1 Wind Turbine Energy Storage

- Most electricity in the U.S. is produced at the same time it is consumed.
- Peak-load plants, usually fueled by natural gas, run when demand surges, often on hot days when consumers run air conditioners.
- **Wind generated power** in contrast, cannot be guaranteed to be available when demand is highest.
- The hourly electric power demand is relatively periodic on a 24 hour cycle with the peak demand occurring in the daylight hours.
- **Wind power generation is not periodic or correlated to the demand cycle.**
- The solution is energy storage.

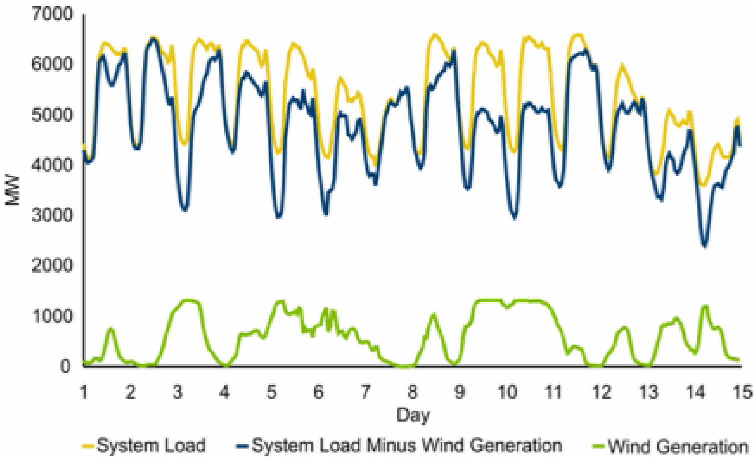

Figure 1: Example of a two week period of system loads, system loads minus wind generation, and wind generation.

- There are many methods of energy storage.
  - electro-chemical energy storage such as batteries
  - chemical storage such as electro-hydrogen generation
  - gravitational potential energy storage such as pumped-storage hydroelectric
  - electrical potential storage such as electric capacitors
  - latent heat storage such as phase-change materials
  - kinetic energy storage such as flywheels
- Short-term energy storage vs very long-term storage
- maximum discharge rate
- possible number of charge-discharge cycles

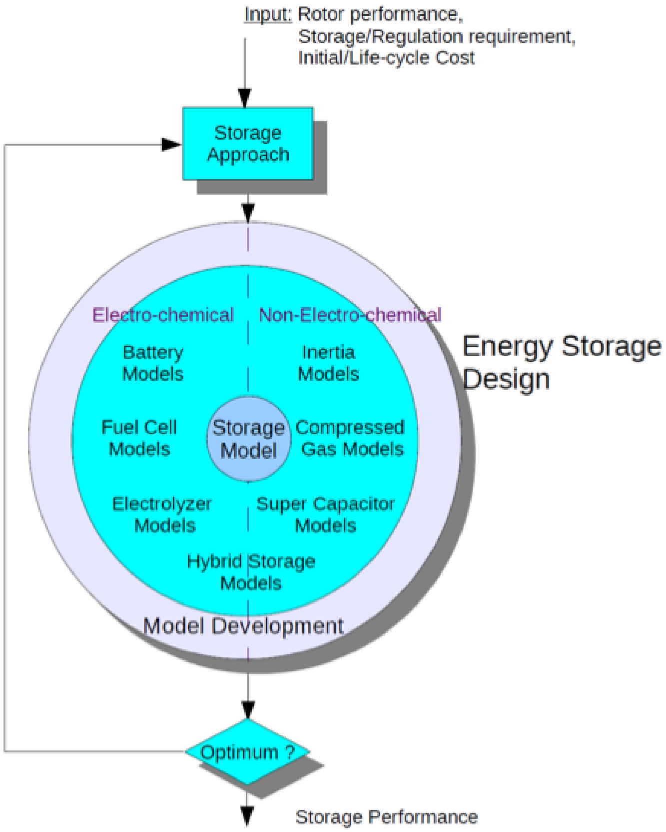

Figure 2: Wind turbine energy storage optimization flow chart.

1.1 Electro-chemical Energy Storage

- Rechargeable batteries are the most common form of electric storage devices
- Three main types: lead-acid batteries, nickel-based batteries, and lithium-based
- Each consist of cells made up of positive and negative electrodes that are immersed in an electrolyte

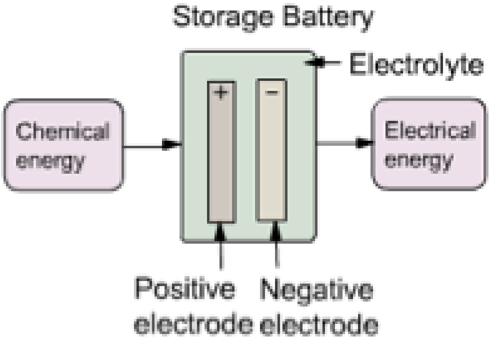

Figure 3: Illustration of an electro-chemical storage battery cell.

Lead-acid Batteries.

- Lead-acid batteries are the oldest type of rechargeable battery, and the most commonly used
- The rated voltage of a lead-acid cell is 2 volts.
- The energy density is around 30 W-h/kg, with a power density of approximately 180 W/kg
- Lead-acid batteries have an energy efficiency between 80%-90%
- They are relatively low maintenance and initial investment cost
- A relatively low self-discharge rate of approximately 2% of the rated capacity per month at 25°C. (**ideal for long-term storage**)
- Low cycle life and battery operational lifetime
    - Typical lifetime between 1200 and 1800 charge/discharge cycles, or approximately 5-15 years of operation
- The cycle life is negatively affected by the depth of discharge and temperature.
    - Fully discharging the battery can damage the electrodes, reducing lifetime
    - High temperatures, up to 45°C (upper limit) improves battery capacity but reduces battery lifetime.

Nickel-based Batteries.

- Consist of nickel-cadmium (NiCd), nickel-metal-hydride (NiMH) and nickel-zinc (NiZn)
- Rated voltage per cell is 1.2 V (1.65 V for the NiZn type)
- Typical energy density is higher than that of lead-acid batteries: 50,W-h/kg for the NiCd, 80 W-h/kg for the NiMH and 60 W-h/kg for the NiZn
- Operational life and cycle-life is also superior to that of the lead-acid batteries
- Typical lifetimes range from 1500-3000 charge-discharge cycles
- Several disadvantages compared to the lead-acid batteries:
  - NiCd battery may cost up to 10 times more than the lead-acid battery
  - Lower energy efficiencies between 65% and 70%
  - Higher self-discharge rate, of 10% of rated capacity per month

Lithium-based Batteries.

