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Mechanical Energy Storage for Renewable and Sustainable Energy Resources

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To Seif. Hoping the world is a much better place when you're in the driver seat.

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1 Introduction to Mechanical Energy Storage

1.1 Introduction to Mechanical Energy Storage

This book will focus on energy storage technologies that are mechanical in nature and are also suitable for coupling with renewable energy resources. The importance of the field of energy storage is increasing with time, as the supply and demand cycles become more and more stochastic and less predictable. To complicate matter further, not only does the storage problem involve purely technical aspects, it surpasses it into an intermingled financial, political, and socioeconomic factors. It is also quite inevitable that storage professionals will be in high demand, whose background would include various intertwining areas of science and engineering, with the purpose to design and implement customizable storage options that responds to individual parameters and inputs. A classical mechanical, chemical, or electrical engineer may not fit the bill anymore, given the interdependence of energy conversion steps on the availability of new materials and new technologies that can be utilized for energy storage purposes.

This being said, the discussions and cases studies of this book will be directed at mechanical energy storage technologies. Naturally, this does not omit the importance of other types of technologies dealing with energy transmission and conversion but rather places a greater emphasis on technologies that can alternate between a charged state (high potential energy) and discharged state (high kinetic energy). This is a subfield that has developed and grown in past decades, yet has not received the deserved attention in the storage literature, nor have some novel technologies (e.g., work of a buoyancy force) been discussed in detail in other textbooks.

1.2 Need for Storage Technology

Power plants have always been designed to supply a certain average demand called the baseload. And while the supplied load level can be controlled to be reliably constant throughout the day, changes and fluctuations in demand from the consumer side impose many challenges on power plant operators. The answer to the question of how to supply inevitable demand peaks that occur when activities of the population require the extra draw on the power resources is not a straightforward one. Figure 1.1 shows a typical demand cycle that starts at a low level in early morning hours, surges upward around midday and early evening hours, and then declines toward late night, only to repeat itself the next day.

The area under the curve marked in red is the extra demand that the power utilities have to supply. If not, these utilities could find themselves operating near their maximum capacity mark, which may cause a blackout if at some point the plant rated power is exceeded. Worse, residents could live through a repeat of the massive blackout that occurred in northeastern United States (and southwestern Canada) in the hot summer of 2013, when higher than usual demand on one power plant caused it to go offline, causing the electrically tethered power plants to automatically jump into the rescue and direct their supply to the fallen part of the network and cause a domino effect of power failures that left the most important economic and industrial hub in the world without power and water for more than 72 h.

Unfortunately, the response to such problems is not a simple matter of building more power plants. Apart from the environmental issues and human health risks that arise whenever a new utilities project is erected, these major

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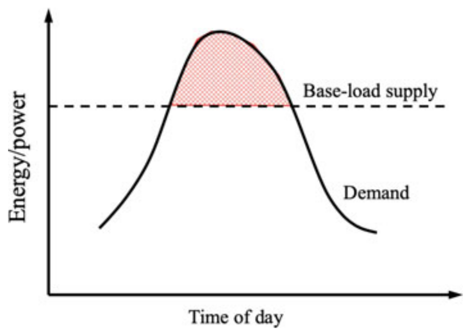

Fig. 1.1 Generic demand and supply of power over the span of a day

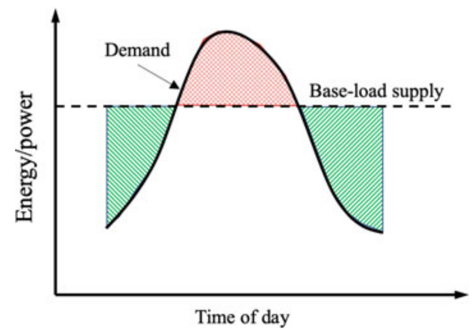

Fig. 1.2 Green areas where storage is permissible to keep power plant operating at baseload

projects require colossal budgeting from governments whom may not have the large sums required to invest in such a long-term solution. Also, building power plants that are capable of continuously supplying peak loads is seen as a waste of money and resources, because they respond to a fleeting surge in demand, only to have that extra capacity either idle or shut down more than half of its operational life. For this reason, expensive, yet temporary solutions in the form of gas turbines or internal combustion engines that can come online almost instantaneously are usually called upon to supply the demand transients, and then be shut off almost as fast as they were fired up.

And with the advent of reliably operational renewables, along with governments' mandates to reduce carbon dioxide emissions caused by the burning of fossil fuels, peak loads have found their match with technologies that are intensively available when those peaks occur. For example, solar photovoltaics and concentrated solar thermal power plants (CSP) are now augmented into the supply grid and their production mainly targets that red peak shown in the figure. For the moment they are not reliable enough to supply the baseload on their own, as their supply availability (the sun) is not always correctly predicted or ensured, but they definitely provide the extra energy needed to supply peak demand.

The missing link in the supply–demand cycle is storage. The proper selection, installation, and operation of storage technologies match the power/energy source in the required application. This means that whenever the supply is abundant, storage systems are charged and ready. Whenever demand supersedes supply, the power plant supplies its baseload, and the stored energy/power is withdrawn from its storage and is discharged to assist in resolving the strain on the power plant caused by peak load.

The green areas in Fig. 1.2 indicate where storage technologies need to be active. These areas will store the utilities supply, while their power plants operate at baseload all the time. This is more economical and efficient for conventional power plants, be it nuclear or fossil fuel based.

The book will also assist in answering the question about the selection of the most appropriate storage technology for a given source of energy. It is well known from thermodynamics that more energy conversion steps will result in a decrease in the available energy, as each energy converter has a certain efficiency that it operates at. Image that one has three energy conversion devices, operating at an unattainably high efficiency of 90% (most energy conversion devices operate at far less efficiency). The overall efficiency of these devices in series would be $0.9 \times 0.9 \times 0.9 = 72.9\%$. This is such a waste, and thus it is better to decouple the electric generators from their driving steam turbines and reduce steam generation in the power plant during times of low demand than to continue generating electricity only to store it in batteries for later use.

1.3 Storage for Renewable Energy Resources

Devising storage technologies for renewable energy resources in particular is a crucial step in the design and implementation of any renewable energy facility. The storage has twofold importance in such installations since they need to respond to the uncertainty of both the demand and the supply. For example, the unpredictability of the availability of wind energy necessitates the full-scale operation of wind turbines whenever wind energy is available regardless of the demand level. However, without proper storage provisions, this energy could be wasted. The "proper" storage provision in this case is a technology that requires least energy conversion steps, which definitely rules out chemical batteries: imagine, with the help of Fig. 1.3, the losses incurred when converting the incoming kinetic energy of a wind stream into rotational energy in the turbine blades, then mechanical rotation of a generator that has friction and eddy losses, and then the thermal and chemical losses in the batteries.

Not omitting the losses that would also have to occur when converting the DC power of the battery into AC, stepping it up in transformers in order to transmit it to the grid also would cause transmission losses.

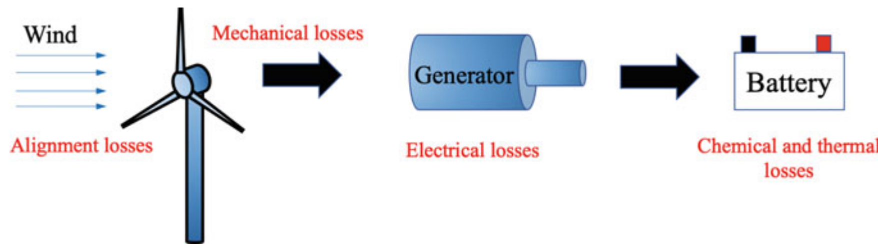

Fig. 1.3 Expected major losses for a wind turbine with chemical battery storage

1.4 World Energy Resources and Consumption

Although a major worldwide drive has been initiated to limit the reliance on the burning of fossil fuels, the high calorific value of such fuels (especially natural gas), the mature technology of drilling, shipping, and distribution as well as the full dependence of all modes of transport on such fuels have made any initiative to change the consumption habits a painfully slow process.

In the United States, although a diverse set of resources are available to contribute to the energy mix, oil and gas have around 67% of the share of the energy consumed in 2018. The statistics are very similar in other countries around the world (Fig. 1.4).

It is also interesting to note that 38% of these resources are directed toward electricity generation, while the rest is used directly by industrial or residential users or for transportation applications. Even more interesting is that 25% of the energy is lost in the form of electrical system energy losses, leaving only 13% of useful electricity generated, as shown in Fig. 1.5.

The whole world is thus "plugged", which means that individuals prefer electrical energy over any type of energy form. The electrical consumption footprint of each individual on earth is increasing every year (just think of how many devices one is charging every day, perhaps more than once a day), and the trend does not seem to be easing off. The need for energy, especially in its refined form that pours out of wall outlets and plugs, is reaching an all-time high all around the world and with it, the need for energy portability,

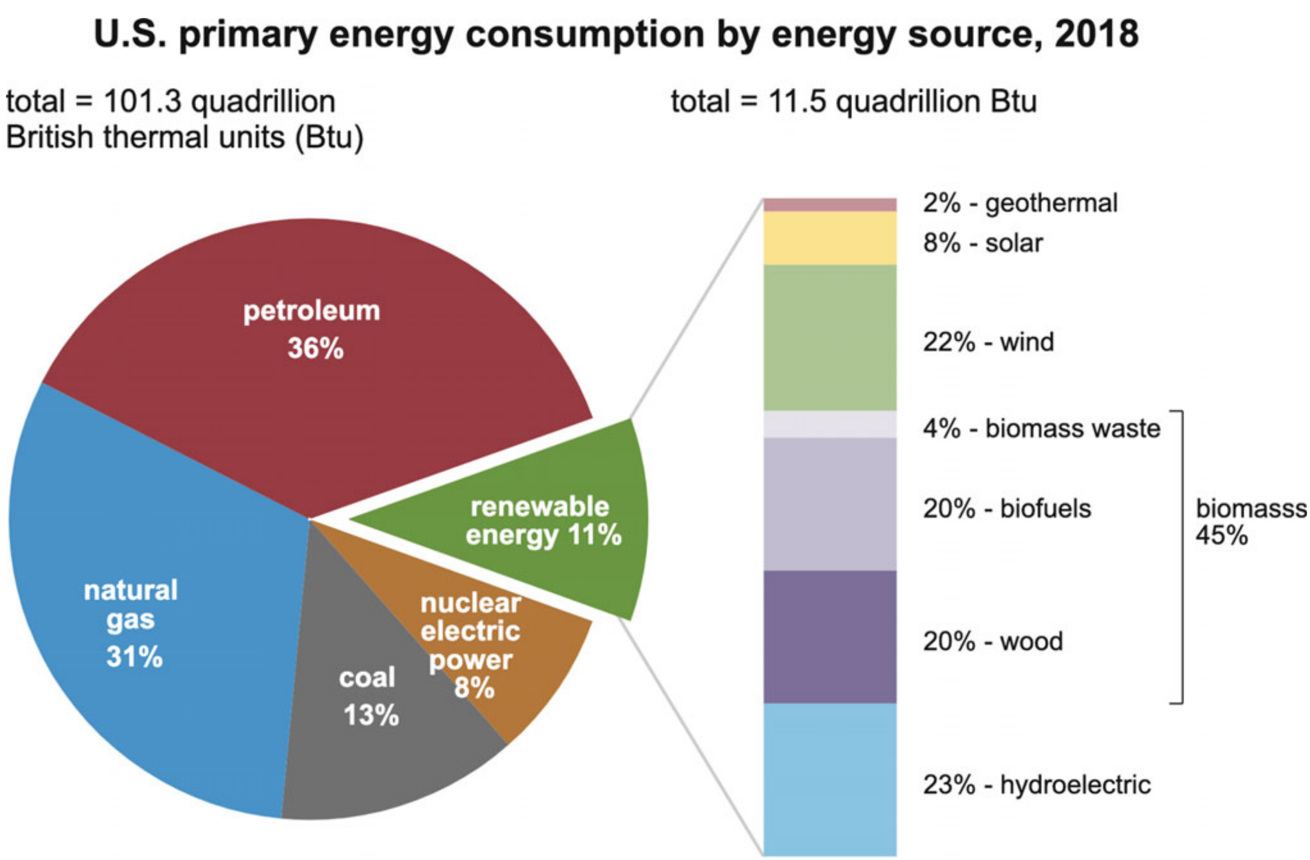

Fig. 1.4 U.S. energy consumption in 2018 classified by energy resource [1]

