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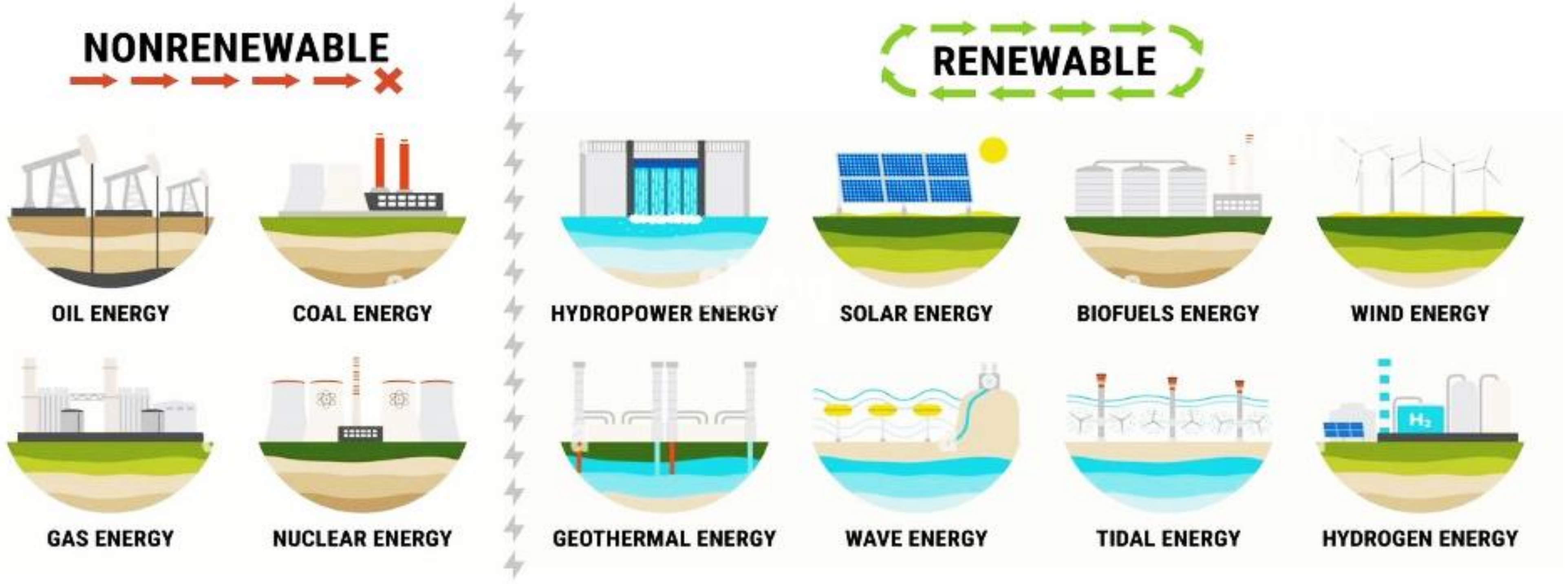
PUMPED-HYDRO ENERGY STORAGE



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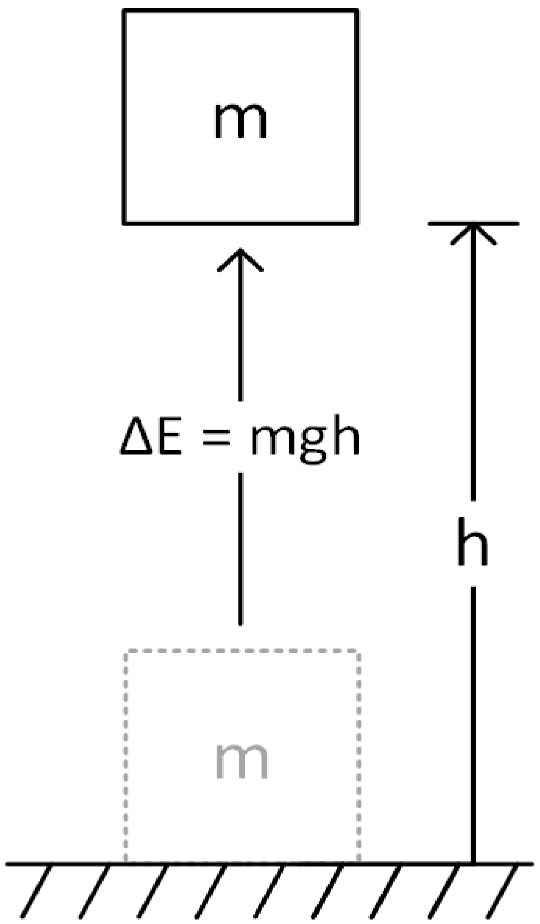
POTENTIAL ENERGY STORAGE

- Energy can be stored as ***potential energy***
- Consider a mass, m, elevated to a height, h
- Its potential energy increase is

$$E = mgh$$

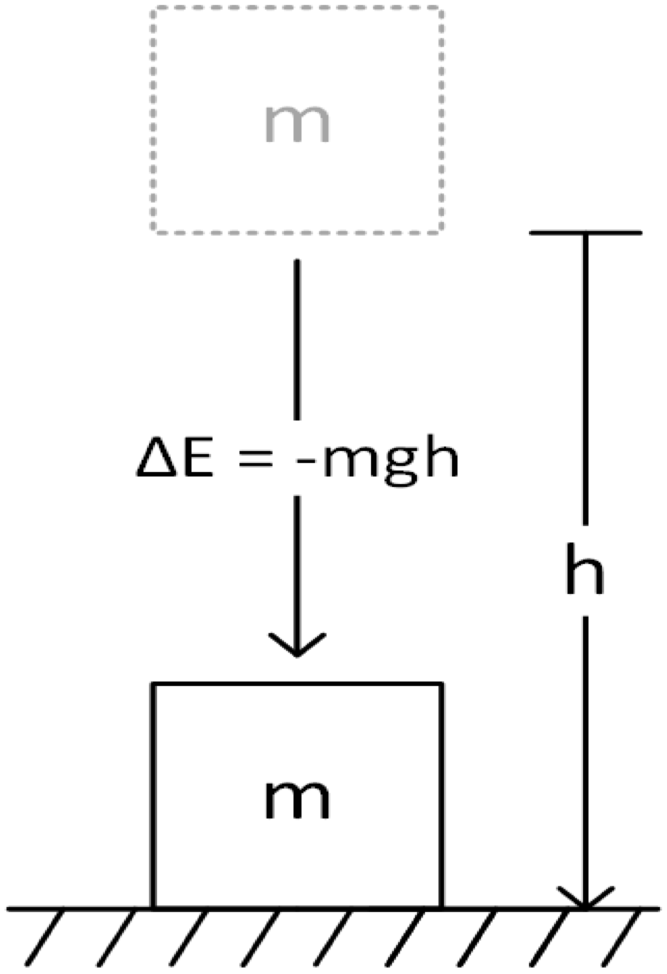
where $g = 9.81\ m/s^2$ is gravitational acceleration

- Lifting the mass requires an input of work equal to (at least) the energy increase of the mass
  - We put energy in to lift the mass
  - That energy is stored in the mass as potential energy

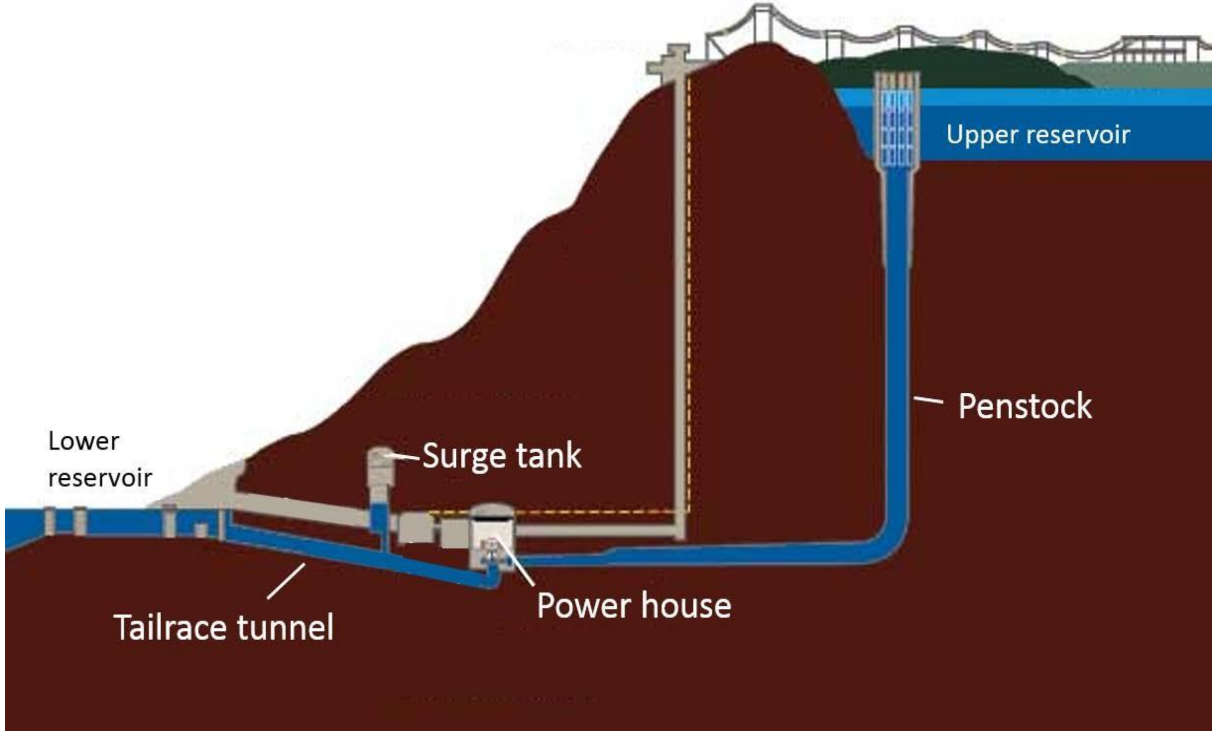


POTENTIAL ENERGY STORAGE

- If we allow the mass to fall back to its original height, we can capture the stored potential energy
  - Potential energy converted to kinetic energy as the mass falls
  - Kinetic energy can be captured to perform work
  - Perhaps converted to rotational energy, and then to electrical energy