- Consists of two main types: lithium-ion and lithium-polymer
- Higher energy density and energy efficiency, lower self-discharge rate, and extremely low required maintenance compared to NiCd and lead-acid batteries
- Nominal cell voltage about 3.7 V
- Energy density from 80 to 150 W-h/kg
- Energy efficiencies from 90% to 100%
- Power density from 50 to 2000 W/kg
- Very low discharge rate of 5% per month
- Lifetime of up to 1500 cycles
    - Depends on temperature, worse at high temperatures
    - Severely shortened by deep discharges
- Very fragile, requiring a protection circuit to maintain safe operation that limits the peak voltage during charging and prevents the cell voltage from dropping too low on discharge
- Cell temperature is monitored to prevent temperature extremes
- Cost is between $900 and $1300 kW-h.

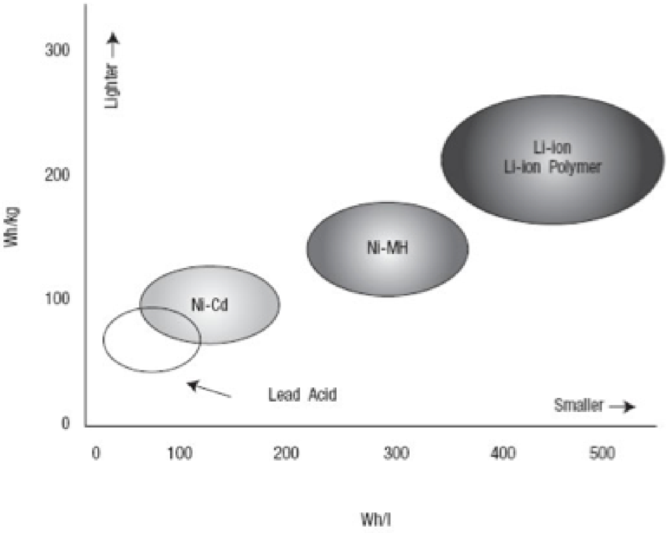

Figure 4: Specific energy, $W-h/kg$, versus energy density, $W-h/kg$, for the three types of electro-chemical storage batteries.

1.1.1 Additional Electro-chemical Storage Technologies

Sodium Sulfur Batteries.

- NaS battery consists of liquid (molten) sulfur at the positive electrode and liquid (molten) sodium at the negative electrode as active materials separated by a solid beta alumina ceramic electrolyte.
- Highly energy efficient (89-92%)
- Inexpensive and non-toxic materials
- High operating temperatures, and highly corrosive nature of sodium makes it only suitable for **large-scale stationary applications**
- Currently used in electricity grid related applications such as peak shaving and improving power quality

Redox Flow Battery.

- A type of rechargeable battery involving two liquid chemical components contained within the system and separated by a membrane
- Ion exchange (providing flow of electrical current) occurs through the membrane while both liquids circulate in their own respective space
- Cell voltage is chemically determined and ranges from 1.0-2.2V

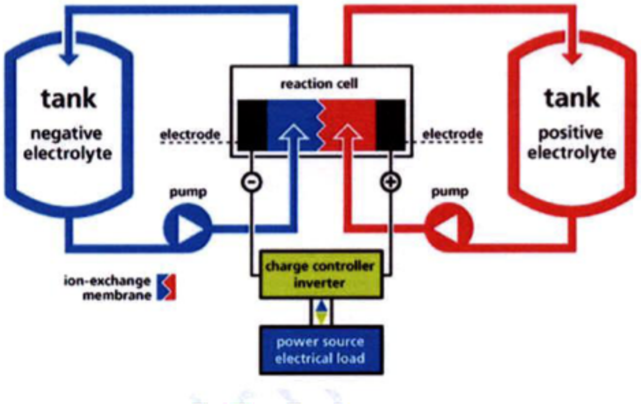

Figure 5: Schematic drawing of a flow battery.

- Technically both a **fuel cell** and an **electro-chemical accumulator cell**
- Significant advantages such as no self-discharge and no degradation for deep discharge
- Appealing only for long-duration stationary energy storage
- Scalable energy capacity: (measured in MW-h) basically requires only an increase in the size of its liquid chemical storage reservoirs

Metal-air Battery.

- An electro-chemical cell that uses an anode made from pure metal and an external cathode of ambient air, typically with an aqueous electrolyte
- Offers high energy density (compared to lead-acid batteries)
- Long shelf life
- Promising reasonable cost levels
- However, limited operating temperature range
- Other **technical issues**: difficulty in developing efficient, practical fuel management systems and cheap and reliable bifunctional electrodes

1.2 Supercapacitor Storage

- Supercapacitors (or ultracapacitors) are very high surface areas activated capacitors that use a molecule-thin layer of electrolyte as the dielectric to separate charge
- The supercapacitor resembles a regular capacitor except that it offers very high capacitance in a small package
- The separation of charge interface is measured in **fractions of a nanometer**, compared with micrometers for most polymer film capacitors
- Energy storage is by means of **static charge** rather by an electro-chemical process

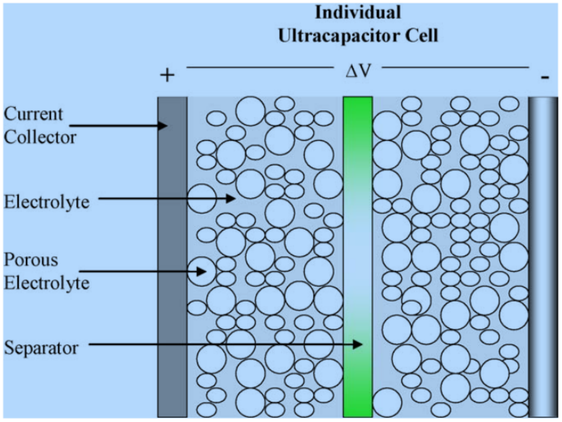

Figure 6: Schematic a super capacitor.