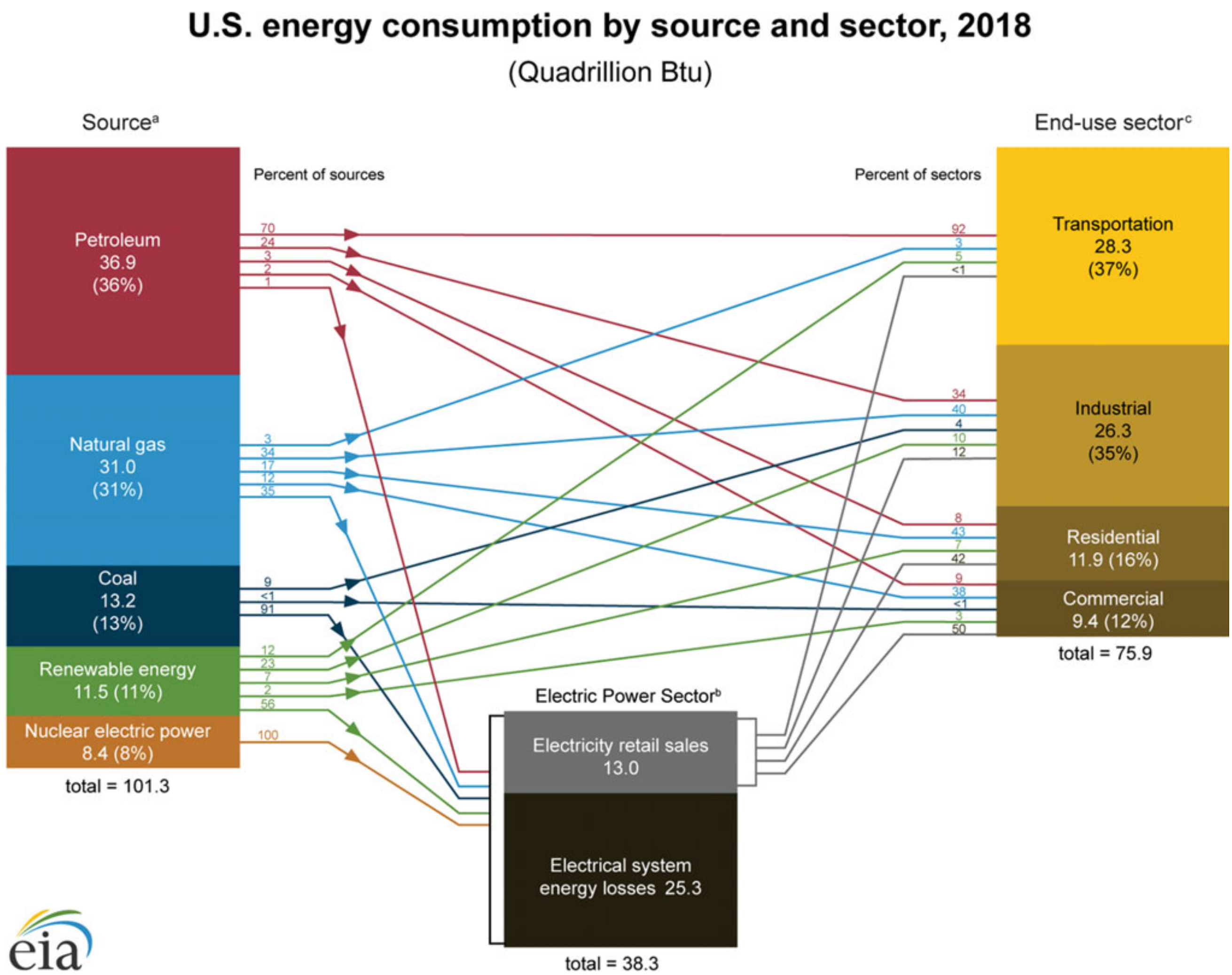

Fig. 1.5 Energy consumption by sector and resource in the United States in 2018 [1]

efficient energy transmission and more importantly energy storage is one of the most important tasks for energy engineers and professionals.

1.6 Available Storage Technologies

Luckily, batteries are not the only option for energy storage. It is true that electricity is the most sought-after form of energy, but this does not mean that only electrochemical storage routes are the most suitable ones. A general classification is shown in Fig. 1.8.

Each of the technologies presented in Fig. 1.8 can be matched with an energy resource and utilized at a certain stage of the energy conversion cycle. It is quite common to implement more than one storage technique whenever the need arises and the technical feasibility in terms of overall system efficiency permits.

The worldwide energy storage reliance on various energy storage technologies is shown in Fig. 1.9, where nearly half of the storage techniques are seen to be based on thermal systems (both sensible and latent, around 45%), and around third of the energy is stored in electrochemical devices (batteries).

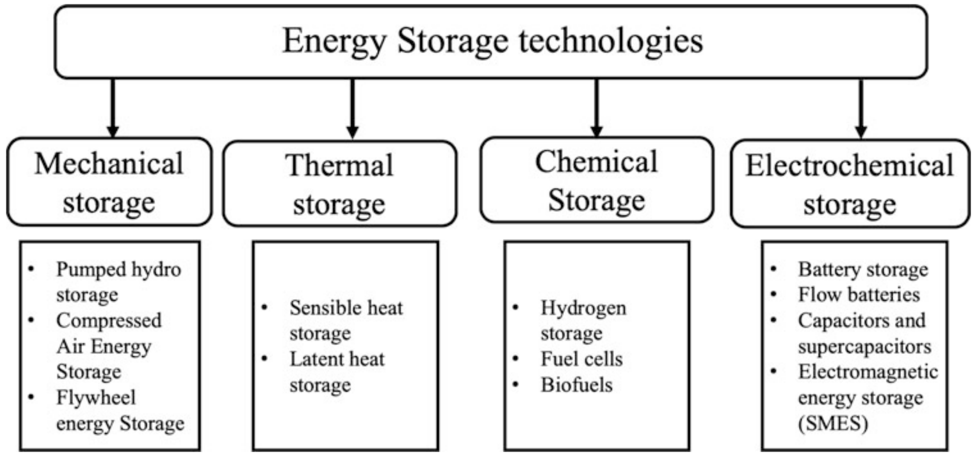

Fig. 1.8 General classification of available storage technologies

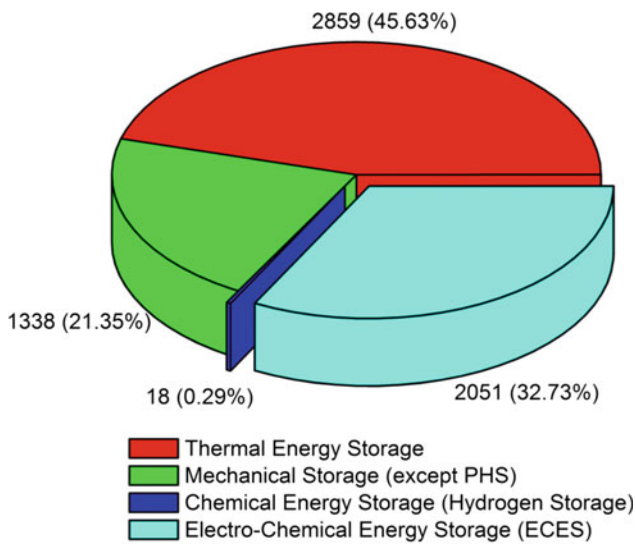

Fig. 1.9 Grid-connected operational capacities of all storage technologies [2]

1.7 Mechanical Storage Systems

The storage branch that is the focus of this book is mechanical technologies of energy storage. In Fig. 1.8, the classification shows that mechanical systems are strictly those who have a distinct and clear conversion of potential and kinetic energies. By examining the available reports in literature, it is clear that other technologies can be added to the original classification, as shown in Fig. 1.11.

The definition of mechanical storage technologies can also be expanded to include thermal storage systems, as it can be argued that the thermal storage mechanism in any material is based on a molecular-level increase in kinetic (vibrational) energy, which eventually leads to microstructural changes once the latent heat necessary to alter the phase of a material is reached. Although not present in Fig. 1.11, this book has a chapter devoted to thermal energy storage (TES) systems.

The common traits of mechanical storage technologies are their technical simplicity, robustness, and economic feasibility. And just like electrical energy being the current ultimate goal for all energy generation and conversion activities, mechanical energy is required to rotate the electrical generators that are connected to the grid, as shown in Fig. 1.12. This is a strong motivation to implement mechanical storage systems as early as possible in the power generation cycle.

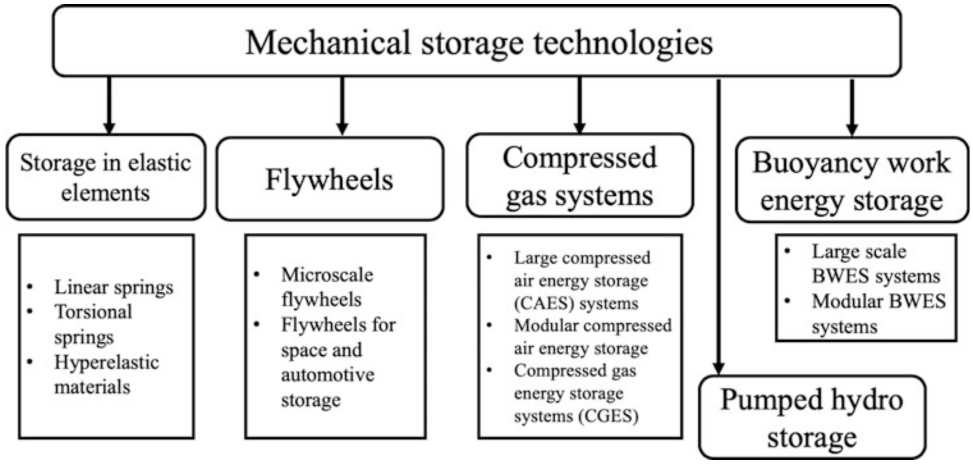

Fig. 1.11 Classification of mechanical energy storage technologies

Note that since energy storage in batteries can only happen after the electrical generator and before the grid connection, excessive conversion losses will be incurred due to attempting to wait till electricity is produced to store energy. It is thus beneficial to design and operate storage technologies that can absorb the kinetic energy and then release it to the generators whenever needed. Most of the technologies presented in Fig. 1.11 are at a level of maturity and commercial availability that they present a viable alternative to battery storage.

Mechanical technologies such as pumped hydro storage provide an enormous potential for load leveling as they can absorb all load abnormalities (be it supplying or storing the energy load). Their concept of operation has been applied on a small scale in water distribution in the past decades in countries with no skyscrapers. Figure 1.13a shows the simple principle of operation of such tank, where water is pumped from the central utilities storage tanks into the elevated tank at the top of the tower during low demand times (nighttime or weekends). Once water distribution is required (mainly at rush hour), the water is allowed to flow down-ward by gravitational pull, transforming the potential energy ($\rho g \Delta h$) into kinetic energy that allows the water to reach the tanks of residential buildings that are usually placed at a lower elevation. These towers are no longer in service with the advent of high-rise buildings and more efficient water pumping schemes. The water towers that did not get demolished are kept as an exhibition of discontinued old technology (see Fig. 1.13b for Al Khazzan Park, Dubai).

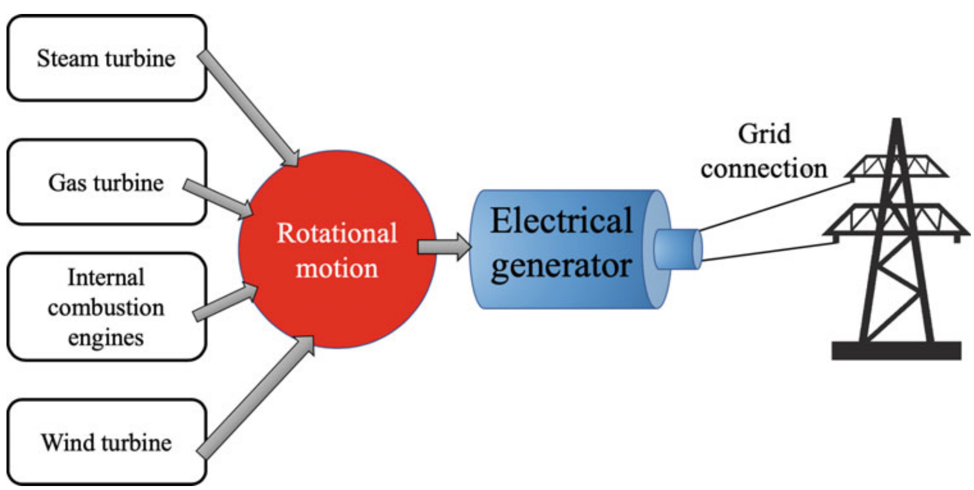

Fig. 1.12 Reliance of electrical power generation on rotational motion

(a)

