## CHAPTER 1

# Introduction *(Electricity & Electrical Energy Storage)*

## 1.1 Energy

Energy is one of the most basic concepts in physics. It is stated as ‘the capacity for doing work.’ Actually, it is a complex conception and rather difficult to define. Everything in the world is one or the other energy (or matter) and it makes things happen. Energy exists in several forms: radiation, chemical, electrical, thermal, gravitational, nuclear, and so on.

All these forms of energy are categorized as ‘potential energy’ or ‘kinetic energy.’ Potential energy is ‘stored’ energy, and when used to do ‘work’, it is called ‘kinetic energy.’ So, the kinetic energy makes things to move or happen; that is, a moving object possesses kinetic energy. An object of definite mass and volume moving at a certain speed has kinetic energy. If a car and truck travel with the same speed both have kinetic energy, but the truck has a more kinetic energy than the car because of its more mass. There are numerous examples in nature showing several kinds of potential energy and several types of kinetic energy. For example, the motion of waves, atoms, molecules, electrons and objects are all kinetic energy. Let’s see each of these forms of energy: *‘Radiant energy’* is electromagnetic energy that includes visible light, X-rays, gamma rays, and radio waves. Sun’s radiation is radiant energy that sustains life on earth. Atoms and molecules in the materials are held together by bonds. And the energy stored in the bonds of atoms and molecules is called ‘*chemical energy.’* The chemical energy in gasoline, natural gas, coal, and biomass converts to thermal energy when they are burned. For instance, when biomass/wood is burned or when gasoline is burned in a vehicle’s engine. Batteries are used to store chemical energy. *Electrical energy* is a type of kinetic energy caused by moving charged particles such as electrons, and the speed of the charges decide the amount of energy they carry. The energy stored in an electric field is also electrical energy. For example, (a) lightening during a thunderstorm is the release of electrical energy stored in the atmosphere, (b) energy that is stored in a power plant's generator is delivered to the consumer through transmission lines; (c) energy stored in a capacitor can be released to drive a current through an electrical circuit. Energy that an object possesses by virtue of its motion or position is called *mechanical energy*. The mechanical energy is termed as kinetic energy or potential energy: the former if the object is in motion or movement, and the latter due to its position (ie, it is stored energy). Examples of stored mechanical energy are compressed springs and a huge rock on a mountain cliff. *Nuclear energy* is the energy stored in the atom's nucleus, the core of the atom, which is huge. This energy can be released by 2 main nuclear processes, fission and fusion. Nuclear energy is used to produce electricity. *Gravitational energy* is the potential energy stored in an object positioned above the Earth and is released (as kinetic) when the object falls. Climbing stairs and lifting objects is work done against gravitational force. This work done against the gravitational force goes into an important form of stored energy. Hydropower is a good example of gravitational energy, where gravity forces water down through a hydroelectric turbine to produce electricity. *Thermal energy* is the energy given by a hot (heated) substance using the process of conduction or convection or radiation. The best examples are heat from the sun's radiation and geothermal energy. The internal energy of a thermodynamic system in equilibrium because of its temperature is an example. Thermal energy provided by concentrated solar radiation can be converted into electrical energy using a Stirling engine with a coupled generator.

Energy cannot be created or destroyed. Energy can be converted from one form to another, and can be 'conserved.' This is the most basic principle in physics, known as 'conservation of energy' or 'first law of thermodynamics' applicable in several physical and chemical processes.

All forms of energy cannot be stored. The forms that are difficult to store are converted into forms that are more suitable and economical and then stored. Some technologies offer short-term energy-storage, while others can sustain for a longer period.

## 1.2 The Power Problem

Electricity is generated at the central power generation sites such as coal- and natural gas-fired power plants and nuclear plants. The (MW) high power current is transmitted to substations by power cables, where the power is step-down to medium voltage and distributed to all types of consumers, domestic to government to industrial and commercial consumers.

The conventional grid design is a considerably centralized set-up. A centralized power system is susceptible to costly line breakdowns; and once the power line is downed, there could be extensive power failures severely affecting all sectors including common customers. With continually increasing population and the people getting used to several types of electronic and other devices, the per capita electricity demand has increased. Consequently, the aging grid infrastructure is likely to become less stable and less reliable if the utilities and other operators do not upgrade the old infrastructure.

The most important problem of recent origin, the electric grid around the world facing, is the addition of power from renewable-energy sources. Sources such as coal, gas or nuclear plants provide a steady flow of energy to the grid, which enables the distribution of a fair quality of power to all sectors or regions. But, in the last few decades, renewable power sources like wind and solar, which are intermittent have been pumping electricity to the grid in large amounts. As a result, the power levels alter with time of the day or with changes in the day's weather, creating several issues to the grid if directly pumped. The utility operators must stabilize the supply and demand constantly to keep up efficient flow of power and to meet the peak demand. As a result, it has become critical for most utility grids to utilize 'energy-storage' systems to store the excess energy generated by the renewables and discharge to the grid at the times of need.