- Minimal degradation in deep discharge or overcharge
- Typical cycle life is hundreds of thousands of cycles – **more than 500,000 cycles at 100% depth of discharge**
- The limiting factor may be the years of operation, with reported lifetimes reaching up to 12 years.
- One limiting factor is the **high self-discharge rate** of 14% of nominal energy per month.
- However, they can be easily charged and discharged in seconds, thus being much faster than batteries.
- Energy efficiency is very high, ranging from 85% to 98%
- **Low energy density**, 5W-h/kg.
- **Extremely high power density** of 10,000 W/kg, which is a **few orders of magnitude higher than that of batteries**
- As a result of the low energy density, this high amount of power is only be available for a very short duration
- Significant cost of $20,000/kW-h, which is much higher than for example, lead-acid batteries

1.3 Hydrogen Storage

- Electricity is used with water to make hydrogen gas through the process of electrolysis
- Approximately 50,kW-h of electric energy is required to produce a kilogram of hydrogen
- The cost of the electricity clearly is crucial
  - At $0.03/kW-h, which is the common off-peak high-voltage line rate in the United States, hydrogen costs approximately $1.50 a kilogram for the electricity

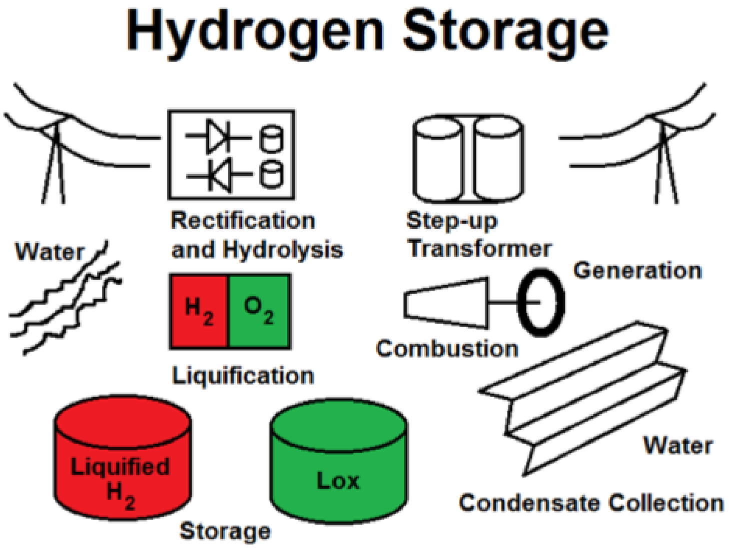

Figure 7: Illustration of the elements in the use of electricity for hydrogen production and possible storage.

- The two most mature methods of hydrogen storage are **hydrogen pressurization** and the **hydrogen adsorption** in metal hydrides
- Pressurized hydrogen relies on materials that are impermeable to hydrogen and mechanically stable under pressure
- Storage tanks with aluminum liners and composite carbon fibre/polymer containers are being used to store hydrogen at 350 bar providing a higher ratio of stored hydrogen per unit weight of up to 5%
- Metal hydrides offer an excellent alternative to pressurized storage
- Metal hydrides bind with hydrogen very strongly. As a result, high temperatures around 120°C are required to release their hydrogen content
- Liquid hydrogen storage technology use is currently limited due to the properties and cost of the materials used in the manufacturing of the container/tank and the extreme temperatures required for such storage (-253°C)
- Liquid Hydrogen self-discharge may reach 3% daily, which translates to a 100% self-discharge in 1 month!

1.4 Mechanical Energy Storage Systems

- Involves the conversion of electric energy into potential or kinetic energy
- Includes **pumped storage hydroelectricity**, **compressed air storage**, and **flywheel energy storage**
- **Pumped Storage Hydroelectricity.** During times of low electricity demand, the excess generation capacity is used to pump water into a reservoir at a higher elevation, when the electric demand is higher, the water is released back into the lower reservoir and passes through a turbine/generator

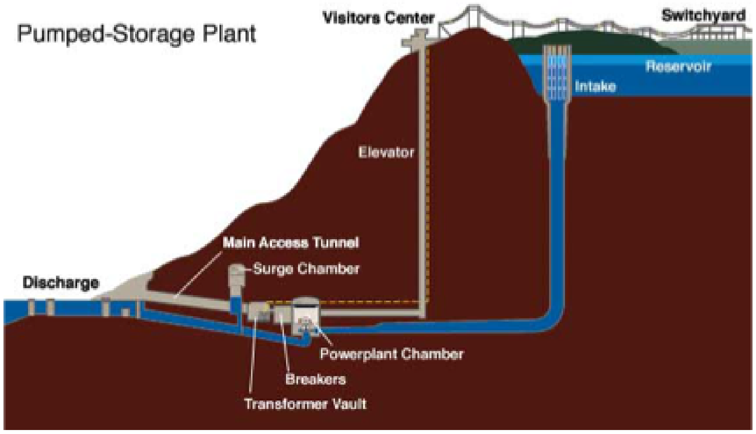

Figure 8: Illustration of pumped storage hydroelectric power plant.

- Worldwide, **pumped storage hydroelectricity is the largest form of grid energy storage available**, accounting for more than 99% of bulk storage capacity, representing approximately 127,000 MW
- Accounting for evaporation losses from the exposed water surface and conversion losses in the pump, turbine and piping, approximately 70-85% of the electrical energy used to pump the water into the elevated reservoir can be regained
- It is currently **the most cost-effective means of storing large amounts of electrical energy** on an operating basis
- Issues:
  - Capital costs and the presence of appropriate geography
  - Relatively low energy density requiring either a very large body of water, or a large variation in elevation
- They can be economical to flatten out load variations on the power grid, permitting thermal power stations to provide base-load electricity at peak efficiency, and reducing the need for peak-load power plants that use costly fuels
  - Pumped storage plants can respond to load changes within seconds

- **Compressed Air Storage** is another method of storing electric energy during off-peak demand and to be used later when the demand is higher
- Electric energy is used to compress air which is typically stored in underground caverns

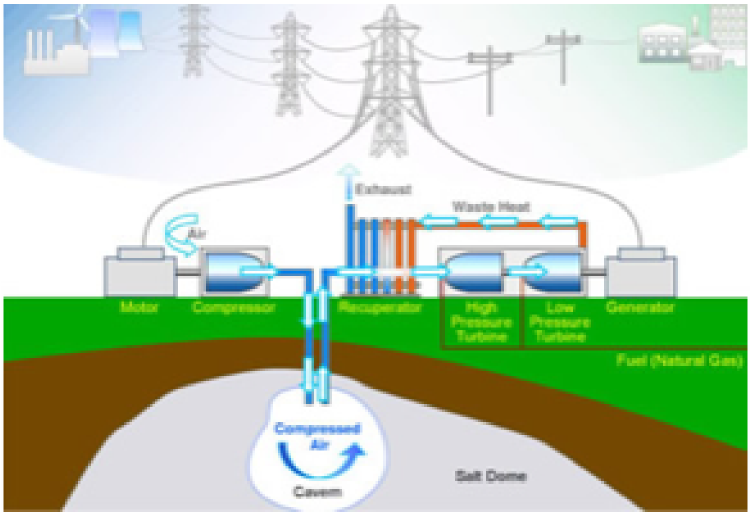

Figure 9: Illustration of compressed air storage power plant.

- Compressed air storage is generally made up of
  1. a motor/generator that employs clutches to provide for alternate engagement to the compressor or turbine power train,
  2. an air compressor that may require two or more stages, intercoolers and aftercoolers to reduce moisture in the compressed air, and to increase the power plant efficiency, and
  3. high and low pressure turbines and a recuperator to again increase the power plant efficiency.