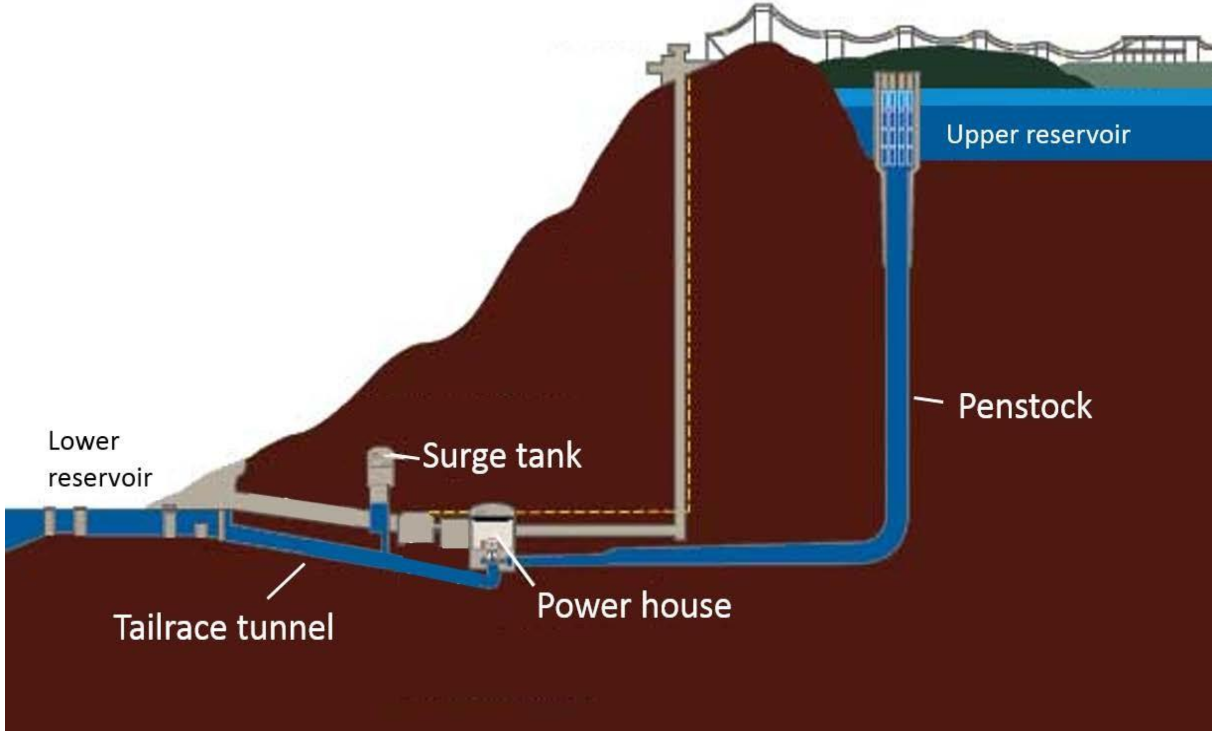
PUMPED-HYDRO ENERGY STORAGE



- Potential energy storage in elevated mass is the basis for ***pumped-hydro energy storage*** (PHES)
  - Energy used to pump water from a lower reservoir to an upper reservoir
  - ***Electrical energy*** input to ***motors*** converted to ***rotational mechanical energy***
  - ***Pumps*** transfer energy to the water as ***kinetic***, then ***potential energy***

PUMPED-HYDRO ENERGY STORAGE

- Energy stored in the water of the upper reservoir is released as water flows to the lower reservoir
  - Potential energy converted to kinetic energy
  - Kinetic energy of falling water turns a turbine
  - Turbine turns a generator
  - Generator converts mechanical energy to electrical energy

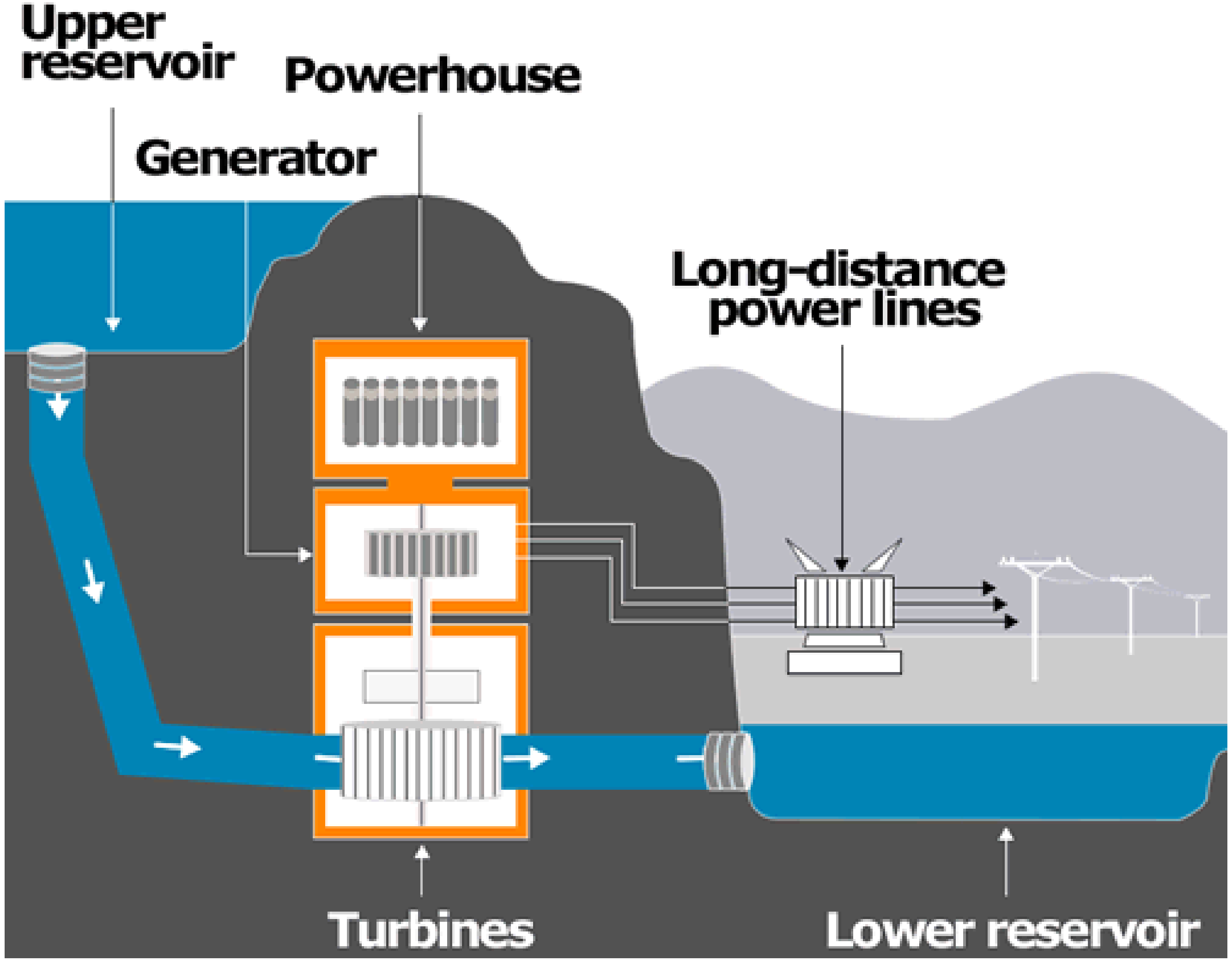


HISTORY OF PHES

- PHES first introduced in Italy and Switzerland in the 1890’s
  - Favorable topography in the Alps
  - Four-unit (quaternary) systems
    - Turbine
    - Generator
    - Motor
    - Pump

HISTORY OF PHES

- First PHES plant in the US:
  - Rocky River hydro plant, New Milford, CT
  - Water from the Housatonic River pumped up into Candlewood Lake
  - 230 feet of head
  - 6 billion ft^3 of water
  - Two-unit (binary) system
    - Reversible pump/turbine – one of the first
  - 29 MW of generating power

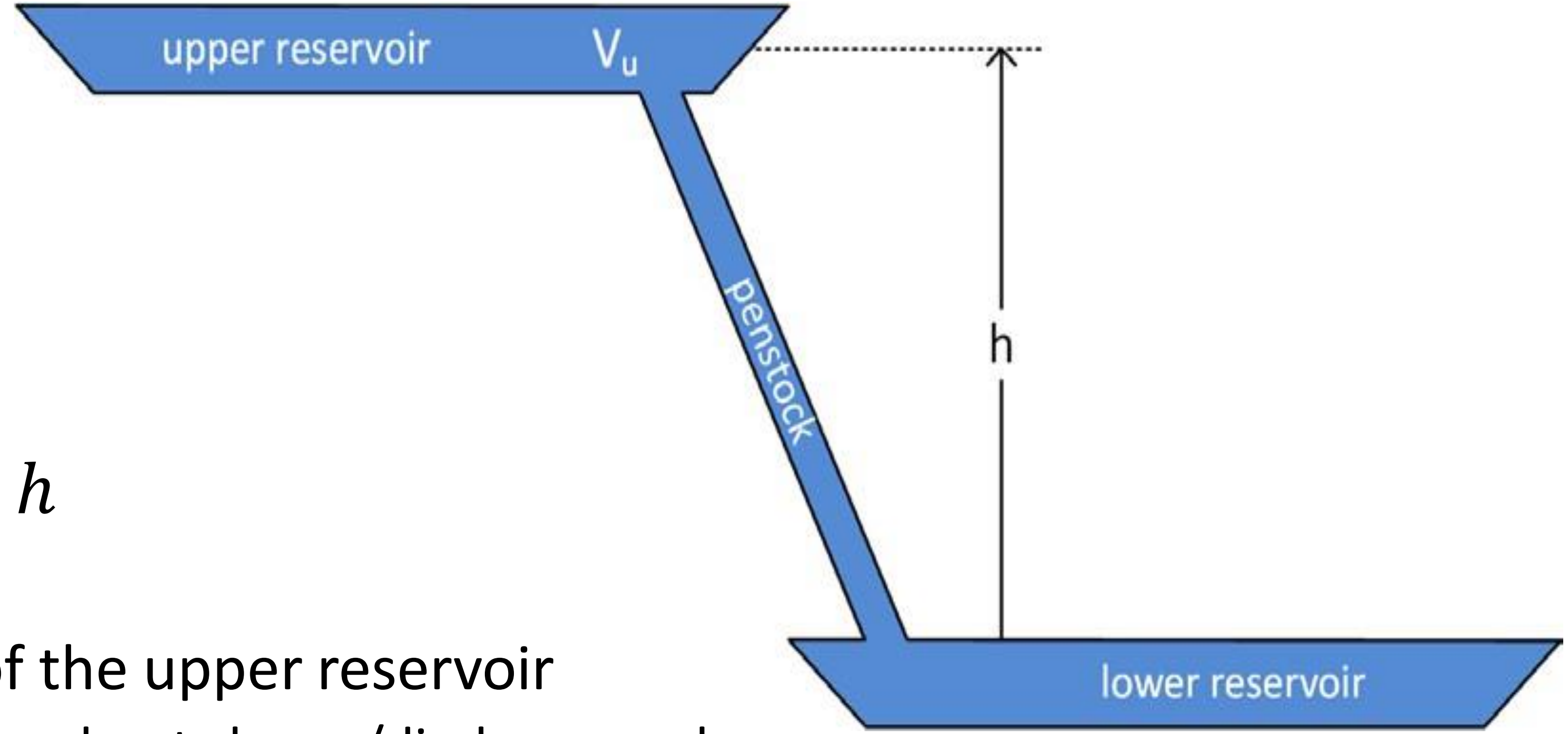


PUMPED-HYDRO STORAGE TODAY

- PHES accounts for 99% of worldwide energy storage
  - Total power: ~127 GW
  - Total energy: ~740 TWh
  - Power of individual plants: 10s of MW – 3 GW
- In the US:
  - ~40 operational PHES plants
  - 75% are > 500 MW – strong economies of scale
  - Total power: ~23 GW
    - Current plans for an additional ~6 GW
  - Total energy: ~220 TWh

