systems, the availability might be reduced, for example, if generator sets are only run during certain hours of the day to reduce fuel costs, or in a solar-powered system if there is insufficient battery capacity to supply power throughout the evening. Availability is important for loads that need to be operated continuously or during certain hours, such as lighting, climate control, and refrigeration. The availability attribute scale is shown in Table 2.9.

Two indicators are used to determine the tier of the availability attribute of a supply: the total number of hours per day the supply is available and the number of evening hours in particular that the supply is available. Here, evening hours is defined as the 4 h after sunset. The tier of the availability attribute is set to the lowest of the two indicators.

Table 2.9 Availability attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Hours available per 24 h period	–	≥4 h		≥8 h	≥16 h	≥23 h
Hours available per evening	–	≥1 h	≥2 h	≥3 h	≥4 h	

Table 2.10 Reliability attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Number of disruptions/week	–	–	–	–	≤ 14	≤ 4 AND aggregate duration < 2 hrs/week

Table 2.11 Affordability attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Cost of consuming 365 kWh/year	–	–	–	< 5% of annual income		

2.7.1.3 Reliability Attribute

The reliability attribute refers to the frequency of unplanned interruptions of service. Although similar to availability, reliability is a distinct concept, and the consequences of poor reliability are different from poor availability. The reliability attribute scale is shown in Table 2.10. If more than 14 disruptions occur each week, the supply is assigned Tier 3 for its reliability attribute.

2.7.1.4 Affordability Attribute

An electricity supply does little to improve the quality of life if it is not affordable. A household's expenditure on electricity is dependent on the price of electrical energy and the level of consumption. However, the amount of the expenditure alone does not fully encapsulate the affordability of the supply—the income of the household must be considered. The affordability attribute scale is shown in Table 2.11.

The affordability attribute of a supply is determined from whether or not an annual consumption of 365 kWh is, or would be, less than of 5% of the household's income. Note this calculation is independent of whether or not the household actually consumes 365 kWh each year. If this is less than 5% of the household's income, then the affordability attribute is Tier 5; otherwise, it is Tier 2.

2.7.1.5 Legality Attribute

In many developing countries, theft of electricity is a pervasive problem. Electricity theft threatens personal safety (through illegal connections) and the financial viability of the supplier (the utility or off-grid system owner). It is also associated with corruption. The legality attribute scale is shown in Table 2.12.

Table 2.12 Legality attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Bill Payment	–	–	–	–	Paid to supplier or authorized agent	

Table 2.13 Health and safety attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Wiring installed per national standards	–	–	–	–	No past accidents and no perception of high shock/electrocution risk	

Table 2.14 Quality attribute scale

Indicator	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Voltage	–	–	–	–	Voltage is within the parameters specified by the grid code	

Determining the legality of a supply is challenging as people might not disclose this information, and utilities might not have an accurate or precise estimate of illegal connections. Like affordability, the legality attribute is based on a binary indicator: if the bill for electricity is paid to the supplier—or one of its agents—then it is Tier 5; otherwise, it is Tier 3.

2.7.1.6 Health and Safety Attribute

An electricity supply can pose a serious threat to safety if improperly installed. For a supply to be safe, it should meet the country's electric code. The indicator for health and safety is whether or not there has been past accidents or perceived future risk of electrocution, as shown in Table 2.13.

2.7.1.7 Quality Attribute

Designers of consumer appliances and electronics assume the electricity supply meets certain quality standards. Voltages and frequencies above or below the range specified in the standards can cause devices to malfunction, become inoperable, or fail. The quality attribute scale is shown in Table 2.14.

2.7.1.8 Overall Supply Tier

To compute the overall tier of a supply, each attribute is assessed independently. The overall tier of the supply is the lowest tier assigned to any attribute. For example, if a supply that is Tier 5 in six of the attributes but Tier 3 in the seventh, then it is a

Tier 3 supply. While this might seem strange, the MTF is useful in that it identifies how this supply can be increased to Tier 5—by improving the deficient attribute.

