

# Chapter 13

## Solar Lanterns and Solar Home Systems



### 13.1 Introduction

We now shift our focus to solar lanterns (SLs) and solar home systems (SHSs). SLs and SHSs are small-scale, stand-alone solar-powered systems. Examples are shown in Figs. 13.1 and 13.2. Some SLs provide just enough electricity for a single light and perhaps to recharge a mobile phone, as shown in Fig. 13.3. Larger SHS can power small appliances such as radios, fans, and televisions as shown in Fig. 13.4. The exact distinction between a SL and SHS has become blurred. However, a useful definition is that solar lanterns have less than 10 W of PV capacity. They are also known as “pico solar.” SHSs typically, but not always, have capacities exceeding 10 W. Both of these technologies also require a battery to properly function.

SLs and SHSs provide lower-tier (less than tier 3) electricity access than mini-grids as defined by the multi-tier framework in Sect. 2.7. However, the electricity they provide is meaningful as evidenced by their robust and rapidly growing sales in recent years (see Fig. 13.5). SHSs are more expensive than SLs, and so fewer SHSs have been sold. Some estimates place the number of SHS sold per year to be around one million units. The leading markets for SLs and SHS are India, Kenya, Tanzania, and Ethiopia [2]. Some projections predict SLs or SHSs will be in one out of every three off-grid households. The contribution of SLs and SHSs to improving access to electricity should not be overlooked.

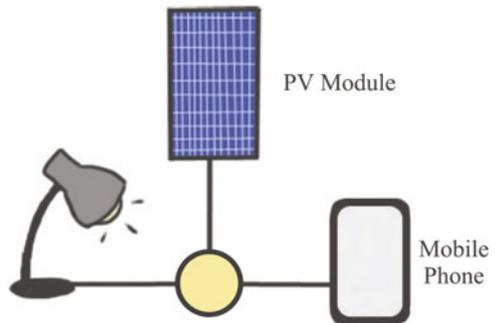
**Fig. 13.1** A solar lantern includes a small solar panel and LED light (courtesy of d.Light)



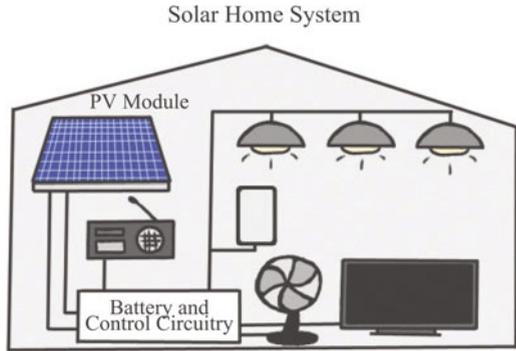
**Fig. 13.2** Solar home systems are often capable of powering several LED lights and small appliances (courtesy of BBOX Ltd.)



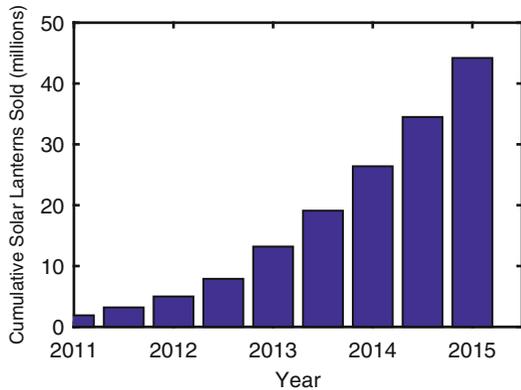
**Fig. 13.3** Solar lanterns provide a modest amount of electricity, usually enough for a single lamp and perhaps enough to recharge a mobile phone each day



**Fig. 13.4** Solar home systems are usually able to supply several lights and even small appliances



**Fig. 13.5** Cumulative sales of pico solar products [2]



*Example 13.1* How long would it take for SLs or SHSs to be in every presently unelectrified household? Assume a combined 20 million units are sold each year and an unelectrified population of 1.1 billion people. Assume that each SHS or SL can serve a single household with five people.

**Solution** The total number of households requiring a SLS or SL is found from

$$\frac{1.1 \text{ billion people}}{5 \text{ people per household}} = 220 \text{ million households.}$$

If 20 million units are installed each year, then it will take 11 years. However, this does not account for the limited life span of the units. This aspect is explored in Problem 13.1.