PHES FUNDAMENTALS

- Two storage reservoirs
  - Upper and lower
  - Lower reservoir may be a river or even the sea
- Separated by a height, h
  - The hydraulic head
  - Assume $h \gg$ depth of the upper reservoir
    - h remains constant throughout charge/discharge cycle
- Upper reservoir can store a volume of water, V_u



PHES FUNDAMENTALS - ENERGY

- ***Total stored energy*** (assuming it is all at a height, h)

$$\boxed{E_t = mgh = V_u \rho g h}$$

where $\rho = 1000\ kg/m^3$ is the density of water

- Verifying that we do, in fact, have units of energy

$$[E_t] = \ m^3 \frac{kg}{m^3}\frac{m}{s^2} m = \frac{kg \cdot m}{s^2} m = N \cdot m = J$$

- The ***energy density*** – energy per unit volume – of the stored water is therefore

$$\boxed{e_v = \frac{E_t}{V_u} = \rho g h}$$

$$[e_v] = \frac{kg}{m^3}\frac{m}{s^2} m = \frac{kg \cdot m^2}{s^2}\frac{1}{m^3} = \frac{J}{m^3}$$

- The energy density of the stored water is also the ***hydrostatic pressure*** at the level of the lower reservoir

$$\boxed{p = \rho g h}$$

$$[p] = \frac{kg}{m^3}\frac{m}{s^2}m = \frac{kg \cdot m}{s^2}\frac{1}{m^2} = \frac{N}{m^2} = Pa$$

- This is the ***energy density*** of the water at the turbine

PHES FUNDAMENTALS - POWER

- The rate at which energy is transferred to the turbine (from the pump) is the power extracted from (delivered to) the water

$$\boxed{P = e_v Q = p Q = \rho g h Q}$$

where Q is the ***volumetric flow rate*** of the water

$$[P] = \frac{J}{m^3}\frac{m^3}{s} = \frac{J}{s} = W$$

- This is the total power available at the turbine
  - Greater than (less than) the power actually delivered to the turbine (from the pump), due to inefficiencies

A GENERALIZED POWER RELATION

- Note that **power** is given by the product of a driving potential, or ***effort***, p, and a ***flow***, Q

$$P = pQ$$

- Similar to power for a ***translational mechanical*** system

$$P = Fv$$

where the effort is force, F, and the flow is velocity, v

- Or, a ***rotational mechanical*** system

$$P = \tau\omega$$

where the effort is torque, τ, and the flow is angular velocity, v

PHES APPLICATIONS

- Pumped hydro plants can supply large amounts of both ***power*** and ***energy***
- Can ***quickly respond to large load variations***
- Uses for PHES:

- ***Peak shaving/load leveling***
  - Help meet loads during peak hours
    - Generating while releasing water from upper reservoir
    - Supplying expensive energy
  - Store energy during off-peak hours
    - Pumping water to the upper reservoir
    - Consuming inexpensive energy

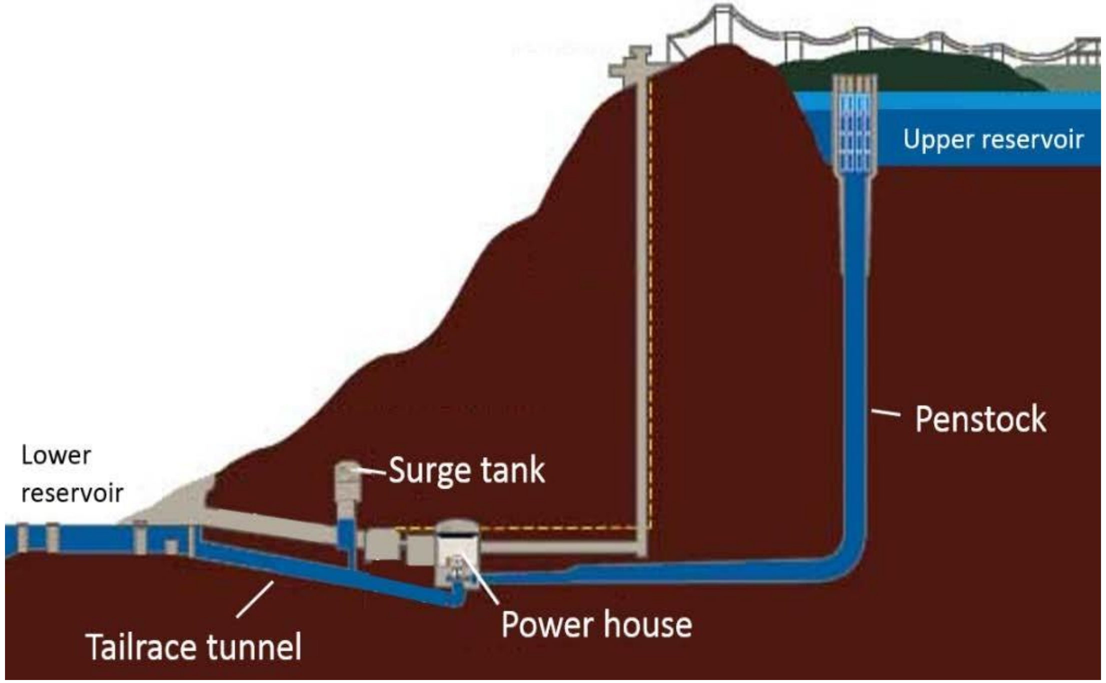
PHES APPLICATIONS

- ***Frequency regulation***
  - Power variation to track short-term load variations
  - Helps maintain grid frequency at 60 Hz (50 Hz)

- ***Voltage support***
  - Reactive power flow control to help maintain desired grid voltage
    - Varying the field excitation voltage of the generator/motor
  - Even at zero real power – not pumping or generating – unloaded motor/generator can serve as synchronous condenser
    - Pump/turbine spinning in air

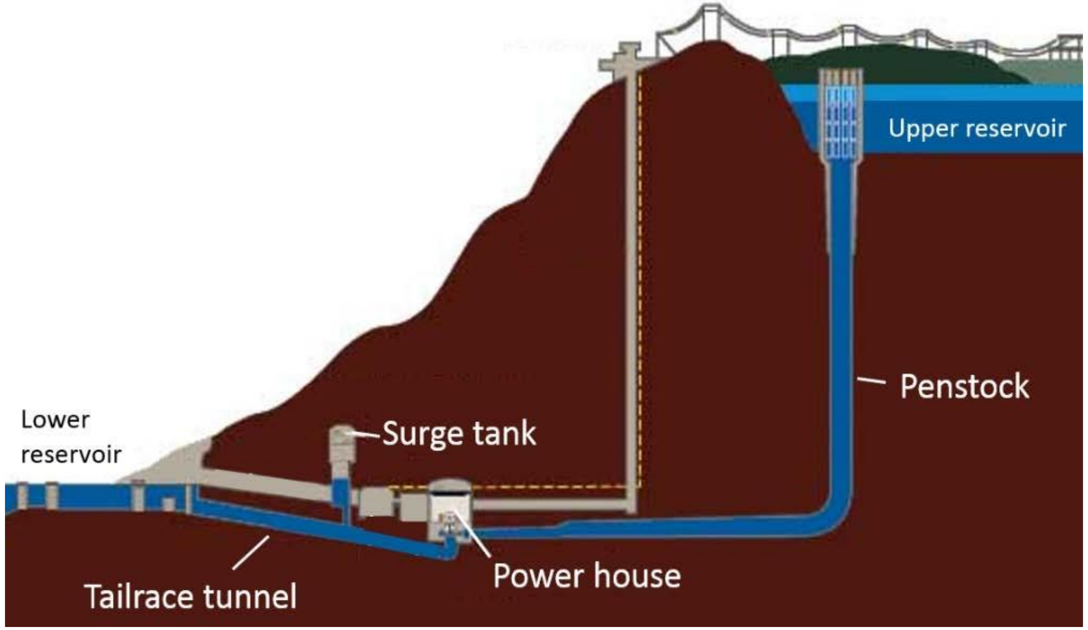
PHES COMPONENTS – RESERVOIRS

- ***Upper and lower reservoirs*** separated by an elevation difference
- Two configurations:
  - ***Open-loop***:
    - At least one of the reservoirs connected to a source of natural inflow
    - Natural lake, river, river-fed reservoir, the sea
  - ***Closed-loop***:
    - Neither reservoir has a natural source of inflow
    - Initial filling and compensation of leakage and evaporation provided by ground water wells
    - Less common than open-loop



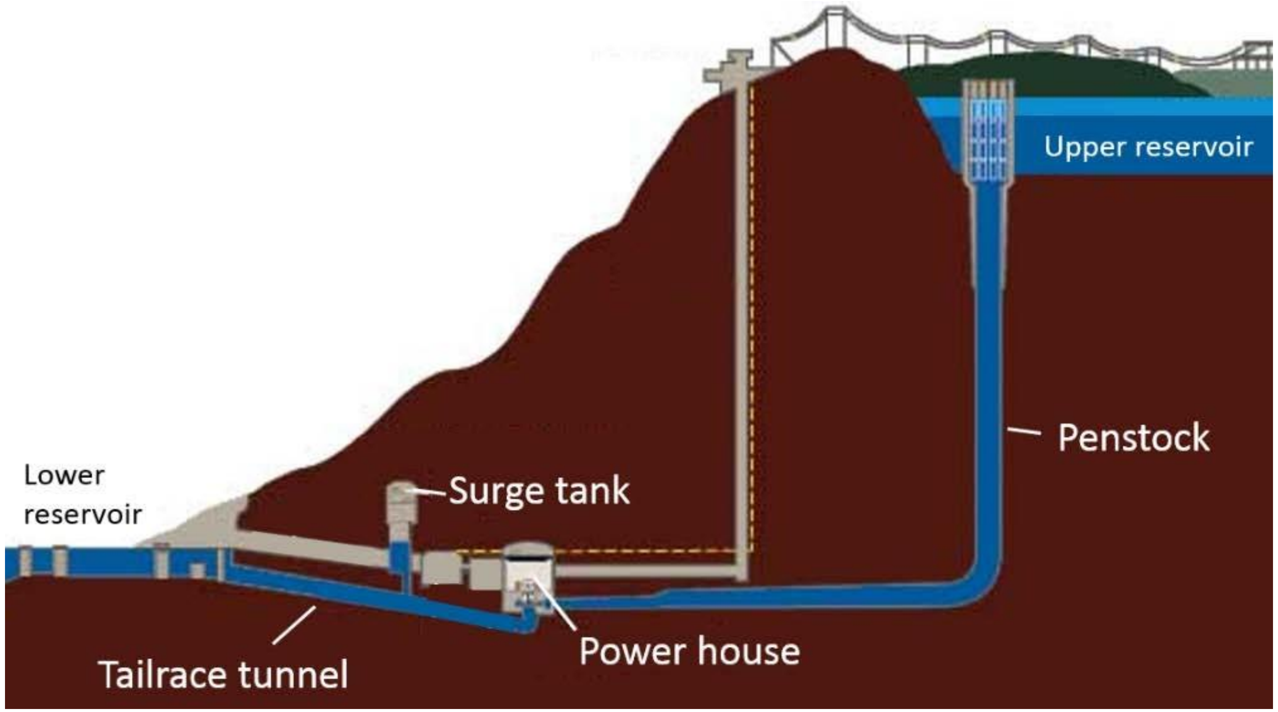
PHES COMPONENTS – PENSTOCK

- ***Penstock***
  - Conduit for water flowing between reservoirs and to the pump/generator
  - Above-ground pipes or below ground shafts/tunnels
    - 5 -10 m diameter is common
    - One plant may have several penstocks
    - Typically steel- or concrete-lined, though may be unlined
  - Flow velocity range of 1 – 5 m/s is common
  - Tradeoff between cost and efficiency for a given flow rate, Q
    - Larger cross-sectional area:
      - Slower flow
      - Lower loss
      - Higher cost



