EPFL

IPESE
Industrial Process and Energy Systems Engineering

Hes·so // VALAIS WALLIS
School of Engineering

CIRAIG

ENV-421
Energy Technologies

Jonas SCHNDIRIG

Week 4

École polytechnique fédérale de Lausanne

This week
Agenda

	Week 2	Week 4	Week 7	Week 9
Lectures	Energy System Fundamentals	Energy Conversion Technologies	Technologies' Impacts	Climate Impact on Energies
Applications & Excercises	The Swiss Energy System Evolution & Perspectives	Efficiencies & Classification	Conference *Is it all about renewable energies?* Closing the Balance & Defining Compromises	*Powerplay Game*

Project: Addressing Contemporary Challenges to the Swiss system
Energy-independent and carbon-neutral Switzerland 2050

AGENDA

Overview of Energy Technologies

Heat Cycles

Emerging Technologies

Infrastructure

Overview of Technologies
What is an Energy Conversion Technology?

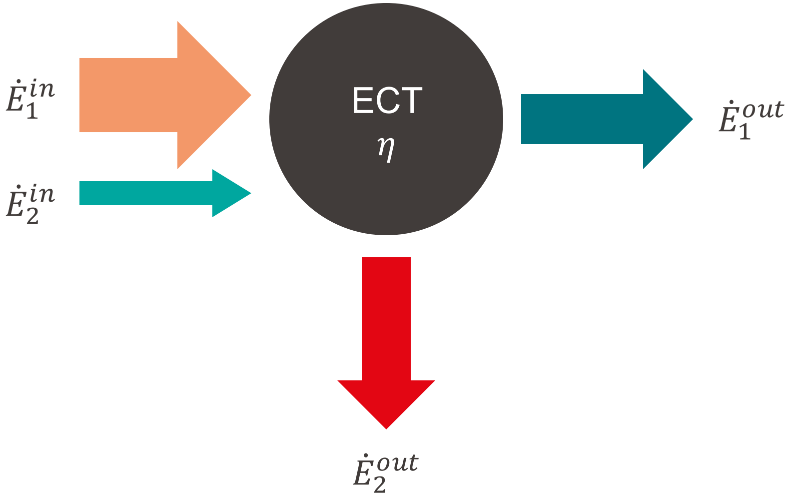
Energy conversion technology refers to any system that **converts energy** from one form to another. Energy comes in different forms, including heat, work and motion. Moreover, energy can be in the form of nuclear, chemical, elastic, gravitational, or radiant energy. All of these can be converted into useful energy (…).

R. Wolfson, "Electricity" in Energy, Environment, and Climate, 2nd ed., New York, NY: W.W. Norton & Company, 2012, ch. 11, sec. 1, pp. 292

Overview of Technologies

What is an Energy Conversion Technology? – 1st law

Energy conversion technology refers to any system that converts energy from one form to another. Energy comes in different forms, including heat, work and motion.



- Energy Balance

$$\sum_{in} \dot{E}_{in} = \sum_{out} \dot{E}_{out}$$

$$\sum_{in} \dot{Q}_{in} + \dot{W}_{in} + \dot{m}_{in} h_{in} = \sum_{out} \dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out} h_{out}$$

- Mass Balance

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out}$$

- First law efficiency

$$\eta = \frac{\text{useful Energy}}{\text{required Energy}} = \frac{\dot{E}_1^{out}}{\sum_{in} \dot{E}_{in}}$$

Adapted from Dr. Nguyen, Energy Conversion and Renewable Energy, EPFL

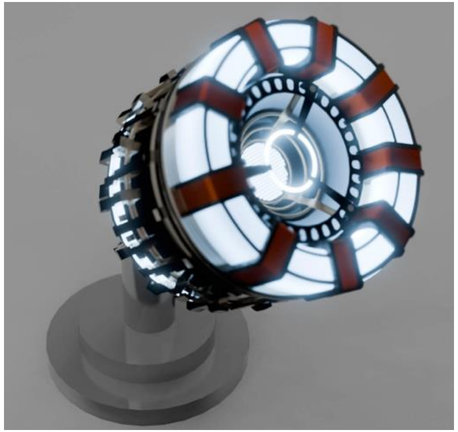
Tony Stark's Iron Man suit is designed to fly continuously for 100 years using its chest arc reactor. The reactor holds only 5 kg of an ultra-dense fuel. In flight mode, the suit draws a constant power of 2 MW, but due to conversion losses, only 70% of the fuel's energy is converted into useful work. Using the first law of thermodynamics and considering mass conservation, what minimum energy density must the fuel have (in J/kg) to support this operation?

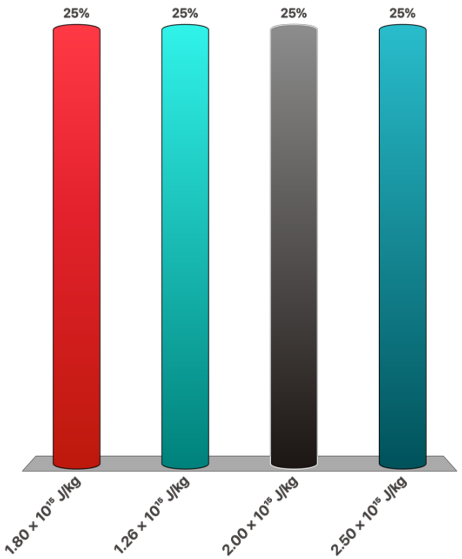
A. 1.80×10^{15} J/kg

B. 1.26×10^{15} J/kg

C. 2.00×10^{15} J/kg

D. 2.50×10^{15} J/kg





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1. Total Energy Requirement (Useful Energy):

- Operation time for 100 years:
- $t = 100 \times 3.156 \times 10^7 s \approx 3.156 \times 10^9 s$
- Useful energy needed (given 2 MW power draw):
- $E_{useful} = P \cdot t = 2 \times 10^6 \times 3.156 \times 10^9 = 6.312 \times 10^{15}$

2. Energy Balance & Efficiency:

- The fuel must supply extra energy to account for the 30% losses. Thus, the total fuel energy E_{fuel} required is:
- $E_{fuel} = \frac{E_{fuel}}{\eta} = \frac{6.312 \cdot 10^{15}}{0.70} \approx 9.017 \times 10^{15}\ \mathrm{J}$

3. Energy Density Calculation:

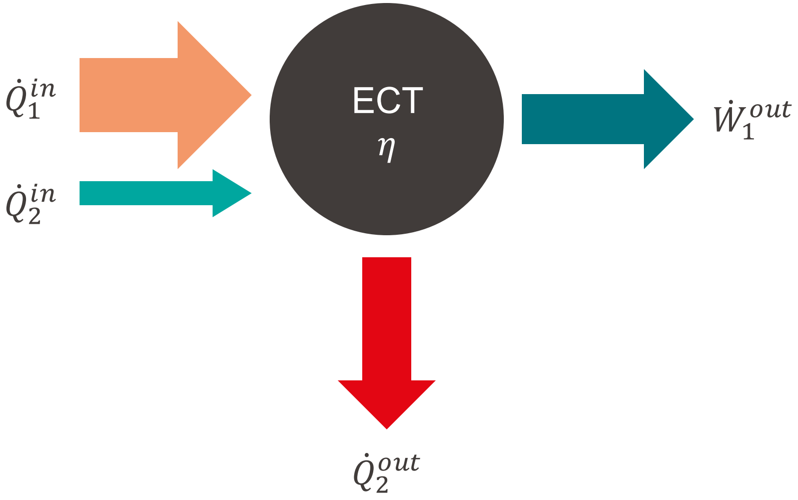
- With 5 kg of fuel available, the energy density (ε) must be:
- $\varepsilon = \frac{E_{fuel}}{m} = \frac{9.017 \times 10^{15}\ \mathrm{J}}{5\ \mathrm{kg}} \approx 1.8034 \times 10^{15}, \frac{J}{kg}$

$$E = mc^2$$

$$e = \frac{E}{m} = c^2 = 9 \cdot 10^{16} \frac{\mathrm{J}}{\mathrm{kg}}$$

Overview of Technologies
What is an Energy Conversion Technology? – 2nd law

Energy conversion technology refers to any system that converts energy from one form to another. Energy comes in different forms, including heat (Q), work (W) and others.



- (Ir)reversibility

$$\delta S^i \geq 0$$

The variation of entropy (δS^i) of any thermodynamic system (i), caused by internal processes, can only be positive (irreversible process) or null (reversible process)

- Clausius

$$\oint \frac{\delta Q}{T} \leq 0$$

*The First Law of Thermodynamics states that heat can be transformed into work, and work into heat through a cyclical process. However, as heat can flow naturally only from a hot to a cold reservoir, heat is naturally **lost** to the environment in a cycle*

- Kelvin-Planck

It is impossible to build a machine operating with a cycle whose only effect is to convert a given quantity of thermal energy into an equal quantity of mechanical work

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Overview of Technologies

What is an Energy Conversion Technology? – 2nd law

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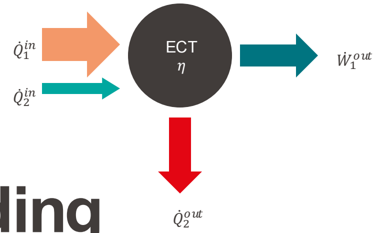
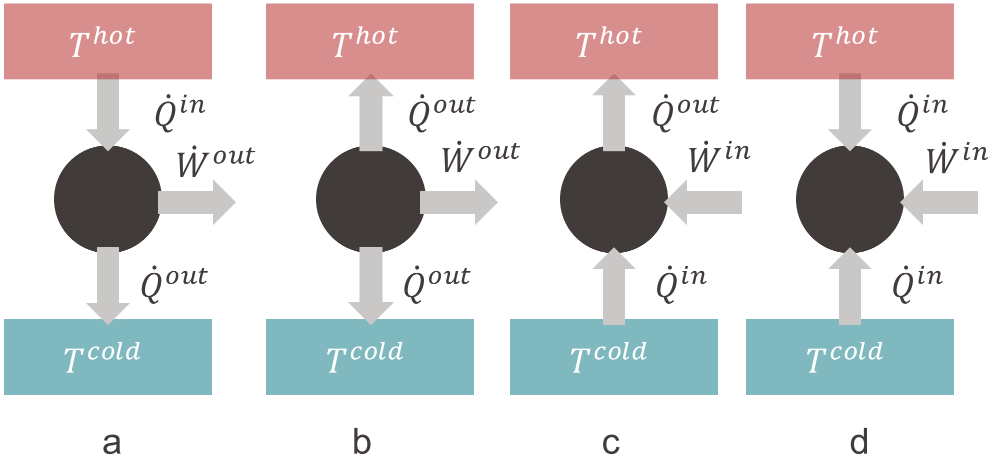
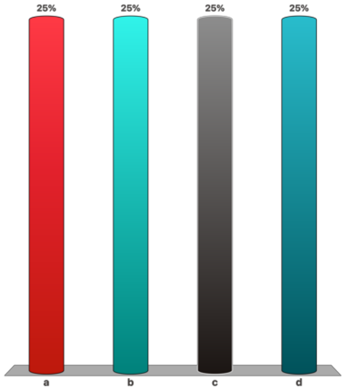


Which of these conversions is feasible according to the 1st and 2nd law?



A. a
B. b
C. c
D. d



Overview of Technologies

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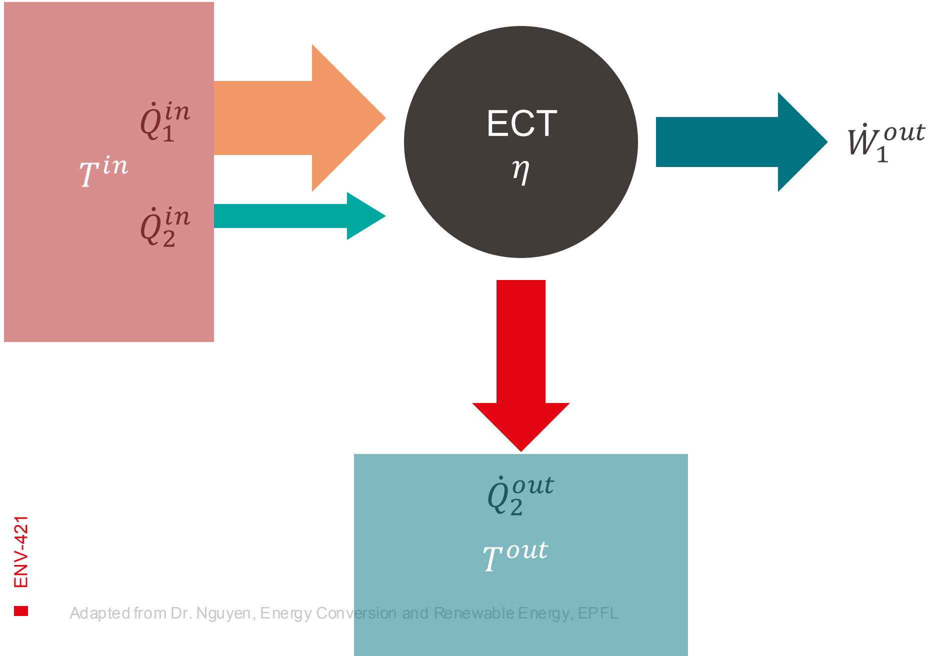

- Carnot

  It is not possible to build a machine operating between two given heat sources (at different temperatures) with an efficiency higher than the efficiency of a reversible cycle operating between the same two heat sources

- Carnot efficiency (Carnot factor) θ_c

$$\eta_{ideal} = \frac{\text{what you can get at most}}{\text{what you have to pay}}$$

$$= \frac{\dot{W}_1^{out,max}}{\dot{Q}_1^{in} + \dot{Q}_2^{in}}$$

$$= 1 - \frac{\dot{Q}_2^{out}}{\dot{Q}_1^{in} + \dot{Q}_2^{in}} = 1 - \frac{T^{out}}{T^{in}} = \theta_c$$

Adapted from Dr. Nguyen, Energy Conversion and Renewable Energy, EPFL

Overview of Technologies

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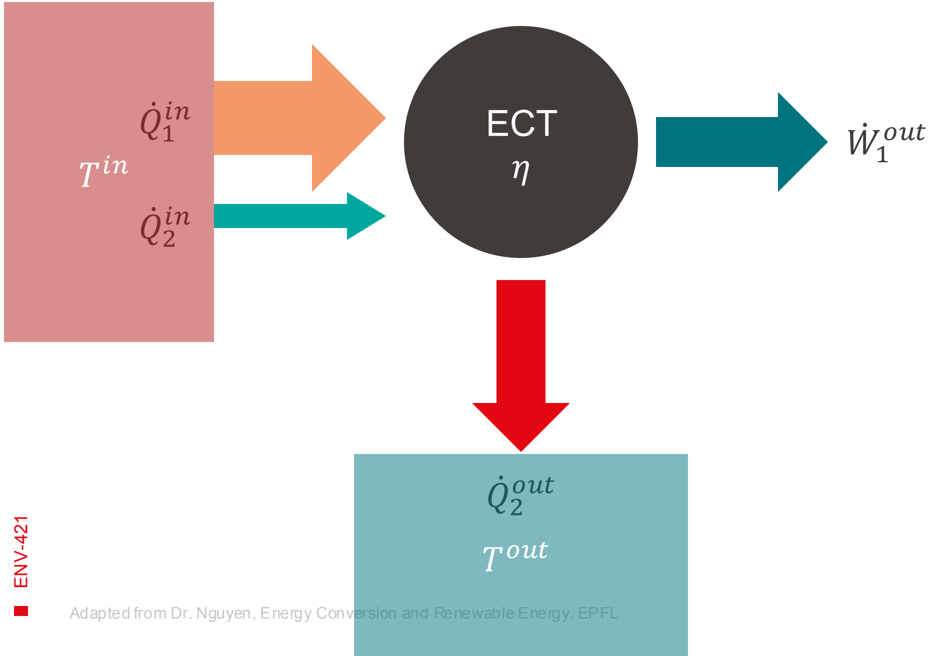

- 2nd law efficiency ϵ

The second-law efficiency (ε) compares the actual performance of the process (η) compared to the maximum possible efficiency (Θc) it could achieve, if reversible.

$$\epsilon = \frac{\text{what you really get}}{\text{what you can get at most}}$$

$$= \frac{\dot{W}_1^{out}}{\dot{W}_1^{out,max}} = \frac{\dot{W}_1^{out}}{(\dot{Q}_1^{in} + \dot{Q}_2^{in}) \cdot \theta_c}$$

$$= \frac{\eta}{\theta_c}$$

Adapted from Dr. Nguyen, Energy Conversion and Renewable Energy, EPFL

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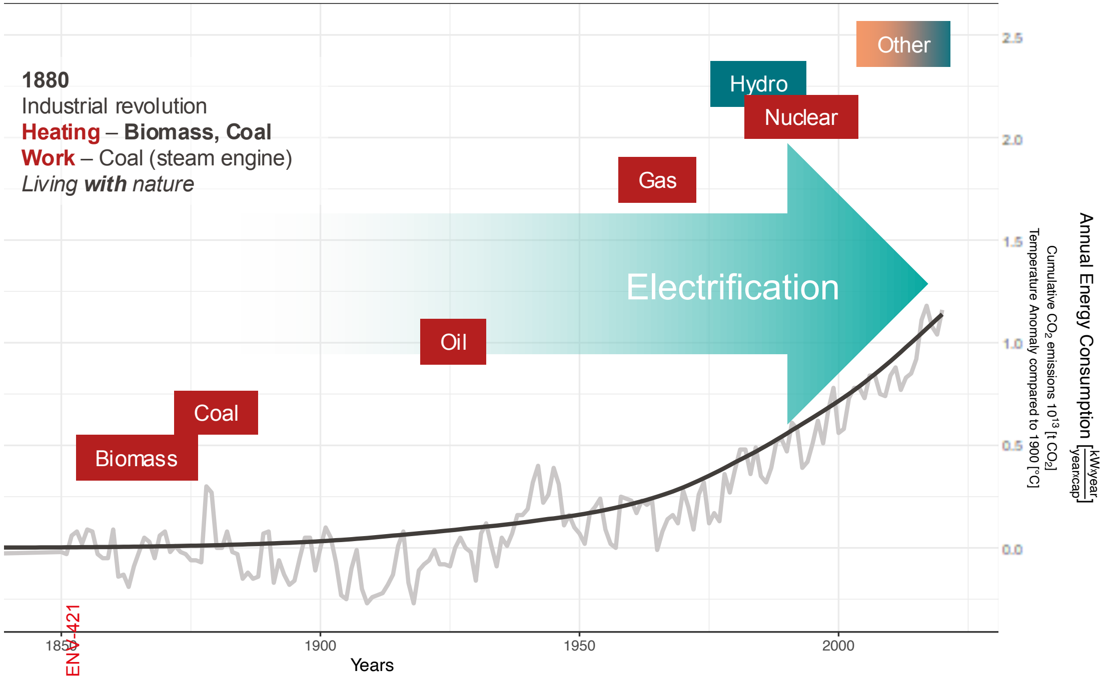
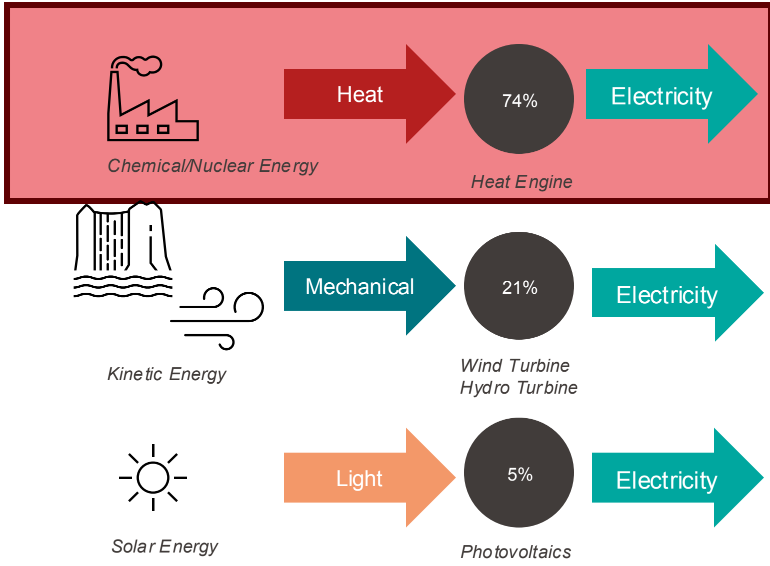
AGENDA

Conventional Technologies
Rankine Cycles - Heat to Electricity

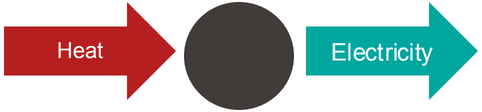


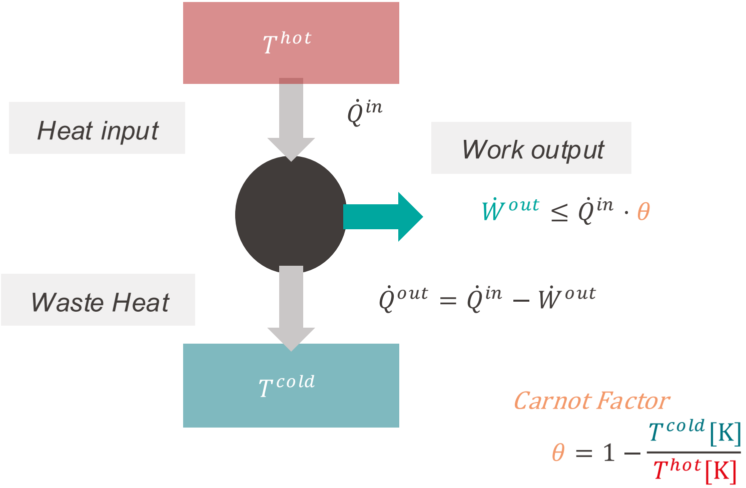
Electricity production 2020



Conventional Technologies

Heat to Work





- **Definition:**
  Heat-to-power engines are systems that convert thermal energy from a heat source into mechanical work or electricity through thermal cycles.
- **Principle:**
  Transferring energy from a high-temperature fuel source to a working fluid that expands and produces work, then rejecting waste heat at a lower temperature. The efficiency is fundamentally limited by the Carnot factor, which depends on the temperature difference between the heat source and the waste heat sink.
- **Key Performance Metrics:**

  Electrical Efficiency $\eta_{el} = \frac{W}{Q_{in}} \leq \theta$ (35-60%).