**Fig. 13.6** Mobile phones can be recharged at businesses with electricity access for a fee (courtesy of the author)

SLs and SHSs are conceptually different from mini-grids in that they are consumer products, rather than industrial assets. Customers typically purchase or lease SLs and SHSs, whereas they purchase energy from mini-grids. Consequentially, the associated business models are very different, as discussed later.

The main drivers for the popularity of SL and SHS are rapidly reducing PV prices, improvements in the efficacy and reduction of costs of LED lighting, and the relatively high cost of traditional lighting methods, kerosene in particular. This makes SHSs and SLs cost-competitive. Mobile phones are another driver. In Sub-Saharan Africa, there are 74 mobile phone subscriptions for every 100 people [3]. This far exceeds the electrification rate. In rural areas, even those without electricity access, mobile phones are common. As you can imagine, recharging mobile phones in these areas is problematic. The owner must either travel to the nearest electrified town, perhaps tens of kilometers away, or pay a merchant with an off-grid system to recharge. See, for example, Fig. 13.6. In either case, the fee is often US\$0.20 to US\$0.50—a large sum given that many in these communities live off less than US\$2.00 per day. The energy required to recharge a mobile phone is very low, often less than 10 Wh, making the effective rate for the energy several orders of magnitude greater than what grid-connected customers pay.

Recently, improvements in batteries—more specifically, lithium iron phosphate ( $\text{LiFePO}_4$ ) chemistries—and cloud connectivity have enabled scalable business models for SHSs in particular.

SLs can be purchased from US\$10 to about US\$40. They are often available in or near rural communities. SHSs are more expensive. Some cost more than US\$350, depending on the capacity and appliances included. It should be kept in mind that grid connection fees are often several hundred dollars. Like other off-grid systems, the levelized cost of energy (LCOE) of a SL or SHS is usually several times greater than the tariff for grid-connected electricity, especially if the tariff is subsidized. Sellers of SL and SHS usually tout the services the SL and SHS can provide—clean, modern lighting, for example—instead of the LCOE. This makes sense because with a SL or SHS, the customer is buying a product that provides services, not electricity.

## 13.2 Solar Lanterns

The first solar lanterns were designed to replace kerosene lamps, candles, and battery-powered torches (flashlights) commonly used in rural settings. They were designed to provide basic task lighting from a single light source and did not require permanent installation. Instead, they were designed to be portable. Portability is particularly useful when walking outside at night. They can also be hung, mounted, or placed on a flat surface. They were typically designed so that a typical day's insolation would be sufficient for the PV module to charge to the battery, allowing the light to be run for several hours in the evening.

LED prices have since dropped considerably, and the efficacy of LED bulbs—the amount of light output per unit of electric power input—increased. The result was a halving of LED costs, in terms of cost per lumen, between 2009 and 2015. With less energy needed for lighting, manufacturers began offering SLs that included additional functionality. Most important is the ability to recharge mobile phones through dedicated charging ports. SLs are now able to save the customer lighting and mobile phone recharging-related expenses. This can be significant. However, the market for SLs providing single-purpose lighting remains strong.

SLs are designed to be economical entry-points for electricity access. As such, reliability is often sacrificed for lower prices. SLs are typically designed to provide electricity only for 3 to 5 h in the evening if charged for a full day. Their batteries are usually smaller for a given PV size than a SHS. The PV module rating versus battery capacity for several SLs and SHSs is shown in Fig. 13.7. Note the difference in axes scaling. It is worthwhile to note that in 2009, nearly 40% of the SLs sold would last between 9 and 24 h on a single day of charging [2]. Most newer models

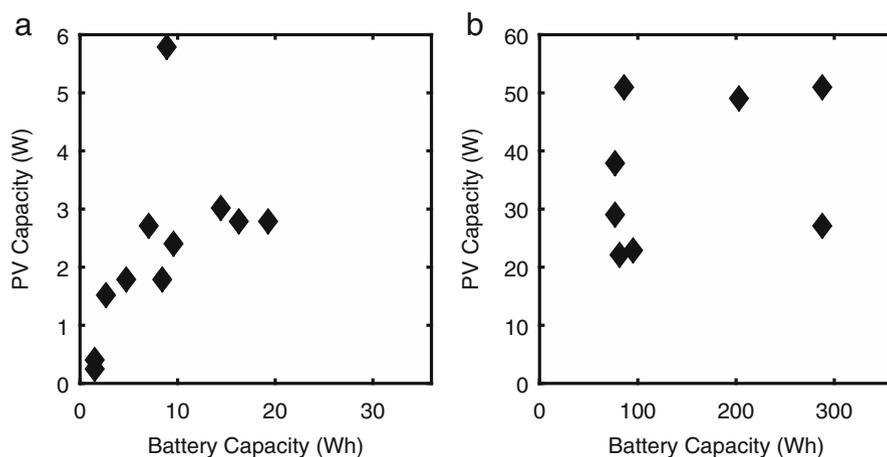


Fig. 13.7 (a) PV size versus battery capacity for SL and (b) SHS

do not offer this level of autonomy. This suggests that the increased reliability was not important to the customers—a less expensive unit with less reliability was more desirable.