PHES COMPONENTS

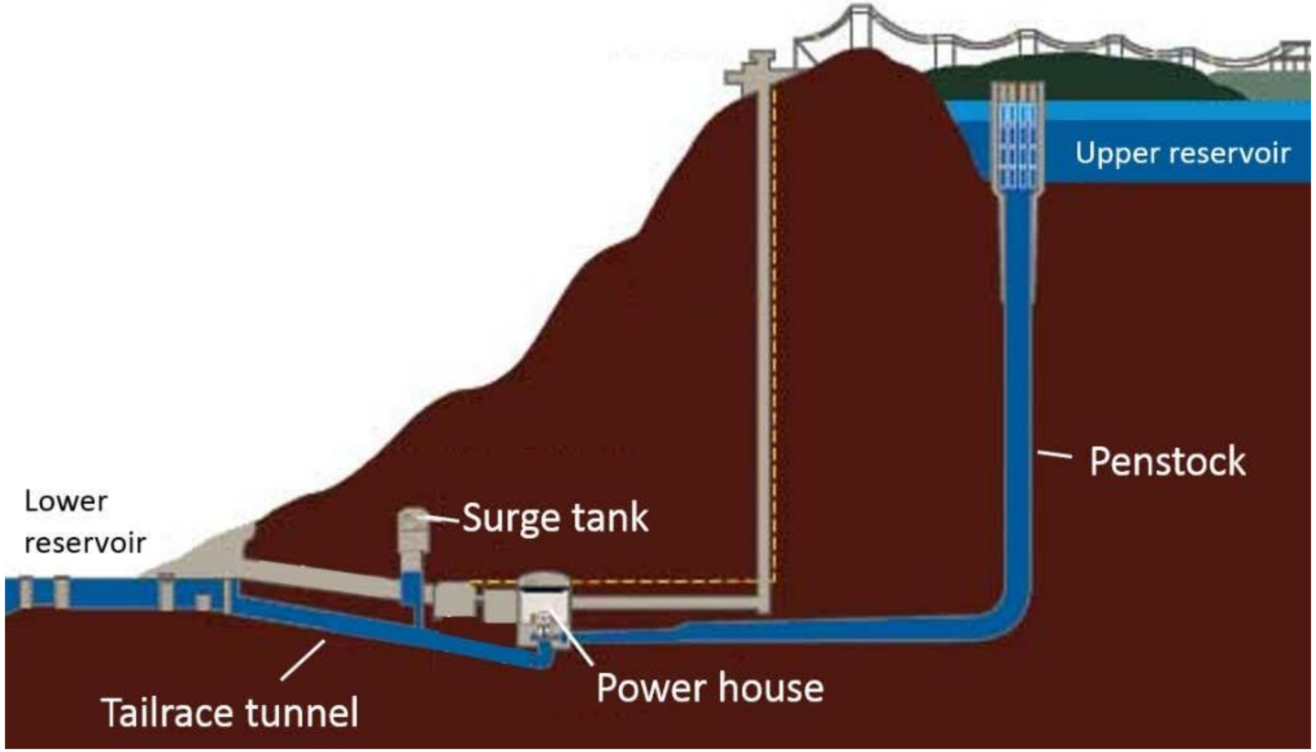
- ***Tailrace tunnel***
  - Typically, larger diameter than penstocks
  - Lower pressure
  - Lower flow rate
  - Downward slope from lower reservoir to pump/turbine
    - Inlet head helps prevent cavitation in pumping mode



- ***Surge tanks***
  - Accumulator tanks to absorb high pressure transients during startup and mode changeover
  - May be located on penstock or tailrace
  - Especially important for longer tunnels
  - *Hydraulic bypass capacitors*

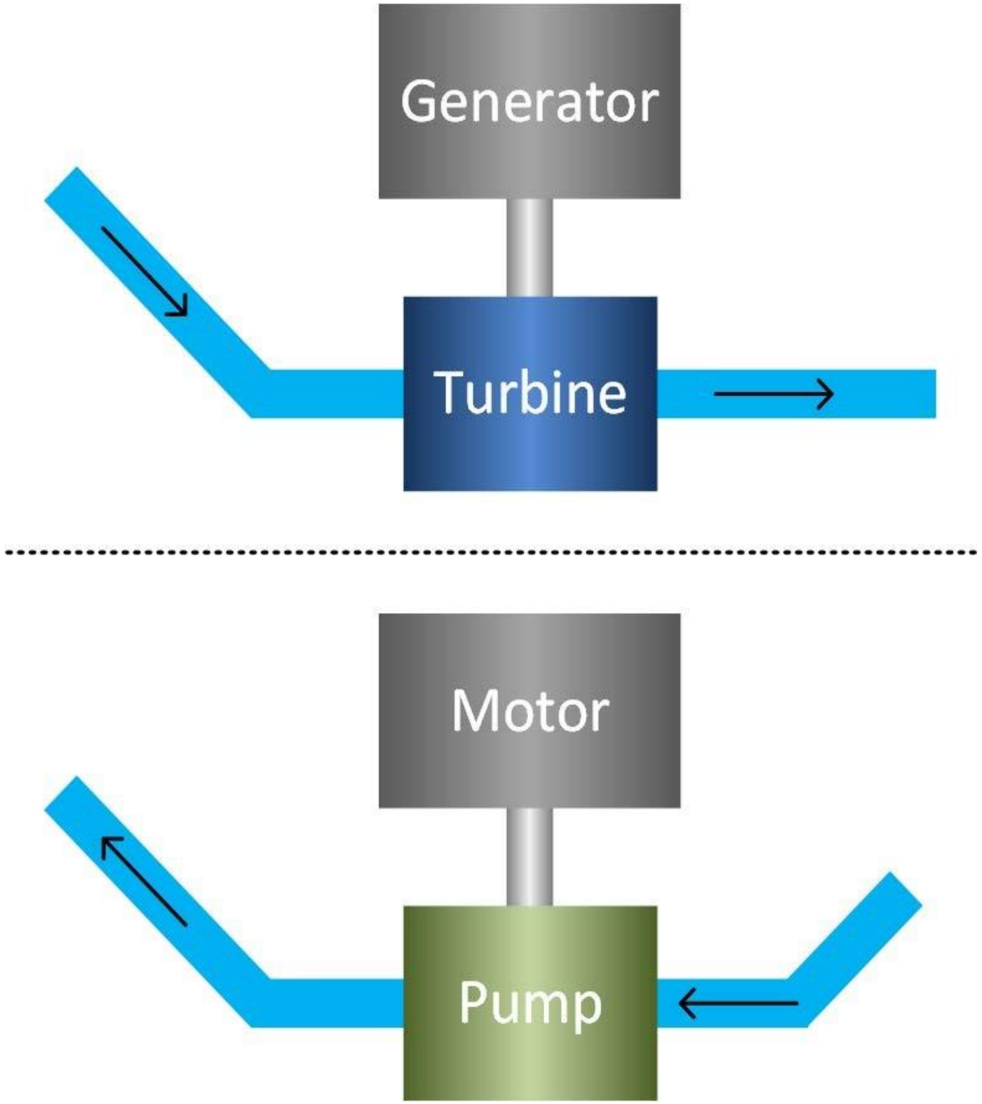
PHES COMPONENTS – POWER HOUSE

- ***Power house***
  - Contains pump/turbines and motor/generators
  - Often underground
  - Typically below the level of the lower reservoir to provide required pump inlet head
  - Three possible configurations
    - ***Binary set***: one pump/turbine and one motor/generator
    - ***Ternary set***: one pump, one turbine, and one motor/generator
    - ***Quaternary set***: separate pump, turbine, motor, and generator