The renewable solar and wind energy sources, though expensive to start with, are not only cheaper now but compete with fossil fuels without subsidy; hence, they are now preferred for electricity generation. Renewables already account for almost 30% of global electricity output, according to the International Energy Agency. The renewable costs have declined rapidly during the last decade, 2010-2019: solar PV by 82%, concentrated solar power (CSP) by 47%, onshore wind by 39% and offshore wind by 29%. The onshore wind and solar PV-generated power have both fallen below 5 US cents/kWh for the first time, and the fossil fuel thermal power generation is estimated to cost between 5 and 18 US cents/kWh according to IRENA [1a].

Following global trend, in India also, the cost of solar PV power generation has been falling and the recent 2GW solar auction in June 2020 by Solar Energy Corporation of India (SECI) had shown the renewable-energy tariff at Rs. 2.36/kWh, so far lowest in India, with zero indexation for 25 years [1b].

Each of these resources, however, has drawbacks. Though efficient and sustainable, they are intermittent because the sun shines in the day-time only and the wind resources are not ideal in many locations. These factors make the grid unstable as they try meeting demand. As a result, the grid needs frequency regulation. As the share of solar and wind energy increases with increased demand from the grid, extra flexibility is necessary for the entire system. This can be solved by a demand response and that is where the *energy-storage* helps. A large amount of solar or wind connected to the grid begin affecting voltage, and the energy-storage may help to balance the grid. For instance, in the U.S., the California state, which installed considerable solar power generation has zeroed in on storage as the key component of the smarter grid. The energy-storage, apart from providing frequency regulation on the grid and helping to stabilize intermittent solar and wind energy, can also provide other effects by moving to smarter grid. Energy storage not only accommodate this demand peaks but enables lesser investments in network expansion, thus avoiding high consumer costs. Storage, thus, offers one possible source of flexibility.

***Challenges in modern electrical power systems:*** A range of ancillary services is already required by current power systems to guarantee a smooth and reliable operation. The supply-demand need to be synchronized to make sure the quality of power supply (e.g., constant voltage and frequency, energy control, peak demand, bi-directional power flow and so on), so that a smooth supply is sustained to all consumers and elude any damage to electrical applications. With the desired flexibility services available to power systems, the grid operators can respond to sudden changes in demand or to the loss of large volumes of supply (e.g. large stations tripping offline, loss of an interconnection, and so on). This flexibility also facilitates operators to expedite the reestablishment of system equilibrium [8; 2a].To address these issues, energy-storage systems, which have many remarkable value functions and benefits are utilized in different ways [e.g. 2b, c].

## 1.3 Energy Storage Benefits

Energy storage plays an important role in creating a more elastic and consistent grid system. Consider a situation when there is more supply than demand of power, say, during the night when power generating plants operate continuously. The excess electricity generated can be used to power/charge storage systems [8].

Energy storage allows de-coupling of energy production from consumption. Thus, it decreases the necessity for constant monitoring and prediction of consumer peak energy demands (Figure 1.1).

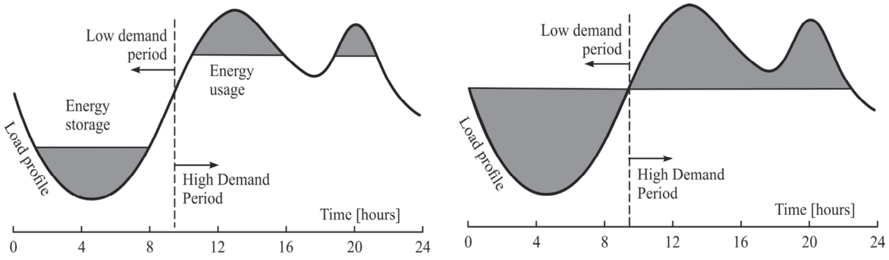

**Figure 1.1:** Energy demand (or load profile) over 24 hours of the day. (Left): figure shows a typical application of energy-storage; the energy-storage is load leveling, as shown in the figure on Right. (Source: [4])

Energy storage allows a decrease in energy production by the plant to meet average demands rather than peak demands. As a result, transmission lines and related equipment can be appropriately sized, thus saving financially.

Energy storage is particularly essential for the delocalized electricity production and to introduce fluctuating solar and wind energy sources. These intermittent sources make it more difficult to stabilize the power network, mainly due to a supply-demand imbalance. It is therefore convenient to generate the energy, convert it to suitable form, and store. The stored energy can then be drawn when required at a greater economic value or demand. More than ever, the storage of electrical energy has become a necessity with increased electricity generation from renewable-energy sources.