### 13.3 Solar Home Systems

SHSs offer more functionality than SLs and greater solar and battery capacities. SHSs are typically rated below 100 W, but even at this size, appliances such as televisions and fans can be powered. Like SLs, SHSs include PV modules, a battery, control, and protection circuitry. They typically feature several ports for multiple LED lights, USB charging of devices, and plugs for DC appliances. Some SHSs feature inverters so that AC appliances can be powered.

SHSs are not intended to be conveniently portable. The PV array is roof-mounted and the lights are designed to be hung or wall mounted. The lights are connected to cables that are long enough to reach different rooms or even be hung outside a home. The batteries are often lithium ion, which offers longer cycle life and reduces disposal concerns when compared to lead–acid batteries. SHSs are designed so that their battery is completely charged by a typical day’s insolation.

### 13.4 Design

The architecture of a SL and SHS mirrors that of a DC-coupled mini-grid with DC load as discussed in Sect. 4.6. The basic components are PV module, charge controller, battery, and DC load. Most have battery discharge protection in the form of a LVD. The sophistication of the charge controller varies: many do not include maximum power point tracking functionality, and some can be recharged by an external AC power supply. An example of a generic SHS design is shown in Fig. 13.8. SHSs and SLs are designed to be user-friendly. Many include battery state-of-charge indicator lights and have special protections to prevent the external sources and loads from being plugged into the wrong ports.

*Example 13.2* A solar lantern provides light through an LED that consumes 1.25 W when on. Determine the required capacity of the battery, in amp-hour, and solar module for the LED to be powered for 6 h each day with an insolation of 5.0 kWh/m<sup>2</sup>/day. Assume the battery is LiNCM and the daily depth-of-discharge is 80%.

**Solution** The energy required each day is

(continued)

$$6 \text{ h/day} \times 1.25 \text{ W} = 7.5 \text{ Wh/day.}$$

The required battery size, in watt-hours, accounting for the depth-of-discharge is at least

$$\frac{7.5 \text{ Wh}}{0.8} = 9.375 \text{ Wh.}$$

The battery is LiNCM, so we use the nominal voltage of 3.7 V to determine the amp-hour rating:

$$\frac{9.375 \text{ Wh}}{3.7 \text{ V}} = 2.534 \text{ Ah.}$$

The discharge current is

$$\frac{1.25 \text{ W}}{3.7 \text{ V}} = 0.338 \text{ A.}$$

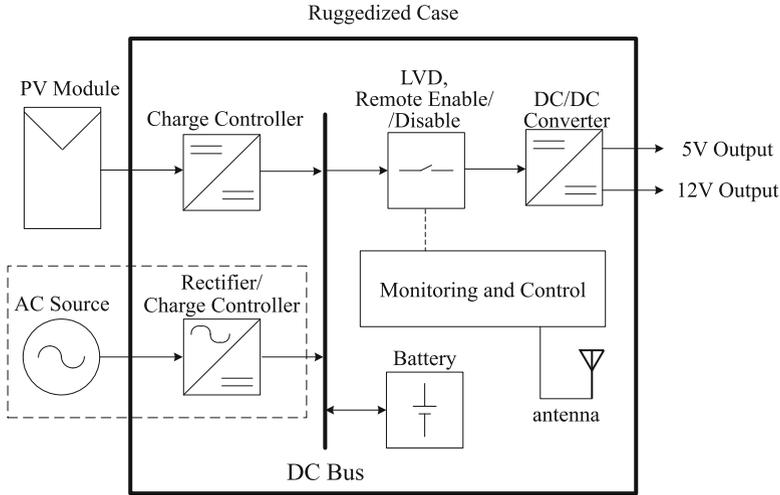
Therefore, the battery should have a rating of  $C_{0.334}=2.58\text{Ah}$ . Recall from Chap. 11 that, for example, a PV module rated a 1 W will produce 5 Wh with an insolation of 5.0 kWh/m<sup>2</sup>/day. Therefore, the required PV capacity rating for the solar lantern is

$$\frac{7.5}{5} = 1.5 \text{ W.}$$

This simple design does not include a design margin or other losses, but nonetheless, it generally agrees with the PV and battery capacities for solar lanterns in Fig. 13.7.