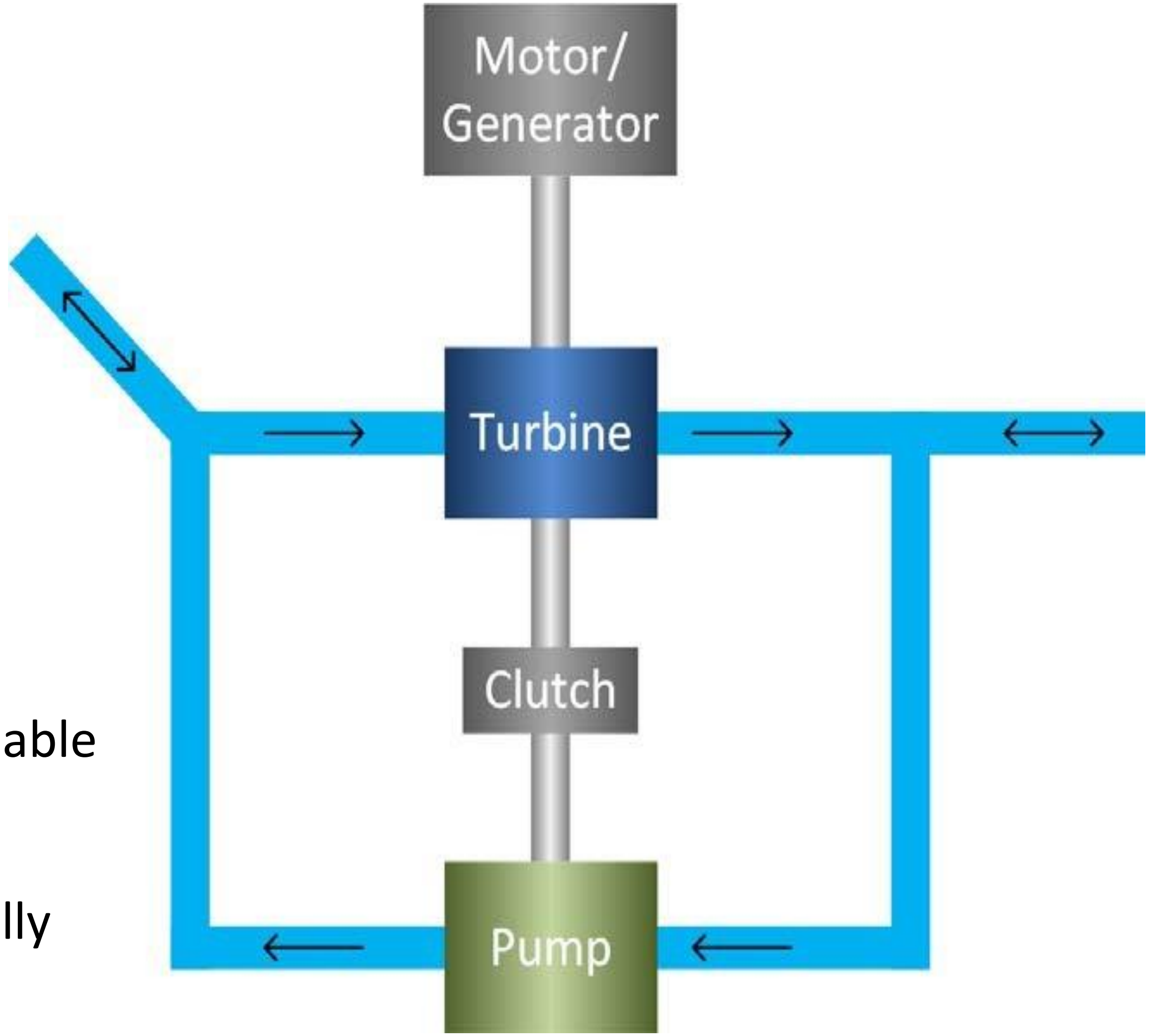
POWER PLANT CONFIGURATIONS – QUATERNARY SET

- ***Quaternary set***
  - Pump driven by a motor
  - Generator driven by a turbine
  - Pump and turbine are completely decoupled
  - Possibly separate penstocks/tailrace tunnels
  - Most common configuration prior to 1920
  - High equipment/infrastructure costs
  - High efficiency
    - Pump and turbine designed to optimize individual performance



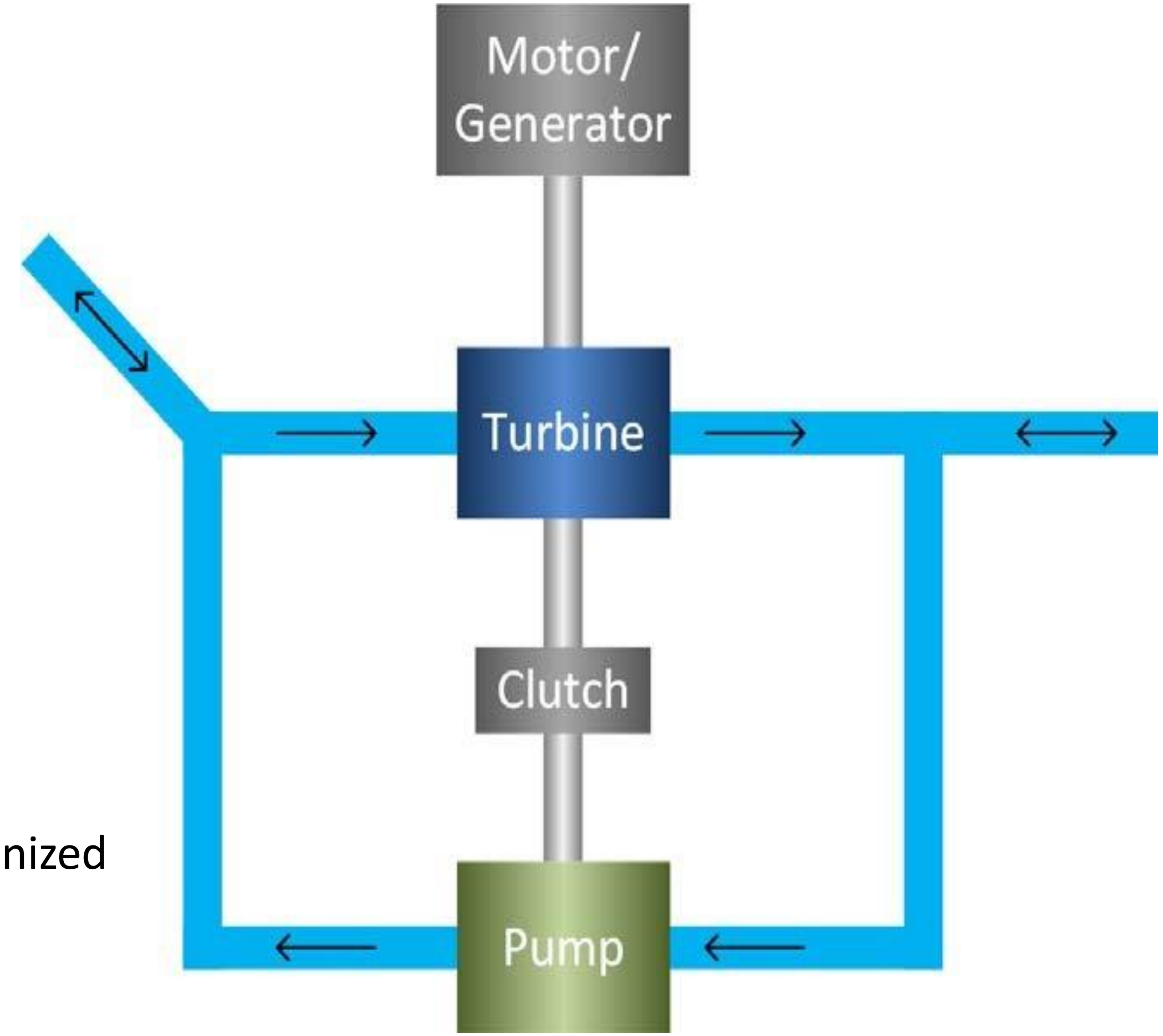
POWER PLANT CONFIGURATIONS – TERNARY SET

- ***Ternary set***
  - Pump, turbine, and motor/generator all on a single shaft
    - Pump and turbine rotate in the same direction
  - Turbine rigidly coupled to the motor/generator
  - Pump coupled to shaft with a clutch
  - Popular design 1920 – 1960s
  - Nowadays, used when head exceeds the usable range of a single- stage pump/turbine
    - High-head turbines (e.g., Pelton) can be used
  - Pump and turbine designs can be individually optimized



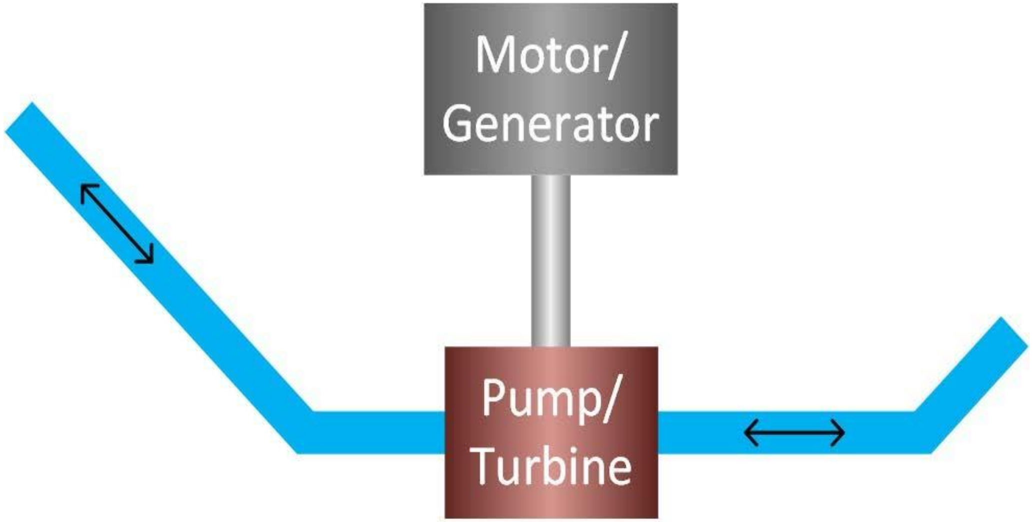
POWER PLANT CONFIGURATIONS – TERNARY SET

- ***Ternary set***
  - Generating mode:
    - Turbine spins generator
    - Pump decoupled from the shaft and isolated with valves
  - Pumping mode:
    - Motor turns the pump
    - Turbine spins in air, isolated with valves
  - Both turbine and pump can operate simultaneously
  - Turbine can be used for pump startup
    - Both spin in the same direction
    - Turbine brings pump up to speed and synchronized with grid, then shuts down
    - Changeover time reduced



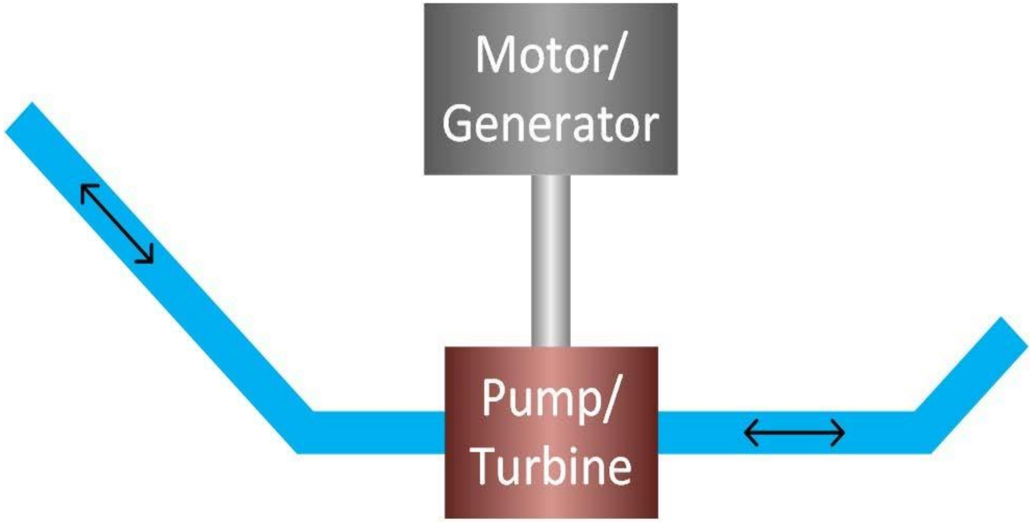
POWER PLANT CONFIGURATIONS – BINARY SET

- ***Binary set***
  - Single reversible pump/turbine coupled to a single motor/generator
  - Most popular configuration for modern PHES
  - Lowest cost configuration
    - Less equipment
    - Simplified hydraulic pathways
    - Fewer valves, gates, controls, etc.
  - Lower efficiency than for ternary or quaternary sets
    - Pump/turbine runner design is a compromise between pump and turbine performance