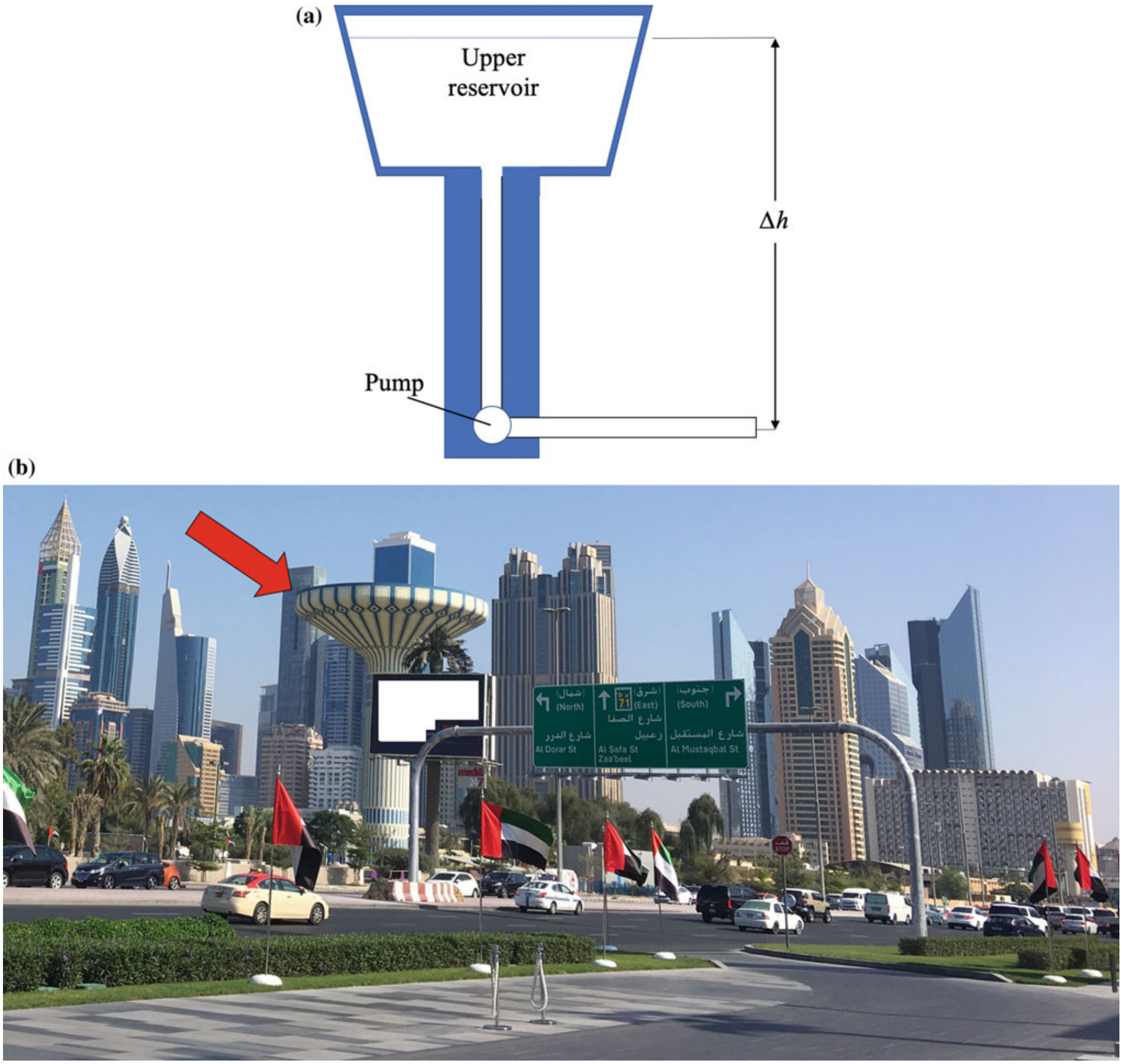

Fig. 1.13 **a** Water tower principle of operation and **b** an old water tower in Dubai, United Arab Emirates that received the status of a historical monument (Al Khazzan Park, Dubai)

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4 Thermal Storage

4.1 Thermal Storage

The thermal storage techniques can be classified in a variety of ways based on the energy source and the intended application. The main classification of thermal energy storage (TES) systems stems from whether or not phase transformation of the material is to be utilized for storage. If phase transformations are permitted, it is known to allow the system to hold on to the heat for longer times. This is known as latent heat storage that uses phase-change materials (PCMs), or materials that can change phase (from solid to liquid or liquid to vapor). This is different than the straightforward thermal storage that occurs without the phase change, which is known as sensible heat storage, that usually happens in well-insulated vessels and containers. An example of such a device is shown in Fig. 4.1.

When it comes to working fluids, water is by far the best thermal storage medium. It has the highest specific heat value at 4.182 kJ/kg, as well as other operational benefits, such as its availability and recyclability from one phase to another with benign effects on the carrying conduits (unless it is contaminated with pH altering substances that can cause unwanted corrosion or erosion). Table 4.1 lists some common materials with the nominal values of specific heat, c_p, thermal conductivity, k, and diffusivity. It should be noted that the thermal diffusivity, α, of a material is an indication of how fast heat can be transferred through it versus how much of this heat is stored within the material $\left(\alpha = \frac{k}{\rho c_p}\right)$ and thus the lower it is, the better the material is for storage.

Sensible heat storage is straightforward. The material with the lowest thermal diffusivity would be most suitable, and the phase chosen (solid, liquid, or gas) depends on the application and available installation. It is interesting to note that in ancient times people would expose bricks to the sun all day long, and then place them at strategic locations (where air circulates) in their dwellings to provide heating for the latter part of the day and into the evening. The concept is still being used in England and Australia (called Storage Heater) but for load shifting purposes. This system utilizes ceramic bricks placed on an electric heater (charging) during times where the electric tariff is cheaper for low demand cycles. Then, once the peak demand occurs with higher cost per kWh, the heater is shut off and the bricks would release the heat (discharge) to the surrounding by radiation, convection, or conduction. Special fans would also be used to enhance the forced convection component of the heat transfer. The bricks are one of the more attractive solid media for this purpose as it has one of the lowest thermal diffusivity values (Table 4.1). Bricks also would not incinerate and be a fire hazard compared with the more thermally attractive wood or break in the case of using glass, which also has an attractive thermal diffusivity value.

The sensible heat equation is quite simple, and by recalling the discussion in Chap. 2, the governing equation is the first law of thermodynamics for heat addition in the absence of any shaft work:

$$Q = mc_p\Delta T \tag{4.1}$$

The straightforward option is for the material with the highest specific heat capacity to be used to ensure sufficient capacity is available to store the heat load during system charging. Alternatively, the utilization of the proper quantity (mass) of a material with moderate heat capacity is required to handle the load. And since the heat in this case is expected *not* to be easily transferred, a layer of insulation (low thermal conductivity with low specific heat) should be applied to the storage reservoir as shown in Fig. 4.1 to prevent losses into the surrounding environment. The same goes for any piping or fittings leading to or from the supply/supplied device to ensure the highest operational efficiency.

4.2 Latent Energy Storage

Changing the phase of the heat storage material means that the energy content of this material is increasing without changing its temperature. Thus, a phase-change material can be utilized within the system, and its latent energy can be

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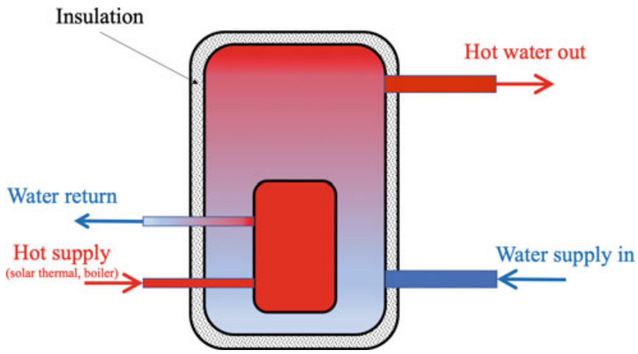

Fig. 4.1 The components of a sensible heat storage system

given to (charge) or extracted from (discharge) the heat transfer medium to achieve this goal. In this case, the material can be originally a solid changing phase into a liquid, or a liquid changing phase into a gas. Figure 2.5 shows how the energy content of a single phase changes almost linearly when heat is added that causes a temperature increase in the heat transfer medium up to the onset of the phase change that happens isothermally.

The equation for the heat transfer that includes the phase-change material is a modification of Eq. (4.1) as follows:

$$Q = mc_p\Delta T + mh_{fg} \tag{4.2}$$

where h_{fg} is the latent heat of fusion (for transformation from solid to liquid) or latent heat of evaporation (for transformations from liquid to solid) in J/kg. Note that there is no pertinent temperature change for the latent part of this equation as the phase transformation takes place at constant temperature ($\Delta T = 0$). Of course, this assumption that the latent heat is added at constant temperature is an idealized one, as the "thermal inertia" of the material does not allow the instantaneous heat addition to take place. This is a positive thing in a latent thermal storage system as it allows abundant input heat to first heat the material up (sensible), change the phase of the material (latent), and finally heat up the second phase of the material (sensible again).

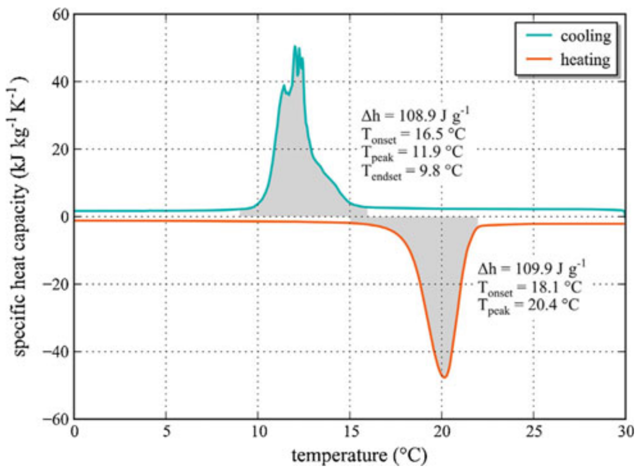

Fig. 4.2 DSC measurement for the eutectic salt hydrate mixture $Zn(NO_3)_2{\cdot}6H_2O$, $Mn(NO_3)_2{\cdot}4H_2O$, and KNO_3 [3]

Figure 4.2 shows a differential scanning calorimetry test of a salt material, with the peaks showing the latent energy intake/release signifying a phase change. Note that the phase change happens over a temperature range, rather than instantaneously at one temperature value, which is beneficial for the storage purpose. Also, notice how the latent energy peaks occur at different temperature values rather than at the same temperature when heating or cooling, which also indicates the hysteresis effect that the material suffers from during adding/removing heat.

Table 4.1 Thermal properties of common materials [4]

Material	Density ($kg\,m^{-3}$)	Specific heat ($J\,kg^{-1}\,K^{-1}$)	Thermal conductivity ($J\,m^{-1}\,K^{-1}$)	Thermal diffusivity ($10^6\,m^2 s^{-1}$)
Clay	1,458	879	1.4	1.10
Brick	1,800	837	1.3	0.86
Sandstone	2,200	712	1.7	1.08
Wood	700	2,390	0.17	0.10
Concrete	2,000	880	1.8	1.02
Glass	2,710	837	1.05	0.46
Aluminum	2,710	896	237	97.60
Steel	7,840	465	54	14.81
Air	1.27	1006	0.024	18.8
Water	988	4,182	0.6	0.14

4.2.1 Available Materials for Latent Heat Storage: Inorganic Materials

There are several candidate materials that can be suitable for latent heat storage applications. They can be classified mainly as either inorganic or organic materials. The former is in the form of salts and hydrated salts usually used for high-temperature applications. The phase transformation here is not limited to solid to liquid and vice versa, but also includes solid-state eutectic reactions. Some pertinent latent heat data is available for some inorganic materials and is shown in Table 4.2 where phase (solid to liquid) transformations occur, while Table 4.3 present similar data for inorganic materials where the solid-state phase transformations take place and is capable of temporary storage of heat. In this case, it is important to quote the accompanying changes in entropy at the transition temperature in order to be able to quantify the thermal capacity of the phase under consideration.

In most solid-state transformation instances, the general crystal structure of the material at or around the solid-state transformation temperature is not very different between the starting and end phases. Thus, the transition entropy values are not expected to be high, and most of the heat added to the material causing entropy change is due to the phase transformation from solid to liquid rather than the solid-state one. This explains the higher value of the melting entropy for a material such as FeS compared with its transition entropy. On the other hand, there are materials where the transition entropy is high due to unusual vibrational amplitude (inter-site mobility) of some atomic species; thus, materials such as AgI have a high mobility and this is reflected at the large value of transition entropy.

4.2.2 Organic Phase-Change Materials

There are several organic materials available for latent energy storage, and the data on the melting temperatures and heats of fusion for organic, fatty acids, and aromatic materials are given in the tables from Tables 4.4, 4.5 and 4.6.

Table 4.2 Latent heat values for inorganic materials [4]

Phase	Melting point (°C)	Heat of fusion $(\mathrm{MJ\,kg^{-1}})$
NH_4NO_3	170	0.12
$NaNO_3$	307	0.13
NaOH	318	0.15
$Ca(NO_3)_2$	561	0.12
LiCl	614	0.31
$FeCl_2$	670	0.34
$MgCl_2$	708	0.45
KCl	776	0.34
NaCl	801	0.50

Table 4.3 Solid-state phase transformation and melting entropy data for some materials [4]

Material	Transition temperature (°C)	Melting temperature (°C)	Transition entropy ($J.mol^{-1}.K^{-1}$)	Melting entropy ($J\ mol^{-1}\ K^{-1}$)
FeS	138	1,190	4.05	21.51
AgI	148	558	14.61	11.33
Ag_2S	177	837	8.86	7.01
Na_2SO_4	247	884	12.5	18.2
Ag_2SO_4	427	660	26.66	19.19
Li_2SO_4	577	860	29.2	7.9
$LiNaSO_4$	518	615	31.2	Small

Table 4.4 Latent heat values for organic PCMs [4]

Material	Melting point (°C)	Heat of fusion ($k.J.kg^{-1}$)
Paraffin wax	64	173.6
Polyglycol E400	8	99.6
Polyglycol E600	22	127.2
Polyglycol E6000	66	190.0

Table 4.5 Latent heat values for fatty acids used as PCMs [4]

Material	Melting point (°C)	Heat of fusion ($k.J.kg^{-1}$)
Stearic acid	69	202.5
Palmitic acid	64	185.4
Capric acid	32	152.7
Caprylic acid	16	148.5

Table 4.6 Latent heat values for aromatic materials used as PCMs [4]

Material	Melting point (°C)	Heat of fusion ($k.J.kg^{-1}$)
Biphenyl	71	19.2
Naphthalene	80	147.7

4.4 Thermal Storage for Solar Thermal Power Plants

To put the role PCM materials play in power cycles into perspective, it is useful to examine the "compulsory" provisions for latent energy storage that is part of solar thermal power plants that utilize concentrated solar power (CSP). Figure 4.5 shows the coupling between such power plant and a classical Rankine power cycle, complete with a steam turbine that generates the mechanical power needed to drive an electrical generator.