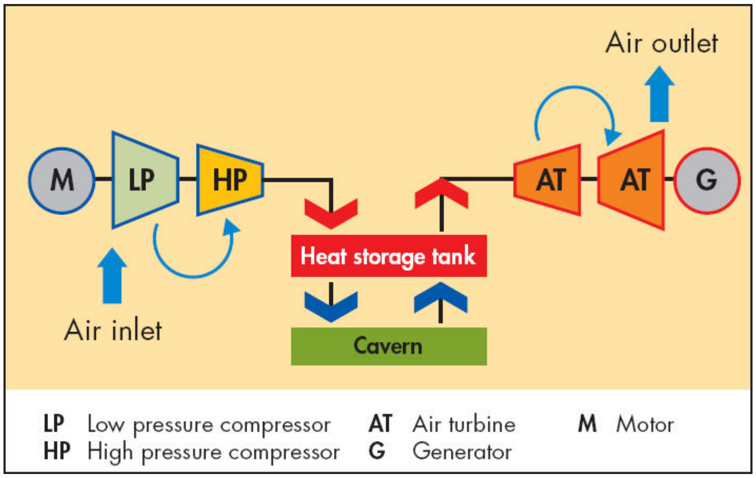

Figure 10: Components of a basic compressed air storage power plant.

- Involves multiple-staged compressors in which **inter-stage heat exchangers** are used to remove heat resulting from compressing the air
- The heat can be stored and utilized in a **combined or recuperated cycle** to improve the plant efficiency

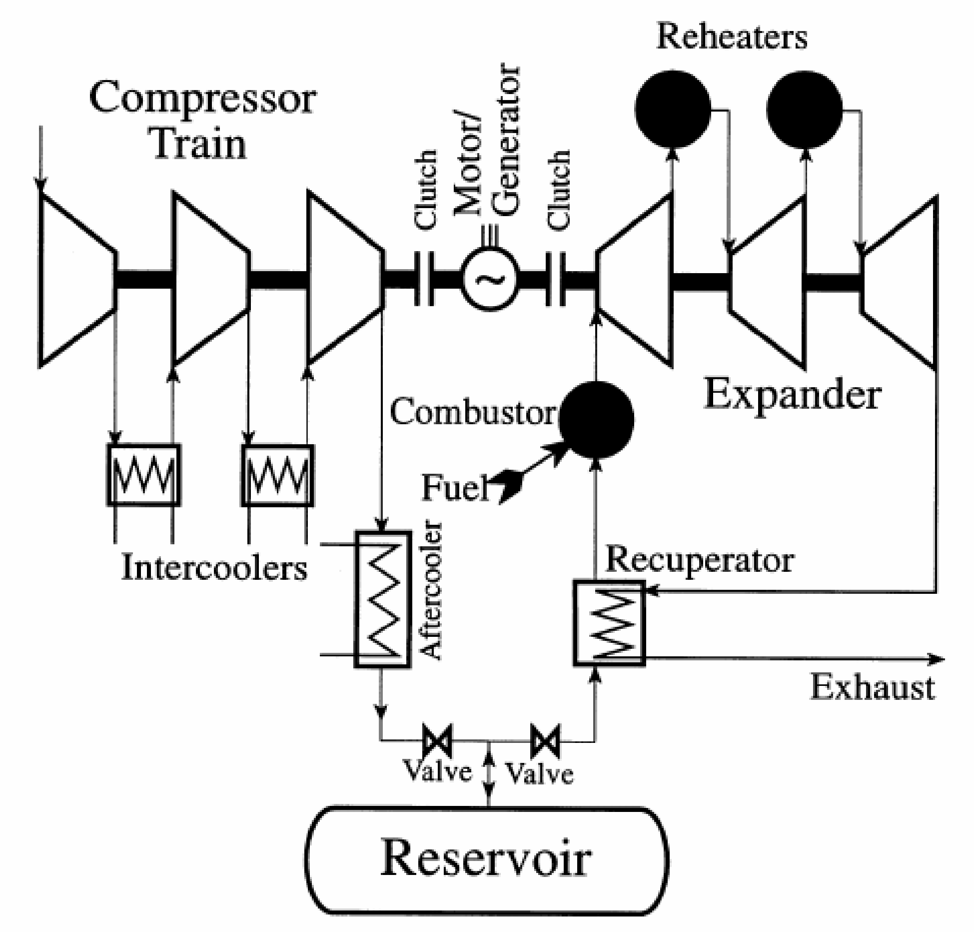

Figure 11: Recuperated cycle compressed air storage power plant.

- The compressed air is released to pass through the turbine
- The air is first heated by passing it through a recuperator that makes use of the stored heat that was released during the air compression
- Fuel is then injected into the air and heated further in a combustor
- The hot gas then expands through the turbine, which is connected to the synchronous motor/generator
- Waste heat from the turbines is used for inter-stage turbine heating or in the recuperator
- Apart from the pumped storage hydroelectric system, no other storage method has a storage capacity that is as large as the CAES.
- Typical capacities are **from 50 to 300 MW**
- The storage period is the longest of the other systems, easily **storing energy for more than a year**
- Start-up times $\mathcal{O}9$ min. in an emergency, and $\mathcal{O}12$ min. under normal conditions
  - Conventional **combustion** turbine peak-load plants typically require 20-30 min. for a normal start-up

- **Flywheel Storage** uses a mass rotating about an axis to store energy mechanically in the form of kinetic energy
- An electric motor is used to accelerate the flywheel to its design rotation speed
- The energy stored is

$$E = \frac{1}{4} M r^2 \omega^2 \;\sim\; M \nu^2 \tag{1}$$

  - M is the mass of the flywheel
  - r is the radius of the flywheel
  - ω is the rotation rate
  - ν is the linear velocity at the outer rim of the flywheel

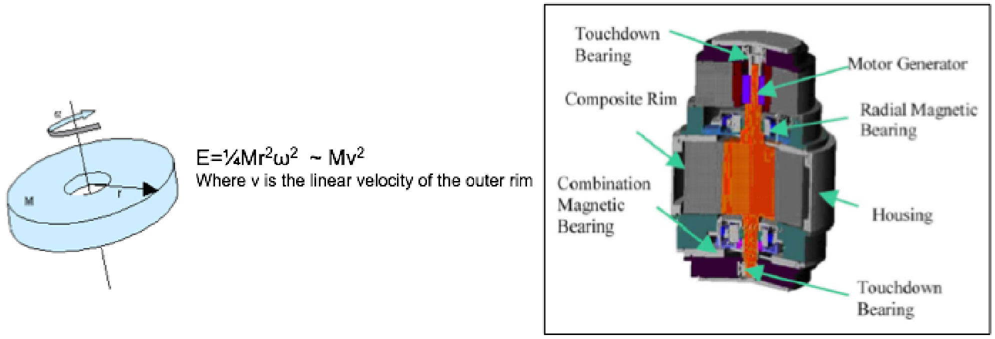

Figure 12: Illustration of a flywheel energy storage system.