POWER PLANT CONFIGURATIONS – BINARY SET

- ***Binary set***
  - Rotation is in opposite directions for pumping and generating
  - Shaft and motor/generator must change directions when changing modes
    - Slower changeover than for ternary or quaternary units
  - Pump startup:
    - Pump/turbine runner dewatered and spinning in air
    - Motor brings pump up to speed and in synchronism with the grid before pumping of water begins



PHES APPLICATIONS

- Hydro turbine design selection based on
  - Head
  - Flow rate
- PHES plants are typically sited to have large head
  - Energy density is proportional to head
  - Typically 100s of meters
- Reversible ***Francis*** pump/turbine
  - Most common turbine for PHES applications
  - Single-stage pump/turbines operate with heads up to 700 m
- For higher head:
  - Multi-stage pump/turbines
  - Ternary units with ***Pelton*** turbines

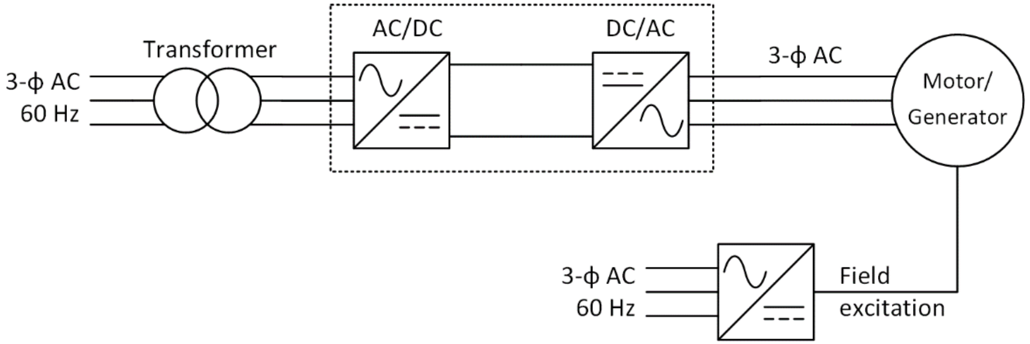
MOTOR/GENERATOR – FIXED-SPEED

- Pump/turbine shaft connects to a motor/generator unit
  - Above the turbine runner in typical vertical configuration
- Motor/generator type depends PHES category:
  - Fixed-speed pump/turbine
  - Variable-speed pump/turbine

- ***Fixed-speed pump/turbine***
  - Motor/generator operates at a fixed speed in both pumping and generating modes
  - ***Synchronous motor/generator***
    - Rotation is synchronous with the AC grid frequency
    - Stator windings connect to three-phase AC at grid frequency
    - Rotor windings fed with DC excitation current via slip rings
    - DC excitation current generated with thyristor AC/DC converters

MOTOR/GENERATOR

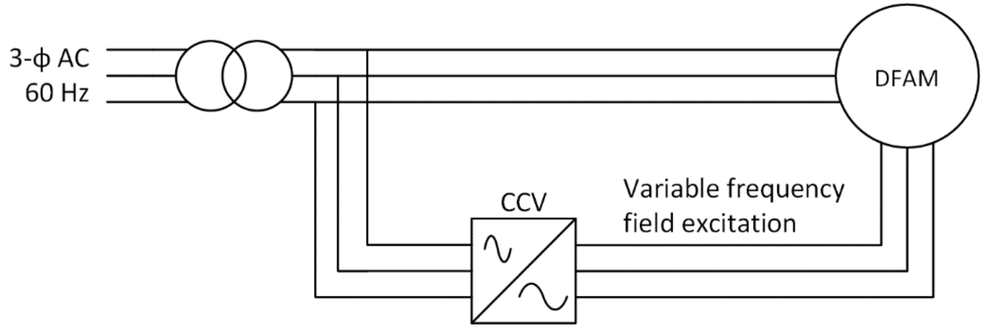
- ***Variable-speed (adjustable-speed) pump/turbine***
  - Rotational speed of motor/generator is adjustable
  - Two options:
    - Variable speed using a synchronous motor/generator (singly-fed)
    - Doubly-fed asynchronous machine (DFAM)
- ***Variable-speed operation with synchronous motor/generator***:



  - Motor driven with variable frequency
  - Decoupled from grid frequency by back-to-back converters
  - Converters must be rated for full motor/generator power
    - Large, expensive

MOTOR/GENERATOR – VARIABLE-SPEED

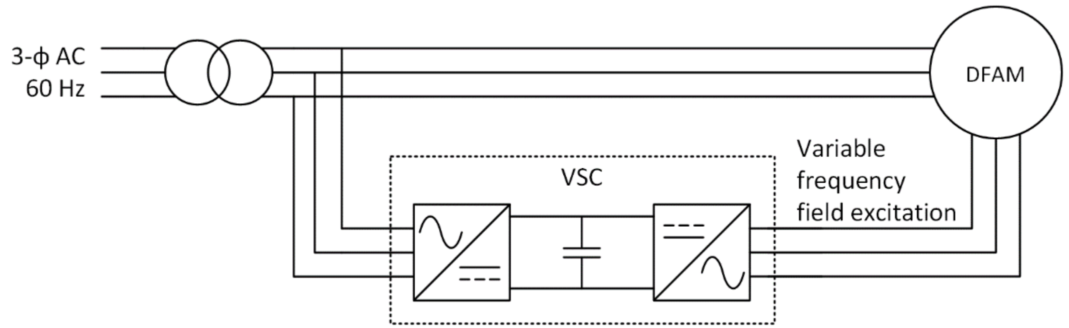
- ***Variable speed using doubly-fed asynchronous machines***
  - Field excitation fed with variable, low-frequency AC, not DC as in synchronous machines
  - Static frequency converter generates variable AC
    - Cycloconverter
    - Back-to-back voltage-source converters
  - Typically small speed range (e.g., ±10%)
- With ***cycloconverter*** generating variable-frequency excitation for rotor:



- Converters need not be sized for rated motor/generator power
  - Only supply lower-power excitation to the rotor

MOTOR/GENERATOR – VARIABLE-SPEED

- DFAM with variable-frequency field excitation generated by back-to-back VSCs:

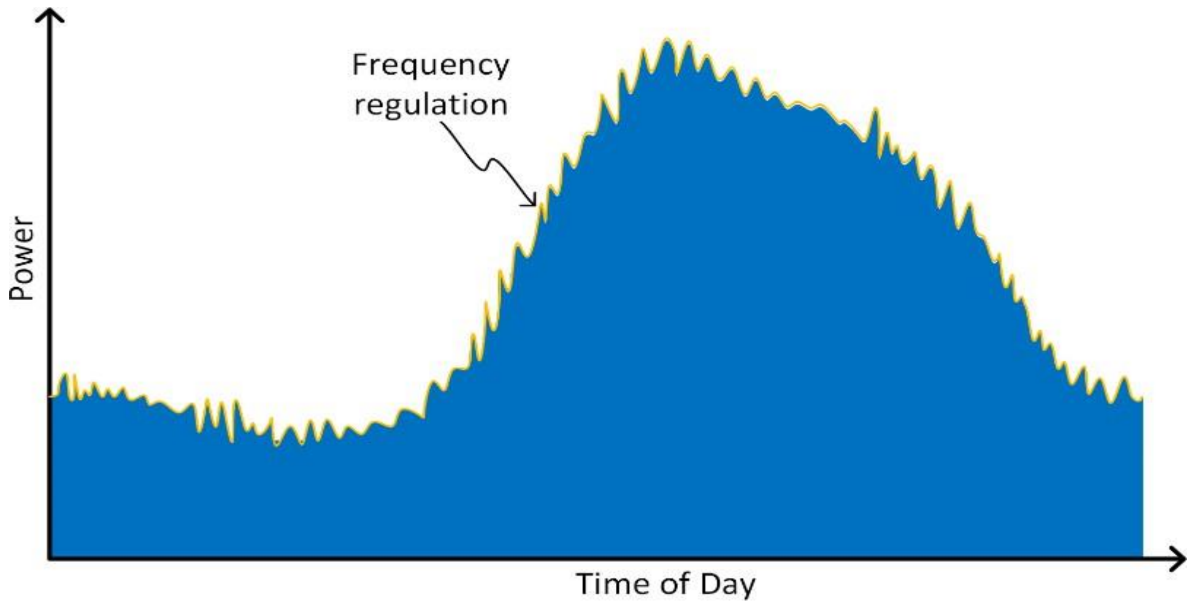


  - The preferred configuration for large (>100 MW) PHES plants nowadays

- Advantages of variable-speed plants
  - Pump and turbine speeds can be independently varied to optimize efficiency over range of flow rate and head
  - Pumping power can be varied in addition to generating power

PHES FOR FREQUENCY REGULATION

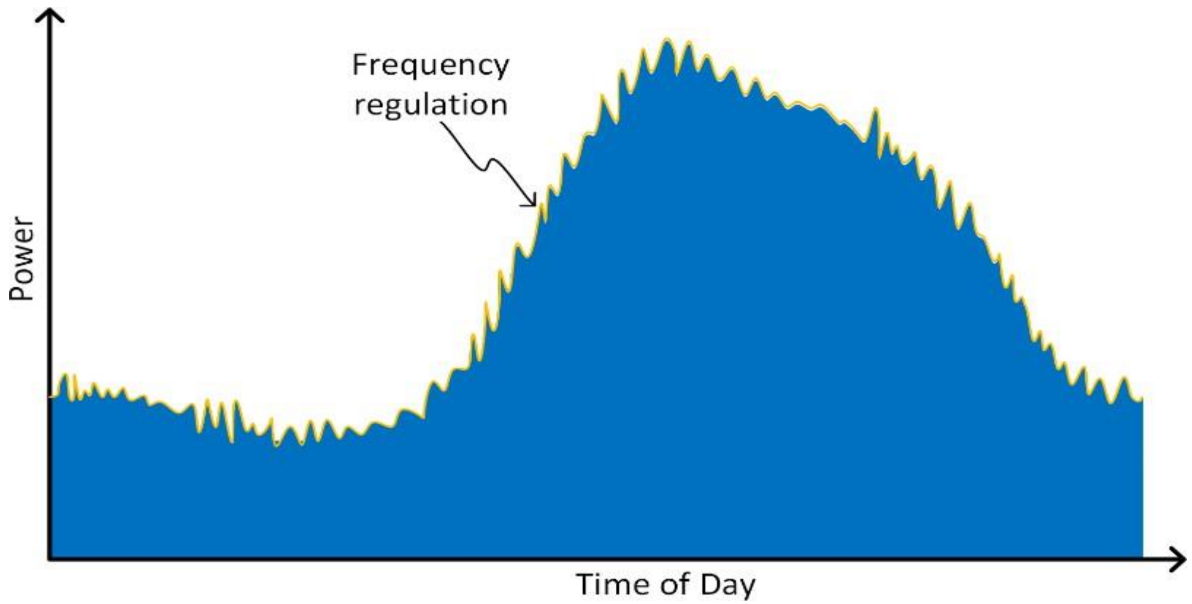
- ***Frequency regulation***
  - Tracking short-term load variations to maintain grid frequency at 60 Hz (or 50 Hz)
- PHES plants can provide frequency regulation
  - Different for fixed- or variable-speed plants