Since water has the highest specific heat, it would be infeasible to use it as the working fluid in a CSP cycle directly. Water will take too long to heat up and will require high pressures to keep water from evaporating at around 100 °C (the higher the pressure, the more energy can be packed into the water without losing it to evaporation, just like in a pressure cooker). There is also the transient nature of incoming solar radiation that necessitates the rapid conversion of the incident energy into sensible heat that will be eventually absorbed by the working fluid. Thus, using a salt (usually a calcium–potassium–sodium–nitrate-based mixture) that has a low melting point, a low value of heat of fusion is widely implemented. This working fluid is passed through the CSP array where it changes phase (becomes molten) and flows into a reservoir that acts as a buffer to ensure no shortage of salt supply will be suffered in the next stage, which is the main heat exchanger that transfers the heat into water. This heat exchanger is unmixed, meaning that the salt and water have their independent conduits and will not come in physical contact with one another, only thermal contact. The same amount of heat is transferred between the two fluids, but since the equilibrium energy equation is $\dot{Q} = \dot{m}c_{p,\text{water}}\Delta T = \dot{m}c_{p,\text{salt}}\Delta T$, the temperature rise in the water is expected to be much less than that in the salt since the specific heat of water is much greater than that of the salt (water has a little less than four times higher specific heat). But at high pressures (operating pressures on the waterside reach 10–15 bar), the thermal energy can be stored in the steam line until it is expanded in the steam turbine, where the Rankine cycle is also closed at the condenser, followed by the pump.

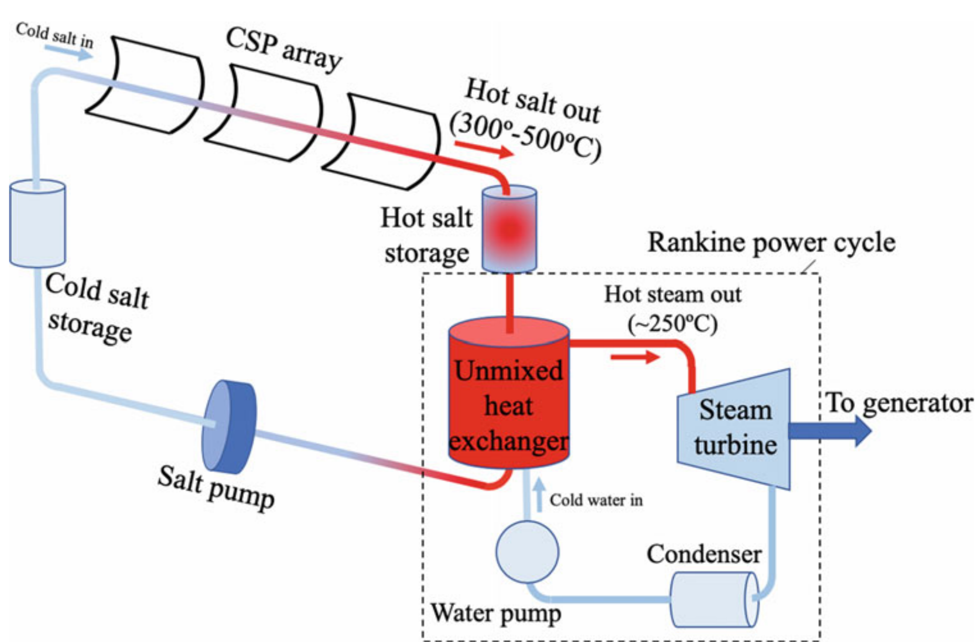

Fig. 4.5 Depiction of a concentrated solar power plant with a Rankine power cycle

The molten salt is then pumped back into the cold reservoir before completing its respective cycle and passing once more through the CSP array. It should be noted that the storage tanks for the molten salt also contain electrical heaters to ensure the salt remains at its pumpable molten state in the absence of thermal energy from the sun (at night or during overcast conditions). The thermal insulation of these tanks is also very important to prevent any heat loss to the environment in a manner similar to that shown in Fig. 4.1.

It is worth noting that the molten salt cycle is applicable also in the case of a heliostat (central receiver with a field of mirror arrays) system instead of the CSP array. Since this is a point-receiver system, as opposed to CSP being a line concentrator, the expected operational temperatures of the salt side are higher and can range in 400–600 °C for the molten salt side. This requires the waterside to operate at higher pressures to accommodate the expected higher temperatures that can range 300–450 °C. Such a system is shown in Fig. 4.6 operated by Solar Reserve [1] where salt storage tanks can be seen integrated around the central receiver installation to handle the molten salt cycle.

The following example will emphasize the importance of using heat transfer relations for steady-state conduction across the molten salt tank. Since the tank can be considered as a large reservoir that is always full of salt, heat transfer problems can be approximated to operate at steady-state conduction conditions. Thus, the thermal resistance circuit approximation can be applied, making the sizing of the reservoir an easy task. Remember that heat, just like electrical current, passes whenever there is a temperature difference between two points (analogous to a voltage difference). There are geometrical parameters, i.e., the surface area, A, length, $\Delta x = L$ as well as parameters related to the material, i.e., thermal conductivity, k, that determines how much heat will pass through the material. The heat conduction equation for the simple case of a plane wall is defined as

$$\dot{Q} = -kA\frac{dT}{dx} \approx -kA\frac{\Delta T}{L} \tag{4.3}$$

The analogy with Ohm's law is obvious: $\Delta V = \frac{I}{R} \equiv \Delta T = \frac{Q}{\frac{L}{kA}} = \frac{Q}{R}$ as summarized in Fig. 4.7. Note that the area in the case of a plane wall is not a function of the heat transfer length, L, but this is not the case when considering heat transfer by conduction in a cylinder or a sphere, where the area is a function of the radial heat transfer since the surface area is $2\pi rL$ and $4\pi r^2$, respectively.

The example at hand examines a spherical container of inner radius r_1 = 40 cm, outer radius r_2 = 41 cm, and thermal conductivity k = 1.5 W/m·°C that is used to store molten salt and to keep it at 300 °C at all times as part of a CSP plant as shown in Fig. 4.8. To ensure the salt remains molten, the outer surface of the container is wrapped with a 1500-W electric strip heater and then insulated. The temperature of the inner surface of the container is observed to be nearly 300 °C at all times. Assuming 10% of the heat generated in the heater is lost through the insulation, the following is required:

(a) express the differential equation and the boundary conditions for steady one-dimensional heat conduction through the container,
(b) obtain a relation for the variation of temperature in the container material by solving the differential equation, and

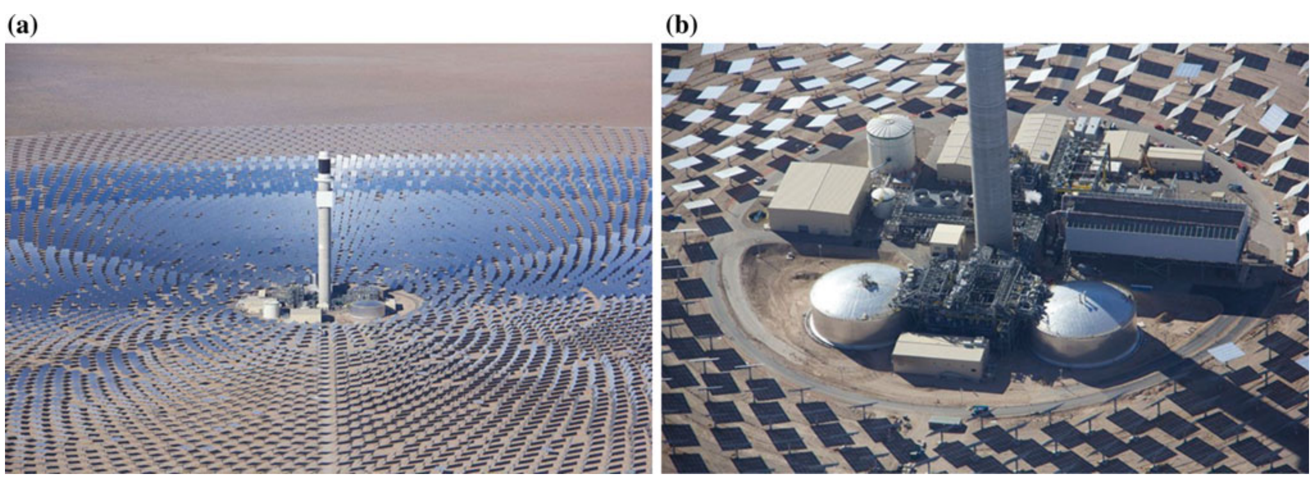

Fig. 4.6 **a** Heliostat field of Solar Reserve where **b** molten salt storage tanks are shown [1]

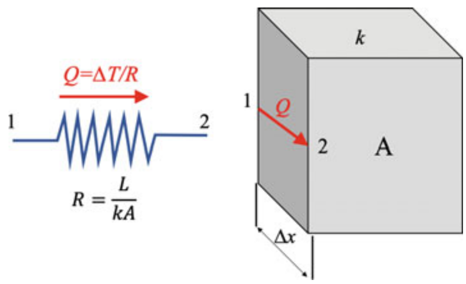

Fig. 4.7 Electrical circuit analogy for steady-state convection through a plane wall

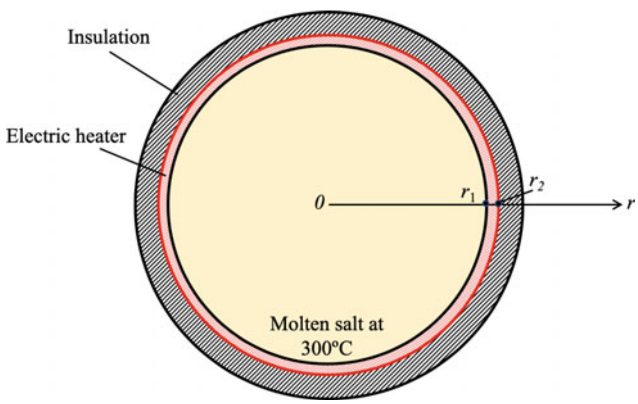

Fig. 4.8 Spherical container for storing molten salt

(c) evaluate the outer surface temperature of the container. Also, determine how much salt at 300 °C this tank can supply steadily if the cold salt enters at 150 °C.

To solve this problem, we first note that only 90% of the strip heater power is transferred to the container, and we can determine the heat flux (heat transfer per unit surface area) through the outer surface by the following formula:

$$\dot{q} = \frac{\dot{Q}}{A_2} = \frac{\dot{Q}}{4\pi r_2^2} = \frac{0.9 \times 1500}{4\pi (0.41)^2} = 639\ W/m^2$$

Assuming that the heat transfer is one-dimensional and in the radial r-direction (see Fig. 4.8), the mathematical formulation is expressed as

$$\frac{d}{dr}\left(r^2 \frac{dT}{dr}\right) = 0$$

With boundary conditions, $T(r_1) = T_1 = 300°$ and $k\left(\frac{dT(r_2)}{dr}\right) = \dot{q}$

The differential equation is integrated once with respect to r to yield: $\left(r^2 \frac{dT}{dr}\right) = C_1$

Dividing both sides with r^2 gives

$$\frac{dT}{dr} = \frac{C_1}{r^2}$$

then integrating again

$$T(r) = -\frac{C_1}{r} + C_2$$

Note that C_1 and C_2 are arbitrary constants. Applying the boundary conditions:

@ $r = r_2$:

$$k\left(\frac{C_1}{r_2^2}\right) = \dot{q} \rightarrow C_1 = \frac{\dot{q} r_2^2}{k}$$

@ $r = r_1$:

$$T(r_1) = T_1 = -\frac{C_1}{r_1} + C_2 \rightarrow C_2 = T_1 + \frac{C_1}{r_1} = \frac{\dot{q} r_2^2}{k r_1}$$

Substituting C_1 and C_2 into the general solution,

$$T(r) = -\frac{C_1}{r_1} + C_2 = -\frac{C_1}{r} + T_1 + \frac{C_1}{r_1} = T_1 + \left(\frac{1}{r_1} - \frac{1}{r}\right)\frac{\dot{q} r_2^2}{k}$$

$$= 300 + \left(\frac{1}{0.4} - \frac{1}{r}\right)\frac{639(0.41)^2}{1.5}$$

$$T(r) = 300 + 174.7\left(2.5 - \frac{1}{r}\right)$$

Thus, the outer surface temperature at $r_2 = 0.41$ m is $300 + 174.7\left(2.5 - \frac{1}{0.41}\right) = 310$ °C.

It is now straightforward to calculate the maximum rate of supply for the salt by using

$$\dot{Q} = \dot{m} c_p \Delta T$$

Knowing that the heater supplies heat at a rate of 1500 × 0.9 = 1350 W, the temperature difference is 150 °C and the specific heat of the salt is 1.3 kJ/kg.°C: the system can supply up to 0.005 kg/s (or 19 kg/h) of the molten salt at 300 °C.