- Low-speed flywheels, operate at up to 6000 rpm
  - Usually consist of steel rotors and conventional bearings
  - Achieve specific energy of approximately 5 W-h/kg
- High-speed flywheels operating at up to 50,000 rpm
  - Use advanced composite materials for the rotor along with ultra-low friction bearing assemblies
  - Achieve specific energies of 100 W-h/kg
  - Come up to speed in a matter of minutes, rather than the the hours needed to recharge a battery
  - The enclosure is either evacuated or filled with helium to reduce aerodynamic losses and rotor stresses
- Advantages of flywheel storage systems are their high charge and discharge rate
- Energy efficiency is typically around 90% at rated power
- Operation lifetime is estimated to be 20 years
- Main disadvantages are their high cost, and the relatively high standing loss
- Self-discharge rates are approximately 20% of the stored capacity per hour!
- Thus they are not a suitable device for long-term energy storage.

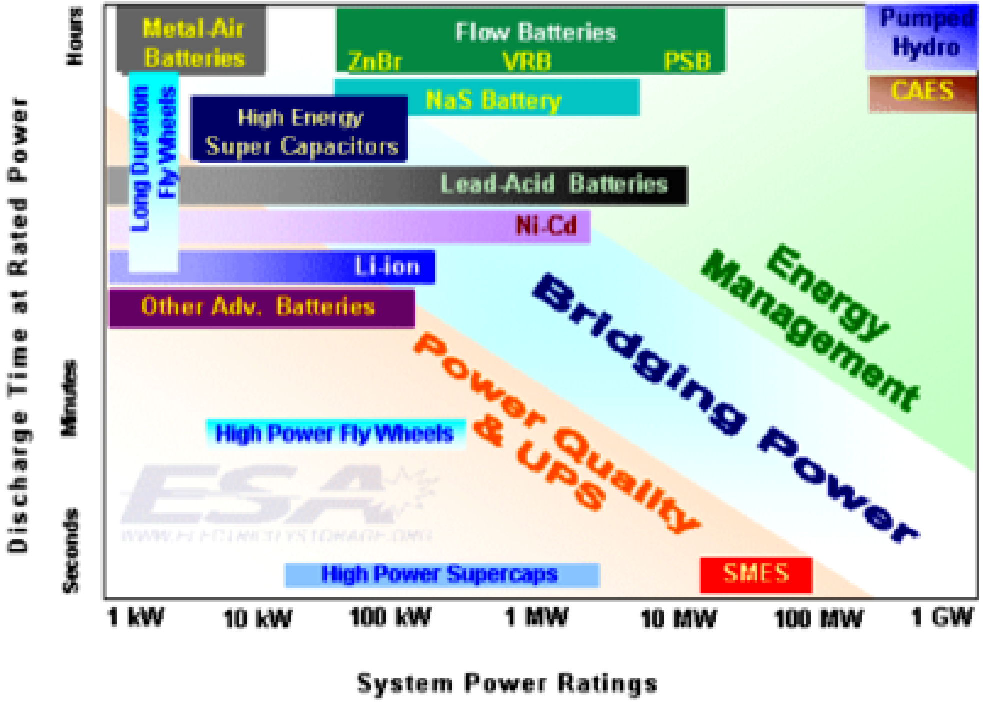

Figure 13: Comparison of different electric power storage systems with regard to power rating and discharge rate.

1.5 CAES Case Study

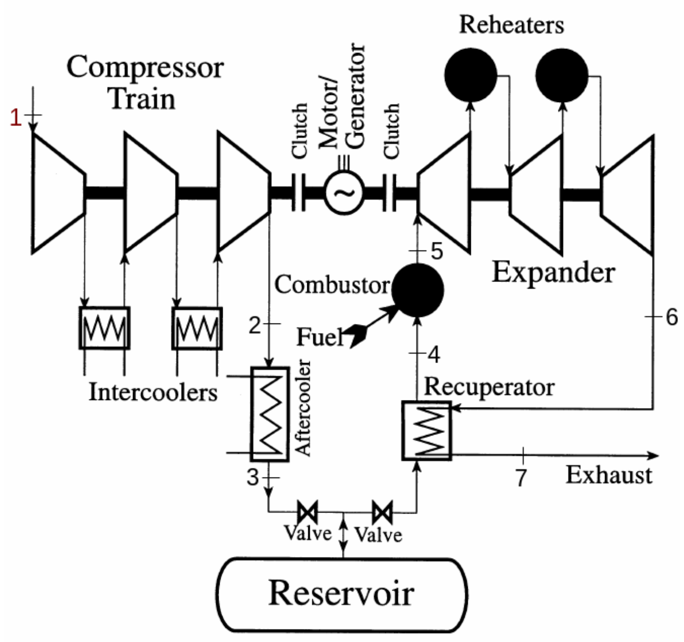

Figure 14: Thermodynamic representation of a CAES power plant.

- The thermodynamic cycle so depicted, is known as an Ericsson cycle.

  1-3 the "charging mode" where the electric motor compresses the air using power either from the wind or from the grid at low demand periods of time, and

  3-7 the "discharge mode" in which the compressed air is expanded through the turbines to drive the electric generator during peak demand periods of time.

- The efficiency of the thermodynamic cycle is

$$\eta_{th} \equiv \frac{w_t}{\frac{w_c}{\eta_{ex}} + q_f} \tag{2}$$

- where η_{ex} is the external efficiency of the base load power plant, that is, **the wind turbine efficiency** source of electricity used to power the electric motor for the air compression

- How do we improve the thermodynamic efficiency of a CAES power plant?
- Considering air to be an ideal gas, and process such as compression or expansion to be **polytropic**

$$pV^k = \text{Constant} \tag{3}$$

so that

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} \text{ which for air, } k = 1.4 \tag{4}$$

- For the compression

$$w_c = \frac{C_p T_1}{\eta_c \eta_{elm}} n \left(\sigma_c R^{1/n} - 1\right) \tag{5}$$

where

$r_{mt} = T_5/T_1$ = maximum temperature ratio (6)
$r_{st} = T_3/T_1$ = storage temperature ratio (7)
η_c = compressor efficiency (8)
η_{elm} = electro-mechanical efficiency (9)
η_t = turbine efficiency (10)
$R = T_2/T_1$ = terminal isentropic temperature ratio (11)
σ = pressure losses factor, with subscripts c and t (12)
$n - 1$ = number of intercoolers (13)
$m - 1$ = number of reheaters (14)
(15)

- The “energy storage effectiveness”, $\beta = w_t/w_c$ is

$$\beta = \frac{\eta_t \eta_c \eta_{elm} r_{mt} m \left(1 - \frac{\sigma_t}{R^{1/m}}\right)}{n\left(\sigma_c R^{1/n} - 1\right)} \tag{16}$$

- The economics of a CAES power plant depends on the instantaneous price of electricity, which in turn depends on the instantaneous demand
- A model for the cost of electricity, $P(t)$ is

$$P(t) \simeq A_0 + A_1 N(t) + A_2 N(t) \tag{17}$$

- $N(t)$ is the time variation in the electric power demand, and the A's are best-fit coefficients that relate the cost of electricity to the demand.