  Carnot Factor $\theta = 1 - \frac{T^{cold}[K]}{T^{hot}[K]}$

Conventional Technologies
Heating – Combustion

A chemical reaction where a fuel reacts with an oxidizer (typically oxygen) to produce heat and light.

$$\text{Fuel} + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$

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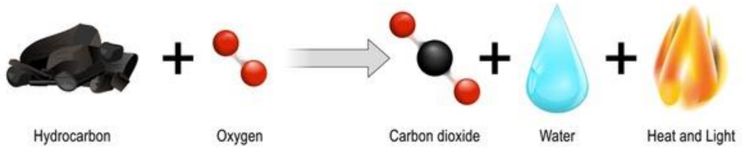
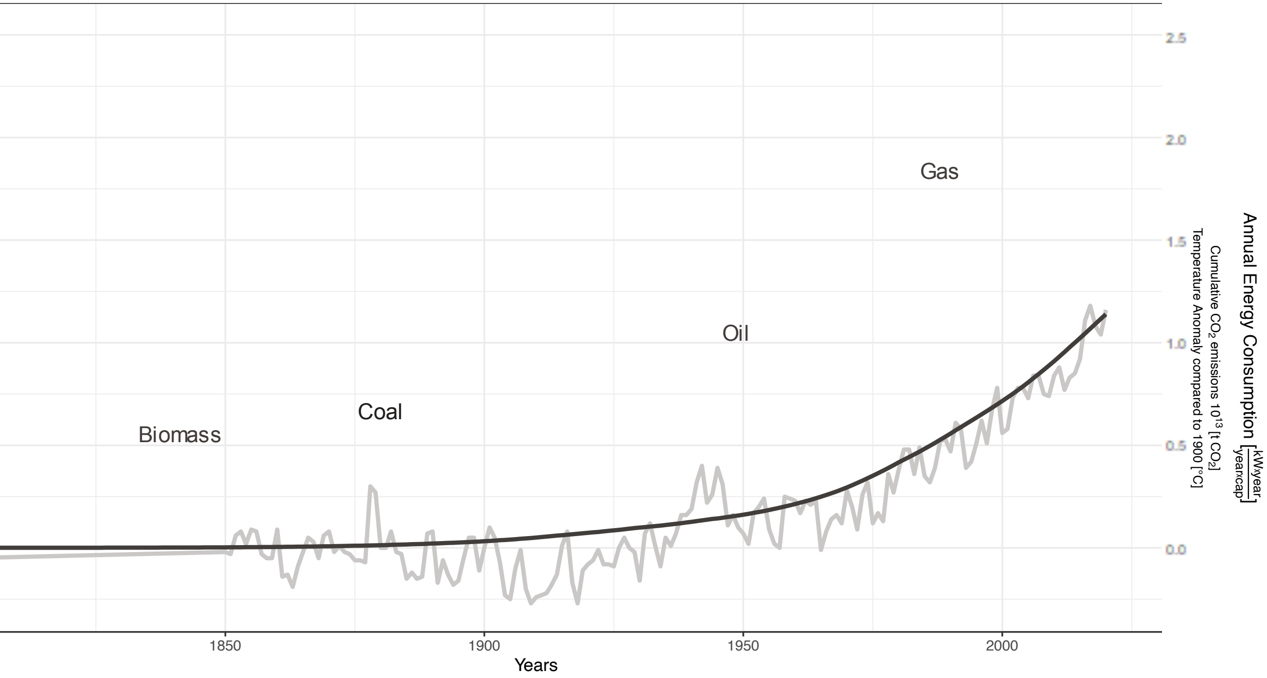


- Key Components
  - **Fuel**: Hydrocarbons (e.g., biomass, coal, oil, natural gas)
  - **Oxidizer**: Typically, atmospheric oxygen (O_2)
  - **Heat**: Initiates and sustains the reaction
- Products of Combustion
  - **Primary**: Carbon dioxide (CO_2), Water vapor (H_2O)
  - **Byproducts**:
    - **Complete Combustion**:
      Only CO_2 and H_2O
    - **Incomplete Combustion**:
      Carbon monoxide (CO), Soot (C), other hydrocarbons (H_xC_y)
- Combustion Types
  - Complete Combustion:
    Sufficient oxygen leads to maximum energy release
  - Incomplete Combustion:
    Limited oxygen results in lower energy efficiency and pollutant formation
- Importance in Heat Production
  - Energy Conversion: Core mechanism in heating systems, power plants, and engines
  - Versatility: Applicable across various fuel types and technologies

Conventional Technologies
Heating – Fuel usage



- **Biomass**
  - Era: Prehistoric to Early Industrial
  - Sources: Wood, agricultural residues
  - Uses: Heating homes, cooking, early industry
- **Coal (solid)**
  - Era: Industrial Revolution (18th-19th Century)
  - Origins: Geologically transformed plant matter
  - Uses: Powering steam engines, electricity generation, industrial processes
- **Liquid Fuels (Oil)**
  - Era: Late 19th Century to Present
  - Origins: Fossilized marine organisms
  - Uses: Transportation (cars, ships), heating, petrochemicals
- **Natural Gas (gaseous)**
  - Era: 20th Century to Present
  - Origins: Associated with oil deposits, microbial activity
  - Uses: Residential/commercial heating, electricity generation, industrial applications

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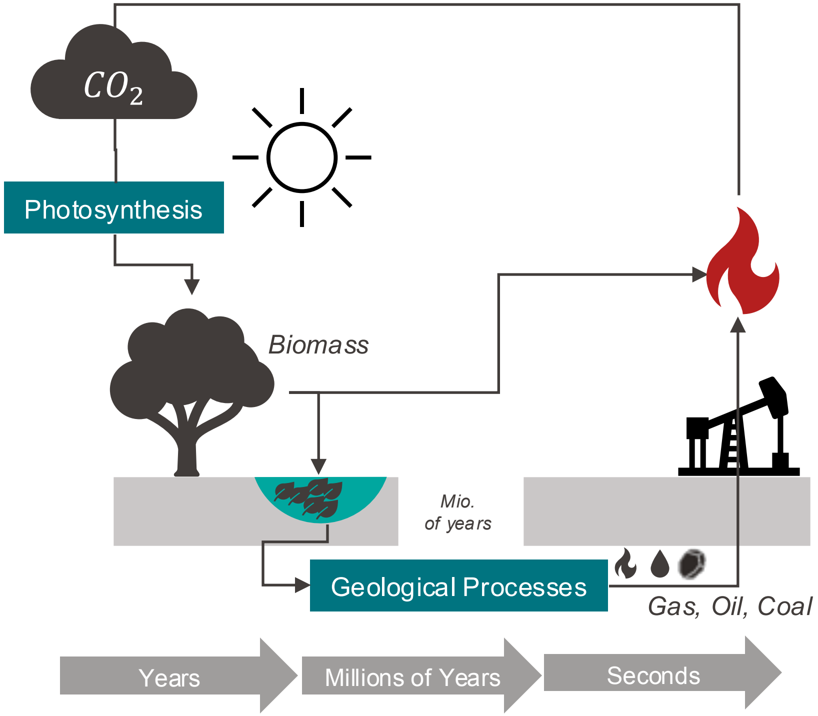
Conventional Technologies

Heating – Origin of Fuels

Resource	State	Composition C-H-O [%]			Energy	Formation
Biomass	Solid	40-50	5-6	40-45	15-20 MJ/kg	Annually
Natural Gas	Gaseous	75	25	-	55 MJ/kg	Millions of years
Oil	Liquid	85-87	13-15	<1	43 MJ/kg	Millions of years
Coal	Solid	60-90	3-5	5-15	15-30 MJ	Millions of years



- Atmospheric CO_2
  - Source: Carbon dioxide present in the Earth's atmosphere
  - Role: Fundamental carbon source for all photosynthetic life
- Photosynthesis
  - Process:
    - Plants absorb CO_2 and sunlight to produce glucose and oxygen
    - $6CO_2 + 6H_2O + \text{Light Energy} \rightarrow C_6H_{12}O_6 + 6O_2$
  - Outcome: Accumulation of biomass (plants, trees)
- Biomass Accumulation
  - Formation: Dead plant material accumulates in environments like forests, swamps, and wetlands
  - Characteristics: High in carbon content, rich organic material
- Geological Processes
  - Transformation:
    - Heat & Pressure: Over millions of years, buried biomass undergoes chemical and physical changes
    - Timeframe: Tens to hundreds of millions of years
  - Result: Formation of fossil fuels
- Formation of Fossil Fuels
  - Coal:
    - Origin: Terrestrial plant material
    - Types: Lignite → Bituminous → Anthracite (increasing carbon content)
  - Oil & Natural Gas:
    - Origin: Marine microorganisms (plankton, algae)
    - Process: Oil forms from liquid hydrocarbons; natural gas from gaseous hydrocarbons
- Characteristics:
  - Energy Density: Higher than original biomass
  - State: Solid (coal), Liquid (oil), Gas (natural gas)

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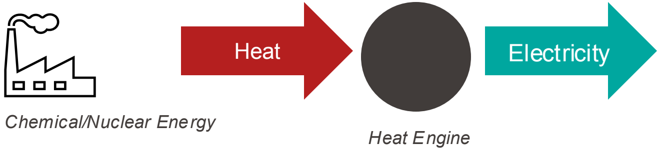
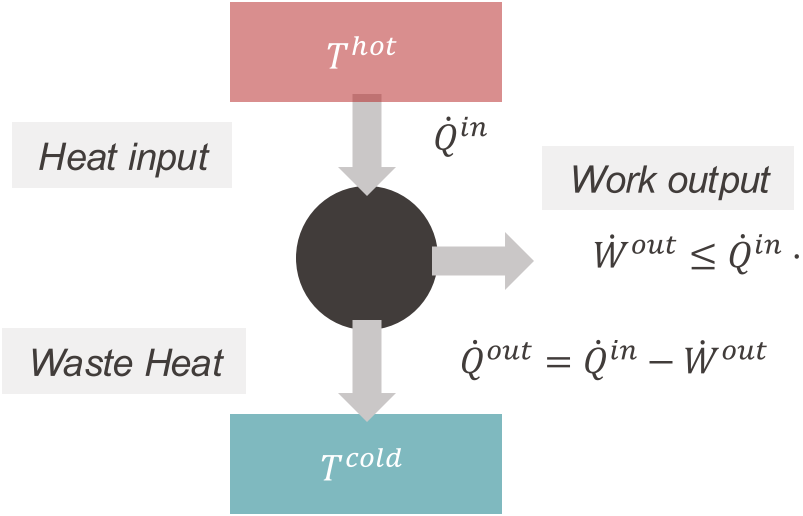
Conventional Technologies

Power Cycles – Carnot (maximum)



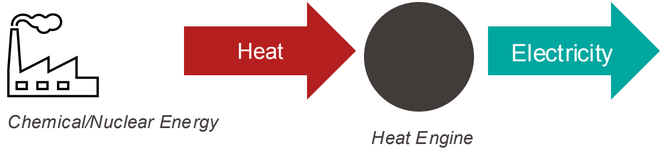


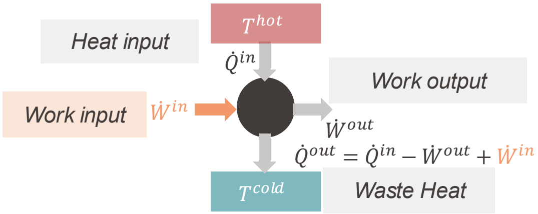
$$\dot{W}^{out} \leq \dot{Q}^{in} \cdot \theta$$

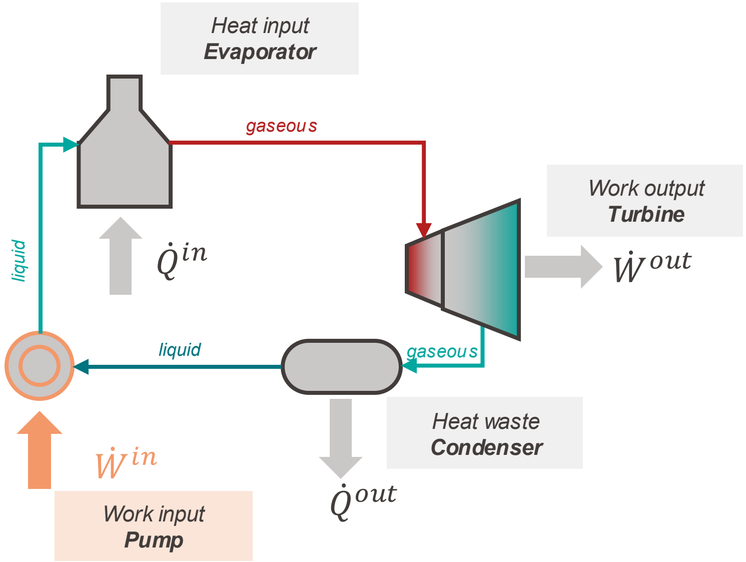
$$\dot{Q}^{out} = \dot{Q}^{in} - \dot{W}^{out}$$

$$\theta = 1 - \frac{T^{cold}[\mathrm{K}]}{T^{hot}[\mathrm{K}]}$$

Conventional Technologies
Power Cycles – Rankine cycle



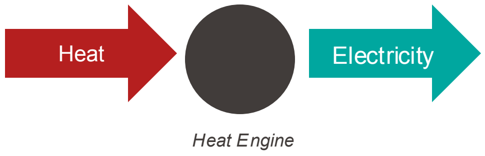


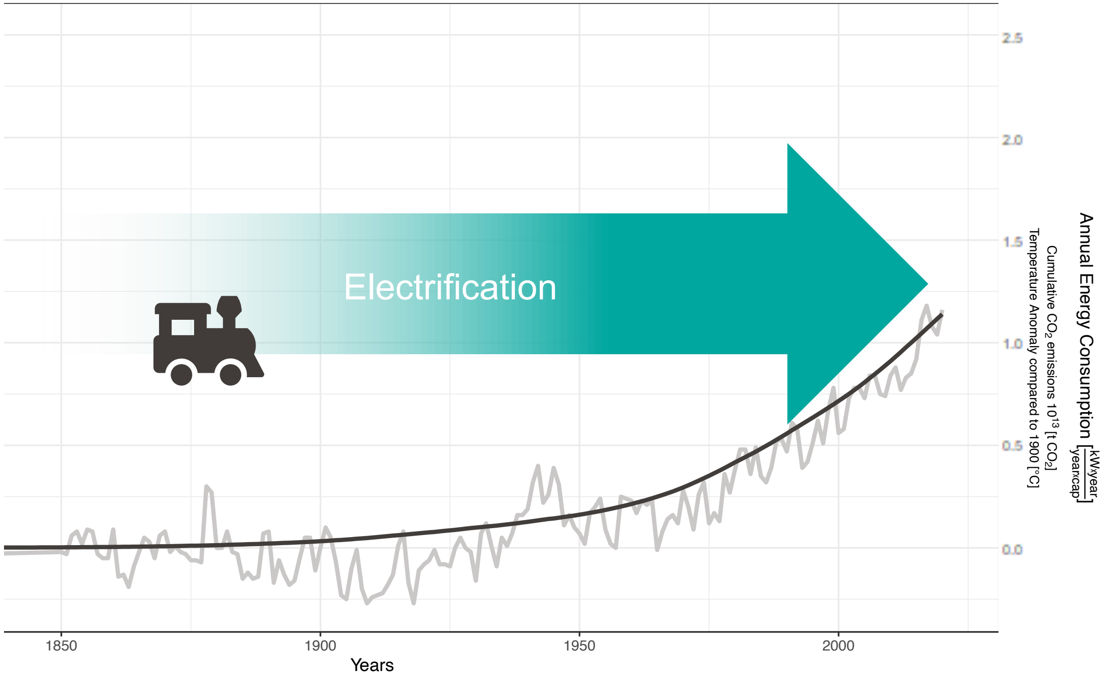


- Most used Power Cycle
- Working fluid passes through phase change (gaseous – liquid)
- 4 Steps
  1. Evaporation
     - Heat input
     - Furnace
  2. Expansion
     - Work output
     - Turbine
  3. Condenser
     - Heat waste
     - Heat exchanger
  4. Pumping
     - Work input
     - Pump