- ***Fixed-speed plants***
  - Generating mode
    - Frequency regulation provided by rapidly varying power output
    - Power varied by using wicket gates to modulate flow rate
    - Same as in conventional hydro plants
  - Pumping mode
    - Pump operates at rated power only – power input cannot be varied
    - ***No frequency regulation in pumping mode***

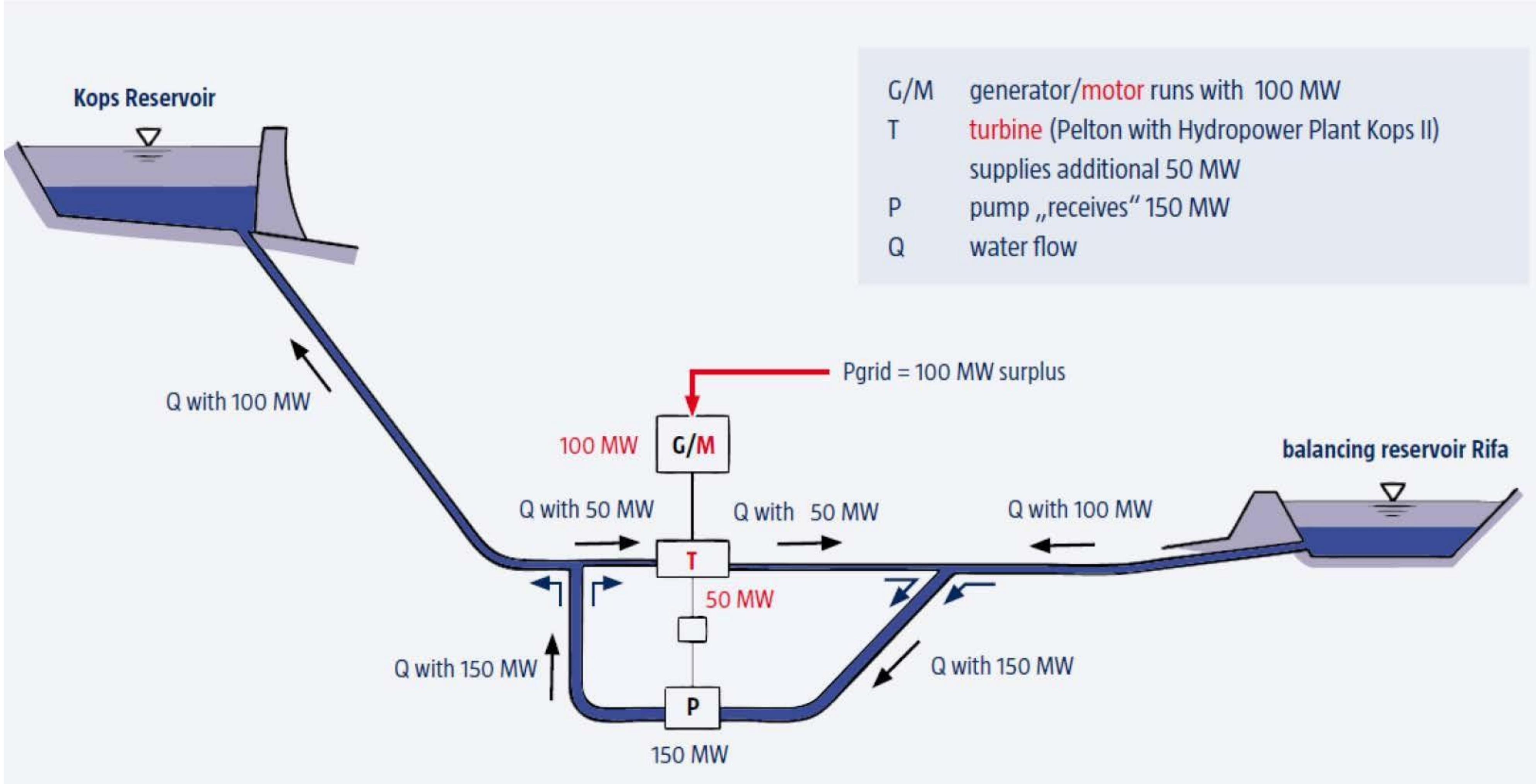
FREQUENCY REGULATION – VARIABLE-SPEED

- ***Variable-speed plants***
  - Pump speed can be varied over some range, e.g. $\pm 10\%$
  - Pump power is proportional to pump speed ***cubed***
    - For $\pm 10\%$ speed variation, power is adjustable over $\pm 30\%$
  - Power variation in pumping mode can track rapid load variations
  - ***Frequency regulation can be provided in both modes of operation***



HYDRAULIC SHORT CIRCUIT

- Kops II PHES plant in Austrian Alps:



PHES SYSTEM EFFICIENCY

- Round-trip efficiency:

$$\eta_{rt} = \frac{E_{out}}{E_{in}} \cdot 100\%$$

where

- E_{in} is the electrical energy that flows in from the grid to the plant in pumping mode
- E_{out} is the electrical energy that flows from the plant to the grid in generating mode

- Typical round-trip efficiency for PHES plants in the range of 70% – 80%

- PHES loss mechanisms
  - Transformer
  - Motor/generator
  - Pump/turbine
  - Water conduit

PHES LOSSES

- ***Transformers***
  - Pumped hydro plants connect to the AC electrical grid
    - Transformers step voltage between high voltage on the grid side to lower voltage at the motor/generator
  - Transformer ***loss mechanisms***:
    - Winding resistance
    - Leakage flux
    - Hysteresis and eddy currents in the core
    - Magnetizing current – finite core permeability
  - Power flows through transformers on the way into the storage plant and again on the way out
  - Typical loss: ~0.5%

PHES LOSSES

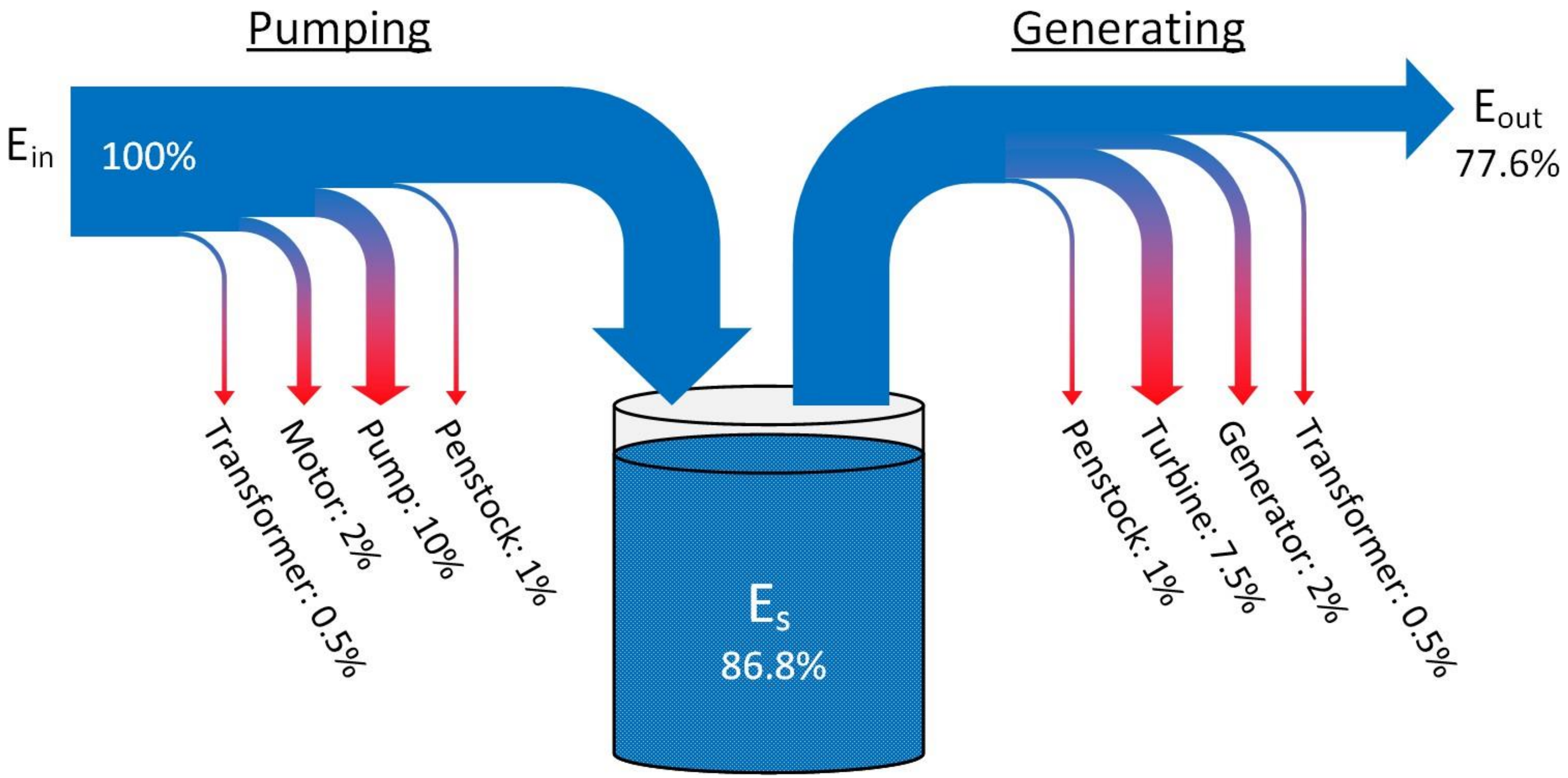
- ***Motor/generator losses***
  - Electrical resistance
  - Mechanical friction
  - Typical loss: ~2%
- ***Pump/turbine***
  - Single runner in binary sets
    - Typically lower efficiency, particularly for fixed-speed operation – design of both compromised
  - Separate runners in ternary, quaternary sets
    - Higher efficiency
  - Typical loss: ~7% - 10%

PHES LOSSES

- ***Penstock***
  - ***Frictional loss*** of water flowing through the conduit
    - Major losses along penstock
    - Minor losses from bends, penstock inlet, turbine inlet, etc.
  - Dependent on
    - Flow velocity
    - Penstock diameter
    - Penstock length
    - Penstock lining – steel, concrete, etc.
  - High head is desirable, but long penstocks are not
    - Steeper penstocks reduce frictional losses for a given head
    - Typical length-to-head ratio: 4:1 – 12:1
  - Typical loss: ∼1%