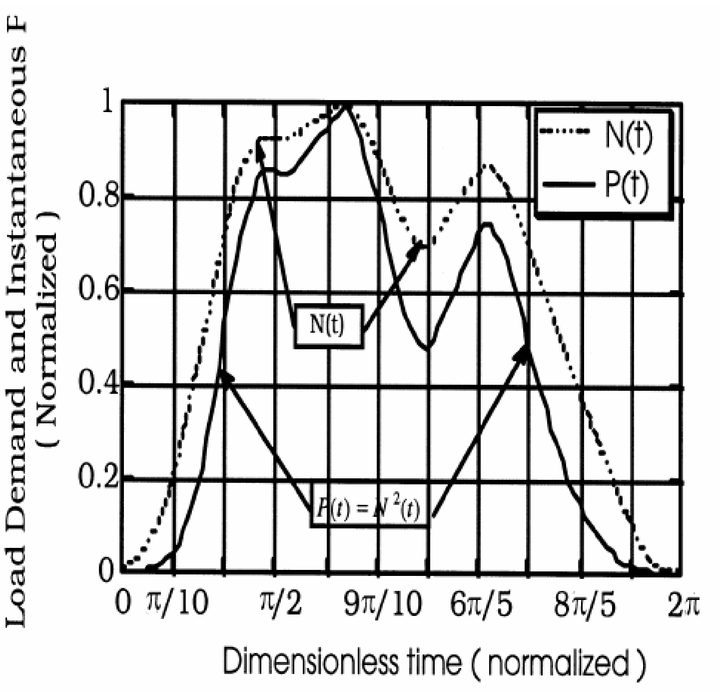

Figure 15: Example of the electric power demand and corresponding consumer price of electricity over a 24 hour period.

- Given the price function, $P(t)$, the charging and discharging price functions, C_{ch}, and C_d, can be developed
- These depend on the **duration** of the charging and discharging, h_{ch} and h_d

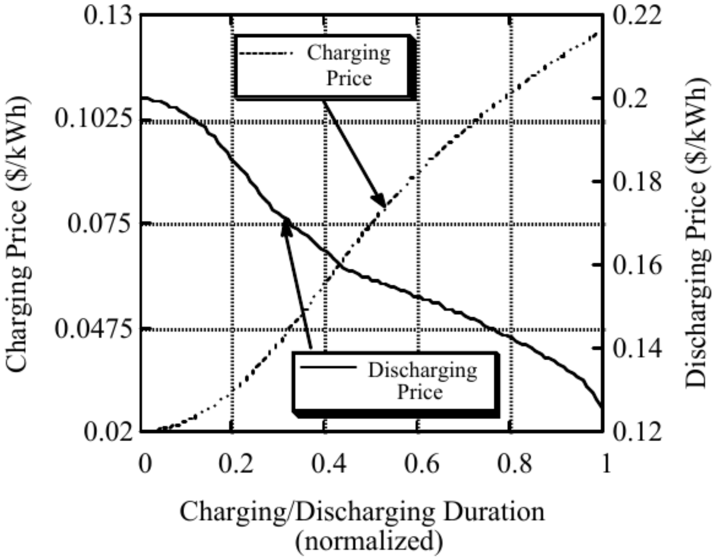

Figure 16: Charging and discharging price functions that correspond to the price function shown in Figure 15.

- The **Cost Function** estimates the costs associated with a CAES plant
- It is broken down into **fixed costs** and **variable costs**

$$
\begin{aligned}
C_{tot} &= C_1 K + S h_d + C_{fom} \ \ [\$/\text{kW-yr}] && (18)\\
C_1 &= \text{capital cost } [\$/\text{kW installed}] && (19)\\
K &= \text{capital recovery factor } [1/\text{yr}] && (20)\\
S &= \text{specific variable cost } [\$/\text{kW-h generated}] && (21)\\
h_d &= \text{plant service factor } [\text{operating hrs/yr}] && (22)\\
C_{fom} &= \text{fixed operating \& maintenance cost } [\$/\text{kw-yr}] && (23)\\
& && (24)
\end{aligned}
$$

- The specific variable cost includes the energy cost of charging, C_{ch}, and discharging, C_d, the energy reserve

$$S = C_{ch} + C_d + C_{vom} \tag{25}$$

  with C_{vom} as the cost of Operation & Maintenance (O&M)

- The **energy cost of charging** is

$$C_{ch} \ = \ P_c \frac{w_c}{w_t} \ = \ P_c \beta^{-1} \ [\$/\text{kW-h generated}] \tag{26}$$

  where P_c is the **charging price function** with units of [\$/kW-h]

- The **ideal situation** (to generate capital) is the $P_c < P_d$ where P_d is the discharging price function with units of [\$/kW-h]
- The **coefficient for discharging**, C_d is defined as

$$C_{ch} = P_f \frac{\dot{m}_f}{\dot{w}_t} \tag{27}$$

where P_f is the **fuel price** with units of [$/kg-fuel], and $\dot{m}_f/\dot{w}_t$ is the **specific fuel consumption** with units of [kg-fuel/kW-h]

- The capital costs, C_1, include all of the costs of installation

  $$C_1 = r_w C_c + C_t + r_g C_g + r_w C_i n + C_r e + C_R C + C_r + C_s \quad [\$/\text{kW installed}] \tag{28}$$

  where the coefficients C_c, C_t, C_g, and C_{in} are the costs/kW installed of the compressor, turbine, generator and intercoolers

- The **discharge-charge ratio**, r_h is

  $$\begin{aligned} r_h &= \frac{h_d}{h_c} && (29) \\ &= \frac{\dot{w}_c}{\dot{w}_t}\frac{w_t}{w_c} && (30) \\ &= r_w \beta && (31) \\ & && (32) \end{aligned}$$

  where h_d and h_c are the hours per year of discharging and charging

- The **Net Benefit**, B, represents a metric of merit

$$B = (P_d - S)\, h_d - C_1 K - C_{fom} \;\; [\$/\text{kw-yr}] \tag{33}$$

where $P_d = f(h_d)$ is the discharging price which is a **function of the discharge duration**