Conventional Technologies

Power Cycles – Rankine Cycles - Coal

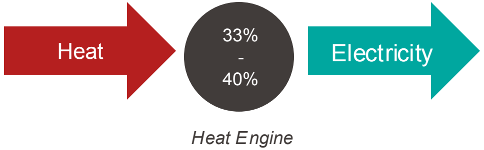


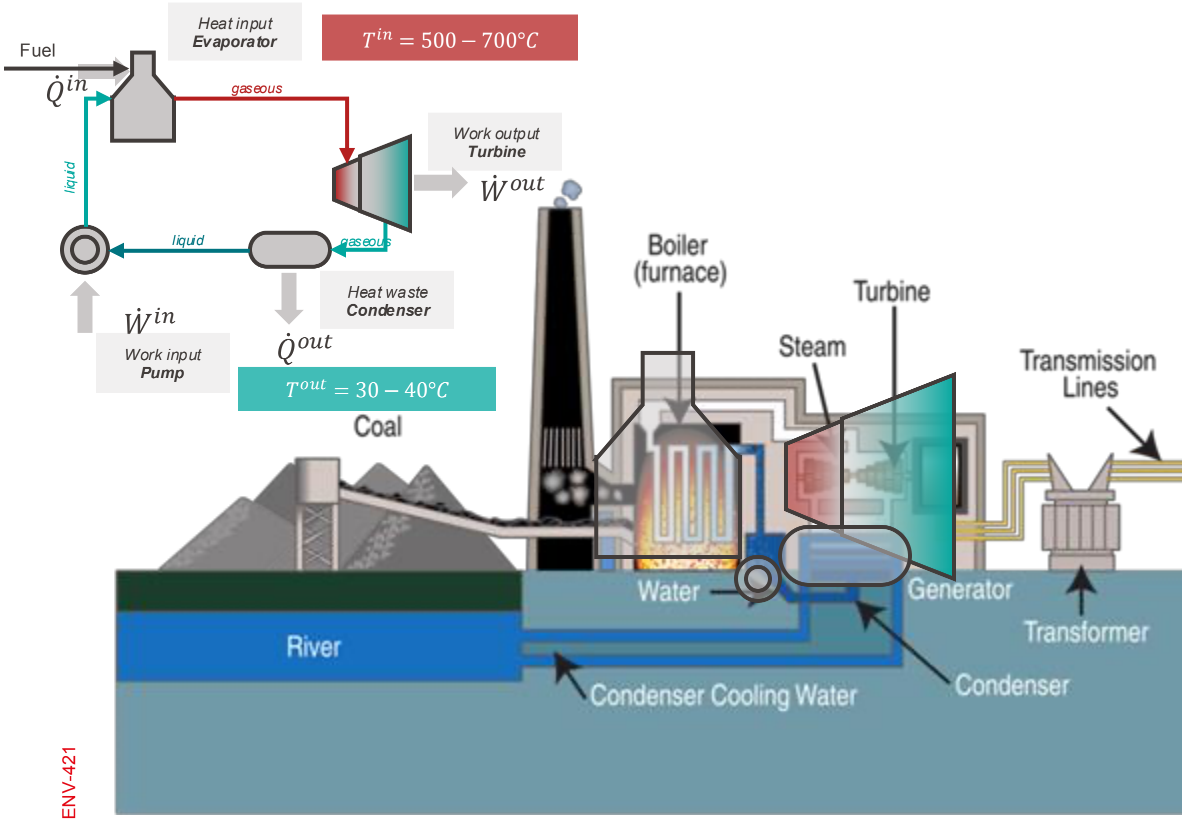


- Coal as fuel for heat
- ~40% of electricity production
  - South-Africa 94%
  - China & India 70-75%
- 9 kt/day coal for 1GW
- Operation
  - Extraction/Mining
  - Unloading
  - Pulverization
  - Combustion

Conventional Technologies

Power Cycles – Rankine Cycles - Coal

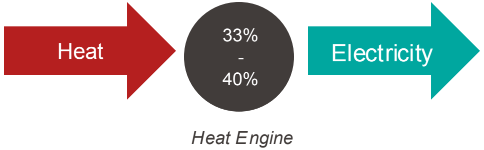




- Rankine Cycle
  - Evaporation
  - Expansion
  - Condensation
  - Pumping

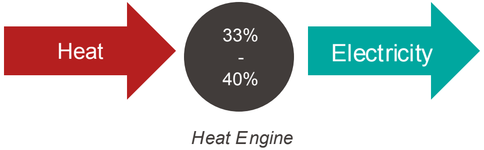
Coal-fired plant: Coal burned in the boiler heats water to produce steam. The steam spins the turbine, which drives the generator.

Conventional Technologies
Power Cycles – Rankine Cycles - Coal



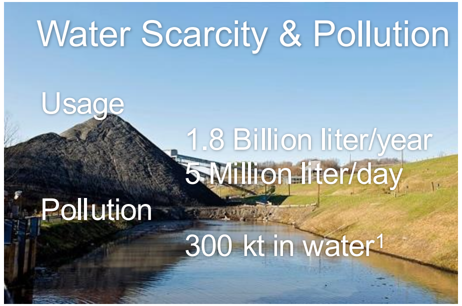
Discuss in groups what advantages/challenges are being faced with coal power-plants?

Conventional Technologies
Power Cycles – Rankine Cycles - Coal



- *The impact of 1GW coal power plant*

Inquinamento sul Taj Mahal



Coal mines, such as this one near Bowen, use water for everything from equipment cooling to dust management. A key challenge for the industry is to maintain mine water storage at an optimal level
[1] according to the global average in 2023

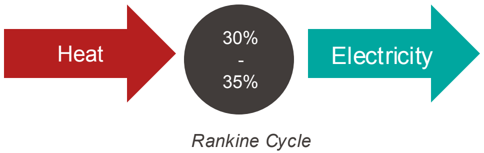
Garzweiler coal mine on April 22

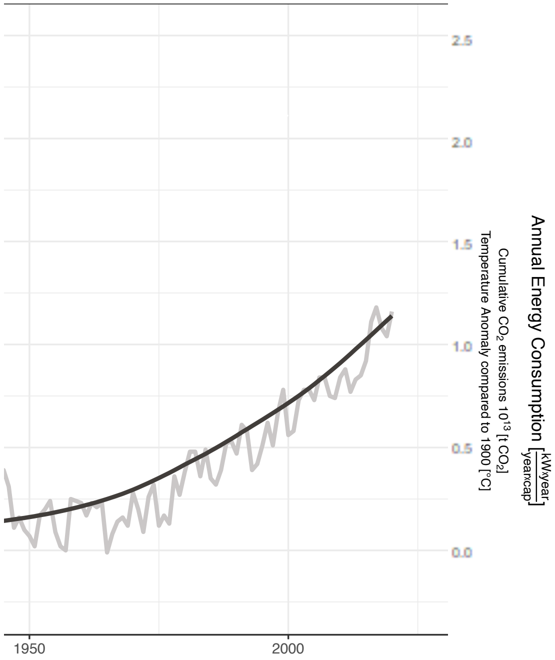
...

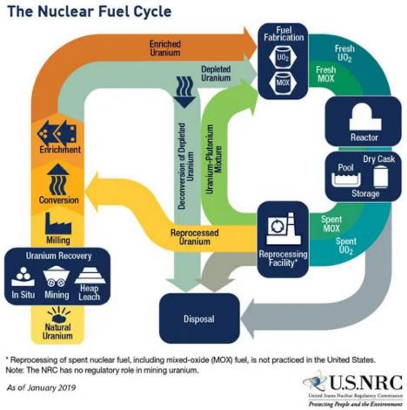
Australian National Railways 160-car train travelling south on the standard-gauge railway line from Leigh Creek coalfield and Port Augusta, South Australia

Sources
1. Global Coal Plant Tracker – Global Energy Monitor
2. International Energy Agency (IEA) Reports – IEA.org
3. World Health Organization (WHO) Air Pollution Data – WHO.int
4. United Nations Environment Programme (UNEP) Water Reports – UNEP.org
5. Global Carbon Project – GlobalCarbonProject.org
6. Energy Information Administration (EIA) Statistics – EIA.gov

Conventional Technologies
Power Cycles – Rankine Cycles – Nuclear Fission





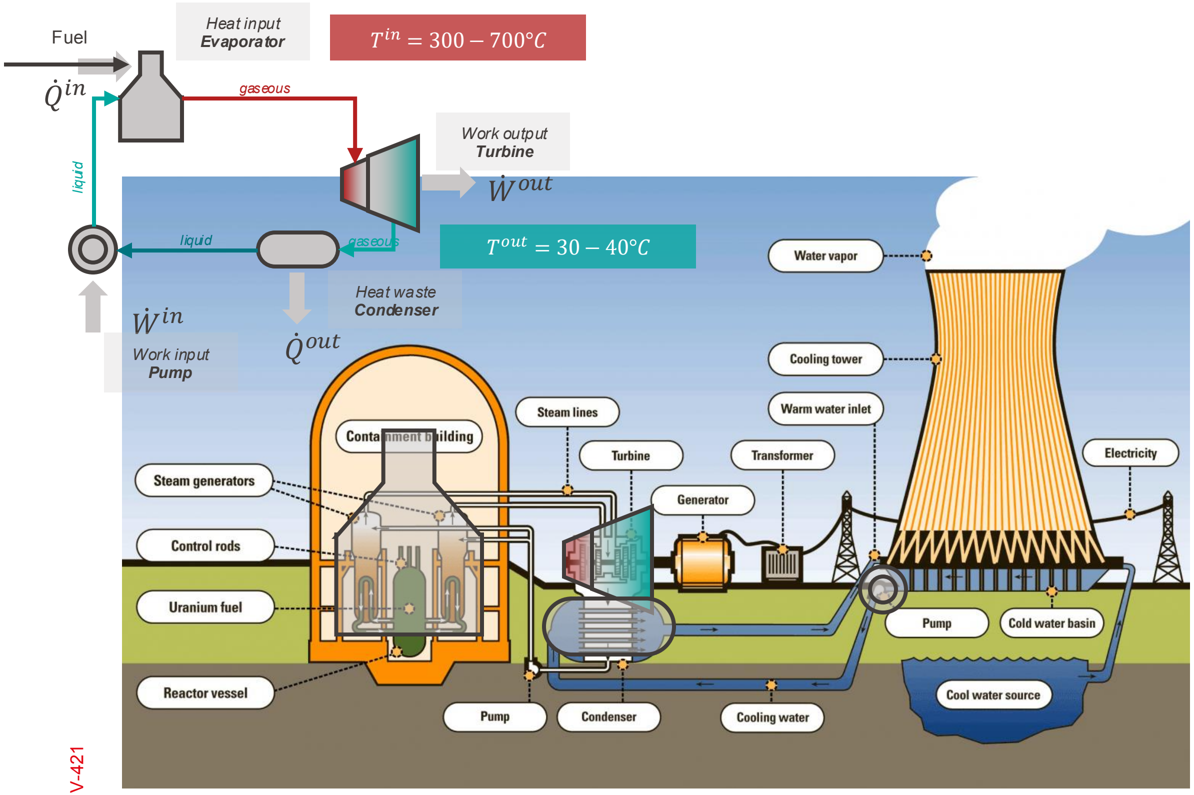


- Nuclear as Fuel for Heat
- ~10% of electricity production globally
  - France: 70%
  - USA: 20%
  - China: 10%
- 200 kg of enriched uranium per year for 1 GW
- Operation
  - Recovery/Extraction/Mining
  - Enrichment
  - Reaction
  - Reprocessing
  - Disposal

Conventional Technologies

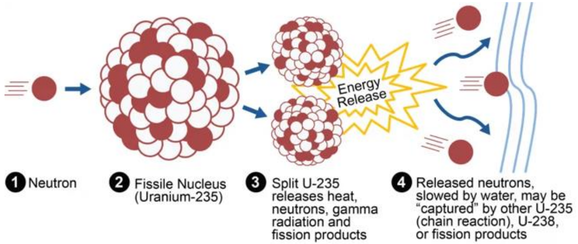
Power Cycles – Rankine Cycles – Nuclear Fission

Rankine Cycle



Coal-fired plant: Coal burned in the boiler heats water to produce steam. The steam spins the turbine, which drives the generator.
© Tennessee Valley Authority

- Rankine Cycle
  - Evaporation
  - Expansion
  - Condensation
  - Pumping



Fission of Uranium-235 in a Nuclear Reactor
©UMICH 2020

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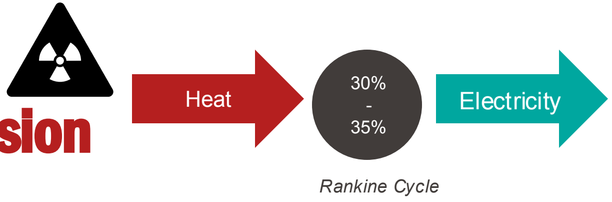
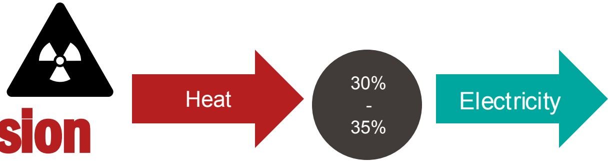
Conventional Technologies

Power Cycles – Rankine Cycles – Nuclear Fission

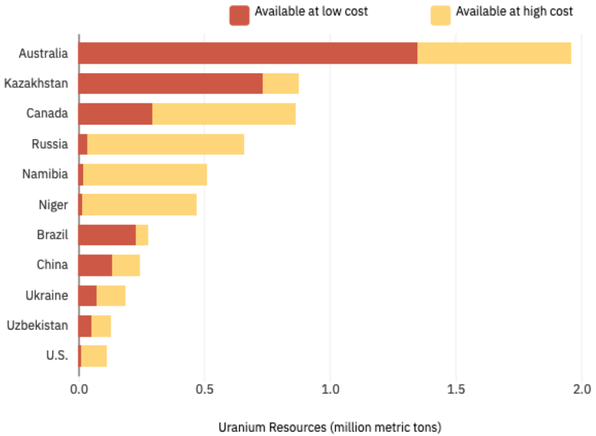


Discuss in groups what advantages/challenges are being faced with nuclear power-plants?

Conventional Technologies
Power Cycles – Rankine Cycles – Nuclear Fission



Rankine Cycle

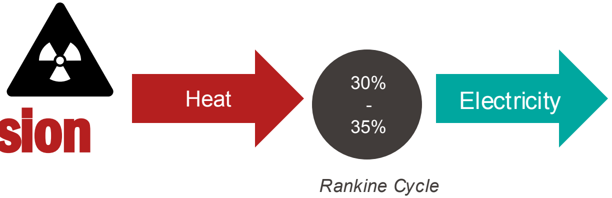


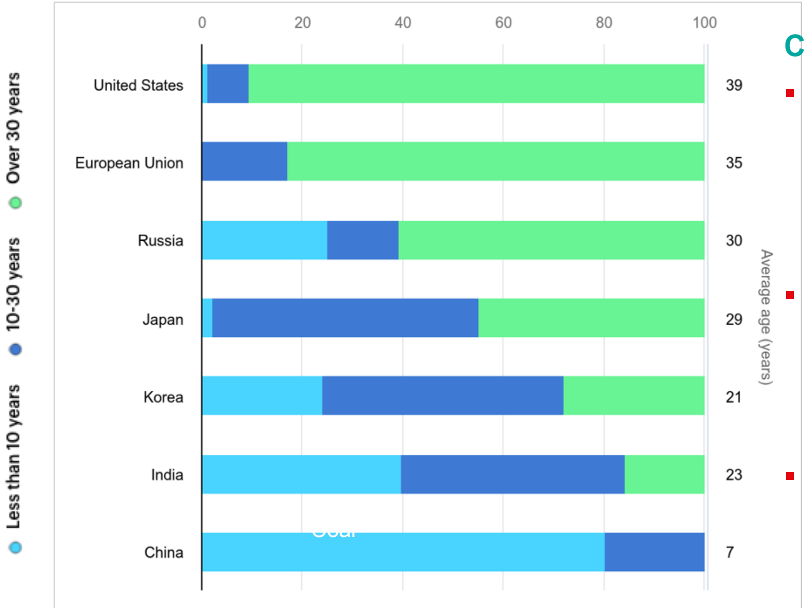
Largest Uranium Resources
Uranium 2022: Resources, Production, and Demand.
© OECD

Advantages

- Low **Greenhouse Gas** Emissions
  - Operational Emissions: Emits no greenhouse gases during electricity generation.
  - CO_2 Avoidance: Has prevented approximately 55 gigatonnes of CO_2 emissions over the past 50 years.
- High **Reliability** and **Capacity** Factor
  - Capacity Factor: Achieves a 93% capacity factor, the highest among all energy sources.
  - Stable Baseload Power: Provides consistent and reliable electricity supply, essential for grid stability.
- **Efficient Land and Fuel Use**
  - Land Efficiency: Requires significantly less land compared to renewable sources like solar and wind.
  - Fuel Efficiency: A single uranium fuel pellet contains the energy equivalent of one ton of coal or 149 gallons of oil.[2]
- Contribution **to Energy Security**
  - Reduced Import Dependence: Lowers reliance on imported fossil fuels, enhancing national energy security.
  - Complementary to Renewables: Balances the variability of renewable energy sources, supporting a stable energy grid.

Conventional Technologies
Power Cycles – Rankine Cycles – Nuclear Fission





Age profile of nuclear power capacity in selected regions, 2019, ©IEA

Challenges

- High **Costs** and Cost Overruns
  - Levelized Cost of Energy (LCOE): Approximately twice that of combined cycle natural gas and three times that of utility solar or onshore wind (2024).
  - Construction Overruns: Projects like the Vogtle reactors in Georgia escalated to $35 billion for 2 GW capacity, 2.5× the projected cost, and were completed 7 years behind schedule.
- **Aging** Fleet and Capacity Decline
  - Fleet Age: Average age of reactors in advanced economies is 35 years.
  - Projected Decline: Without intervention, nuclear capacity could decrease by two-thirds from 280 GW in 2018 to just over 90 GW by 2040.
- Nuclear **Waste** Management
  - Spent Fuel Storage: As of 2021, the U.S. stored 89,178 metric tons of commercial spent fuel across 39 states with no permanent repository.[6]
  - Long-Term Hazards: Spent fuel emits 10,000 rem/hr of radiation ten years after use, necessitating management plans spanning one million years.
- **Limited New Projects** and Dependency on Subsidies
  - Project Initiation: Only two new U.S. nuclear power projects have begun since 1990, both reliant on substantial federal subsidies.
  - Investment Barriers: High upfront costs, long lead times, and risks of delays deter private investment, necessitating government intervention and support.

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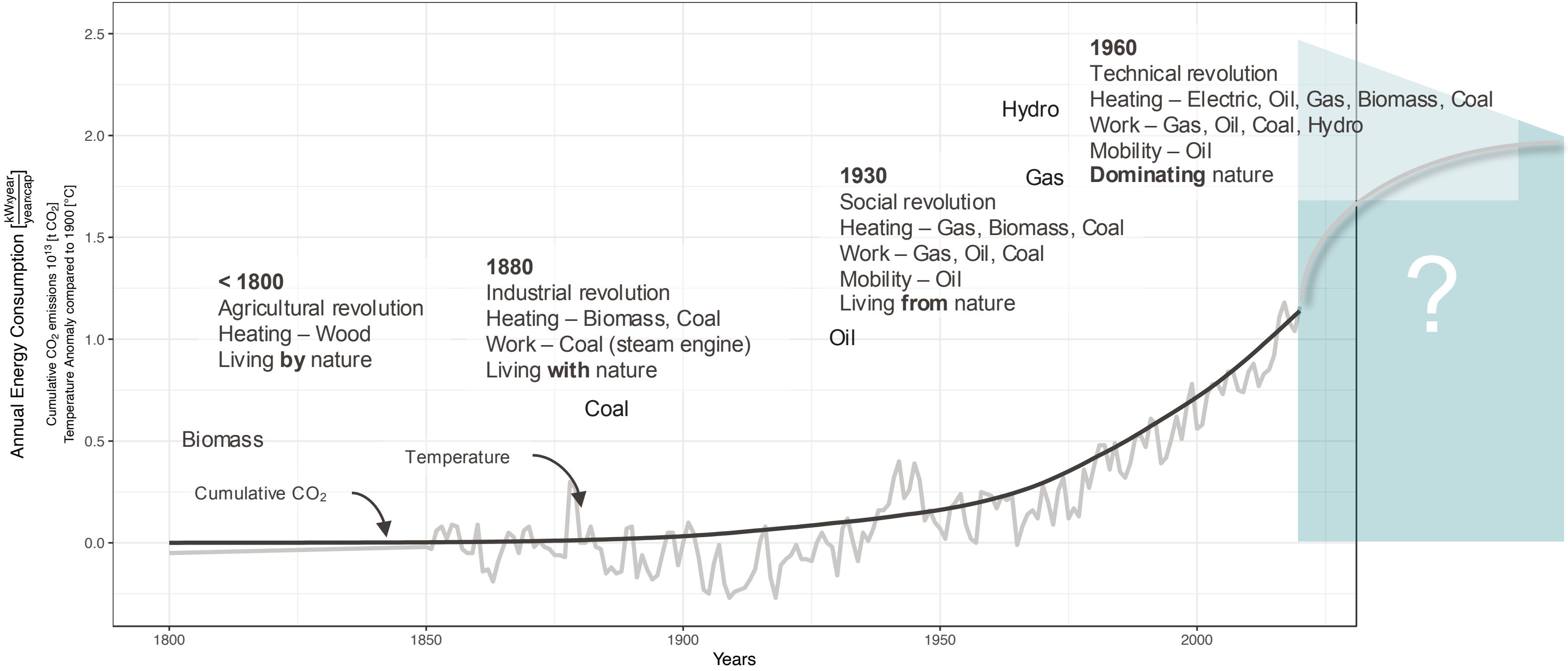
Recap week 2

Introduction to Energy Systems
a brief history of time

Jonas Schnidrig

2020
Environmental revolution
Heating – Electric, Oil, Gas, Biomass,…
Work – Renewables, Nuclear, Gas, …
Mobility – Electric, Gas, Oil ,…
Protecting nature



Global energy consumption per capita and temperature evolution.
The temperature anomaly was calculated using the reference year 1900 by [49]. The specific energy use is determined as the ratio between annual energy consumption [50] [W·year] and the respective population [51]. The CO_2 emissions are calculated as the cumulative sum of year emissions since 1800 [52].