## 13.5 Light Output

Providing light is one of the most beneficial uses of electricity. It is the primary reason why SLs and SHSs are in demand. The brightness of a light is associated with its luminous flux, measured in “lumens” (lm). Luminous flux is the power of the electromagnetic radiation emitted by a light source that is within the visible spectrum as perceived by the human eye.



**Fig. 13.8** A generic design for a SHS system cable of PV module and AC source inputs and multiple DC voltage output. External charging from an AC source is becoming less common in SHS design

**Table 13.1** Typical lumen output

Technology	lumens (lm)
White LED (1 W)	25–120
Kerosene lamp	10–100
Incandescent (40 W)	325
White LED (7 W)	450
Fluorescent (18 W)	1250
Incandescent (100 W)	1750

Table 13.1 shows the luminous flux associated with different light sources. The luminous efficacy  $\eta_L$  of a source, for example, an LED bulb or kerosene lamp, is defined as the luminous flux  $F$  divided by the input power to the lamp  $P_{lamp}$

$$\eta_L = \frac{F}{P_{lamp}} \tag{13.1}$$

A lamp whose emitted radiation is largely outside the visible spectrum has low efficacy. The efficacy of kerosene lamps is low, around 0.1 lm/W. The efficacy of an LED is very high by comparison, about 50 to 100 lm/W. Most SLs and SHSs use LED lights, with each light fixture consisting of one or more LEDs, providing between 100 and 200 lm total. The lumen output of an LED slowly fades over time. A quality target for SL and SHS is that their lights maintain at least 85% of the rated lumen output after 2000 h of use.

How large of a space can be meaningfully lit by a solar lantern? The answer depends on type of space being lit and the activities being done in the space. For

example, classrooms and offices should have an “illuminance” of about 250 lm/m<sup>2</sup>. Using this target, two SLs each outputting 125 lm are needed to illuminate a 1 square meter surface, about the size of a large desk. In practice, not all of the light produced is cast upon the surface and so more SLs are needed. Many rural homes are lit by just one SL or SHS. While this is inadequate by illumination standards in developed countries, the light is still meaningful and much safer, cheaper, and more convenient than alternatives such as kerosene lamps or candles.

## 13.6 Remote Data Capture and Control

A recent trend is to equip SHSs with remote data capture and control capability. SHSs with this capability are outfitted with sensors measuring quantities such as battery terminal voltage, charging/discharging current, and temperature. The data are locally stored on a memory device and perhaps compressed or preprocessed. An internal radio periodically transmits the data to a remote server over the cellular network, where it is included in a centralized database. It is possible to transmit the data using a low-speed technology such as GPRS (General Packet Radio Service), which is widespread in Africa, even in remote areas.

There are technological and commercial uses of this capability. In-field measurements of voltage, current, and temperature provide insight into how the products are used. These data are valuable in improving designs of next-generation SHS and can be used to monitor battery degradation and predict failure. This allows for planned maintenance and replacement of the SHS, which can be done more efficiently and cheaply than waiting for failure to occur. Understanding the typical use of SHS can help researchers and engineers select appropriate battery technologies and chemistries and design charge controllers that are better-suited to how the SHS is actually used. It is also possible to track the location of SHSs using GPS (if included) or through triangularization from the cellular network.

Some SHSs have remote control capability. Commands can be sent to the SHS using a mobile network to enable or disable it through an internal solid-state switch or adjust the LVD set-point. This effectively disconnects the ports on the SHS from the internal battery, rendering the SHS inoperable. There is also a commercial reason for this functionality, as discussed next.

## 13.7 Business Models

The upfront cost of a SHS is a barrier to ownership. A large SHS can cost several hundred dollars, equivalent to several month’s wages in many parts of the world. There are multiple strategies to lowering this barrier.

### ***13.7.1 Rent-to-Own***

In a “rent-to-own” business model, instead of paying the full price of the SHS upfront, periodic payments are made by the customer over an extended but definite period, for example, 6 to 24 months. At the end of the rental period, the SHS is owned outright by the customer and further payments are not necessary. The customer is now in sole ownership of an asset, which they can continue to use, resell, or offer as collateral. However, should the SHS fail after the rental period, the system will likely not be replaced by the seller.