PHES LOSSES

- Typical losses for PHES:



PUMPING-MODE EFFICIENCY

- ***Efficiency of the pumping operation*** is given by

$$\eta_p = \frac{E_s}{E_{in}} \cdot 100\%$$

where

  - E_s is the energy stored
    - Potential energy of the volume of water, V_u, pumped to the upper reservoir

$$E_s = V_u \rho g h$$

  - E_{in} is the energy input from the grid during the pumping operation
- The mechanical energy input to the pump is

$$E_{in,pump} = E_{in} \cdot \eta_{trans} \cdot \eta_{motor}$$

where

  - η_{trans} and η_{motor} are the efficiencies of the transformer and motor, respectively

PUMPING-MODE EFFICIENCY

- The volume of water pumped to the upper reservoir is

$$V_u = \frac{E_{in,pump}}{\rho g h} \cdot \eta_{pump} \cdot \eta_{pipe,p}$$

where

- η_{pump} is the pump efficiency
- $\eta_{pipe,p}$ is the penstock efficiency in pumping mode

- So, the total pumped volume of water is

$$V_u = \frac{E_{in}}{\rho g h} \cdot \eta_{trans} \cdot \eta_{motor} \cdot \eta_{pump} \cdot \eta_{pipe,p}$$

- The ***pumping-mode efficiency*** is therefore:

$$\boxed{\eta_p = \frac{E_s}{E_{in}} = \eta_{trans} \cdot \eta_{motor} \cdot \eta_{pump} \cdot \eta_{pipe,p}}$$

PUMPING-MODE EFFICIENCY

- Efficiency of the generating operation is given by

$$\eta_{gg} = \frac{E_{out}}{E_s} \cdot 100\%$$

- Due to frictional losses in the penstock, the hydraulic energy that reaches the turbine is

$$E_{in,t} = E_s \cdot \eta_{pipe,gg}$$

- The amount of rotational energy at the turbine output/generator input is

$$E_{in,gg} = E_{in,t} \cdot \eta_t = E_s \cdot \eta_{pipe,gg} \cdot \eta_t$$

- After generator and step-up transformer losses, the energy output to the grid is

$$E_{out} = E_{in,gg} \cdot \eta_{ggen} \cdot \eta_{trans}$$

$$E_{out} = E_s \cdot \eta_{pipe,gg} \cdot \eta_t \cdot \eta_{ggen} \cdot \eta_{trans}$$

PUMPING-MODE EFFICIENCY

- ***Generating mode efficiency*** is

$$\eta_{gg} = \frac{E_{out}}{E_s} = \eta_{pipe,gg} \cdot \eta_t \cdot \eta_{ggen} \cdot \eta_{trans}$$

- The ***overall round-trip efficiency*** is therefore

$$\eta_{rt} = \frac{E_{out}}{E_{in}} = \eta_p \cdot \eta_{gg}$$

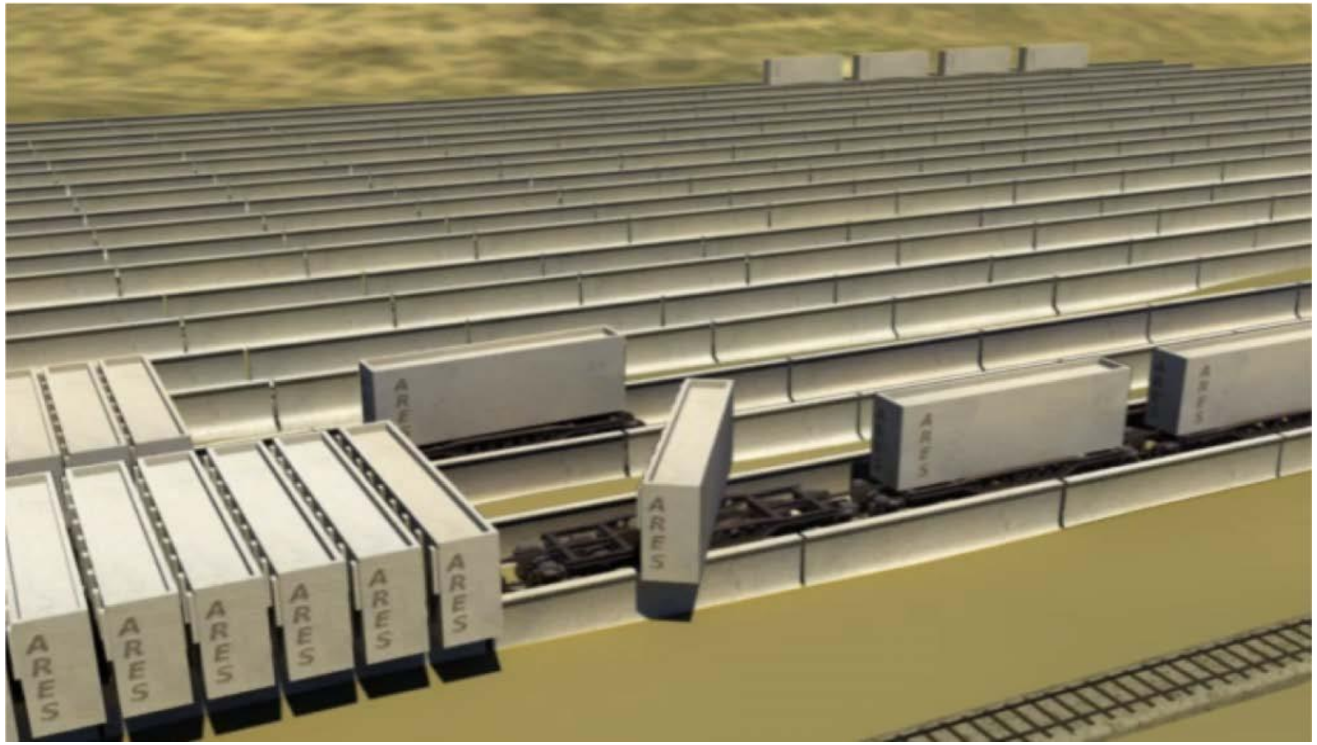
$$\eta_{rt} = \eta_{trans} \cdot \eta_{motor} \cdot \eta_{pump} \cdot \eta_{pipe,p} \cdot \eta_{pipe,gg} \cdot \eta_t \cdot \eta_{ggen} \cdot \eta_{trans}$$

DISADVANTAGES OF PHES

- ***Disadvantages of PHES***
  - Environmental issues
    - Water usage
    - River/habitat disruption
  - Head variation
    - Pressure drops as upper reservoir drains
    - Efficiency may vary throughout charge/discharge cycle
    - Particularly an issue for lower-head plants with steep, narrow upper reservoirs
  - Siting options are limited
    - Available water
    - Favorable topography
    - Large land area
- Possible alternative potential energy storage:
  - ***Rail energy storage***

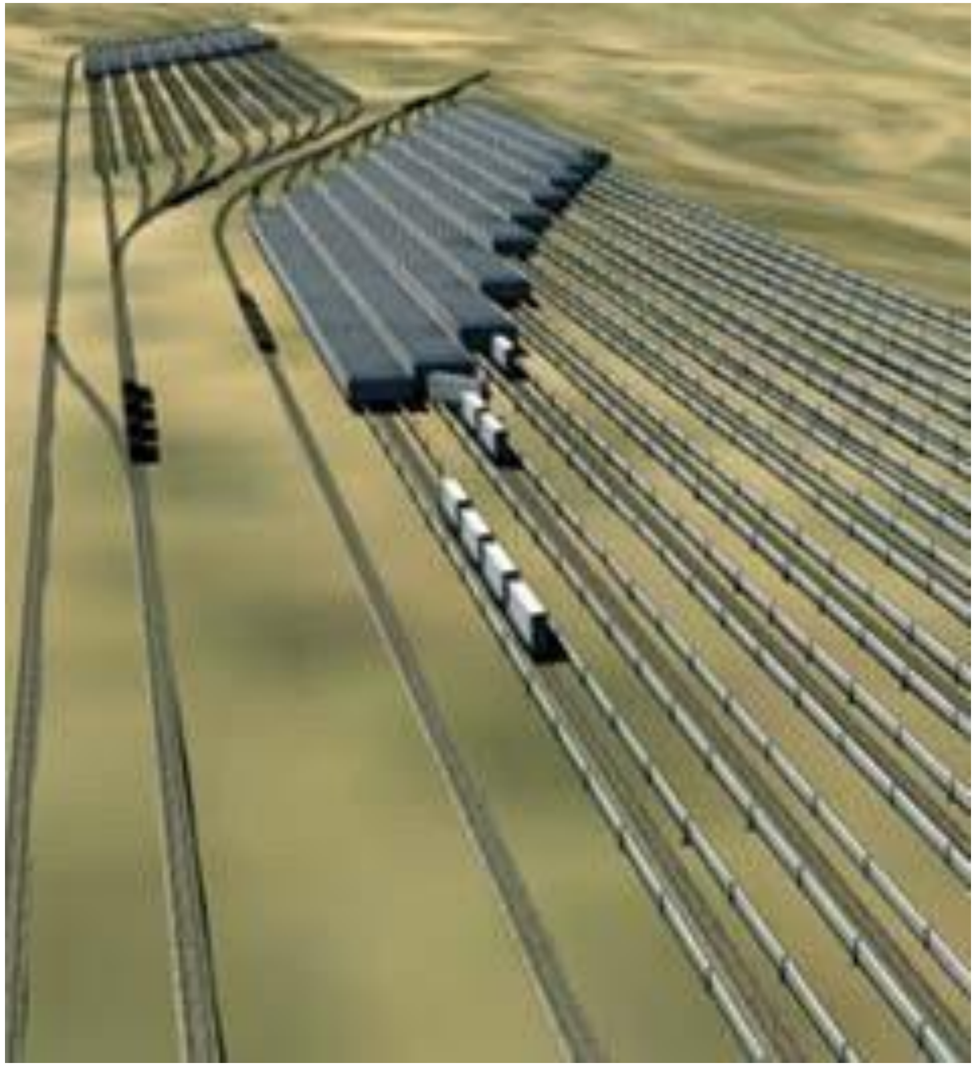
RAIL ENERGY STORAGE

- ***Rail energy storage***
  - Electric-motor-driven railcars
  - Weights are shuttled up and down an incline between upper and lower storage yards
  - Power input drives motors to move weights up the track
  - Regenerative braking on the way down supplies power to the grid
  - Weights are loaded and unloaded at storage yards
    - Large quantities of energy can be stored with few trains



ADVANTAGES OF RAIL ENERGY STORAGE

- More siting options than for PHES
  - Open space
  - Elevation change
  - No need for water or topography conducive to reservoirs
- Lower capital cost than PHES
- Easily scalable
- Efficient
  - RT efficiency: 78% - 86%
  - Constant efficiency, independent of SoC
- No standby losses
  - No evaporation/leakage



HOW DOES IT WORK?

Thank you very much for your attention!

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