Long-duration storage can help avoid transmission and distribution improvements that involve huge capital cost. It would also add resilience and consistency by being available when the need is greatest, say, for peak demand conditions or supporting critical load during power outage.

Energy storage can provide back-up power during disruptions. The back-up idea can be extended to an entire building or even the grid in general. Energy storage offers flexibility for the grid to make sure continuous power supply to consumers, needed at any time and place. This flexibility is critical to both reliability and resilience. Energy storage supports achieving smart grids.

Energy storage is commonly used to smooth out the minor variations in energy output for small and large electricity generation sources.

Energy storage is also used in running electric vehicles (EVs) and trains, which further help reduce environmental effects.

Energy storage enables electricity to be saved for future days, when it is most needed. Storage makes the electric grid more efficient and capable, including the ability to reduce greenhouse gas emissions. It can increase the capacity factor of existing resources, and eliminate the need for constructing new peak power plants that contribute to pollution.

By introducing more flexibility into the grid, energy-storage can help integrate more solar, wind and distributed energy-resources (DERs).

As the energy supply mix becomes cleaner by including more low-carbon resources, energy-storage helps in developing such supply mix more easily and reliably.

Generally, energy-storage is a *technology* that allows for improved management of energy supply and demand. And a single unit of energy-storage set-up can provide multiple energy and power services.

In the coming years, as the grid progresses and adds new generation resources and consumption patterns, various combinations of capacity, power, reliability, and cost viability in storage technologies might prove useful [5].

Installations associated with grid and ancillary services are projected to grow by roughly 40 times over the decade, 2014 - 2024 (from 538.4 MW in 2014 to 20,800 MW in 2024) due to newly emerging factors such as renewables integration, energy demand, asset withdrawals, and technological innovation [6]. Energy storage among both commercial and residential users is expected to see much greater growth of about 70 times during the same period (from 172 MW in 2014 to 12,147 MW in 2024) due, in large part to the smart grid technology, *which optimizes power supply by using information on both supply and demand. The concept of smart grid is discussed in detail in later pages.* The range of storage technologies that fuel these exponential growth rates spans the states of energy and the principles of physics [6].

## 1.4 Energy Storage System Technology

Energy storage system technology is a method for converting energy from one form to a storable form and storing it in several media. The stored energy can be converted into electrical energy when needed [e.g. 2, 3]. The well-known battery is a simple device to store energy in the chemical form. The development of a technology to store electrical energy so that it can be available to meet demand whenever needed would represent a breakthrough in electricity distribution.

Energy storage technologies can be implemented on large- and small-scales allover the energy system. A few of these technologies are developed or near development, and most are still in the initial stages of progress.

Energy storage systems (ESS), however, have been expensive and non-viable economically on a commercial scale. However, continuous R&D in energy-storage technologies have led to gradual decreases in costs and improved technology applications, especially for Battery energy-storage systems.

Recently, high costs and low round trip efficiencies obstructed large-scale deployment of battery energy-storage systems. Nevertheless, increased use of lithium-ion batteries in consumer electronics and electric vehicles has led to a growth in worldwide production capacity, resulting in a significant cost decrease which is likely to continue over the next few years. Both the low cost and high efficiency of lithium-ion batteries have contributed to the surge of BESS deployments recently for both small-scale, behind-the-meter installations and large-scale, grid-level deployments [7].

## 1.5 Classification based on the Needs of the Grid[1]

It is the first grouping methodology differentiating the flexibility options based on their ability to balance the load and demand in the grid: (a) Electricity to electricity, (b) Electricity to non-electricity form, and (c) non-electricity form to electricity.

### 1.5.1 ‘Electricity to Electricity’ Storage Technologies

All storage systems, which ‘draw electrical power from the grid’ and ‘pump electrical power to the grid are referred to ‘electricity to electricity’ storage technologies.

As the grid is concerned, it is inappropriate how the energy is stored between these two functions. The main storage technologies under ‘electricity to electricity’ type storage systems, according to the *physical way* of storing the energy are the following. This sort of classification based on the ‘physical’ energy-storage is quite often used.