- B is a function of many variables:

$$B = f\left(r_{mt}, R, r_b, h_d, \epsilon_{RC}, m, n\right) \tag{34}$$

where

$$r_{st} \leq r_{mt} \leq 4.91 \qquad ;\, r_{mt} = T_4/T_1 = \text{max. temp. ratio} \tag{35}$$

$$;\, r_{st} = T_3/T_1 = \text{max. temp. ratio} \tag{36}$$

$$0 \leq r_h \quad ;\, r_h = \text{discharge-charging duration ratio} \tag{37}$$

$$0 \leq h_d \leq \gamma \qquad ;\, h_d = \text{discharge duration} \tag{38}$$

$$;\, \gamma = \text{a constraint that prevents charging} \tag{39}$$

$$;\, \text{discharging at the same time} \tag{40}$$

$$;\, \text{therefore, } h_d \left(1 + \frac{1}{r_h}\right) \leq 8760 \tag{41}$$

$$0 \leq \epsilon_{RC} \leq 1 \qquad ;\, \epsilon_{RC} = \text{recuperator effectiveness} \tag{42}$$

$$1 \leq m \leq m_{max} \tag{43}$$

$$1 \leq n \leq n_{max} \tag{44}$$

$$0.01 \leq P_{HF} \leq 0.1 \qquad ;\, \text{heat price } [\$/\text{kW-h}] \tag{45}$$

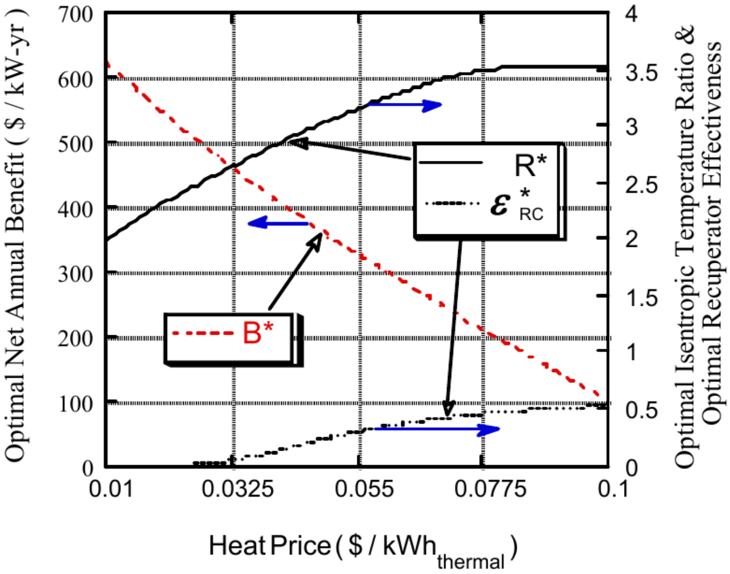

Figure 17: Result of optimization based on a range of heat price for a CAES power plant.

1.6 Battery Case Study

- Consider an electro-chemical battery energy storage with rated energy stored given as

$$E_{rated} = C_{rated} V_{nominal} \;\; [W - h] \tag{46}$$

  - C_{rated} is the amp-hour capacity of the battery
  - $V_{nominal}$ is the nominal voltage of the battery

- There is a general restriction on the "depth of discharge" (DOD) of **50% of capacity** to ensure a long operating life
- The **average lifetime** battery efficiency is approximately 68%
  - 80% at the start, 50% at the end
- Example. Consider a deep-cycle lead acid battery in which $V_{nominal} =$ 60V, and $C_{rated} =$ 1200A-hr. The usable energy is then

$$\begin{aligned} E_{usable} &= E_{rated} \cdot \text{DOD} && (47)\\ &= (1200)(60)(0.5) && (48)\\ &= 36[\text{kw-h}] && (49) \end{aligned}$$

We can define the efficiency for the battery "system" to include the battery and the power inverter that converts A.C. to D.C. for charging. Thus

$$\eta_{battery/inverter} = \eta_{battery}\eta_{inverter}. \tag{50}$$

The average efficiency of a voltage inverter is approximately 85%. Therefore the overall efficiency of the battery-inverter combination is

$$\eta_{battery/inverter} = (0.68)(0.85) = 0.578 \; (57.8\%) \tag{51}$$

1.7 Hydro-electric Storage Case Study

- Considers the energy that can be stored and the efficiency of hydro-electric storage
- The energy generated in this process is

$$E_{hydro} = \rho g h VOL \eta \tag{52}$$

where

$$VOL = \text{water volume stored } [\text{m}^3] \tag{53}$$
$$h = \text{stored water elevation (pressure head) } [\text{m}] \tag{54}$$
$$\rho = \text{water density } [1000 \text{ kg/m}^3] \tag{55}$$
$$g = \text{gravitational constant } [9.8 \text{ m/s}^2] \tag{56}$$
$$\eta = \eta_t \eta_{pipe} \tag{57}$$
$$\eta_t = \text{turbine efficiency } (0.60) \tag{58}$$
$$\eta_{pipe} = \text{pipe flow efficiency } (0.90). \tag{59}$$

- Noting that $1J = 1W$, the stored energy in units of [kW-h] is

$$E = \frac{gVOLh\eta}{3600} \tag{60}$$

- The required volume of water needed to supply a given amount of energy is

$$VOL = \frac{3600E}{gh\eta} \tag{61}$$

  - Note that 3600 s/hr is a conversion between hours and seconds

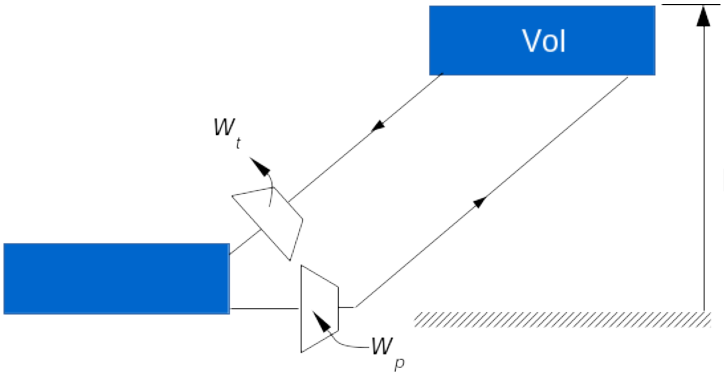

Figure 18: Schematic of a hydro-electric storage configuration.