4.5 Thermal Storage for Compressed-Air Energy Storage (CAES) Systems

The compressed-air energy storage systems will be discussed in full detail in Chap. 7. This section deals only with storing the heat generated due to the compression of air to utilize it later when the system is discharging, and the air is decompressing. The low temperatures that accompany the expanding air can cause the moisture content to either liquify or freeze, which has detrimental effects on the subsequent air turbine that is used to run the electrical generator.

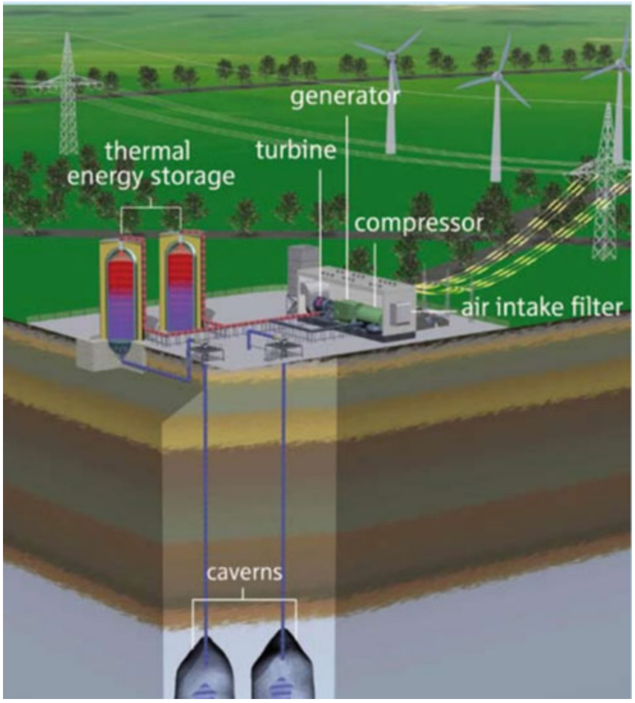

Fig. 4.9 ADELE compressed-air energy storage (CAES) system showing the heat exchangers for thermal energy storage

The heat storage in such cases takes place in a container similar in concept with the one shown in Fig. 4.1, but for the purpose of the rapid flow of air during charging and/or discharging, the heat exchangers will also act as thermal storage whenever the need arise. The process uses the same heat generated during compression (note the relationship between the temperature and pressure: $PV = \rho RT$) and supplies it back to the stored air during decompression. This is analogous to checking in your coat at a ball for storage, and later gets it back when it is time to leave. The heat exchangers fit at the inlet of the underground storage caverns where air is stored (heat extraction) and the outlet of the caverns (heat recovery) as shown in ADELE installation of Fig. 4.9, which will be discussed in detail later.

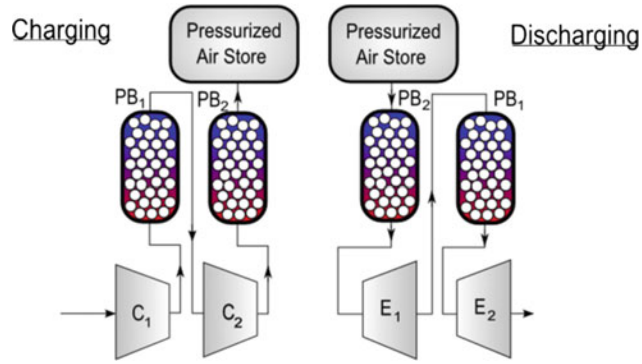

Fig. 4.10 Packed-bed heat exchangers for heat storage during air compression (charging) and heat supply during expansion (discharging) in a CAES system [2]

Such heat exchangers have to extract/supply the heat to the compressed/expanding air, respectively at a high rate. Thus, the heat exchangers are usually selected to have a high surface area and internal components (i.e., pipes) with high thermal conductivity so as not to impede the heat flow. One such system is shown in Fig. 4.10 [2] where packed-bed heat exchangers are used for storing the heat during the compression cycle at a maximum operating pressure of 80 bar and an air storage volume of 182 m^2. The reported efficiency of such a system is over 70%, which means that external heaters may be used but are not necessary to compensate for the heat loss to the environment.

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Flywheel Storage Systems

5

5.1 Flywheel Storage Systems

The first known utilization of flywheels specifically for energy storage applications was to homogenize the energy supplied to a potter wheel. Since a potter requires the involvement of both hands into the axisymmetric task of shaping clay as it rotated, the intermittent jolts by the potter foot meant that the energy supply would have short-term peaks when a pulse of energy is supplied, then it will trail off during the time it takes the potter foot to reach the wheel again. The friction from the bearings of the setup and the applied torque from the potter hands will rapidly consume the energy supplied by the initial kick. The addition of a flywheel is expected to assist in the stabilization of the operation of the device. The flywheel in fact is simply just an extra mass that will keep the kinetic energy of the system, defined as $\frac{1}{2}I\omega^2$, as steady as possible by normalizing the discrepancy of energy charge/discharge levels. In this particular case, this is achieved through increasing the physical inertia of the system (the resistance of the system to any change of its motion). Figure 5.1 shows examples of the progression of flywheel applications through time and different technologies. Note that the common factor of utilizing a flywheel for energy storage is the reciprocating nature of the energy supply, where the input energy peaks and then diminishes. Most intermittent or reciprocating prime movers that are characterized by providing a power stroke as part of their operational cycle need a flywheel to store excess energy during input peaks that would prove useful during the return/exhaust stroke for the normalization of the chrono-energetic exchange cycle of the system.

Just like the mass, m, in the linear kinetic energy equation $\left(\frac{1}{2}mv^2\right)$, the moment of inertia, I, in the rotational kinetic energy definition $\left(\frac{1}{2}I\omega^2\right)$, represents the resistance of the moving body to changes in its momentum. This term increases with the increase of the mass of the wheel as well as with the increase in its radius, r, around the axis of rotation (remember that $I = \frac{1}{2}mr^2$). Thus, the bigger the radius of a rotating body, the more difficult it would be to get it to rotate but at the same time it would be difficult to slow it down or instantaneously bring it to a complete stop. In this inertia/applied force, interaction lays the basic concept behind the utilization of flywheels for energy storage in any mechanism. Some common values of the moment of inertia are given in Fig. 5.2 for different shapes and configurations.

Table 5.1 gives examples of flywheel characteristic based on the technology available.

The flywheel storage technology is best suited for applications where the discharge times are between 10 s to two minutes. With the obvious discharge limitations of other electrochemical storage technologies, such as traditional capacitors (and even supercapacitors) and batteries, the former providing solely high power density and discharge times around 1 s and the latter providing solely high energy density discharge times of over 100 s, flywheels have significant advantages for discharge times between 1 and 100 s and discharge powers above 20 kW as shown in Fig. 5.3.

The components of a flywheel energy storage systems are shown schematically in Fig. 5.4. The main component is a rotating mass that is held via magnetic bearings and enclosed in a housing. The magnetic bearings have the same polarity as the rotor itself and thus generate repulsive forces that keep the flywheel magnetically levitating, and thus reduce friction losses within the bearings. The housing of the flywheel should support vacuum conditions that minimize windage losses synonymous with (and proportional to) high rotational speeds. There is also a clutch system that is physically engaged through an electromechanical control system (not shown) to supply/absorb energy from the prime mover whenever the need arises; otherwise, the system keeps rotating at a prescribed constant rotational velocity, ω, that is not expected to decrease or increase without external interaction. The motor/generator connection can either be AC or DC along with the appropriate rectification/inversion circuit.

Another version of flywheels would have the rotor of the motor/generator complete with winding capable of performing the function of the flywheel mass, and thus the

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Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-030-33788-9_5

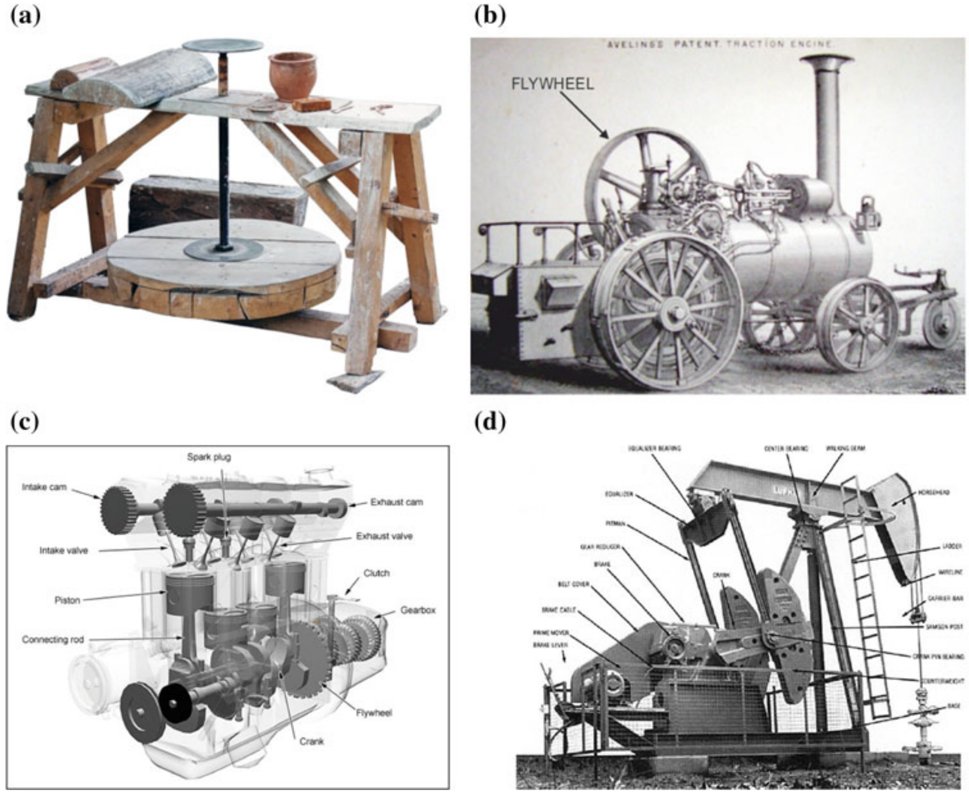


Fig. 5.1 Flywheel examples in **a** potter wheel [1], **b** early steam engine [2], **c** internal combustion engine [3], and **d** pumpjack counterweight in a reciprocating pump

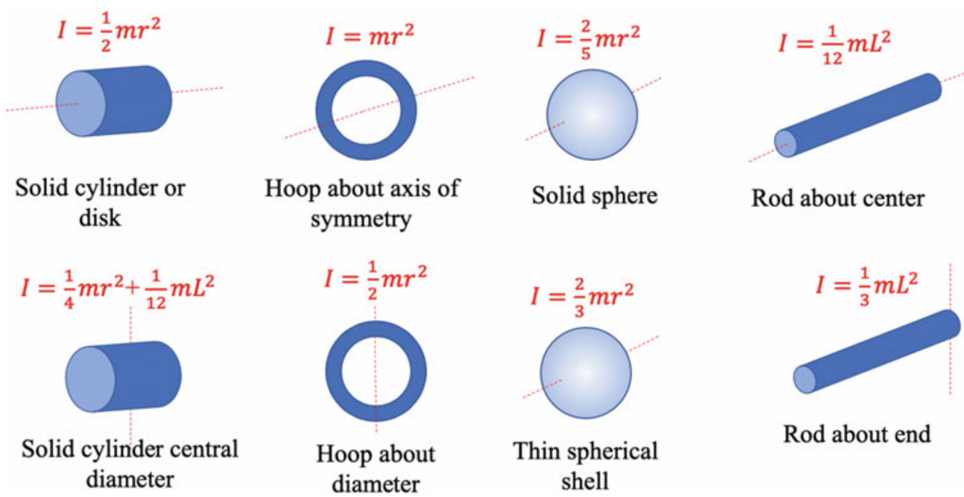


Fig. 5.2 Moment of inertia for common shapes around various axes [4]

housing would be the stator. This configuration would be more efficient in terms of space saving but would complicate the flywheel construction and maintenance.