### ***13.7.2 Perpetual Lease***

In a “perpetual lease” model, the customer never owns the SHS outright. They make payments as long as they wish to use the SHS. The advantage to the customer is that the payments are smaller compared to those under a rent-to-own model, and the risk of malfunction or failure of the SHS is transferred to the manufacturer. The seller repairs or replaces the SHS as needed as long as payments are being made. The customer payments are usually pegged to a period of service—for example, US\$0.75 per day, not energy consumed, as is done with grid or mini-grid electricity. Conceptually then, the perpetual lease model is similar to selling lighting as a service, rather than a SHS as a product. Some perpetual lease agreements also require an upfront payment by the customer. Typically the user prepays, meaning they pay before they can use the SHS. This arrangement is commonly referred to as “pay-as-you-go” (PAYGO).

From the perspective of the seller, a rent-to-own arrangement reduces their financial risk as the money is repaid faster than under a perpetual lease scheme. However, some sellers see value in maintaining an ongoing relationship with customers through the perpetual lease model. Over time, customers can be “up-sold” to more expensive and higher-quality SHSs, as well as appliances.

### ***13.7.3 Payment Models***

There are several considerations in designing a payment model for SHSs which apply to the rent-to-own and perpetual lease models. These considerations also apply to mini-grids.

*Payment method:* the transfer of money from the customer to the SHS seller can be done in several ways. The payment can be made in cash to the seller or an agent of the seller. However, this requires the seller to have a presence in rural locations and places an administrative burden on collecting and tracking cash payments.

In countries where mobile money<sup>1</sup> is available, it is possible for the customer to transfer money to the seller via a mobile phone. This is often more convenient for the customer and seller than in-person cash payments.

*Frequency of payment:* the frequency of payment is linked to the payment method. There is a burden placed on the seller and customer with each transaction, especially for in-person cash payments. This consideration favors weekly or monthly payments (typically, the customer prepays rather than post-pays). However, as the frequency of payments decreases, the amount per payment increases, which requires more financial planning and saving by the customer. Mobile money on the other hand facilitates more frequent payments. Daily payment requirements are common in mobile money schemes.

*Amount of payment:* the amount charged by the seller per payment depends on whether or not the customer is on a rent-to-own or perpetual lease arrangement. The pricing is often set to be cost-competitive with other fuel sources, typically kerosene. Payments ranging from US\$0.30 to US\$2.00 per day, depending on the size of the system, are common. Of course, the payment amounts and frequency and duration of payment must be sufficient for the seller to profit in the long term.

*Example 13.3* An off-grid family has two mobile phones and uses three kerosene lamps for lighting. Each mobile phone requires 5.0 Wh of energy to recharge and must be recharged every 3 days. Each kerosene lamp produces 20 lm and consumes 0.02 liters of kerosene each hour. The lamps are used for 4 h each night. The family pays US\$0.20 to recharge their mobile phone in the nearest electrified town. Kerosene costs US\$1.4/liter. What is the maximum daily amount that can be charged for a SL or SHS that is capable of recharging the mobile phones and replacing the kerosene use without increasing the family's expenditure?

**Solution** The average daily kerosene expense is

$$3 \text{ lamps} \times 0.02 \text{ liters/h} \times 4 \text{ h/day} \times \text{US\$}1.4/\text{liter} = \text{US\$}0.336/\text{day}$$

The average daily expense for mobile phone charging is

$$2 \text{ phones} \times \text{US\$}0.2/\text{charge} \times \frac{1}{3} \text{ charges/day} = \text{US\$}0.133/\text{day}$$

(continued)

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<sup>1</sup>Mobile money is common in developing countries. It is a payment service platform that enables individuals to transfer and receive money using mobile phones.

The total expenditure is  $\text{US}\$0.336 + \text{US}\$0.133 = \text{US}\$0.469/\text{day}$ . This is the maximum amount that can be paid by the family each day. While it might not seem like much money, a SL providing this functionality would likely cost less than  $\text{US}\$40$ . If the family paid for it under a rent-to-own plan at  $\text{US}\$0.50/\text{day}$ , they would own it outright in less than 3 months.

### ***13.7.4 Payment Technologies***

There are also technological considerations in choosing a SHS payment scheme. The primary consideration is how payment terms are enforced. There must be a consequence of nonpayment. This is typically removal or disablement of the SHS until payments are made. A low-technology way of enforcing payment is by physically repossessing a SHS if payments are not made. This method is time-consuming and could incite conflict between the seller and the customer as the SHS is being repossessed.