- Example. Determine the volume of water at an elevation of 50 m. that is needed to produce 100,kW-h of electric power.

$$VOL = \frac{3600E}{gh\eta} \tag{62}$$

$$= \frac{(3600)(100)}{9.8(50)(0.60)(0.90)} \tag{63}$$

$$= 1359\,\mathrm{m}^3 \tag{64}$$

$$= 50\,\mathrm{m} \text{ by } 20\,\mathrm{m} \text{ by } 1.4\,\mathrm{m} \text{ deep} \tag{65}$$

1.8 Buoyant Hydraulic Energy Storage Case Study

- Wind turbines in deep off-shore locations are supported by floating structures
- This has led to a concept for storing electric energy that is similar to pumped hydro-electric storage but instead used **buoyant hydraulic energy storage** of the floating structures

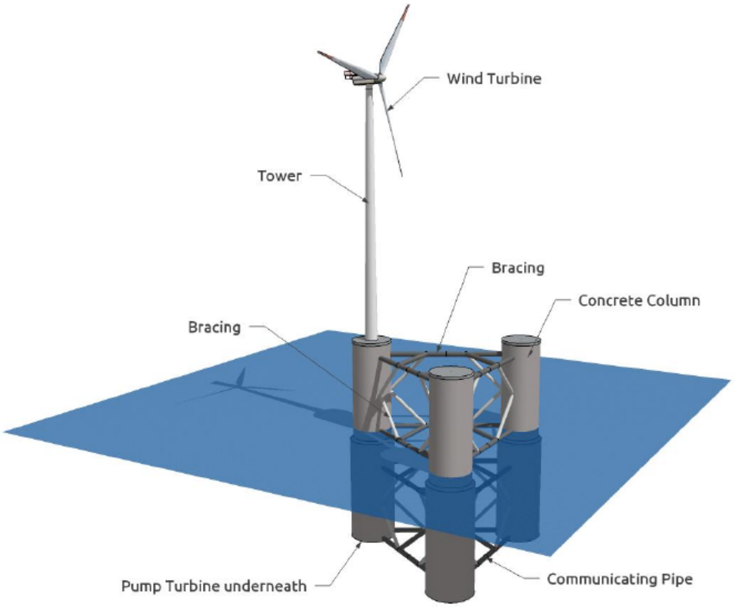

Figure 19: Example of a floating off-shore platform supporting a wind turbine.

- The buoyant energy is stored through the potential energy of the mass of the floating structure

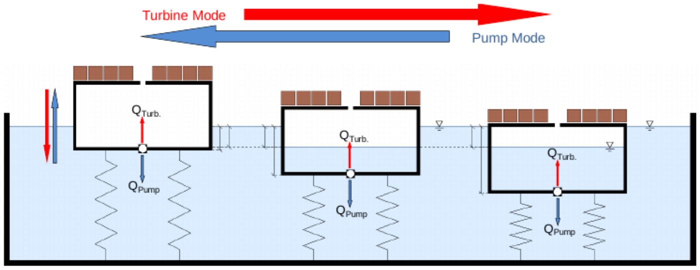

Figure 20: Example of a floating off-shore platform supporting a wind turbine.

1. The floating structure has an opening at its lowest point that can allow water to enter an internal compartment
2. When the water enters the compartment, it passes through a turbine to generate electricity, and the floating structure sinks lower in the water
3. Electric power is used to pump out the compartment by reversing the turbine to act as a pump, and the floating structure rises higher in the water

- When the floating structure is at its highest elevation, it stores the largest amount of energy

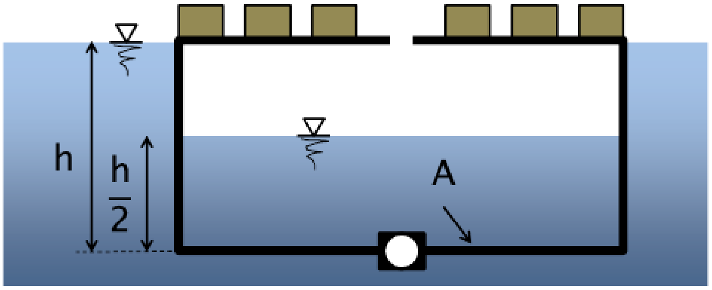

Figure 21: Schematic representation of the buoyant energy storage.

- Consider the reservoir to be cylindrical in shape
- The maximum occurs when the compartment is half full, at which point the immersion depth is h
- The maximum amount of stored energy is then

$$\begin{aligned} E &= mg\tfrac{h}{2} && (66)\\ &= \rho A\tfrac{h}{2}g\tfrac{h}{2}\eta_t && (67)\\ &= \rho Ag\tfrac{h^2}{4}\eta_t && (68) \end{aligned}$$

  - A is the projected area of the floating structure
  - $A(h/2)$ is the volume of displaced water
  - η_t is the efficiency of the turbine ($\simeq$60%)

- Rearranging the previous equation,

$$\begin{aligned} m &= \rho A\tfrac{h}{2} && (69)\\ &= \tfrac{2E}{gh}. && (70) \end{aligned}$$

- The gravimetric energy density is

$$\begin{aligned} \rho_{grav} &= \tfrac{E}{m} && (71)\\ &= g\tfrac{h}{2}. && (72) \end{aligned}$$

- The volumetric energy density is

$$\rho_{vol} = \frac{E}{hA} \tag{73}$$

$$= \frac{m}{2}\frac{g}{A} \tag{74}$$

$$= \rho g \frac{h}{4}. \tag{75}$$

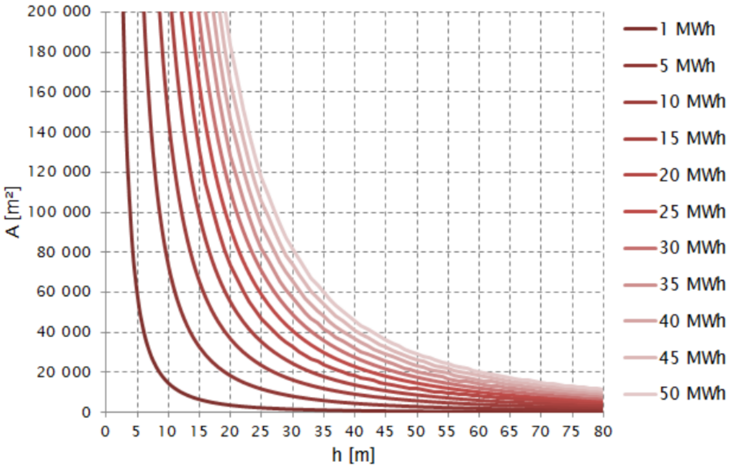

Figure 22: Relation between the projected area of the floating structure and the immersion depth for a given stored power level.

- A floating structure with a projected area of 40,000 m2 that can change elevation by 20 m, can store 10 MW-h of energy
- Like the pumped hydro-electric system, the buoyant energy system has a short response time, and an unlimited number of charge-discharge cycles