The main available technologies for generators/motors (prime movers) that flywheels are expected to play a major role in providing storage for are gas turbines, natural gas engine generators, and fuel cells. In the event of a sudden load (demand) drop in the case of an industrial process turning off, the flywheel steps in and absorbs the load from a fuel cell or other prime mover without disrupting its generation, granting it time to adjust (lower) its output and then the flywheel would disengage either physically (clutch off) or electromechanically if the flywheel was the rotor of the generator. On the other hand, if the load (demand) suddenly increased when an industrial process is suddenly brought online, the flywheel is able to shed some of its power to cover the instantaneous spike in demand, while the prime mover is catching up and would then also disengage. These

Table 5.1 Example of flywheel characteristics [5]

Object	Mass (kg)	Diameter (m)	Angular velocity (rpm)	Energy stored (J)	Energy stored (kWh)
Bicycle wheel	1	0.7	150	15	4×10^{-7}
Flintstone wheel	245	0.5	200	1680	4.7×10^{-4}
Train wheel (60 km/h)	942	1	318	65,000	1.8×10^{-2}
Large truck wheel (60 km/h)	1000	2	79	17,000	4.8×10^{-3}
Train braking flywheel	3000	0.5	8000	33×10^{6}	9.1
Electrical power backup flywheel	600	0.5	30,000	92×10^{6}	26

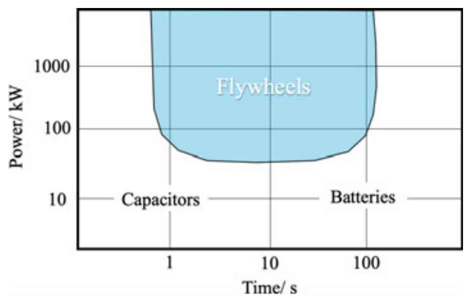


Fig. 5.3 Advantage of flywheels over batteries and capacitors for a specific energy range (power and time) [5]

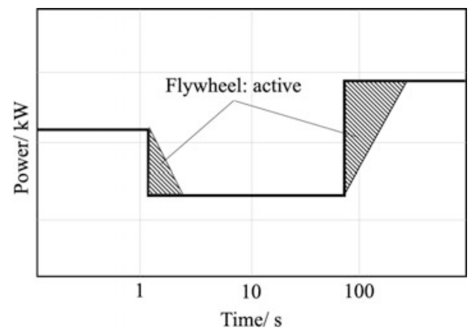
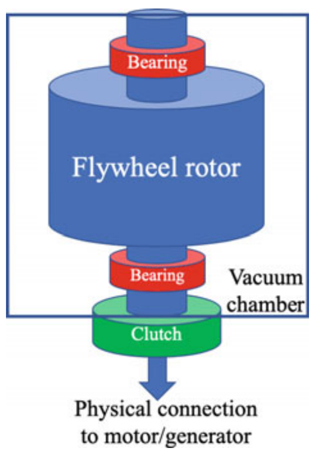


Fig. 5.5 Gradual energy smoothing by flywheel of step load changes [5]

Fig. 5.4 Illustration of the main components of a flywheel storage system



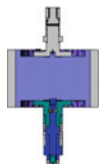
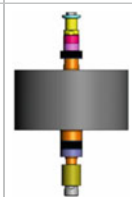
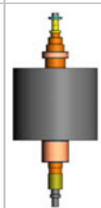
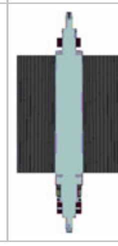
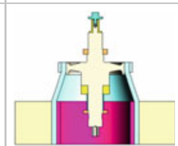
two cases where the flywheel eliminates power disturbances and keeps the voltage constant are shown as the shaded triangles in Fig. 5.5.

5.2 Flywheel Design

In order to achieve maximum kinetic energy absorption/release during the operation of the flywheel, it is more appealing to have faster rotational speeds rather than increase the volume of the flywheel, since the kinetic energy is proportional to the square of ω but (only) directly proportional to I. However, care must be taken during the selection of operational rotational velocities of the flywheel because the linear velocity at the furthest point of the rotating disk equals $v = \omega r$, where r is the radius of the disc, and whenever the velocity approaches the sound velocity within the material, there is the danger of developing dangerous shockwaves that are detrimental to the disk integrity and will cause it to uncontrollably shatter. For example, the speed of sound within steel is ~5120 m/s, and if a 1 m flywheel disk is rotating at 10,000 rpm (1047.2 rad/s), the linear velocity of the rim of the disk would be ~523 m/s, which is 0.1 M. This should be one of the limiting cases during the material selection phase of the flywheel.

The rapid advances in materials and discovery of reinforced polymers and ceramics have provided flywheel designers with a comprehensive list of materials that can behave favorable under the high values of centrifugal forces that will stem from the high speeds of flywheel rotation. These materials were not available (or at least were not commercially mature) half a century ago and thus the reliance was mostly on metals that were strong enough to handle the load without failure and at the same time contribute to the inertia portion of the energy equation by having high densities or large volumes. Fortunately, this is not the case anymore with the fabrication and implementation of very reliable composite materials such as fiberglass or

Table 5.9 NASA rotor development for flywheel energy storage onboard the ISS [12]

Flywheel	HSS	Dev1	D1	G2	FESS	G3
Features	Steel hub	Single-layer composite	Multilayer composite 750 m/s	Multilayer composite 750 m/s	Multilayer composite 950 m/s	Composite arbor 1100 m/s
Energy (Wh)	17	300	350	581	3000	2136
Specific energy/ ($\mathrm{Whkg^{-1}}$)	1	23	20	26	40	80
Life (yr)	NA	<1	1	1	15	15
Temperature (°C)	NA	NA	25–75	25–75	NA	–25–95
Illustration						

modules, power electronics, sensors, and controllers) of 25 Wh/kg, and an efficiency of 85% (efficiency is also measured at the system level as the ratio of energy recovered in discharge to energy provided during charge), a lifetime of around 15 years (compared to a couple of years for batteries), and a tested operational temperature range of −45° to 45 °C.

The progress in flywheel development for NASA is quite interesting. Table 5.9 shows the development of various rotor materials that serves the purpose of providing attitude control of the ISS as well as energy storage. Starting from the classical steel hub flywheels (that is added for reference), the composite material flywheels made it far more attractive to install flywheels instead of the more conventional battery banks. This is a major benefit with the intermittent availability of the solar photovoltaic modules. Flywheels have flexible charge/discharge profiles, so these solar arrays are more fully utilized. More importantly, flywheels can operate over extended temperature ranges, reducing thermal control requirements that would arise with chemical battery banks, and their state of charge is precisely known from their velocity profiles, thus limiting any unpleasant surprises and power outages, especially toward the end-of-life period of batteries.

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6 Pumped Hydro Storage

6.1 Pumped Hydro Storage

Pumped hydro storage is analogous to the operation of a massive battery, capable of storing hundreds of megawatts of energy in a simple and sustainable manner. Hydrogeneration projects are strategic in nature and always involve an investment on a national scale. Hydroelectric power is the gift of nature for countries that have water resources (rivers or lakes) and also the topography that supports such projects.

Pumped hydro storage is complementary to hydroelectric generation, and its concept of operation is quite simple, as shown in Fig. 6.1. During periods of high demand, water from the upper reservoir is released with large momentum through water turbines, where the substantial water head stored behind dam walls converts the potential energy into mechanical energy through the rotation of the turbines. The turbines are coupled with generators that produce steady electrical supply that can quite comfortably cover the baseload requirement without interruption. This operation phase, shown in Fig. 6.1, pertains to the hydrogeneration part of such an installation.

The pumped hydro storage part, shown in Fig. 6.2, initiates when the demand falls short, and the part of the generated electricity is used to pump water from the lower reservoir back into the upper reservoir. Since this operation is allowed to take place for a time duration from six to eight hours (before the demand surges up again the next day), the power used up by the pump motors is not expected to be substantial and is only a fraction of the power generated via potential energy conversion. Pumps only need to have enough energy to surmount the elevation head demand, and the rate of energy consumed can extend overnight. One can think of this in terms of energy needed to climb a flight of stairs. You can either go up one step at a time, or you can run up the stairs, skipping two steps at a time. In both cases, the energy required is the same, but the power expended (energy/time) is different. And thus, such installations capitalize on the relatively long periods of no demand to secure the water back into the upper reservoir.

It is also important to note that run-of-river systems share the same operational concept as shown in Fig. 6.1, with no need of a reservoir to hold the water at a certain elevation. These systems capitalize on the kinetic energy already provided by the flow of the river (or more preferably a waterfall). For example, Niagara Falls Hydropower Plant on both the Canadian and the American sides have a height of 51 and 54 m and 600,000 and 2,400,000 L per second, respectively. Figure 6.3 shows the location of the Niagara Falls power station, along with a cross section of the enormous original 70,000 hp cast iron water turbine coupled with the electric generators. As the river and waterfall are moving continuously, pumped hydro storage options seem infeasible, as there is little benefit from pumping the water back into the upper reservoir, and perhaps other storage technologies (like flywheels) can be employed.

Table 6.1 lists some examples of large pumped hydro stations around the world. It is interesting to note that the Niagara Falls station (and other run-of-river stations) is not mentioned there as they are not considered pumped hydro storage facilities.

6.2 Governing Equations

Fluid flow is governed by the complex Navier–Stokes equations that are partial differential equations that originate from Newton's second law, $\vec{F} = m\vec{a}$, and include all types of forces that affect a fluid element, with all resultant accelerations that are induced. In contrast to solids, the Second Law applied to fluids involves the inclusion of a host of forces, such as body forces, friction (viscous) forces, and pressure forces that have multiple effects on the body resulting in more than mere translation of the particle. Remembering that a particle velocity is the undisputed indicator of its direction of motion, and that accelerations resulting from applied forces pertain not only to changes in the magnitude of the

A. H. Alami, *Mechanical Energy Storage for Renewable and Sustainable Energy Resources*, Advances in Science, Technology & Innovation, https://doi.org/10.1007/978-3-030-33788-9_6

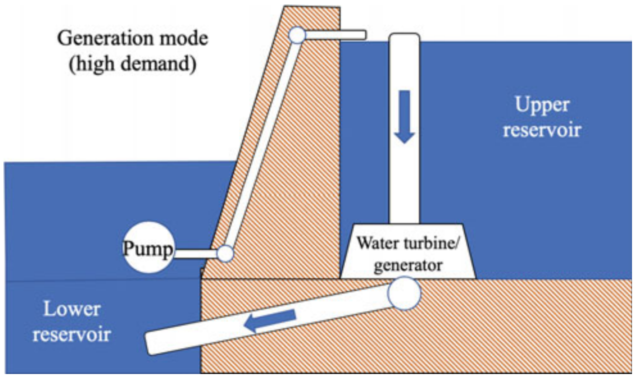

Fig. 6.1 Generation operation mode where water is routed through the turbines

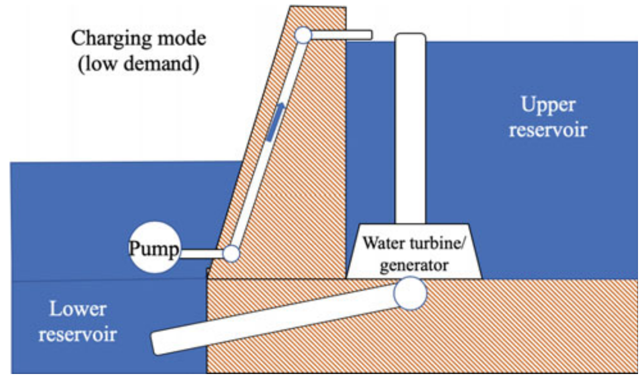

Fig. 6.2 Charging operation mode where water driven by pumps from lower reservoir to upper reservoir

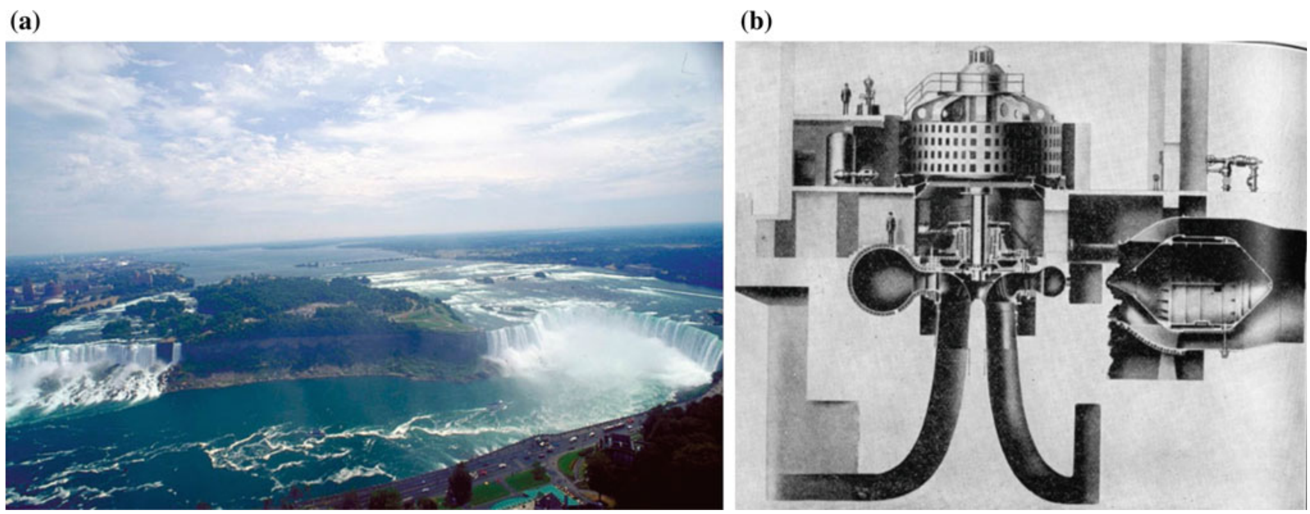

Fig. 6.3 **a** Niagara falls run-of-river hydropower station with **b** the 70,000 hp ~50 m head 107 rpm water turbine [1]

velocity but also changes in the direction of motion, too, then one can expect an extremely complicated vector equation to govern fluid flow. One should rely on a solid mathematical model in order to predict the effect of the forces applied on the fluid as a whole (and not just the constituent particles). Remember that in fluid mechanics, Navier–Stokes is also known as the energy equation, and in order to isolate the energy exchange with a fluid, one should describe the system in terms of these equations.

Just to appreciate the magnitude of the computational power that has to be availed to solve these equations (no one has successfully managed to solve or apply these equations analytically), they are reproduced in the following simplified vector form shown in Fig. 6.4.