Example 2.7 Determine the energy access tier of a customer whose supply has the following characteristics:

- Power Capacity: 700 W
- Daily Capacity: 15,400 Wh
- 22 h of availability per day, 4 h of which are after sunset
- 7 disruptions per week
- Consumption of 1 kWh per day costs 4% of daily income
- Bill for electricity supply is paid to the supplier
- No past accidents and no perceptions of future risk; supply meets local electrical code
- Voltage spikes and sags are common, occasionally damaging equipment

What would the energy access index be if the peak power capacity was improved to 1000 W and the voltage quality was within the parameters specified by the grid code?

Solution We begin by assessing each attribute separately.

Capacity: Tier 3 (Tier 3 power capacity rating and Tier 5 daily energy potential)
Availability: Tier 4 (Tier 4 h per 24-h period and Tier 5 h per evening)
Reliability: Tier 4
Affordability: Tier 5
Legality: Tier 5
Health and Safety: Tier 5
Quality: Tier 3

The energy access tier of the connection is the lowest tier of any attribute. In this case it is Tier 3. If capacity and quality were improved as indicated in the problem statement, then the household would have a Tier 4 supply.

2.7.2 Aggregate Index

The indices of a set of households can be aggregated and combined into a single Aggregate Index (*Aggregate Index*) using the following formula:

$$Aggregate\ Index = \sum_{T=0}^{5} 20 \times P_T \times T \tag{2.2}$$

where P_T is the proportion of the population with tier T supply.

Table 2.15 Portion of population with each access tier (Example 2.8)

	Tier 0	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Portion of population	30%	20%	10%	20%	10%	10%

Table 2.16 Service-based tiers

	Service
Tier 0	–
Tier 1	Phone charging and task lighting
Tier 2	General lighting, television, and air circulation (if needed)
Tier 3	Medium-power appliances
Tier 4	High-power appliances
Tier 5	Very high-power appliances

Example 2.8 Compute the Aggregate Index of a country with the following energy access tiers in Table 2.15.

Solution The Aggregate Index is found using (2.2):

$$\begin{aligned} \textit{Aggregate Index} = 20(&0.30 \times 0 + 0.20 \times 1 + \\ &0.10 \times 2 + 0.20 \times 3 + 0.10 \times 4 + 0.10 \times 5) = 38.0. \end{aligned}$$

The Aggregate Index gives a general sense of the electrical system quality, but it mixes so many concepts that it cannot be interpreted in a strictly quantitative manner.

2.7.3 Services Multi-Tier Framework

The second framework is the Service MTF. It assesses electricity access from the electricity-based services available to the household. Application of the Supply MTF and the Service MTF to a household can yield different results. For example, a household might have a high-tier supply, but if the household is unable to acquire or use basic appliances, their access tier as determined by the Service MTF will be low.

The service-based tier framework is shown in Table 2.16. The listed appliance power descriptions is in reference to Table 2.5.

Table 2.17
Consumption-based tiers

	Daily (Wh)	Annual (kWh)
Tier 0	–	–
Tier 1	≥12	≥4.5
Tier 2	≥200	≥73
Tier 3	≥1000	≥365
Tier 4	≥3425	≥1250
Tier 5	≥8,219	≥3,000

2.7.4 Consumption Multi-Tier Framework

The third MTF that is used to assess a household's access to electricity is the Consumption MTF. The Consumption MTF is based on the daily or equivalent annual energy used by the household according to the scale in Table 2.17. It generally mirrors the Supply MTF and the Service MTF.

The MTF is particularly useful when planning an off-grid project. Not all systems need to provide Tier 5 quality in order to be useful and beneficial to the community. For example, an organization might target Tier 3 access and design their system accordingly.

2.8 Summary

Energy poverty is the lack of access to modern fuels such as electricity and LPG. Approximately 40% of the world, primarily those living in rural areas in developing countries, are energy impoverished. They often rely on fuels such as animal dung, crop waste, fuel wood, charcoal, and kerosene. The household energy consumption in rural areas ranges between 5 and 15 GJ (1389 to 4167 kWh) per person year, with additional energy needed for community services and to enhance productivity. Procuring fuel is often an economic burden and requires considerable time.

Energy-impoverished households tend to fuel stack, relying on several fuel sources, and the transition to fuels with higher desirability depends on income but also access to the fuel and other local factors. The electricity requirements of a household depend on the services rendered and range from 1 to over 3000 kWh per year per person.