The repossession method of payment enforcement is falling out of favor as SHS sellers adopt more technologically advanced methods. One method is analogous to the prepaid method used in some grid- and mini-grid-connected systems. Upon payment, the customer is issued a unique code. The code is entered into a key pad on the SHS, which enables it until the next payment is due.

In systems that have remote control capability, the seller can remotely enable and disable the SHS. If a payment is missed, then the SHS is disabled.

There is another benefit of remote payment aside from the direct commercial and technological benefits of remote monitoring. The consumption patterns and payment profiles of the SHS can be stored and analyzed over time. This can lead to the construction of credit profiles of households, which can unlock and de-risk loans to rural individuals. It is too early to see if this application will be used, but the potential is at least interesting.

### ***13.7.5 Practical Considerations***

SLs and SHSs are products sold to individual customers. Like most products, branding and marketing are important. The leading companies strive to be associated with reliable, high-quality products. To this end, they strive to meet the quality standards set forth by independent organizations such as the Global Off-Grid Lighting Association (GOGLA) [1]. The GOGLA quality standards include targets for lumen maintenance, battery protection, physical quality (drop test), water

protection, and warranty, among others. With so many fake and imitation products in the marketplace, it is good practice to check which, if any, quality standards are met before purchasing a SL or SHS.

## 13.8 Summary

Solar lanterns (SLs) and solar home systems (SHSs) offer lower-tier electricity access on an individual or household basis. SLs provide sufficient light for basic tasks, and some can recharge mobile phones. SHSs are more expensive but can power multiple lights and in some cases small appliances. Over 40 million units have been sold, with sales now exceeding 10 million per year. The popularity of SLs in particular can be attributed to their low cost, coupled with the high price and low quality of competing lighting sources, especially kerosene.

There are several business models that can be used to lower the financial barrier to solar home system ownership. Rent-to-own and perpetual lease with pay-as-you-go payment plans are popular. These payment plans are enabled by remotely controllable SHSs, which can enable and disable SHSs depending on if payments have been made.

Most experts expect the markets for SLs and SHSs to continue to grow for the foreseeable future. The capabilities should increase as appliances designed for the off-grid market increase in availability and decrease in cost. Although the electricity access tier is modest, some see them as a reasonable transitional solution until higher-tier mini-grid or national grid access is available.

## Problems

**13.1** Repeat Example 13.1 but assume the SLs and SHSs require replacement every 6 years.

**13.2** The LED used in a SL has a luminous efficacy of 130 lm/W. The total lumen output is 90 lm. Compute the power required by the LED.

**13.3** A certain SHS includes four 5 W lights and one 7.5 W television. The battery is rated at 17 Ah at 12 V. Compute the number of hours the SHS can operate for under the following scenarios: (1) the four lights only, (2) the television only, and (3) the four lights and the television. Assume the daily depth-of-discharge is 60%.

**13.4** Determine the required capacity of the PV module of the SHS in the previous example assuming an average daily insolation of 5.0 kWh/m<sup>2</sup>/day. Assume the generation and storage losses are 20%. Do not include a design margin for the PV array.

**13.5** Determine the required charge capacity of the battery in a SHS designed to supply three 1.5 W LEDs for 8 h per night and a 15 W television for 3 h per night. The battery should be sized so that the daily depth-of-discharge is 40%. The nominal voltage is 14.4 V.

**13.6** Determine the required capacity of the PV module of the SHS in the previous example assuming an average daily insolation of 5.0 kWh/m<sup>2</sup>/day. Assume the generation and storage losses are 20%. Do not include a design margin for the PV array.

**13.7** Describe, in your own words, the difference between a perpetual lease and rent-to-own payment models.

## References

1. GOGLA: Global off-grid lighting association (2018). URL <https://www.gogla.org/>
2. Sturm, R., Njagi, A., Blyth, L., Bruck, N., Slaibi, A., Alstone, P., Jacobson, A., Murphy, D., Elahi, R., Hasselsten, J., Melnyk, M., Peters, K., Appleyard, E., Orlandi, I., Tyabji, N., Chase, J., Wilshire, M., Vickers, B.: Off-grid solar market trends (2016). URL <http://documents.worldbank.org/curated/en/197271494913864880/Off-grid-solar-market-trends-report-2016>
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