Table 6.1 Examples of pumped hydropower stations around the world [2]

Country	Station name	Capacity (MW)
Argentina	Rio Grande-Cerro Pelado	750
Australia	Tumut Three	1,500
Austria	Malta-Haupsufe	730
Bulgaria	PAVEC Chaira	864
China	Guangzhou	2,400
France	Montezic	920
Germany	Goldisthal	1,060
	Markersbach	1,050
India	Purulia	900
Iran	Siah Bisheh	1,140
Italy	Chiotas	1,184
Japan	Kannagawa	2,700
Russia	Zagorsk	1,320
Switzerland	Lac des Dix	2,099
Taiwan	Mingtan	1,620
United Kingdom	Dinorwig, Wales	1,728
United States	Castaic Dam	1,566
	Pyramid Lake	1,495
	Mount Elbert	1,212
	Northfield Mountain	1,080
	Ludington	1,872
	Mt. Hope	2,000
	Blenheim-Gilboa	1,200
	Raccoon Mountain	1,530
	Bath County	2,710

6.3 Technical Consideration Pumped Hydro Storage Systems

For a particular site to be favorable for pumped storage hydropower, there are some key technical considerations to be assessed. They include the following:

1. Topographic conditions that provide sufficient water head between upper and lower reservoirs,
2. Strong geotechnical site where no avalanches or landslides expected,
3. Availability of sufficient quantities of water, and
4. Access to electrical transmission networks.

It is also important to design a hydroelectric system with provisions for pumped hydro storage when possible. This should also be done with the consideration of long-term variation of power demand/supply patterns in mind to facilitate the expansion of the operation of a hydro facility in the future. The minimum practical head for an off-stream pumped storage project is generally around 100 m, with higher heads being preferred. Some projects have been built with heads exceeding 1000 m. These projects involve the

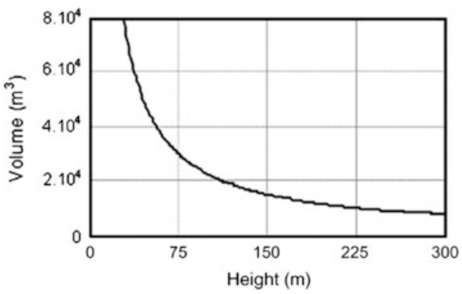

Fig. 6.6 Water volume needed at a given height to store 6 MWh [2]

use of separate pumps and turbines for the pumping and generation operations, respectively, or the utilization of multiple-stage pump/turbines to minimize operational losses resulting from equipment overload. The volume of water available is also an important factor, and hence the need of a permanent and dense water supply to back up the system operation. Figure 6.6 shows the water flow needed versus water head height required to store 6 MWh of energy.

Flow rate of water is another important design factor, and it is determined to achieve a desired cycling time of generation/pumping. Higher flow rates lower the cycling time and require larger size of the generating and pumping units, and waterways diameter. Benefit–cost optimization is generally carried out to optimize the design flow rate, and hence the plant capacity. The optimum flow rate is constrained by the head loss associated with particular waterways diameter and also the cost of the system. The economic diameter of waterways is optimized by balancing the loss of energy benefits due to higher head losses associated with smaller diameters versus waterways construction costs associated with larger diameters.

The reservoir size is another important design parameter, but it is mostly dependent on the geological location. Both upper and lower reservoirs have usually enough storage to provide generation at full capacity for about six to eight hours, as this is the amount of time where low demand is expected.

6.4 Pumped Hydro Storage System Efficiency

The efficiency of pumped hydro storage facility is usually quite high. The overall efficiency is a function of each of the efficiencies of the component in the system. Data for past decades of operating large stations in the United States show the reported efficiencies to be between 60 and 80% for years 1963–1995. With access to more efficient components (pumps, turbines, pipe network design), it is now possible to achieve efficiencies as high as 80%. Table 6.3 shows representative values of component efficiency for a typical pumped hydro storage plant.

6.4.1 Major Losses for Pumped Hydro Storage Systems

Mechanical and electrical components are not the only culprits contributing to the decline of the system efficiency. The following are other major contributors to overall system losses:

Reservoir evaporation

Evaporative losses depend on the size and location of reservoirs. Shallow reservoirs located in tropical climates and with a large surface to storage ratio are far more impacted by evaporative losses than reservoirs in moderate climates. Similarly, a large shallow reservoir will evaporate

Table 6.3 Representative cyclic efficiency values of a pumped hydro storage plant [3]

	Component	Indicative value (%)
Pump cycle	Water conductors	98.0–98.6
	Pump	90.0–92.0
	Motor	97.8–98.3
	Transformer	99.0–99.6
	Overall	*85.4–88.8*
Generate cycle	Water conductors	98.6–98.0
	Turbine	75.0–91.0
	Generator	97.8–98.3
	Transformer	99.0–99.6
	Overall	*71.6–86.4*
Overall	Losses and Leakage	98.0–99.8

faster than a small and deep reservoir. Evaporation is extreme in conditions of dry heat and wind. Whenever evaporative losses are significant, supplemental water supply may be required to refill some of the reservoir volume. Some innovative solutions are proposed to mitigate this problem, including the deployment of shade balls that float on top of the reservoir to limit the radiation reaching the surface and cause evaporation, as shown in Fig. 6.7.

Leakage losses

Depending on geological conditions, a liner may be required in one or both reservoirs to prevent leakage. Seepage through the reservoir liner could still occur, although lining systems may include a leak detection provision coupled with a seepage collection system designed to capture water lost through the lining, if it occurs. A main source of leakage is cracks that develop in concrete-lined sections of the waterways.

Transmission Losses

Electric power transmission losses are a function of transmission line length, voltage, and conductor size and type. Planning is important to take into account several transmission interconnection options. The selection of a point of connection could involve a study of whether the point of connection should be a nearby substation or if it should be connected to an existing transmission line.

6.4.2 Response Time for Pumped Storage

As expected, the operation generation mode is similar to that of a conventional hydro generator operation. The output of a hydro generator can be adjusted by changing wicket gate opening. Changing gate opening changes the amount of water passing through the turbine, and this capability allows turbine units to be used for automatic generation control and to regulate frequency and load when the plant is in generation mode. Operating a single-speed pump-turbine unit in a regulating mode as a generator results in considerable losses of efficiency. In the pump mode, the unit operates at the gate openings that allow the most efficient operation for a given head.

Some values for typical turnaround and starting times for reversible pump-turbine units are as follows:

- From pumping to full-load generation: 2 to 20 min,
- From generation to pumping: 5 to 40 min,
- From shutdown to full-load generation: 1 to 5 min, and
- From shutdown to pumping: 3 to 30 min

With adjustable-speed machines, it is possible to reduce some of these times since synchronization can occur at a lower speed. The control systems can match the rotor electrical speed and the system frequency within seconds. Synchronization can thus occur more rapidly and well before a machine reaches full speed. Further, when the adjustable-speed machine is in the pumping mode, speed

Fig. 6.7 Shade balls in Ivanhoe Reservoir in Silver Lake [3]

does not need to be brought to or even near its nominal speed for synchronization. A potential reduction in time of 5 to 15% can usually be achieved.

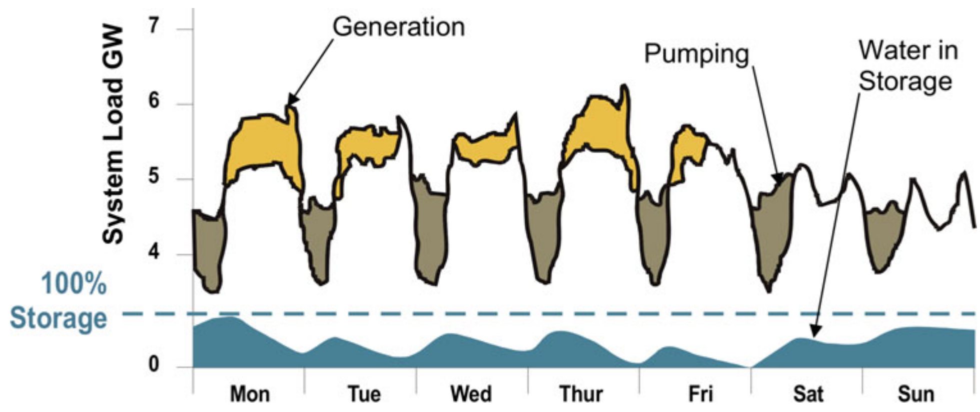

Fig. 6.8 Representative operating cycle of a pumped hydro storage plant [4]

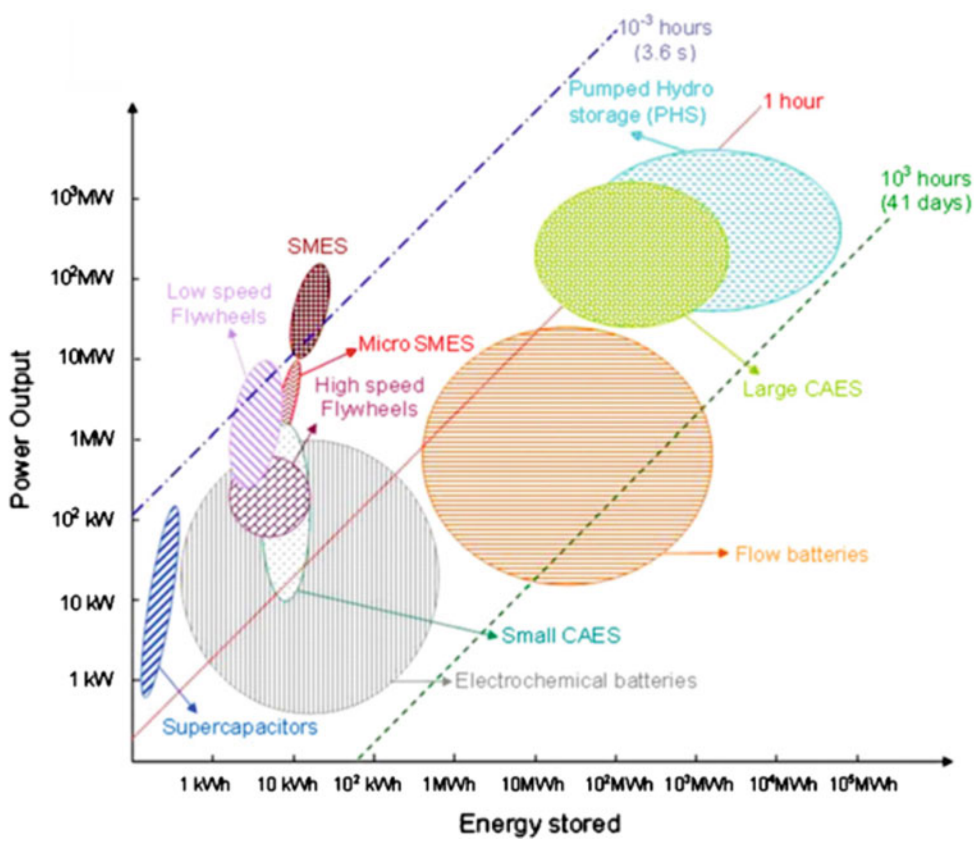

Fig. 6.9 Ragone plot depicting the location of pumped hydro storage systems [5]

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7 Compressed-Air Energy Storage Systems

7.1 Compressed-Air Energy Storage Systems

The utilization of the potential energy stored in the pressurization of a compressible fluid is at the heart of the compressed-air energy storage (CAES) systems. The mode of operation for installations employing this principle is quite simple. Whenever energy demand is low, a fluid is compressed into a voluminous impermeable cavity, where it is stored under high pressure for the long term, as shown in Fig. 7.1a. For periods where the demand is high, the electrical supply is to be augmented. In this case, the fluid is released from its high-pressure storage and into a rotational energy extraction machine (an air turbine) that would convert the kinetic energy of the fluid into rotational mechanical energy in a wheel that is engaged with an electrical generator and then back into the grid, as shown in Fig. 7.1b.

Just like pumped hydro storage, the large-scale CAES systems benefit from the existence of underground reservoirs that are both cavernous and also impermeable. Depleted natural salt mines, as well as depleted oil and gas fields are perfect candidates for such major storage space requirement, but of course those are not widely available. These reservoirs, however, are key to the pressurized storage of the working fluid, and thus having them available topographically is a natural factor in considering CAES systems as a prominent storage facility. As will be discussed through this chapter, the global efforts for carbon dioxide capture and sequestration can be coupled with CAES systems. Not only would this benefit in facilitating the pumping of oil from wells and also store CO_2 away, it benefits the geology of the oil field after all oil is extracted in order to prevent sinkholes from forming. Also, it would introduce a generalized form of compressed gas energy storage (CGES), which would rely on another gas (CO_2, for example) to be the working fluid instead of air in a closed-loop cycle. It should be mentioned that the energy density of compressed-air systems is lower than that of combustion-based processes, and losses due to airflow are particularly high. However, because the implementation of CAES systems is relatively inexpensive, eco-friendly, mechanically simple, and is easy to maintain, these systems have a great promise. These advantages and more, as more discussion on such systems will unfold in this chapter, explain the reason why air-powered drives could be the answer to the energy storage question.