(i) *Electrical*: (a) Electrostatic fields, e.g. capacitors, super capacitors; and (b) Electrodynamic fields, e.g., superconducting coils

(ii) *Electrochemical:*

  (a) With *internal* energy-storage (here, power conversion and storage capacity are directly linked):

  - Redox-flow batteries [e.g., zinc–bromine with limited capacity due to material deposition in the stack during discharging]
  - Batteries (Pb–acid; Lithium–ion; Ni–Cd; Ni–Metal hydride; NaS & $NaNiCl_2$ batteries and several more)

  (b) With *external* energy-storage (here, power conversion and storage capacity are independent and not linked; sizing of power and energy capacity is separately possible):

  - Redox-flow batteries (components: Stacks, redox pairs in liquid solution in tanks);
  - Gas (components: electrolyzer for hydrogen production, optional: hydrogen to methane converter, gas storage system, fuel cells or gas turbines for generating power)

(iii) *Mechanical:* (a) Pumped Hydro Storage (PHS); (b) Compressed air energy-storage (CAES): diabatic; adiabatic; isothermal; isobar; and (c) Flywheels

(iv) *Thermal:* (a) Liquid air storage system, and (b) High-temperature thermal storage system

### 1.5.2 ‘Electricity to Non-electrical Energy’ Storage [1]

This category has flexibility options allowing the consumption of electricity and converting it into another form and stored for other uses. The stored energy is not used for generating electricity. Electricity usage currently is about one-fourth to one-third of the total energy consumption. Transport and space heating are the major energy consuming sectors apart from the power sector.

To cut down carbon emissions, it is necessary to practice energy savings (energy efficiency measures) and to use clean energy in all sectors. Hence, the conversion of low-carbon electricity into other forms of energy is necessary.

‘Electricity to nonelectrical form’ technologies may include storage.

(i) Thermal energy technologies *with energy-storage*: (a) thermo-chemical heat storage; (b) cold storage; (c) sorption storage; (d) latent heat storage, and (e) sensible heat storage;

(ii) Electricity to gas (e.g., hydrogen, methane); (iii) electricity to chemicals (e.g., methanol);

(iii) Thermal energy technologies *without energy-storage*: (a) Thermal energy (e.g., electrical space heating); (b) Demand-side management (switching on electrical loads in industry or private houses); (c) Shutdown of renewable power generators (loss of energy)

### 1.5.3 ‘Non-electrical Energy form to Electricity’ Storage

This category includes power generation units using fuels, which can generate electricity on demand. But, capital costs are high and the operation is expensive if they are not regularly used.

(i) Conventional power plants utilizing fossil or nuclear fuels

(ii) Power plants using biogas or biomass

(iii) Demand-side management (shutdown of loads in industry or private houses, including shutdown of charging processes for electric vehicles)

(iv) Stored thermal energy for power generation (e.g. concentrated solar power plants)

There are other types of classification in practice, which are explained in the next chapter.

## References

[1] Dirk Uwe Sauer (2015): Classification of Energy Storage Systems, in “Electrochemical Energy Storage for Renewable Sources and Grid Balancing,” editors: xxx, Elsevier, 2015.

[1a] Boom, Douglas (2020): 5-charts show the rapid fall in the costs of renewable-energy, Energypost.eu, Nov. 16, 2020 @ https://energypost.eu/5-charts-show the rapid fall in-costs-of renewable-energy/

[1b] Shah, K. (2020): Solar is displacing-coal in India’s electricity-market, Energypost.eu, November 19, 2020 @https://energypost.eu/solar-is-displacing-coal-in-indias-electricity-market/

[2a] Chen H, Cong T.N, Yang W, Tan C, Li Y, and Ding Y. (2009): Progress in electrical energy-storage system: a critical review. Progress in Natural Science. **19 (3)**, 291–312.

[2b] Baker, J. (2008): New technology and possible advances in energy-storage, Energy Policy, **36 (12),** 4368–4373

[2c] Grundy, A, and Colthorpe, A. (2019): Contenders – Long-duration Technologies and who is behind them, Storage & Smart Power, Energy Storage Technical briefing, p114-118, Nov. 2019.

[3] Dti Report. (2004): Review of electrical energy-storage technologies and systems and of their potential for the UK. DG/DTI/00055/00/00, URN NUMBER 04/1876, UK Department of Trade and Industry; p 1–34

[4] Sabihuddin, S, Kiprakis, A.E, and Mueller, M. (2015): A Numerical and Graphical Review of Energy Storage Technologies, Energies, **8,** 172-216; doi: 10.3390/en8010172 (Open access)

[5] Hart, D.M, Bonvillian, W.B, and Austin, N. (2018): Energy Storage for the grid: Policy options for sustaining innovation, paper presented at an expert workshop on Energy storage hosted by MIT Energy Initiative, Dec 7-8, 2017; MITIE-WP-2018-04.

[6] Deloitte (2015): Energy storage: Tracking the technologies that will transform the power sector @ https://www2.deloitte.com/content/dam/Deloitte/us/Documents/energy-resources/us-er-energy-storage-tracking-technologies-transform-power-sector.pdf (retrieved on 9/21/2018)

[7] Asian Development Bank (2018): Handbook on Battaery Energy Storage System, December 2018.

[8] IRENA (2017): Energy Storage and Renewables – Costs and Markets to 2030. International Renewables Agency, Abu Dhabi