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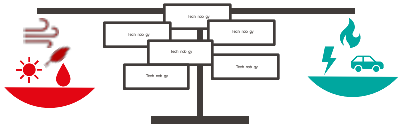
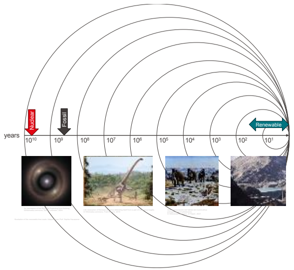
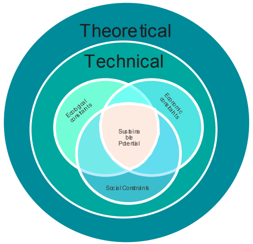
Recap week 2

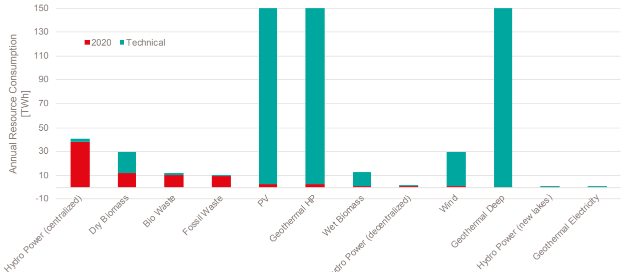
Energy Balance Fundamentals

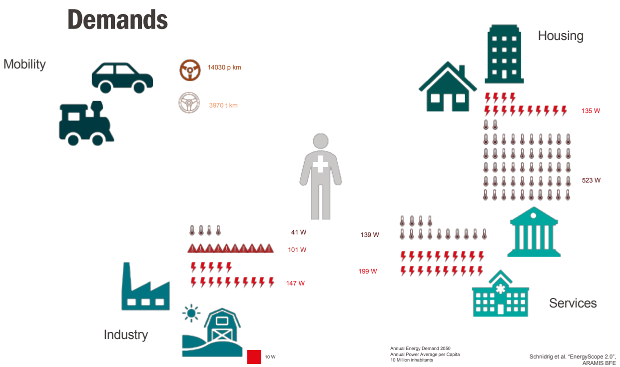


Resources	Technology	Energy demands
Costs & Emissions Annual availability	Fossils & Renewables Investments & O&M Efficiencies & Emissions Storage	

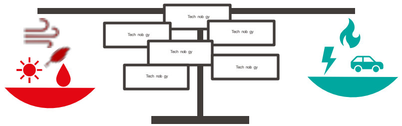








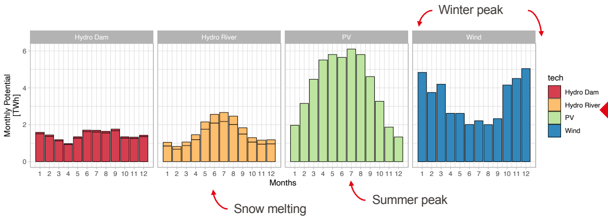
Recap week 2
Energy Balance Fundamentals

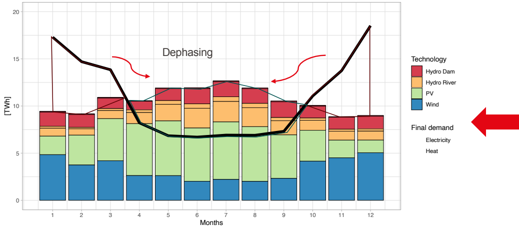


Resources
Costs & Emissions
Annual availability

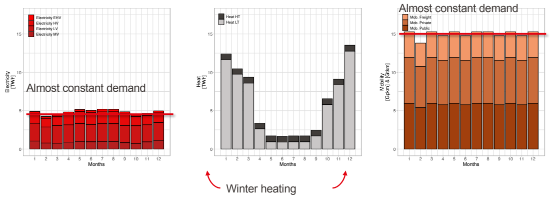
Technology
Fossils & Renewables
Investments & O&M
Efficiencies & Emissions
Storage

Energy demands





Schnidrig et al. "On the role of energy infrastructure in the energy transition", Frontiers in Energy 2023



- Capacity factor: $c_p(t)$
  Defined as the ratio between installed capacity and the useful amount of power to be delivered.
  Enables modeling of intermittency $c_p(t)$ and maintenance shutdown c_p
- Seasonality Output

$$E_i\,(t)\left[\frac{\mathrm{kWh}}{\mathrm{Period}}\right] = \dot{E}_i\,[\mathrm{kW_{installed}}]\cdot c_p(t)[-]\cdot t_{op}(t)\left[\frac{\mathrm{h}}{\mathrm{Period}}\right]$$

- Annual Output

$$E_i\left[\frac{\mathrm{kWh}}{\mathrm{year}}\right] = \dot{E}_i\,[\mathrm{kW_{installed}}]\cdot c_p[-]\cdot 8670\left[\frac{\mathrm{h}}{\mathrm{year}}\right]$$

$$\approx \dot{E}_i\,[\mathrm{kW_{installed}}]\cdot \Sigma_t\left(c_p(t)[-]\cdot t_{op}(t)\left[\frac{\mathrm{h}}{\mathrm{Period}}\right]\right)$$

Example: Wind turbine operation $\dot{E}_{Wind} = 2\,[\mathrm{MW}]$

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
c_{pt}^{Wind}	32%	28%	28%	18%	17%	14%	15%	14%	16%	28%	30%	34%

- January

$$E_{Wind}(Jan) = \dot{E}_{Wind}\cdot c_p(Jan)\cdot t_{op}(Jan)$$

$$= 2\,[\mathrm{MW}]\cdot 32[\%]\cdot 24[\mathrm{h}]\cdot 31\,[\mathrm{days}]$$
$$= 476\,[\mathrm{MWh}]$$

- Annual

$$E_{Wind}^{year} = \dot{E}_i\,[\mathrm{kW_{installed}}]\cdot\sum_t\left(c_p(t)[-]\cdot t_{op}(t)\left[\frac{\mathrm{h}}{\mathrm{Period}}\right]\right)$$

$$\approx \dot{E}_i\,[\mathrm{kW_{installed}}]\cdot\frac{\Sigma_t\,c_p(t)}{12}\cdot 8670\left[\frac{\mathrm{h}}{\mathrm{year}}\right] = 400\,[\mathrm{GWh}]$$

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Recap week 2

Analysis and Evaluation of Energy Systems

- Primary Energy

$$E_{primary} = \sum_{r \in Resources} E_r$$

- Secondary Energy

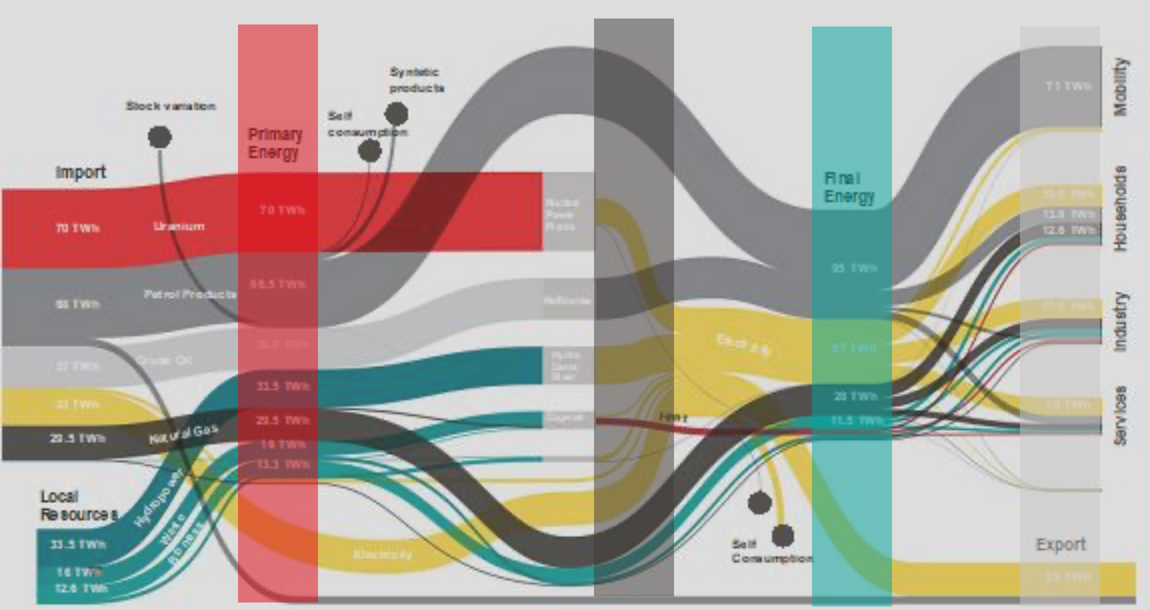
$$E_{secondary} = E_{primary} \cdot \eta_{conversion} = E_{primary} - L_{conversion}$$

- Final Energy

$$E_{Final} = E_{secondary} \cdot \eta_{distribution} = E_{secondary} - L_{distribution}$$

- End-Use Demand

$$E_{demand} = E_{Final} \cdot \eta_{end-uses} = E_{final} - L_{end-use} = \sum_{s \in Sectors} E_s$$



- Conversion efficiency

$$\eta_{conv}(t) = \frac{E_{secondary}(t)}{E_{primary}(t)}$$

- Distribution efficiency

$$\eta_{dist}(t) = \frac{E_{final}(t)}{E_{secondary}(t)}$$

- End-use efficiency

$$\eta_{end-use}(t) = \frac{E_{end-use}(t)}{E_{final}(t)}$$

- Combination of efficiencies

$$\eta_{system}(t) = \eta_{conv}(t) \cdot \eta_{dist}(t) \cdot \eta_{end-use}(t)$$

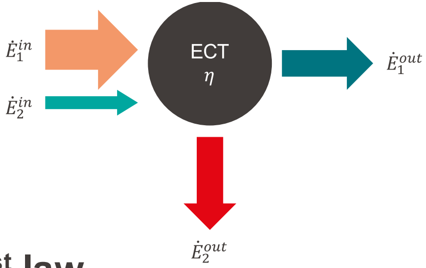
Primary energy is any extraction of energy products in a useable form from natural sources. This occurs either when natural sources are exploited (for example, in coal mines, crude oil fields, hydro power plants) or in the fabrication of biofuels.

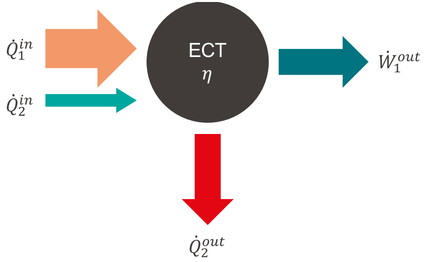
Secondary Energy, is the energy after the conversion technology, prior the distribution losses.

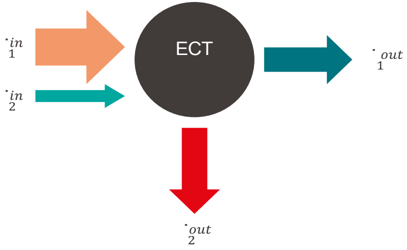
Final energy consumption is the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer's door and excludes that which is used by the energy sector itself.

End-use energy demand, or useful energy, is the last measurable energy flow before the delivery of energy services.

Recap week 2+
Energetic principles







1st law

- Energy Balance

$$\sum_{in} \dot{E}_{in} = \sum_{out} \dot{E}_{out}$$

$$\sum_{in} \dot{Q}_{in} + \dot{W}_{in} + \dot{m}_{in} h_{in} = \sum_{out} \dot{Q}_{out} + \dot{W}_{out} + \dot{m}_{out} h_{out}$$

- Mass Balance

$$\sum_{in} \dot{m}_{in} = \sum_{out} \dot{m}_{out}$$

- First law efficiency

$$\eta = \frac{\text{useful Energy}}{\text{required Energy}} = \frac{\dot{E}_1^{out}}{\sum_{in} \dot{E}_{in}}$$

2nd law

- (Ir)reversibility

$$\delta S^i \geq 0$$

The variation of entropy (δS^i) of any thermodynamic system (i), caused by internal processes, can only be positive (irreversible process) or null (reversible process)

- Clausius

$$\oint \frac{\delta Q}{T} \leq 0$$

*The First Law of Thermodynamics states that heat can be transformed into work, and work into heat through a cyclical process. However, as heat can flow naturally only from a hot to a cold reservoir, heat is naturally **lost** to the environment in a cycle*

- Kelvin-Planck

It is impossible to build a machine operating with a cycle whose only effect is to convert a given quantity of thermal energy into an equal quantity of mechanical work

- Carnot (link between heat and work)

It is not possible to build a machine operating between two given heat sources (at different temperatures) with an efficiency higher than the efficiency of a reversible cycle operating between the same two heat sources

- Carnot efficiency (Carnot factor) θ_c

$$\eta_{ideal} = \frac{\text{what you can get at most}}{\text{what you have to pay}} = \frac{\dot{W}_1^{out,max}}{\dot{Q}_1^{in} + \dot{Q}_2^{in}}$$

$$= 1 - \frac{\dot{Q}_2^{out}}{\dot{Q}_1^{in} + \dot{Q}_2^{in}} = 1 - \frac{T^{out}}{T^{in}} = \theta_c$$

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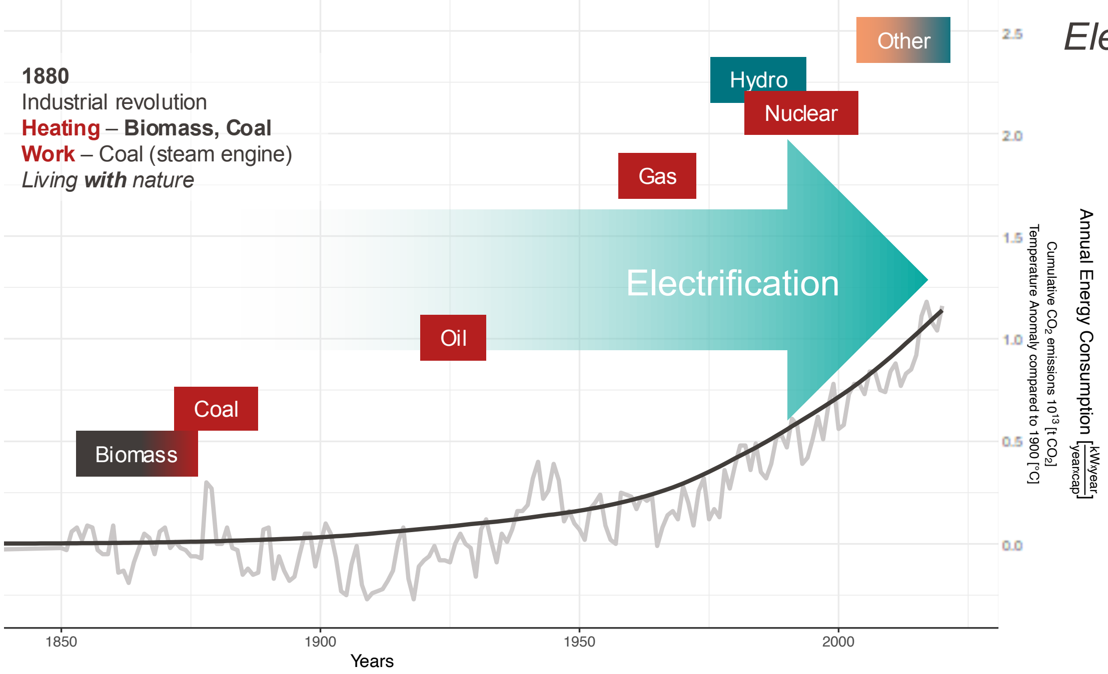
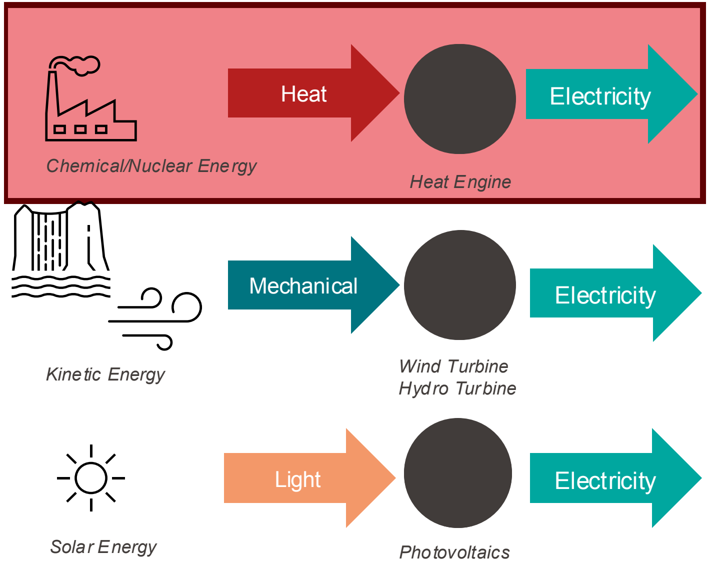
Recap week 2+

Heat Engines



Electricity production 2020



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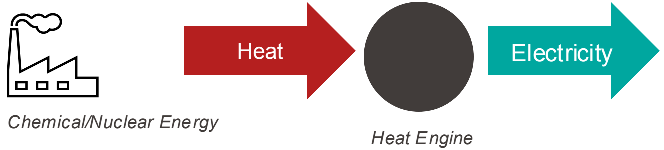
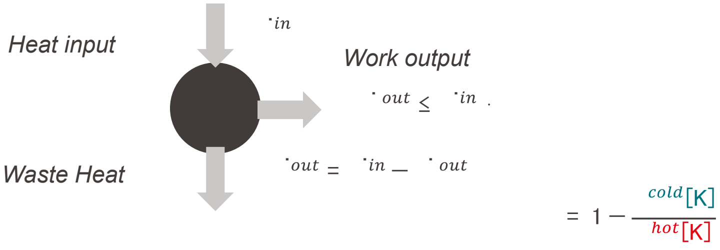
Recap week 2+
Heat Engines





Key Performance Metrics:

Electrical Efficiency $\eta_{el} = \frac{W}{Q_{in}} \leq \theta$ (35-60%).