Electricity access is often quantified by the electrification rate, which is the proportion of the population with grid-supplied electricity access. When assessing electrification progress, the Annual Growth Rate should be used as it captures the dynamics of a population. More recently, a Multi-Tier Framework, which provides a more holistic picture of electricity access, is used. The Supply Multi-Tier Framework considers capacity, availability, reliability, affordability, legality, health and safety, and voltage and frequency quality of the electricity supply.

Problems

2.1 A health clinic in a rural area requires 3.5 kWh of electricity each day. The diesel generator set that serves the health clinic has an average efficiency of 15%. Compute the annual fuel requirements of the gen set assuming the energy content of diesel is 36 MJ per liter.

2.2 A rural school is to be supplied with five desktop computers (100 W each), five CFL lightbulbs (16 W each), and two radios (15 W each). The desktop computers will be used for 3 h per day, 5 days a week. Three of the CFLs are used indoors to hold classes in the evening. These bulbs are used 2 h each day, 5 days per week. The other bulbs are used for overnight security, for 10 h each day. The radios are used 1 h per day, 5 days per week. Estimate the average daily consumption and the total yearly consumption.

2.3 The average annual per person energy use in Cameroon is 14.3 GJ. Assume that 75% of this energy is used for cooking and heating. Compute the required mass of dry wood needed for cooking and heating. Repeat the calculation assuming only charcoal is used and again assuming only dried animal dung is used.

2.4 Evaluate and compare the desirability of fuel wood and charcoal considering its quality, convenience, and cost attributes.

2.5 A kerosene lamp consumes 0.15 liters of kerosene when used for 3.5 h per day. The kerosene lamp can be replaced by an electric LED lamp that consumes 3.5 Wh each day. Compute the equivalent daily energy, in watthours, consumed by the kerosene lamp. What is the effective cost per kilowatthour of operating the kerosene lamp assuming the price of kerosene is US$1.40 per liter. How does this compare using an LED lamp, assuming the price of electricity is US$0.15/kWh?

2.6 A certain mobile phone requires 12 Wh of energy to recharge. The phone can be recharged for a fee of US$0.20. Compute the rate, in dollars per kilowatthour that is being paid to recharge the mobile phone. How does this compare to the rate for grid-connected electricity in your country? If a solar lantern capable of recharging mobile phones costs US$40, how long will it take to pay for itself if the mobile phone is recharged every 4 days?

2.7 Compute the AGR of the countries in Table 2.18.

Table 2.18 Electrification data

	2010		2012	
Country	Rate (%)	Population (millions)	Rate (%)	Population (millions)
Indonesia	94.2	242.5	96.0	248.8
India	76.3	1231	79.9	1263
Nepal	67.5	27.02	75.6	27.65
Zimbabwe	35.6	14.09	36.2	14.71

2.8 The population of Zambia in 1990 was 8.03 million with an electrification rate of 13.9%. How many Zambians did not have access to electricity in 1990?

2.9 The world AGR of electricity access in 2012 was 0.51%. If this rate continues, how many people will be without access in the year 2030? Assume the population in the year 2030 is 8.5 billion, the population in 2012 is 7.10 billion and the electrification rate in 2012 is 85.3%.

2.10 What will the AGR of electricity access need to be in order to achieve universal (100%) access by the year 2030?

2.11 Compute the energy access tier for the following conditions. Determine the tier for each attribute.

- Power Capacity: 1000 W
- Daily Capacity: 2400 Wh
- 10 h of daily availability and 6 h during the night
- 4 disruptions per week with total duration of less than 2 h
- Consumption (365 kWh/year) is less than 5% of income
- Bill is paid to the supplier
- No past accidents and no perception of future risk
- Voltage spikes and sags are not common

2.12 Use the Consumption Mult-Tier Framework to evaluate the electricity service described in the previous problem.

2.13 Compute the energy access tier for the following conditions. Determine the tier for each attribute.

- Power Capacity: 5000 W
- Daily Capacity: 10,000 Wh
- 22 h of daily availability and 4 h during the night
- 1 disruption per week less than 2 h
- Consumption (365 kWh/year) is less than 5% of income
- Connection is illegal
- No past accidents and no perception of future risk
- Voltage spikes and sags are not common

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