7.2 Large-Scale CAES Systems

The availability of underground caverns that are both impermeable and also voluminous were the inspiration for large-scale CAES systems. These caverns are originally depleted mines that were once hosts to minerals (salt, oil, gas, water, etc.) and the intrinsic impenetrability of their boundary to fluid penetration highlighted their appeal to be utilized as reservoirs where air can be compressed with no or little leakage out of the system. This guaranteed that the energy stored will not be lost and that the high levels of pressure needed to operate such installations are attainable and sustainable.

For example, the first large CAES installation was the 290 MW plant at Huntorf, Germany, developed by E. ON-Kraftwerk in 1978, as shown in Fig. 7.2a. The plant mitigated any grid supply/demand irregularities by storing electricity as pressurized air during low demand time (at night or weekends) and releasing it again when demand increased as shown in Fig. 7.2b. The plant is still operational and used as a backup power “battery”. The compressed air is indeed stored in underground depleted salt caverns that can fill up in 8 h at a rate of 108 kg/s. In discharge mode (supporting the grid during high demand), the compressed air is released and heated up by burning natural gas. The expansion of the air drives a 320 MW turbine for two hours, after which the caverns become depleted (the pressure remaining is not enough to give high quality of energy) and have to be refilled.

The second major CAES plant is run by PowerSouth Energy Cooperative in McIntosh Alabama, as shown in Fig. 7.3a. The 110-megawatt CAES Unit was declared

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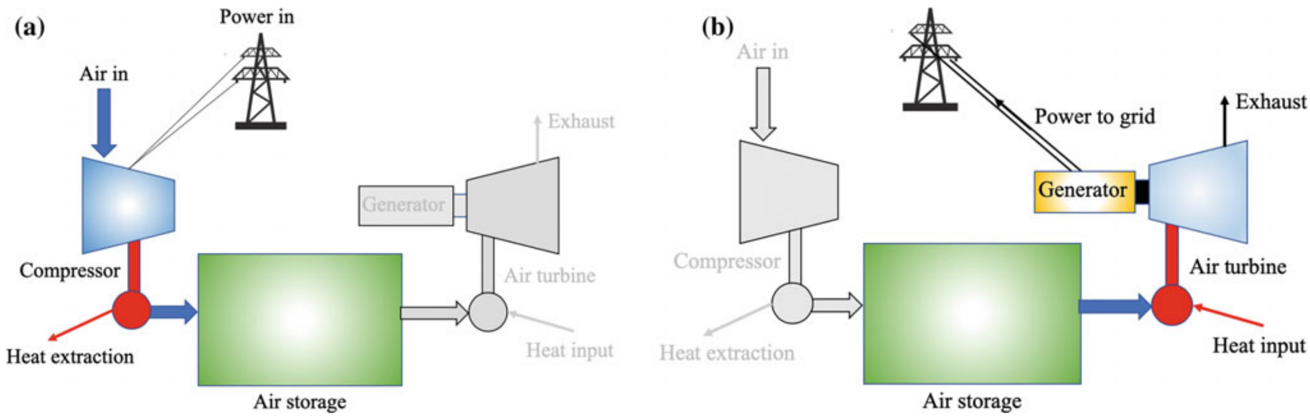

Fig. 7.1 Depiction of operation of a large-scale CAES system in **a** charging mode and **b** discharge mode

commercial in 1991 and is the only one of its kind in the U.S. During off-peak hours, air is pumped into the cavern in a process they label as "compression mode." At full charge, air pressure in the cavern reaches nearly 1,100 lb per square inch (7.5 MPa) as shown in Fig. 7.3b.

During periods of peak, the plant is put into "generation mode." Air from the cavern is released, routed through more than 1,000 feet of pipe and fed into a heat exchanger called a recuperator. Here, it is heated to approximately 600 °F (315 °C). The main difference from the Huntorf facility is that the McIntosh plant allows this hot air to enter a high-pressure combustion chamber, where natural gas is used to further heat the air to around 1,000 °F (537 °C) before entering the high-pressure expander. The exhaust in the high-pressure expander is re-heated to 1,600 °F (871 °C) before entering the low-pressure expander where it is fed back through the recuperator, providing an efficient source of heat for this stage of the process. Excess heat is discharged into the atmosphere at a temperature of around 280 °F (137 °C). Together, th`e high-pressure and low-pressure expanders rotate the generator to produce enough electricity to power nearly 110,000 homes for up to 26 h. Table 7.1 offers a comparison between these two major CAES power plants currently in service.

Remember that the role of the decision-maker is matching the most suitable energy storage technology with the energy resource. For example, wind farms operate around the clock to generate electricity regardless of demand, as the accurate forecasting of demand is far easier than accurately forecasting wind energy availability. This necessitates the usage of a reliable, sustainable, and sizeable energy storage system that would absorb excess generation and then supply the grid back with energy when needed. In this case, CAES systems are a very attractive alternative to chemical or electrochemical storage options. Note that CAES systems can either be charged (air compression into the cavern) mechanically via compressors driven by coupling the mechanical motion of the wind turbines or by the electrical energy generated from the wind turbines driving electrical motors that operate the compressors as summarized in Fig. 7.4. Of course, the electrical option could be more logical as it would be technically difficult to provide and transmit mechanical energy from the nacelle up the tower of the turbine all the way down to the base of the tower to drive the compressor. The mechanical drive option should still be considered if access to the gearbox on top of the tower is available, since this omits one energy conversion step, and hence will increase the roundtrip storage efficiency.

7.3 Sample Specifications of Components of Large-Scale CAES Systems

There are many practical considerations that arise when operating a large-scale CAES system that may not be too obvious during the abstract design stage. The following lists some of the key components of CAES systems used in the Huntorf of the McIntosh installations that would help the reader form an idea of such considerations.

7.3.1 The Air Compressor

The compressor is a core component of CAES systems, operating at pressure ratios of 40–80 if not more. The Huntorf power plant uses axial flow and centrifugal multistage compression with inter-stage and post-stage cooling (as you probably remember from the power cycle T-s diagrams in thermodynamics, these decrease the required power input and enhance the overall system performance). For smaller CAES systems, it could be more suitable to use a single-stage or multistage reciprocating compressor to reduce the volume of the gas storage device and ensure higher pressure values in storage.

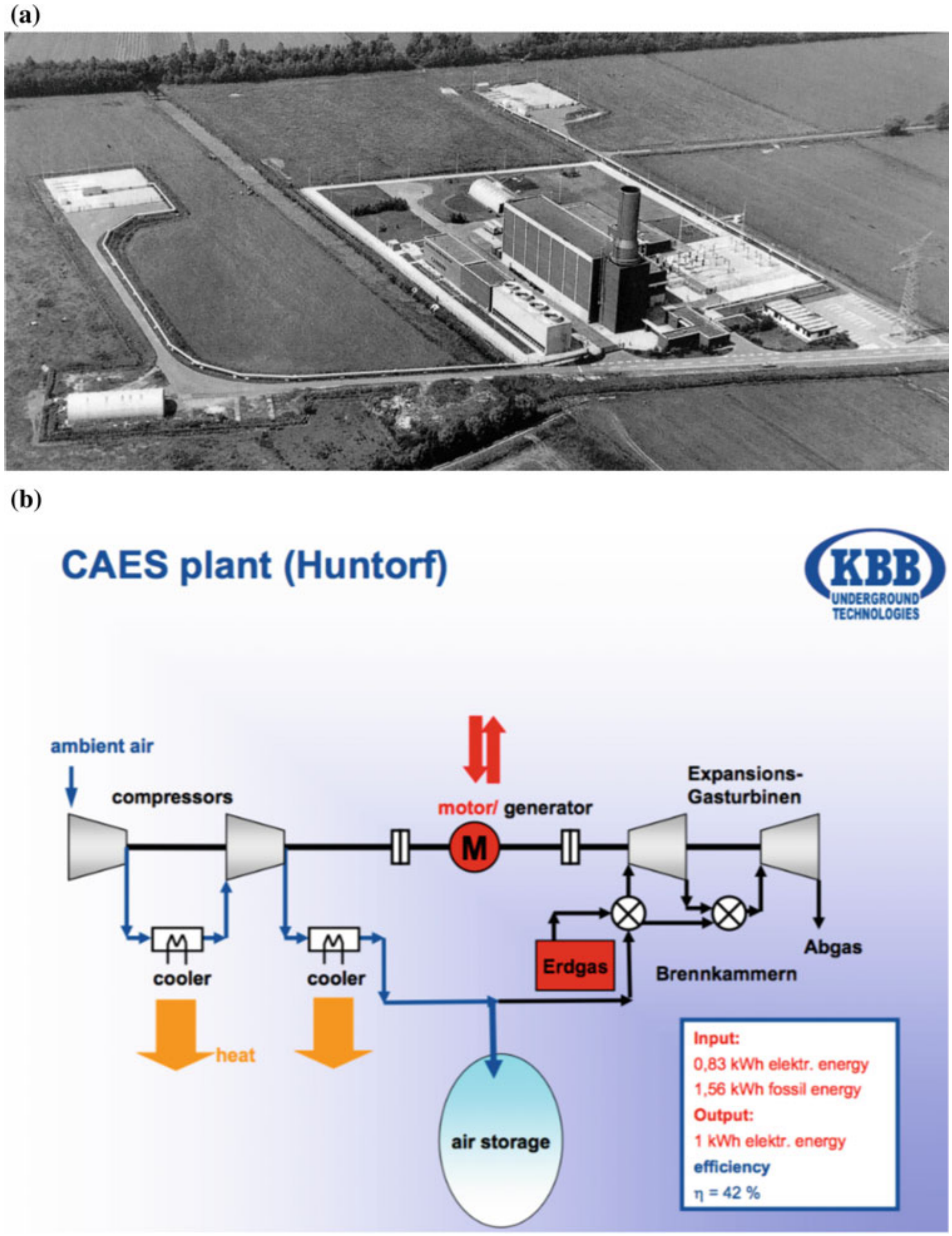

Fig. 7.2 **a** Image of the Huntorf CAES facility in Germany and **b** its principle of operation [1]

7.3.2 Expander

The sudden depressurization of the stored air entails great losses, as well as unpredictable behavior of the compressible gas. And just like with stage-wise compression, it is beneficial to have expansion that takes place also in stages before reaching the air turbine (or combustion-based gas turbines). The Huntorf power station uses a modified steam turbine as its first stage to contend with the expansion of air from high storage pressures. Small CAES systems would use micro gas turbine components, reciprocating expanders, or screw air engines, which are less efficient. These expanders may not be necessary for small-scale CAES systems.

7.3.3 Air/Gas Storage Vessels

This is the heart of any CAES storage system. Large-scale CAES usually involves storing gas in depleted salt, water, oil, or gas fields underground. Smaller scale CAES systems can use aboveground high-pressure silos or gas storage containers depending on the selected operational pressures.

7.3.4 Thermal Storage System

Heat exchangers with high effectiveness, ϵ, are required for the expected issue of heat generated due to air/gas

Fig. 7.3 **a** The PowerSouth energy cooperative McIntosh CAES power plant and **b** the pertinent salt cavern dimensions [2]

Table 7.1 Operational parameters for the Huntorf and McIntosh CAES facilities [3]

	Huntorf	McIntosh
Cycle efficiency (%)	42	54
Maximum electrical input power (MW)	60	50
Maximum air mass rate (kg/s)	108	~90
Charge time (h)	8	38
Discharge time (h)	2	4
Cavern pressure range (bar)	46–72	46–75
Cavern volume (m^3)	310,000	538,000
Maximum electrical output power (MW)	321	110
Control range (output) (MW)	100–321	10–110
Setup time (normal/emergency) (min)	14/8	12/7
Maximum mass flow rate (kg/s)	455	154
High-pressure turbine inlet (bar)	41.3 @ 490 °C	42 @ 538 °C
Lower pressure turbine inlet (bar)	12.8 @ 945 °C	15 @ 871 °C
Exhaust gas temperature (°C)	480	370 (before recuperator)

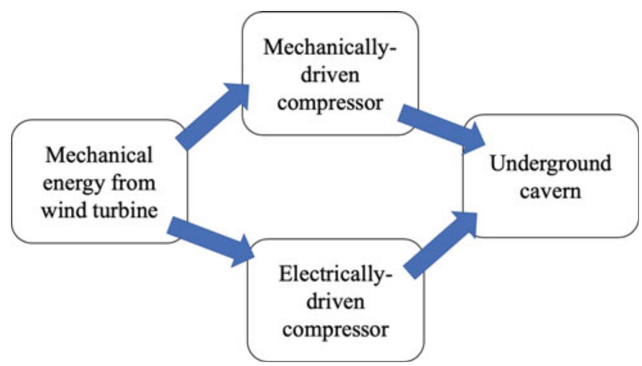

Fig. 7.4 Options for supplying the compressor with work during charging mode

pressurization, and the counter phenomenon of freezing during depressurization, just like the nozzle of a can of aerosol becoming almost frozen after continuous use. From an ideal gas law perspective, we note that there is a correlation between pressure, p, and temperature, T: $PV = nRT$, where n is the number of moles and R is the gas constant. Thus the selected heat exchangers need to be airtight, allow low heat loss, and be adaptable to the working range of the associated turbomachinery, at an economical cost. There are also numerous requirements on the material of the heat storage device. Although all CAES plants operate along the same principle, they have tended to focus on retaining the heat produced during the compression process to use as supply heat during decompression, which will increase the overall efficiency of the plant.

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