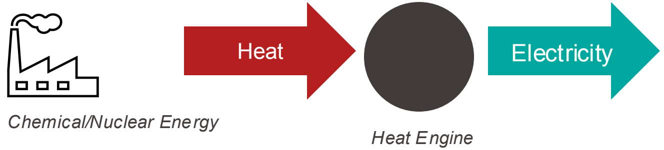
Carnot Factor $\theta = 1 - \frac{T^{cold}[\mathrm{K}]}{T^{hot}[\mathrm{K}]}$

- **Definition:**
  Heat-to-power engines are systems that convert thermal energy from a heat source into mechanical work or electricity through thermal cycles.
- **Principle:**
  Transferring energy from a high-temperature fuel source to a working fluid that expands and produces work, then rejecting waste heat at a lower temperature. The efficiency is fundamentally limited by the Carnot factor, which depends on the temperature difference between the heat source and the waste heat sink.
- **Heat source**
  - Combustion (chemical)
  - Nuclear
  - Geothermal
  - …

Recap week 2+

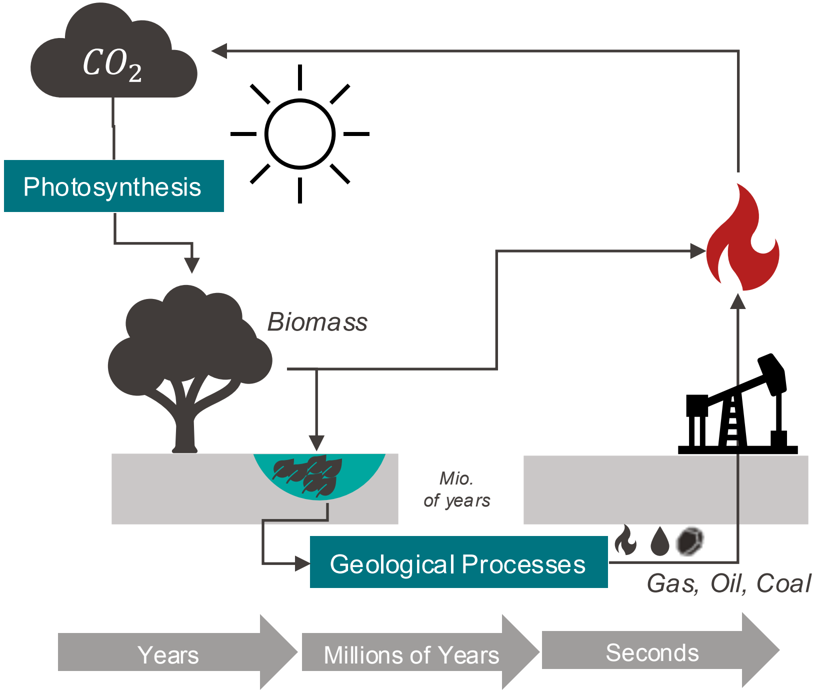
Heat Engines

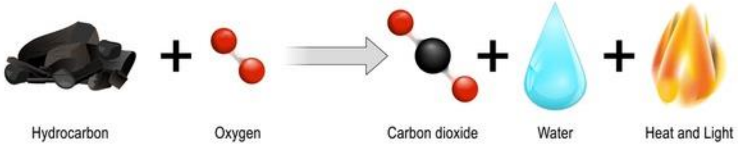
Fuels & Combustion



A chemical reaction where a fuel reacts with an oxidizer (typically oxygen) to produce heat and light.

$$\text{Fuel} + O_2 \rightarrow CO_2 + H_2O + \text{Energy}$$

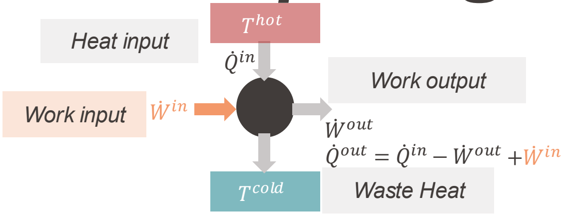




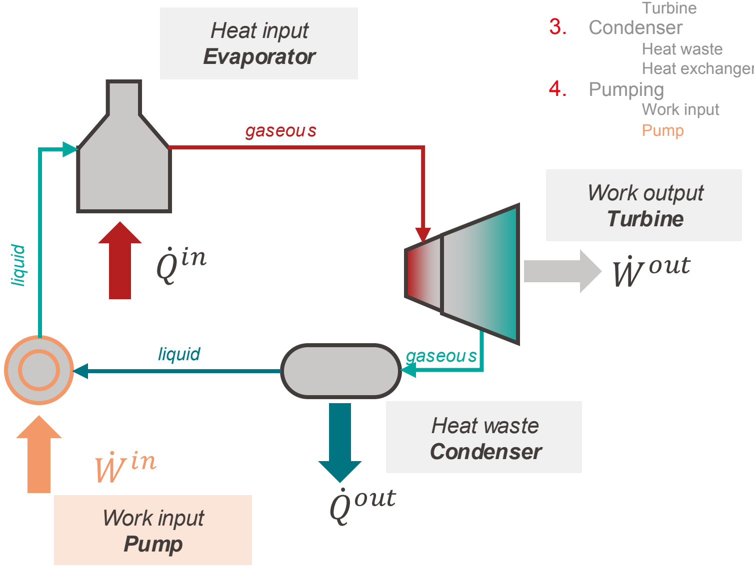
Resource	State	Composition C-H-O [%]			Energy	Formation
Biomass	Solid	40-50	5-6	40-45	15-20 MJ/kg	Annually
Natural Gas	Gaseous	75	25	-	55 MJ/kg	Millions of years
Oil	Liquid	85-87	13-15	<1	43 MJ/kg	Millions of years
Coal	Solid	60-90	3-5	5-15	15-30 MJ	Millions of years

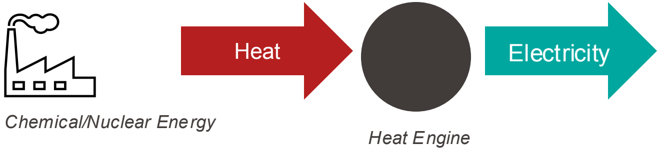
Recap week 2+

Heat Engines: *Rankine Cycle*
liquid – gaseous - liquid

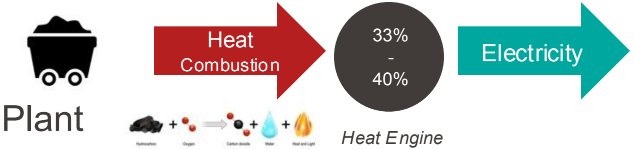


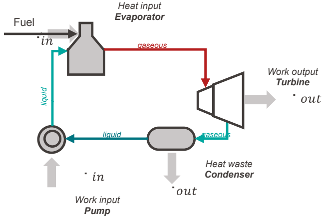
- Most used Power Cycle
- Working fluid passes through phase change (gaseous – liquid)
- 4 Steps
  1. Evaporation
     - Heat input
     - Furnace
  2. Expansion
     - Work output
     - Turbine
  3. Condenser
     - Heat waste
     - Heat exchanger
  4. Pumping
     - Work input
     - Pump

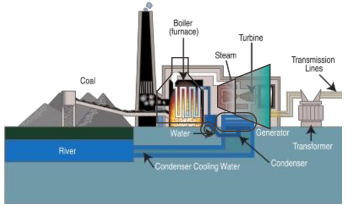




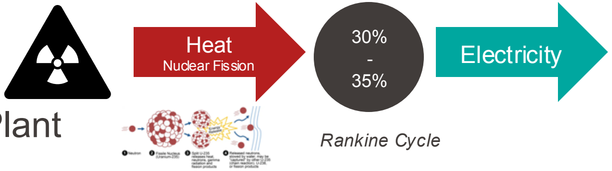
Coal Power Plant

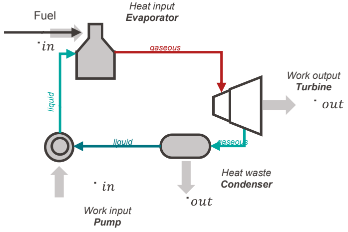


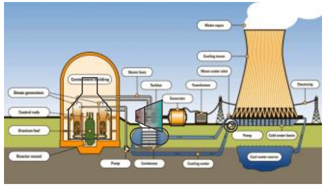




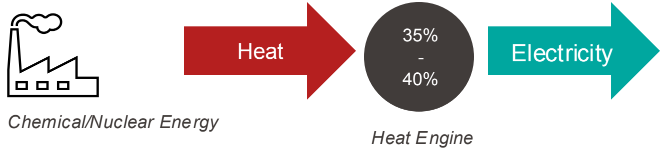
Nuclear Power Plant

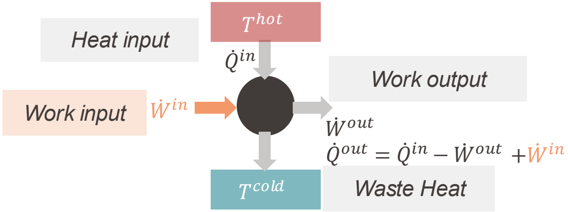


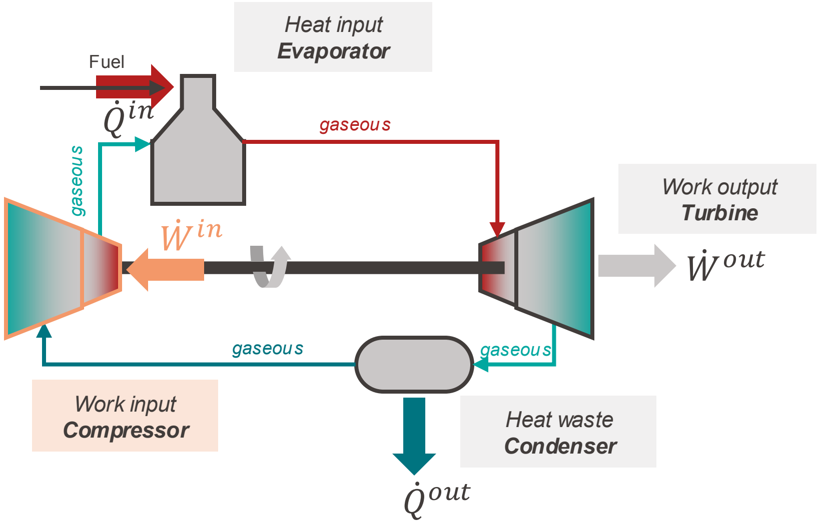




Conventional Technologies
Power Cycles – Brayton Cycle (gas only)







- Working fluid passes only in **gas phase**
- 4 Steps
  1. Evaporation
     - Heat input
     - Furnace
  2. Expansion
     - Work output
     - Turbine
  3. Condenser
     - Heat waste
     - Heat exchanger
  4. Compression
     - Work input
     - Compressor

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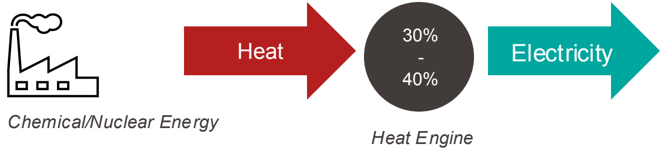
Conventional Technologies
Power Cycles – *Open* Brayton Cycle



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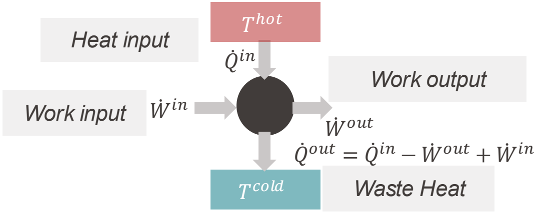
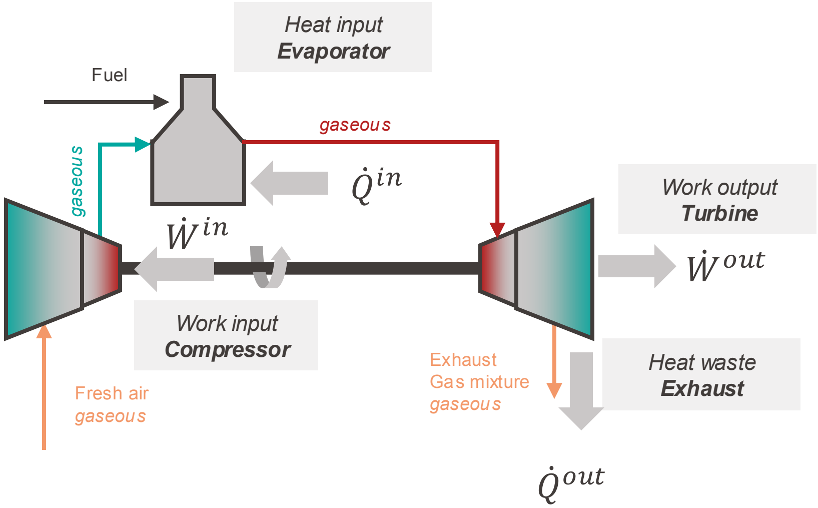
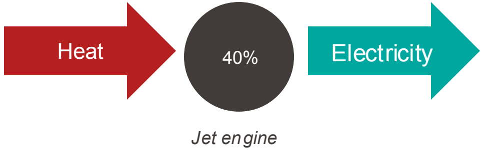
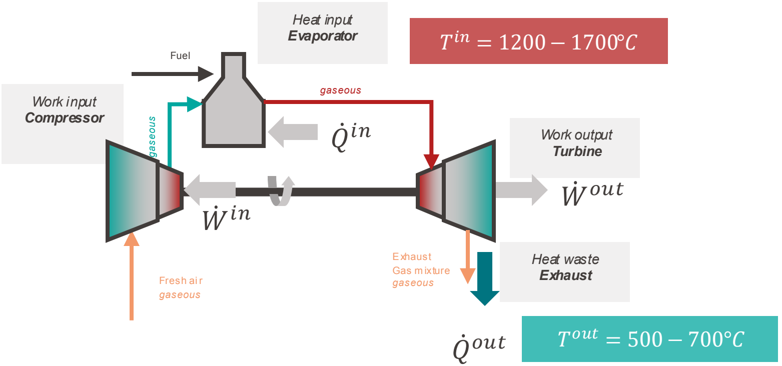




- Working fluid passes only in gas phase
- 4 Steps
  1. Evaporation
     - Heat input
     - Furnace
  2. Expansion
     - Work output
     - Turbine
  3. Condenser
     - Heat waste
     - Heat exchanger
  4. Compression
     - Work input
     - Compressor

Conventional Technologies
Power Cycles – Open Brayton Cycle – Jet engine





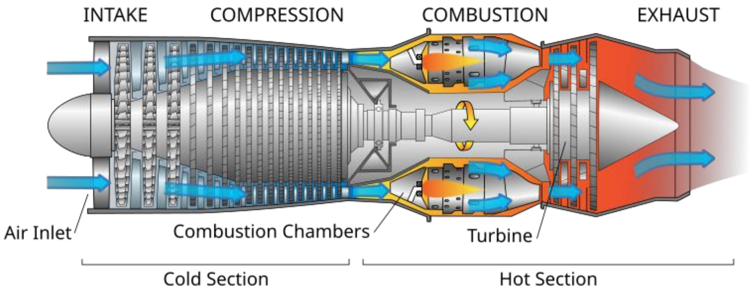


Diagram of a typical gas turbine jet engine.
Air is compressed by the fan blades as it enters the engine, and it is mixed and burned with fuel in the combustion section. The hot exhaust gases provide forward thrust and turn the turbines which drive the compressor fan blades.
© Wikimedia Commons, Jeff Dahl, 2007

- Overview
  - Generates electricity or provides kinetic energy for aircraft
  - Operates on the Brayton cycle using fuels like natural gas, kerosene, propane, or jet fuel
- Main Components
  - Compressor
    - Increases incoming air pressure up to 30×
  - Combustor
    - Burns fuel with compressed air to produce high-pressure, high-velocity gas
  - Turbine
    - Extracts energy from gas to drive compressor and generate power
    - Can produce up to 110,000 hp in large airplanes
      twice the Titanic's engines
- Operation Process
  - Air → Compressor → Combustor → Turbine → Output shaft
  - **~40%** efficiency

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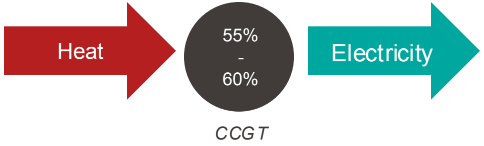
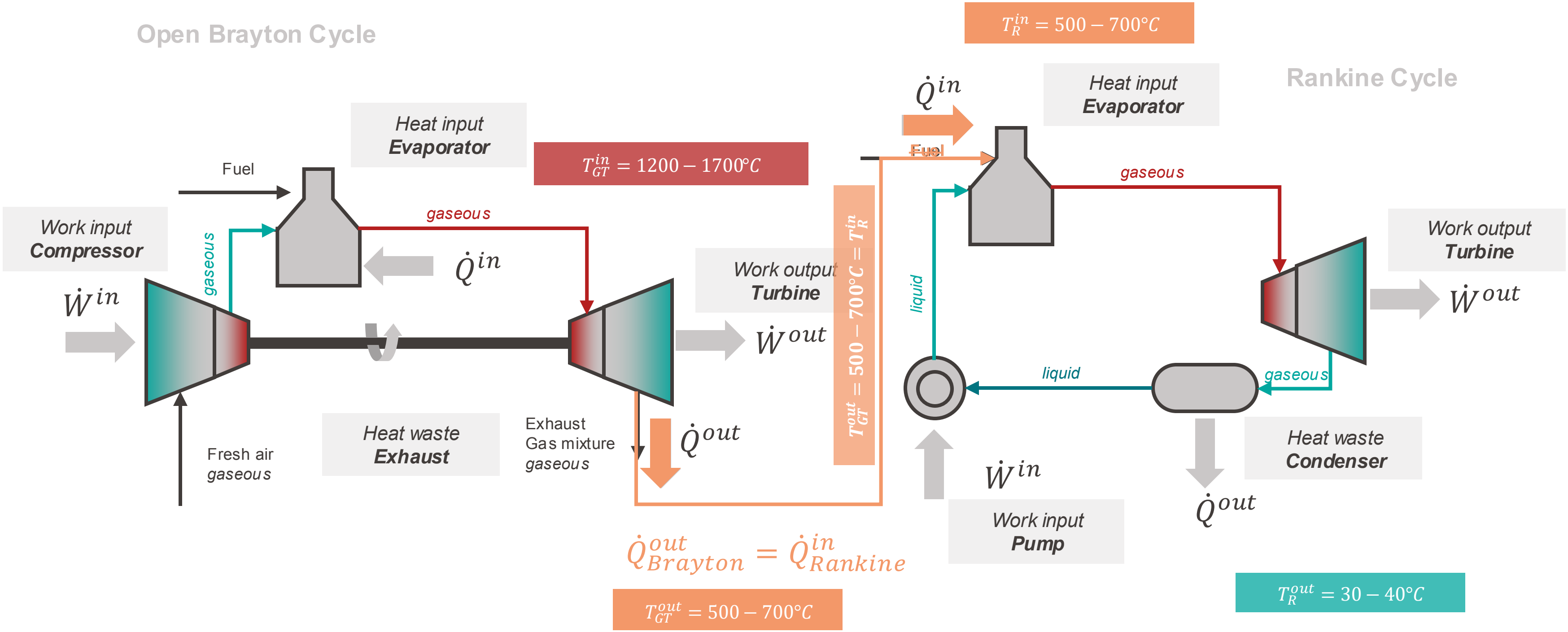
Conventional Technologies
Power Cycles – Combined Cycle CCGT





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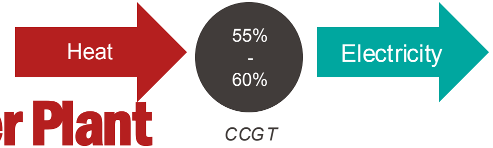
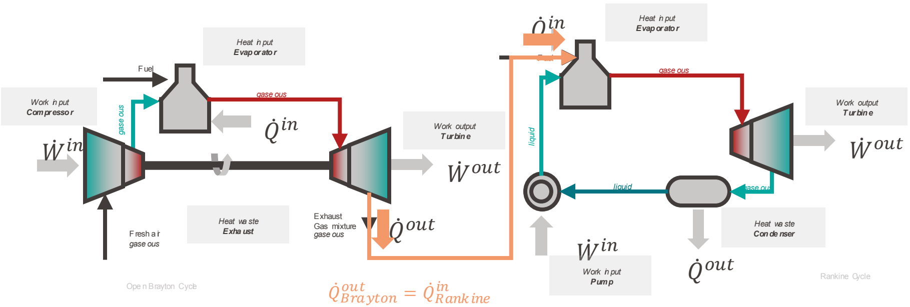
Conventional Technologies
Power Cycles – Combined Cycle CCGT – Gas Power Plant





Combustion turbine - Combined cycle animation.

- Combined Cycle Gas Turbine (CCGT)
  - Integrates gas turbine (Brayton cycle) with steam turbine (Rankine cycle) for enhanced efficiency
  - Utilizes multiple fuel types like standalone gas turbines
  - CCGT systems utilize waste heat from the gas turbine to power the steam turbine, maximizing energy extraction and reducing fuel consumption
- Main Components
  - Gas Turbine (Brayton Cycle)
    - Compresses incoming air and burns fuel to produce high-pressure, high-velocity gas
    - Generates primary electricity
    - Emits hot exhaust gases
  - Heat Recovery Steam Generator (HRSG)
    - Captures and utilizes exhaust heat from the gas turbine
    - Evaporates water to produce steam for the Rankine cycle
  - Steam Turbine (Rankine Cycle)
    - Uses steam from HRSG to generate additional electricity
    - Enhances overall power output and efficiency
- Operation Process
  - Air → Compressor → Gas Turbine → Exhaust → HRSG → Steam → Steam Turbine → Output Shaft
- Key Advantages
  - Increased Efficiency
    - Combined cycle can achieve efficiencies up to **~60%,** higher than open Brayton cycle alone
  - Effective Heat Utilization
    - Exhaust gases from Brayton cycle provide sufficient heat to drive the closed Rankine cycle

CCGT – Example

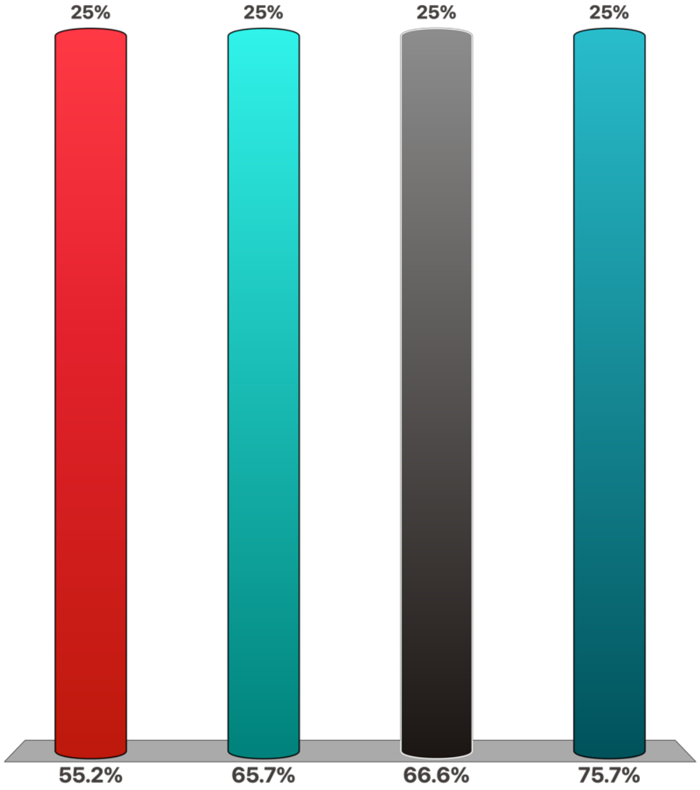
A combined cycle power plant employs a gas turbine (Brayton cycle) with combustion at 1,400 K and an exhaust temperature of 550 K. Waste heat is recovered to drive a steam turbine (Rankine cycle) where steam enters at 600 K and condenses at 300 K. Only 30% of the Brayton cycle's rejected heat is available for recovery. Using Carnot efficiencies for both cycles, determine the overall efficiency (expressed as a percentage of the fuel input).

A. 55.2%

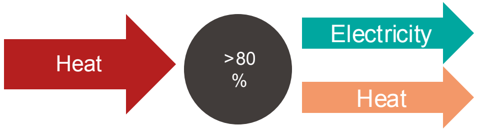
B. 65.7%

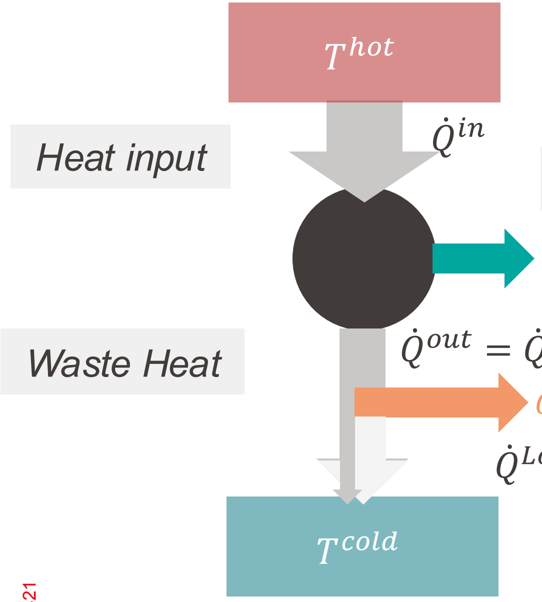
C. 66.6%

D. 75.7%



Emerging Technologies
Cogeneration - Fundamentals





$$\dot{W}^{out} \leq \dot{Q}^{in} \cdot \theta$$

$$\theta = 1 - \frac{T^{cold}[\mathrm{K}]}{T^{hot}[\mathrm{K}]}$$

$$\dot{Q}^{out} = \dot{Q}^{in} - \dot{W}^{out}$$

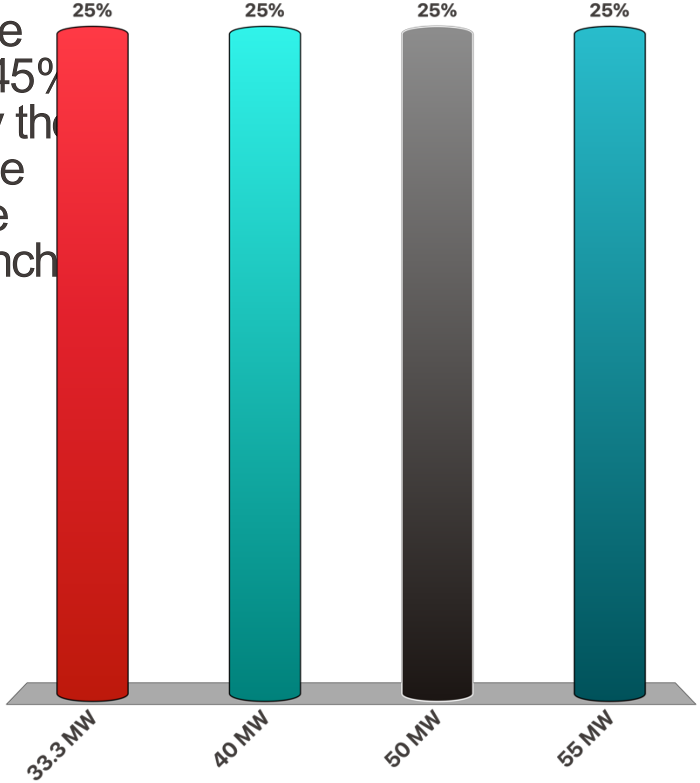
$$\dot{Q}^{Loss} = \dot{Q}^{in} - \dot{W}^{out} - \dot{Q}^{useful}$$

- Definition:
  Cogeneration (Combined Heat and Power - CHP) is the simultaneous production of electricity and useful heat from a single energy source, such as biomass, coal, or natural gas.
- Principle:
  - In conventional plants, ~60% of energy is lost as waste heat. CHP utilizes this heat, achieving higher overall efficiency.
- Key Performance Metrics:
  - Electrical Efficiency $\eta_{el} = \frac{W}{Q_{in}}$ (35-60%).
  - Thermal Efficiency $\eta_{th} = \frac{Q_{useful}}{Q_{in}}$ (35-45%).
  - Utilization Factor $\epsilon = \frac{W+Q_{useful}}{Q_{in}} = \eta_{el} + \eta_{th}$ (>80%)

Cogeneration – Tridel Lausanne

A cogeneration plant is designed to supply both electricity and heat. The useful demand is 15 MW of electricity and 40 MW of heat. The plant operates at an electrical efficiency of 45% and a thermal efficiency of 80%. Using only the useful output for each branch, determine the minimum fuel input (in MW) required for the plant sizing (the design must cover the branch with the higher fuel demand).

A. 33.3 MW
B. 40 MW
C. 50 MW
D. 55 MW



Emerging Technologies

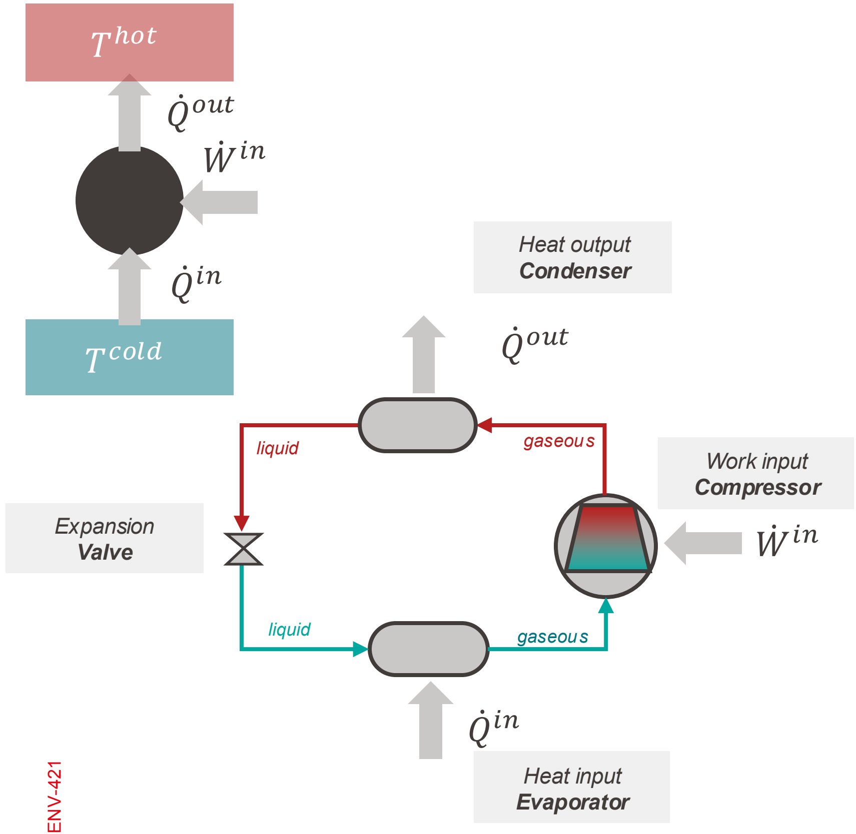
Cogeneration - Types and Applications

- Technologies:
  - Gas turbines, internal combustion engines, steam turbines, fuel cells.
  - Scale: From micro-CHP for households (~5 kWe) to large-scale plants (>10 MWe).
- Applications:
  - District Heating: Large-scale CHP plants in cities and industries.
  - Industrial Processes: Combined heat and electricity for drying, steam, or chemical processes.
  - Residential: Micro gas turbines or fuel cells for small-scale heat and power needs.

Conventional Technologies
Heating Cycles – Heat Pumps

Basic Principle:

Moves thermal energy against the natural flow of heat (from cooler to warmer areas) by utilizing a cycle.



- Definition:

  A device that transfers **heat** from one location to another using **mechanical energy**, **providing** both **heating and cooling**.

- Cycle:
  - **Evaporation**:

    Working fluid absorbs heat from the cold space and evaporates.
  - **Compression**:

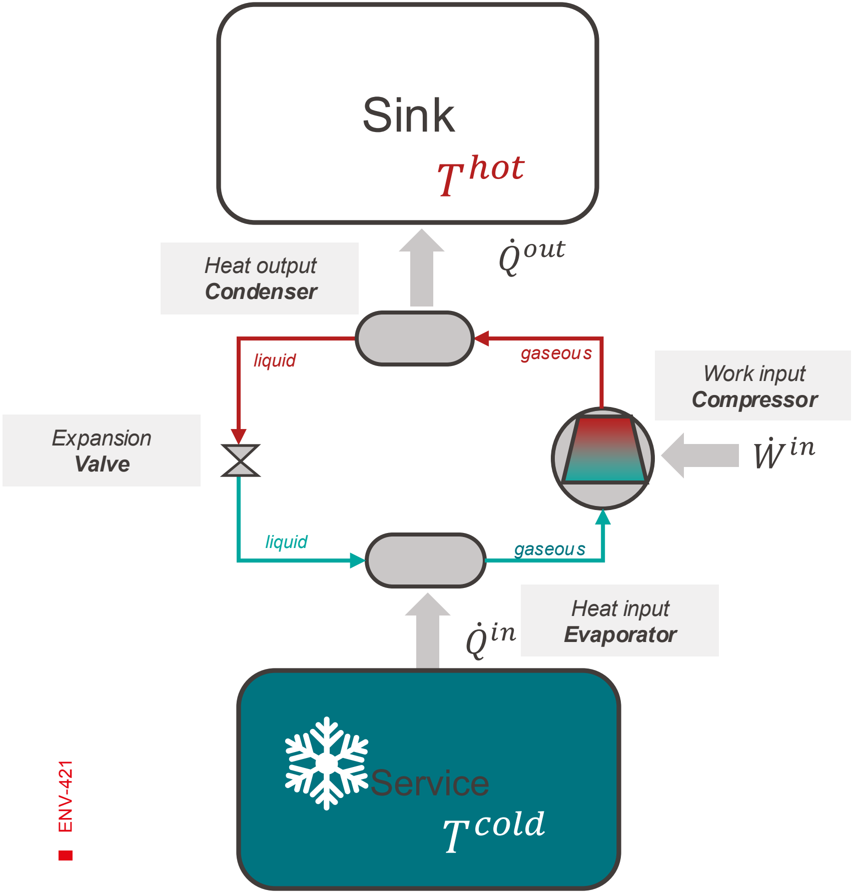
    Compressor increases the working fluid's pressure and temperature.
  - **Condensation**:

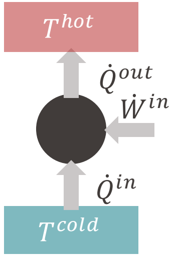
    Hot working fluid releases heat to the hot space and condenses back to liquid.
  - **Expansion**:

    Working fluid expands, lowering its pressure and temperature, ready to absorb heat again.

Conventional Technologies

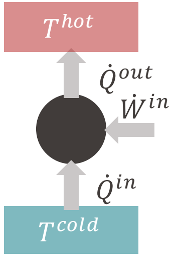
Heating Cycles – Heat Pumps - Cooling

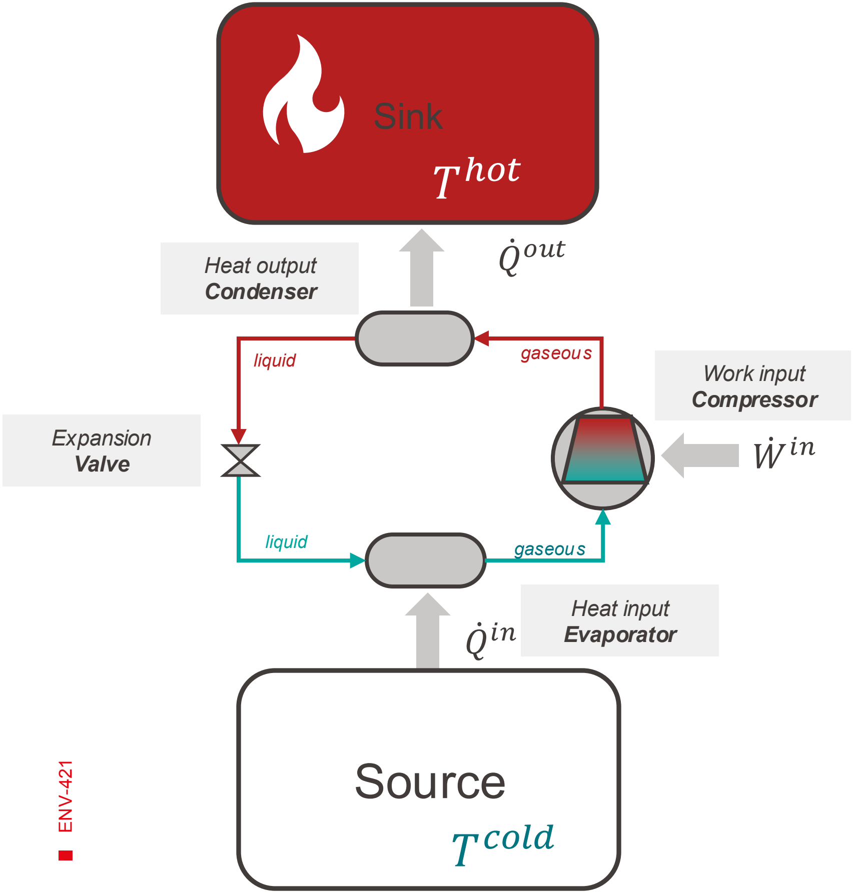




- Extracting heat from Cold area
  - Fridge etc.
- Releasing heat in hotter area
  - Ambient surrounding
- $COP_{Cooling} = \frac{\dot{Q}^{in}}{\dot{W}^{in}} > 1$
- $COP_{Cooling}^{Carnot} = \frac{\dot{Q}^{in}}{\dot{W}^{in}_{min}} = \frac{T^{cold}\,[K]}{T^{hot}\,[K] - T^{cold}\,[K]}$
- $\epsilon = \frac{COP_{Cooling}^{Carnot}}{COP_{Cooling}}$

Conventional Technologies
Heating Cycles – Heat Pumps - Heating





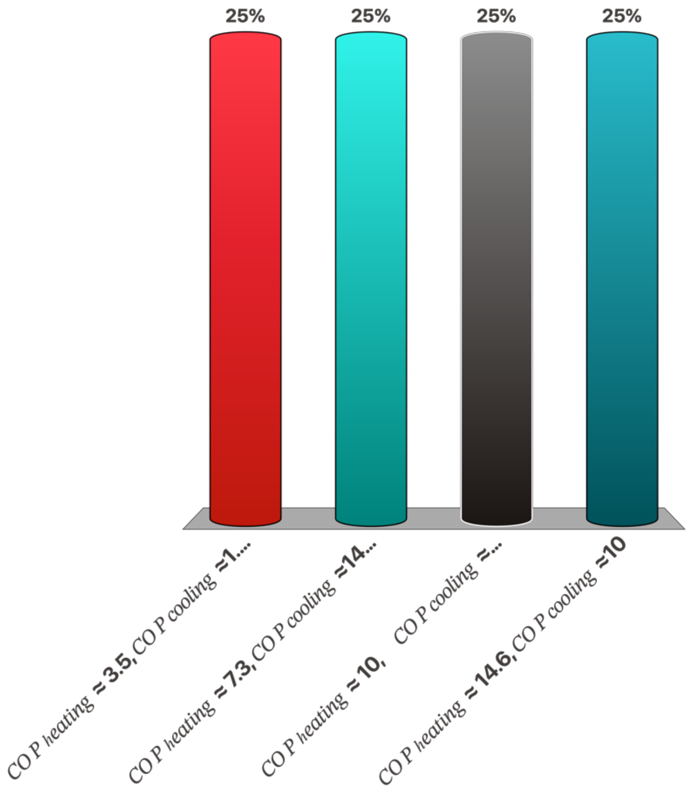
- Extracting heat from source
  - Ambient air
  - Ground Source (Geothermal)
  - Water (Lake e.g., EPFL)
- Increasing temperature of sink

- $COP_{Heating} = \frac{\dot{Q}^{out}}{\dot{W}^{in}} > 1$
- $COP_{Heating}^{Carnot} = \frac{\dot{Q}^{out}}{\dot{W}^{in}_{min}} = \frac{T^{hot}\,[K]}{T^{hot}\,[K] - T^{cold}\,[K]}$
- $\epsilon = \frac{COP_{Heating}^{Carnot}}{COP_{Heating}}$

Heat Pump – Example

A reversible heat pump provides both heating and cooling. In winter mode, the indoor temperature is 20°C and the outdoor temperature is 0°C; in summer mode, the indoor temperature is maintained at 20°C while the outdoor temperature is 30°C.
If real devices achieve about 50% of the ideal performance, what are the approximate actual COP values?

A. $COP_{heating} \approx 3.5, COP_{cooling} \approx 1.25$
B. $COP_{heating} \approx 7.3, COP_{cooling} \approx 14.6$
C. $COP_{heating} \approx 10, \quad COP_{cooling} \approx 21.3$
D. $COP_{heating} \approx 14.6, COP_{cooling} \approx 10$



EPFL

Jonas Schnidrig

A G E N D A

Overview of Energy Technologies

Conventional Technologies

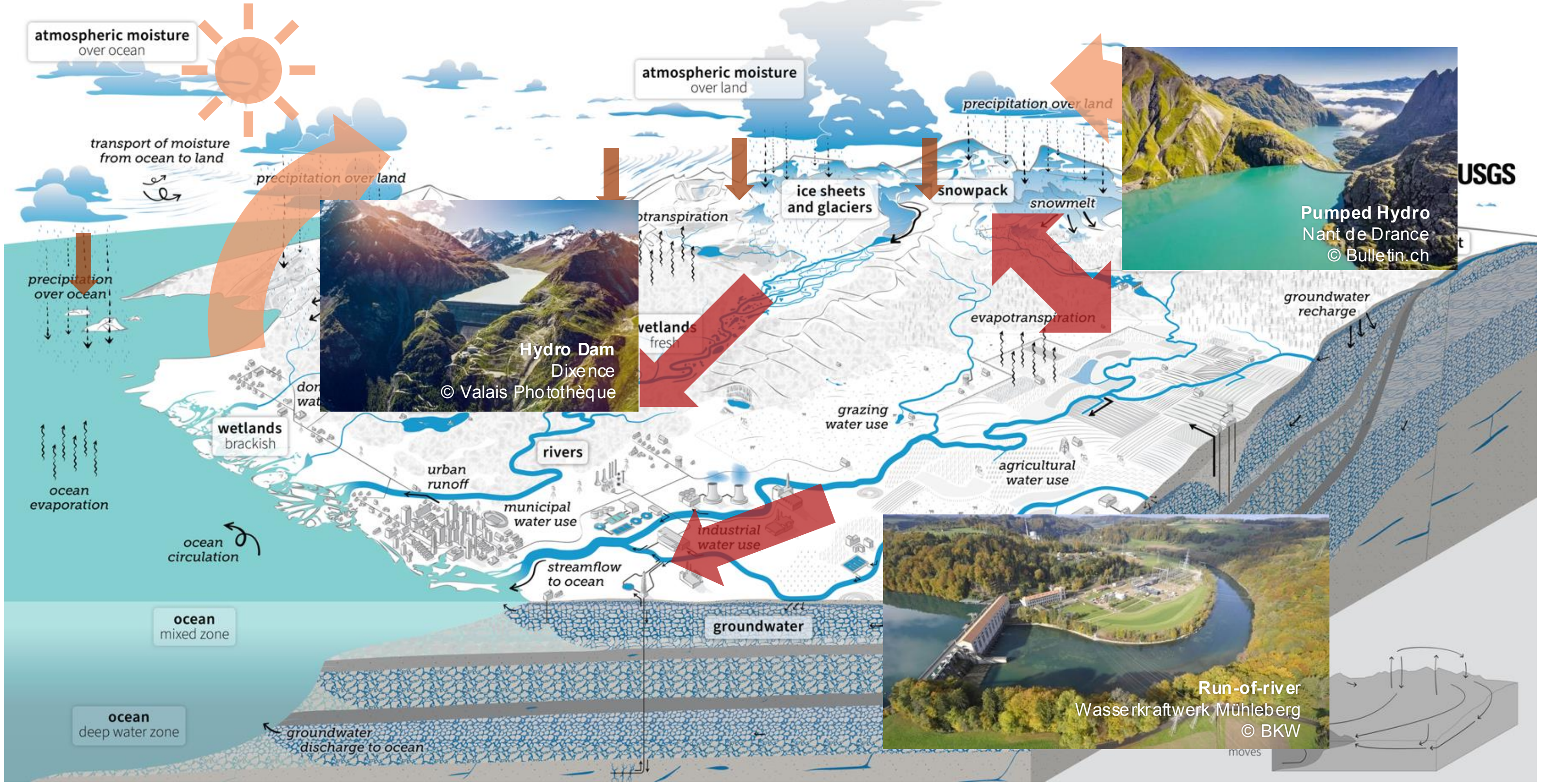
Renewable Energy Technologies

Infrastructure

EPFL

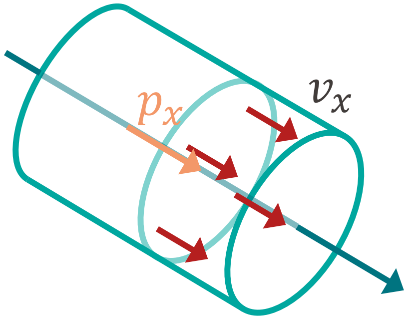
Emerging Technologies
Hydropower - origin

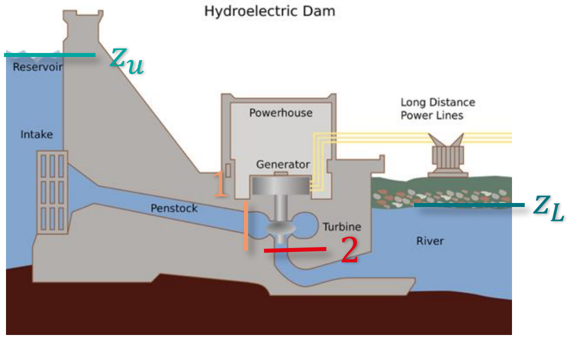
Jonas Schnidrig



USGS Water Cycle English

Emerging Technologies
Hydropower – working principle





Bernoulli:

$$gH_x = gz_x + \frac{p_x}{\rho} + v_x^2$$

High energy side (head):

$$gH_u = \frac{p_{atm}}{\rho} + gz_u + 0 = gH_1 + \sum_{head} gH_r$$

Low energy side (tail):

$$gH_L = \frac{p_{atm}}{\rho} + gz_L + 0 = gH_2 + \sum_{tail} gH_r$$

At turbine:

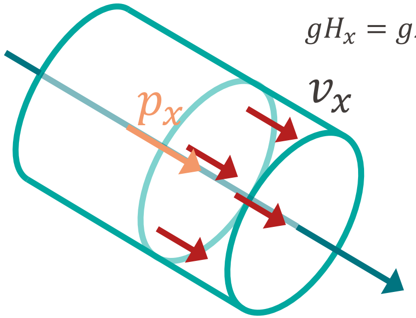
$$e_{12} = g(H_1 - H_2) = g(z_u - z_L) - \sum gH_r$$

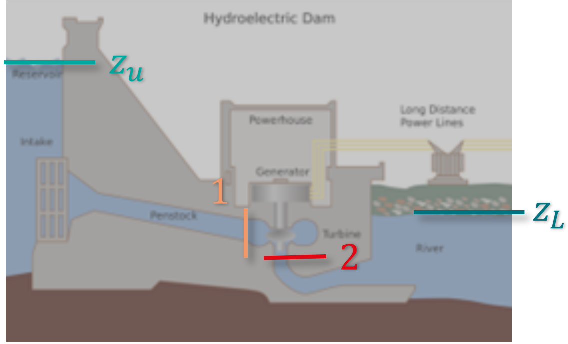
$$\boldsymbol{e_{12}} = (\boldsymbol{gz_1} - \boldsymbol{gz_2}) + \left(\frac{\boldsymbol{p_1}}{\boldsymbol{\rho}} - \frac{\boldsymbol{p_2}}{\boldsymbol{\rho}}\right) + \frac{1}{2}\left(\boldsymbol{v_1^2} - \boldsymbol{v_2^2}\right) - \boldsymbol{e_{loss}}$$

Emerging Technologies
Hydropower – working principle

Bernoulli:

$$gH_x = gz_x + \frac{p_x}{\rho} + v_x^2$$





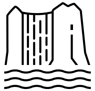
- Potential Energy: $E_{Pot} = mgh$
  - m: Mass of water
  - g: Acceleration due to gravity
  - h: Height difference (head) $h = z_1 - z_2$
- Kinetic Energy: $E_{Kin} = \frac{1}{2} m v^2$
  - m: Mass of water
  - v: Velocity of water
- Power output: $\dot{E} = \eta \rho Q g H$
  - η: Efficiency of turbine and generator
  - ρ: Density of Water ($\sim 1000\ \mathrm{kg/m^3}$)
  - Q: Flow rate $Q = Av$
  - g: Acceleration due to gravity
  - H: Effective head
  - A: Area
- Effective head: $H = h + \frac{p}{\rho g} + \frac{v^2}{2g}$
- Transferred specific energy

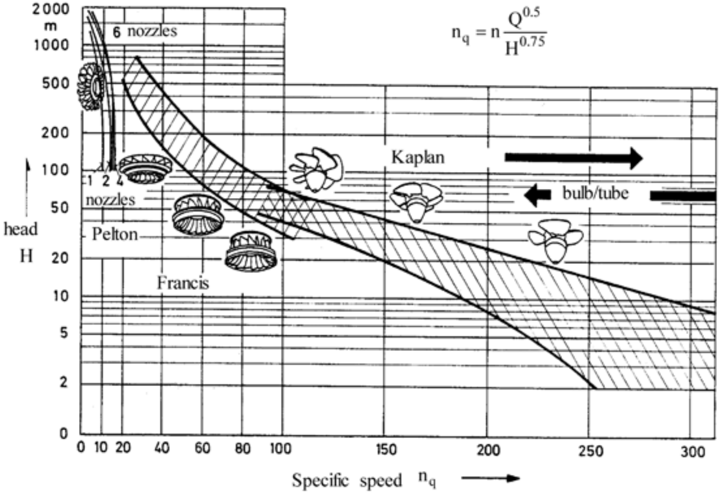
$$e_{12} = g(z_1 - z_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{losses}$$

Emerging Technologies
Hydropower – Turbine applications

$$e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$$

Water wheels displacement impulse





Range of application for various types of hydraulic turbines.

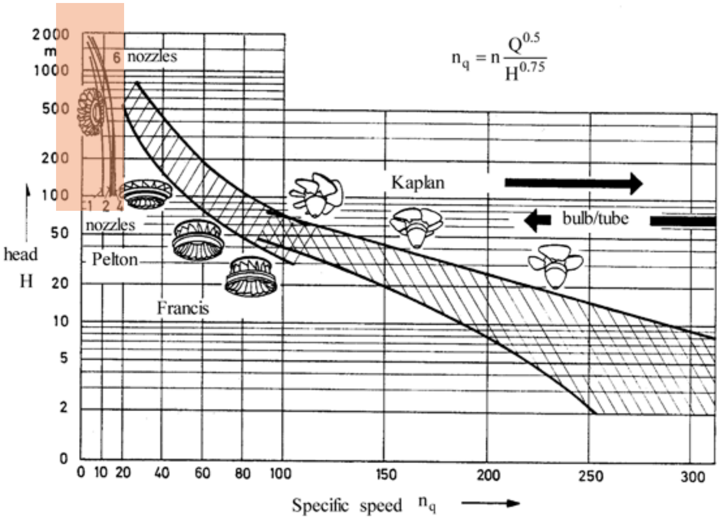
Emerging Technologies
Hydropower – Turbine applications

$$e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$$

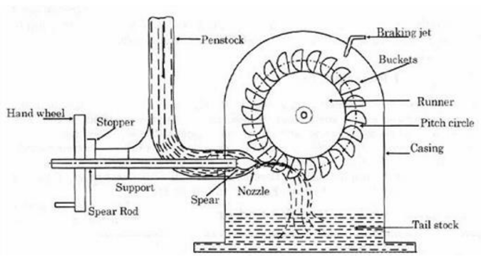
Water wheels displacement impulse

Jonas Schnidrig

- Pelton
  - $e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$
  - Type: Impulse turbine – 92%
  - Best For: High head (300m+) and low flow
  - Design Features: Spoon-shaped buckets mounted on a runner
  - Applications: Mountainous regions, small-scale hydro projects



Range of application for various types of hydraulic turbines.

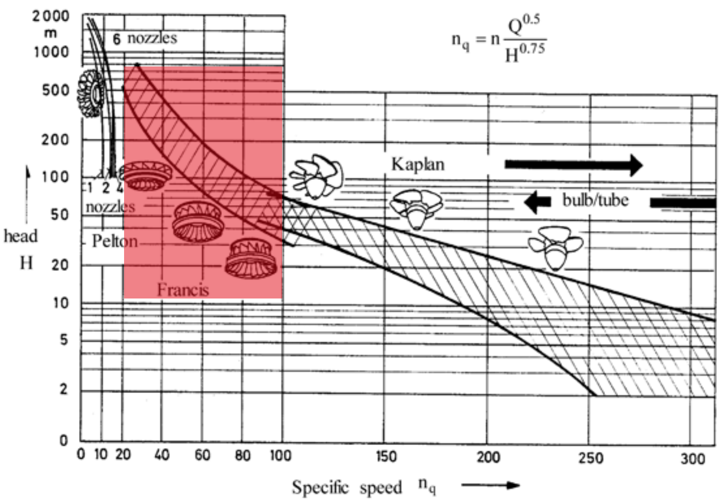


Emerging Technologies
Hydropower – Turbine applications

$$e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$$

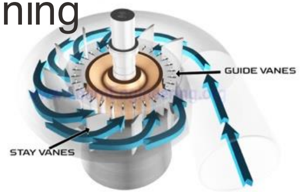
Water wheels displacement impulse

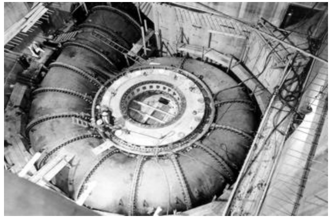
Jonas Schnidrig



Range of application for various types of hydraulic turbines.

- Francis
  - $e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$
  - Type: Reaction turbine – 96-97%
  - Best For: Medium head (10-300m) and medium flow
  - Design Features: Mixed radial and axial flow
  - Applications: Most common in large hydroelectric plants
  - Reversible!
    Pumping & Turbining





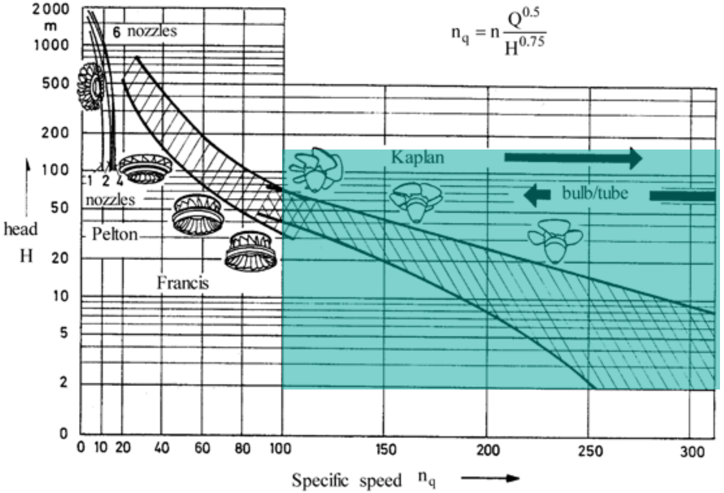
Francis Runner, Grade Coulée Dam

Emerging Technologies
Hydropower – Turbine applications

$$e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$$

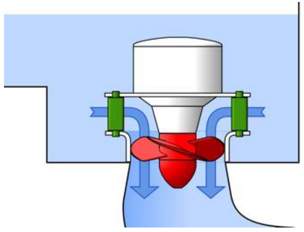
Water wheels displacement impulse

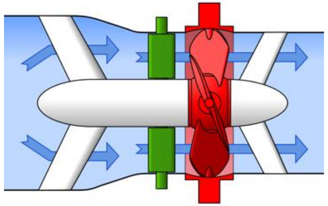
Jonas Schnidrig



Range of application for various types of hydraulic turbines.
© Dietzel F (1980) Turbinen, Pumpen und Verdichter. Vogel Verlag, ISBN 3-8023-0130-7

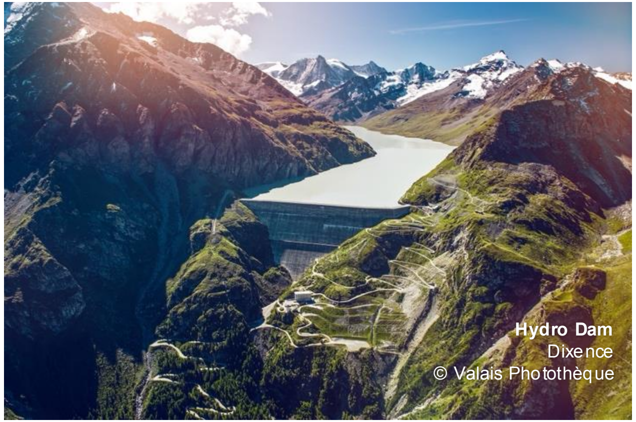
- Kaplan/Bulb
  - $e_{12} = (gz_1 - gz_2) + \left(\frac{p_1}{\rho} - \frac{p_2}{\rho}\right) + \frac{1}{2}(v_1^2 - v_2^2) - e_{loss}$
  - Type: Reaction turbine – 90-95%
  - Best For: Low head (below 10m) and high flow
  - Design Features: Adjustable blades (Kaplan) or integrated generator housing (Bulb)
  - Applications: Large river systems, run-of-river hydro projects

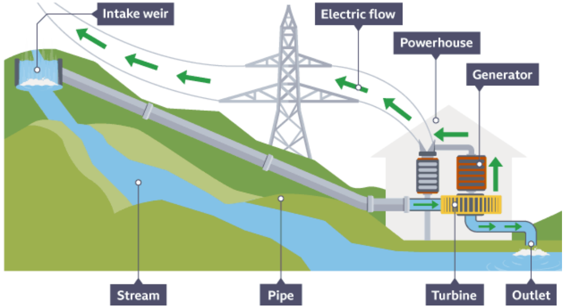




Bulb Turbines: Ybbs-Persenbeug, Vertical & Horizontal installation
© Wikimedia Commons

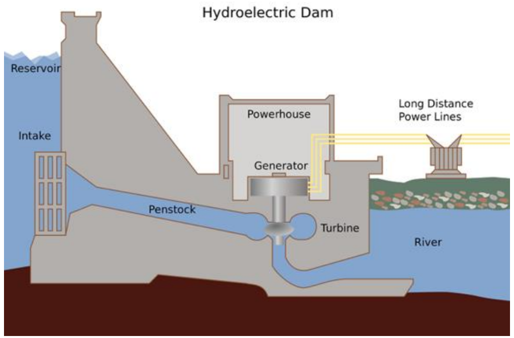
Emerging Technologies
Hydropower – Hydro Dam





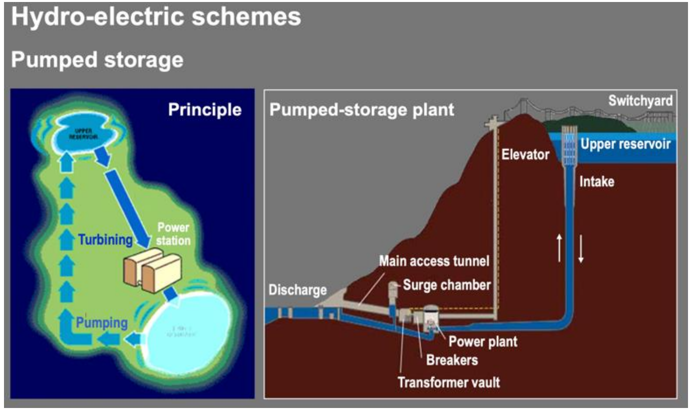
- Working Principle
  - Water Storage: Dam creates a reservoir to store water
  - Flow Control: Release water through turbines as needed
  - Electricity Generation: Flowing water drives turbines to generate electricity
- Key Components
  - Dam and reservoir
  - Intake structures
  - Penstocks (water conduits)
  - Turbines and generators
  - Tailrace (water discharge)
- Advantages
  - Reliable and controllable power source
  - Provides flood control, irrigation, and water supply
  - Long operational lifespan

Emerging Technologies
Hydropower – Run-of-River Hydropower Plant



- Working Principle
  - Natural Flow Utilization: Harnesses the river's natural flow and elevation drop
  - Minimal Storage: Little to no reservoir; relies on continuous flow
  - Electricity Generation: Water diversion directs flow through turbines to produce electricity
- Key Components
  - Diversion structures (weirs or intake)
  - Canals or penstocks
  - Turbines and generators
  - Natural river channel (tailrace)
- Advantages
  - Lower environmental and ecological impact
  - Reduced initial construction costs
  - Minimal displacement of communities
- Challenges
  - Dependent on seasonal and river flow variability
  - Limited storage for energy generation flexibility

Emerging Technologies
Hydropower – Pumped Storage



- Working Principle
  - Energy Storage: Uses two reservoirs at different elevations
  - Pumping Phase: During low demand, excess electricity pumps water to the upper reservoir
  - Generation Phase: During high demand, water is released back to the lower reservoir through turbines to generate electricity
- Key Components
  - Upper and lower reservoirs
  - Pump/turbine units
  - Penstocks (water conduits)
  - Switchyard and grid connections
- Advantages
  - Balances grid demand and supply
  - Provides rapid response for peak load management
  - Enhances grid stability and reliability

  - $\eta_{Rountrip} = \frac{E^{out}}{E^{in}} = \sim 80\%$

EPFL

Hydro Power - Example

A hydro energy storage installation is designed to operate in both generating and pumping modes. At the site, water is available at a flow rate of 40 m³/s from an upper reservoir with a vertical head of 300 m.

a) Which turbine type is most appropriate for this reversible operation?

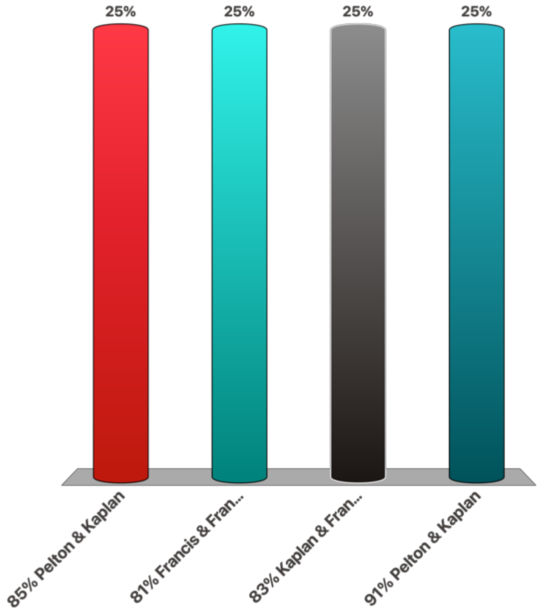
- A) Pelton turbine ($\eta = 93\%$)
- B) Kaplan turbine ($\eta = 91\%$)
- C) Francis turbine ($\eta = 90\%$)

b) Using the given data and assuming:

- Water density ρ = 1000 kg/m³
- Gravitational acceleration g = 9.81 m/s²

Compute the overall round-trip efficiency

A. 85% Pelton & Kaplan
B. 81% Francis & Francis
C. 83% Kaplan & Francis
D. 91% Pelton & Kaplan

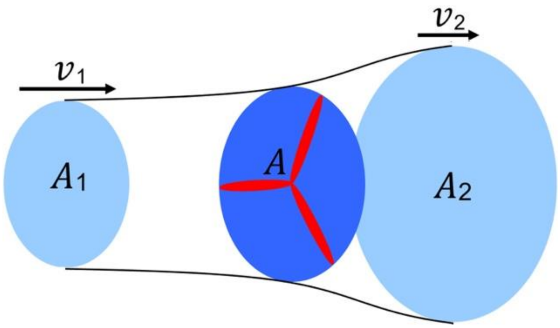


Emerging Technologies
Wind – Origin of wind energy

- Wind Generation Factors:
  - Differential Solar Heating:
    - Uneven heating of Earth's surface creates temperature and pressure differences.
  - Coriolis Force:
    - Earth's rotation deflects wind direction, influencing global wind patterns.
  - Pressure Gradients:
    - Air moves from high to low-pressure areas, driving wind flow.

→ "Secondary" Solar Energy

Emerging Technologies
Wind – Working Principles

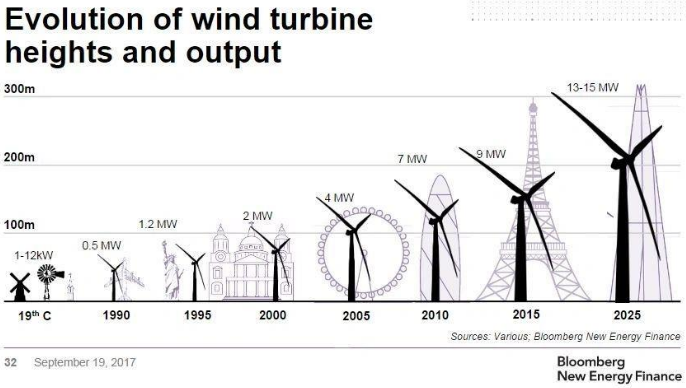


- Energy Conversion Process:
  - Wind Kinetic Energy → Mechanical Energy → Electrical Energy
- Key Forces on Rotor Blades:
  - Lift:
    - Primary force driving blade rotation.
    - Generated by the pressure difference on the blade surfaces.
  - Drag:
    - Resistive force opposing blade movement.
- Betz's Law:
  - Maximum Theoretical Efficiency: 59% of wind's kinetic energy can be captured

$$P_{max} = \frac{16}{27} \times ½\rho\, A\, v^3 \approx\ 59\%\ \times ½\, \rho\, A\, v^3$$

- Practical Efficiency:
  - Real-world turbines achieve up to 40% efficiency due to various losses.

Emerging Technologies
Wind – Key equations

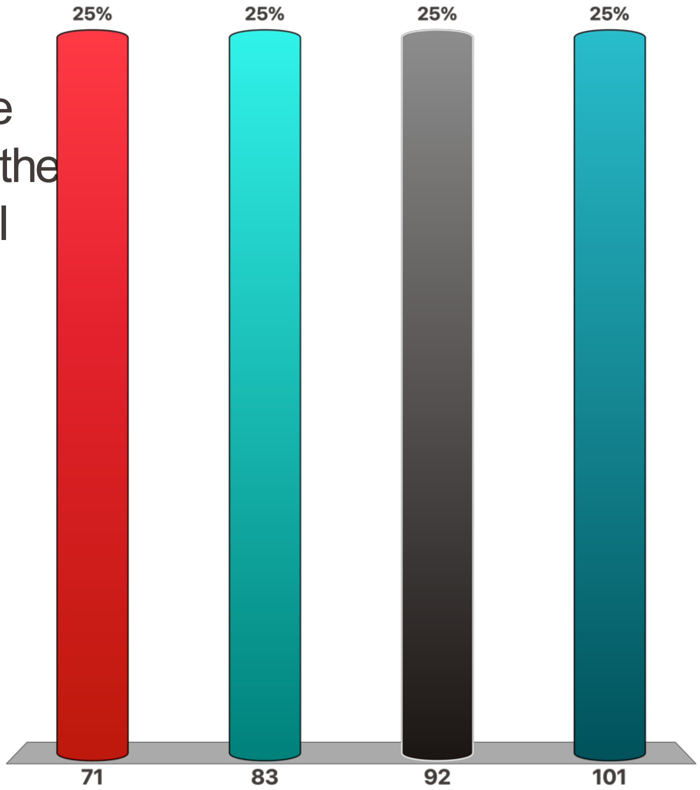


- Kinetic Energy of Wind:
  - $E_{Kin} = \frac{1}{2}mv^2 = \frac{1}{2}\rho A v^3$
    - ρ: Air density (~1.225 kg/m³ at sea level)
    - A: Swept area of the turbine ($A = \pi r^2$)
    - v: Wind speed (m/s)
- Extractable Power:
  - $\boldsymbol{P = \frac{1}{2}\rho A v^3 \cdot c_p = \frac{1}{2}\rho \cdot \pi r^2 \cdot v^3 \cdot c_p}$
    - c_p : Power coefficient ($\leq\ 0.59$ as per Betz's Law)

Wind Turbine – Example 1

A wind turbine has a rotor radius of 40 m. Assume the air density is 1.2 kg/m³ and the wind speed is 10 m/s. If the turbine extracts 40% of the available wind power, determine the extractable power per turbine and then the number of turbines needed to supply a total power demand of 100 MW.

A. 71
B. 83
C. 92
D. 101



Emerging Technologies
Wind – Efficiency and Design Considerations

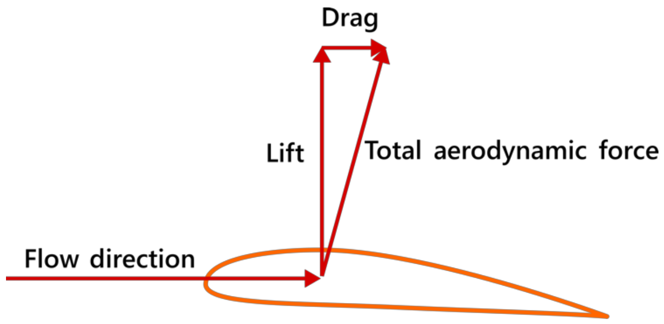
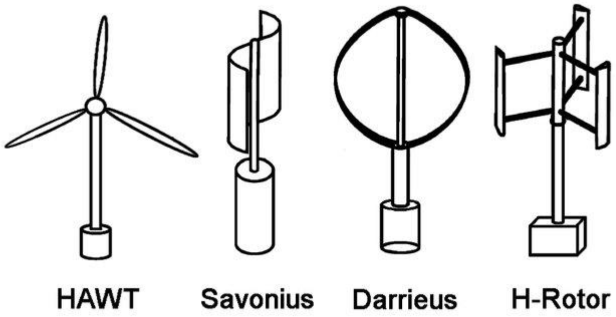


Illustration of drag, lift and resulting aerodynamic force

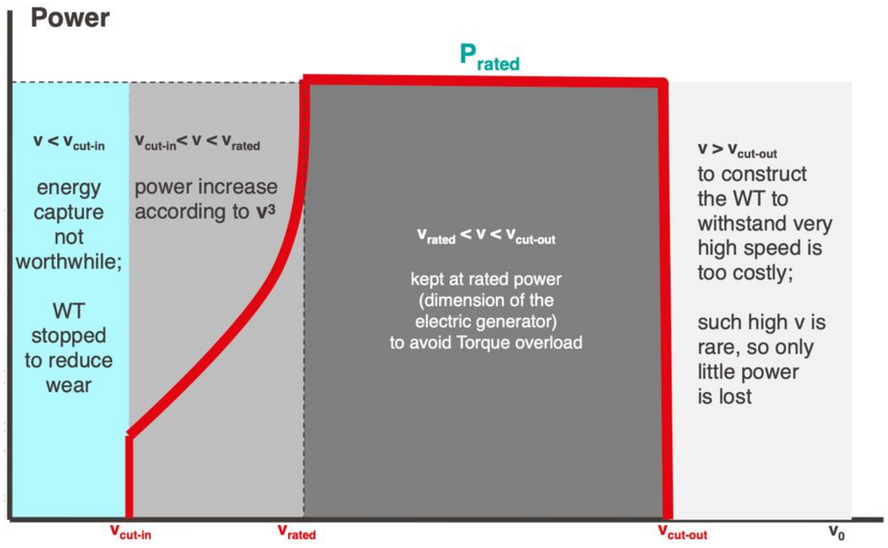


The major wind turbine types including the propeller-type horizontalaxis wind turbine (HAWT), drag-based Savonius design, and the lift-based Darrieus and H-rotor vertical-axis wind turbines (VAWTs)
© Eriksson, 2008

- Losses Reducing Efficiency:
  - Wake Losses:
    - Turbulence behind turbine reduces wind speed for downstream turbines.
  - Tip Losses:
    - Energy lost at the blade tips due to air spilling over.
  - Drag Losses:
    - Resistive forces opposing blade movement.
  - Overall Real-World Efficiency: ~40%
- Blade Design:
  - Aerofoil Shape:
    - Optimizes lift-to-drag ratio for maximum energy capture.
  - Variable Pitch:
    - Adjusts blade angle based on wind speed to optimize performance and protect against high winds.

Emerging Technologies

Wind – Wind Turbine Operation



- Operational Wind Speed Range:
  - **Cut-in Speed**: Minimum wind speed to start generating power (~3-4 m/s)
  - **Rated Speed**: Wind speed at which turbine generates its rated (maximum) power (~12-15 m/s)
  - **Cut-out Speed**: Wind speed at which turbine shuts down to prevent damage (~25 m/s)
- Power Output Relationship:
  - **Below Cut-in Speed**: No power generation.
  - **Between Cut-in and Rated Speed**: Power increases with the cube of wind speed.
  - **Above Rated Speed**: Power output remains constant at rated power until cut-out speed.
  - **Above cut-out Speed**: No Power

Wind Turbine – Example 2

A wind turbine has a rotor radius of 40 m. Assume the air density is 1.2 kg/m³ and the wind speed is 10 m/s. If the turbine extracts 40% of the available wind power

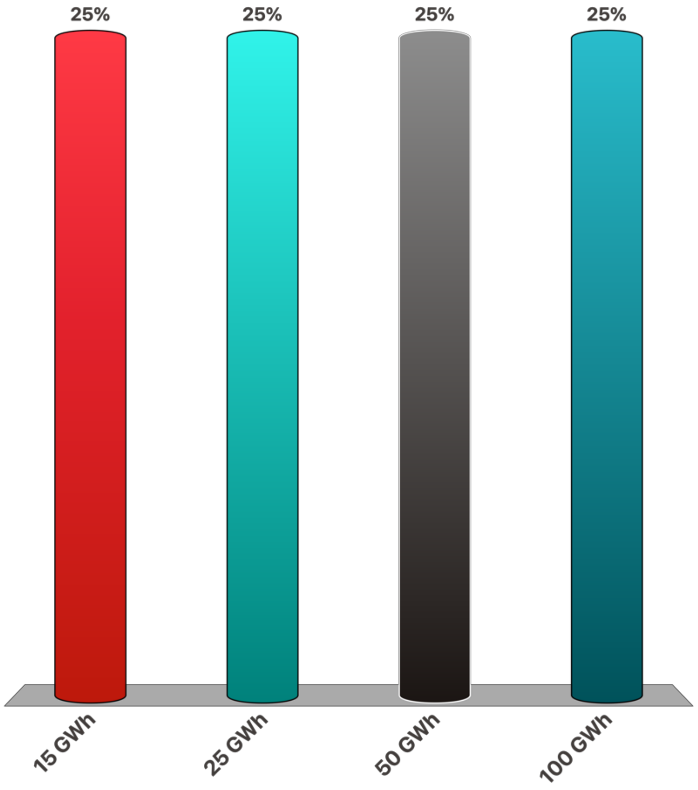
The previous wind turbine has a cut-in speed of 3 m/s, reaches full rated power at 12 m/s, and cuts out at 25 m/s.

Over one year, assume:

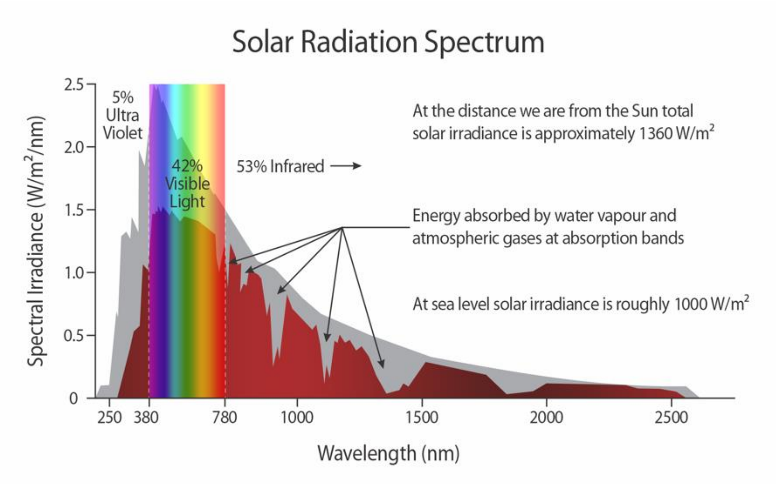
- 2000 hours with wind speeds below 3 m/s
- 4000 hours with wind speeds between 3 and 12 m/s
- 1500 hours with wind speeds between 12 and 25 m/s
- 260 hours with wind speeds between 25 and 50 m/s

Determine the annual energy production (in MWh).

A. 15 GWh
B. 25 GWh
C. 50 GWh
D. 100 GWh



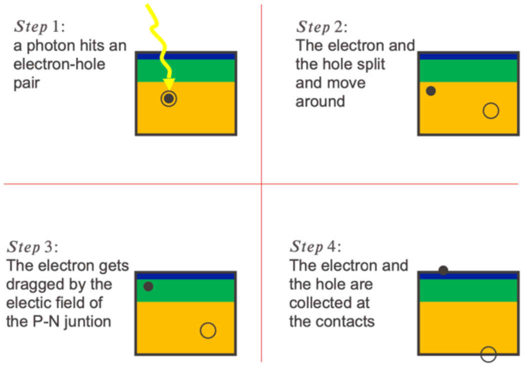
Emerging Technologies
PV - Origin and Potential of Solar Energy



©sunwindsolar.com

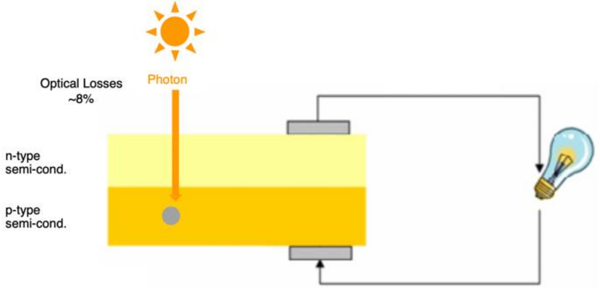
- Solar Radiation:
  - The sun emits energy as a black-body radiator at ~5780 K, reaching Earth with irradiance:
  - In space: ~1367 W/m²
  - At Earth's surface: **~1000 W/m²** (varies by location, time, and atmospheric conditions).
- Air Mass Coefficient (AM):
  - Describes the path of sunlight through the atmosphere, influencing irradiance:
  - AM0: Spectrum outside atmosphere (~1367 W/m²).
  - AM1.5G: Includes diffuse radiation, standardized at 1000 W/m².
- Global Energy Context:
  - Solar energy potential far exceeds global energy needs, with 0.1% of Earth's surface covered by 20% efficient PV panels sufficient to meet annual global demand

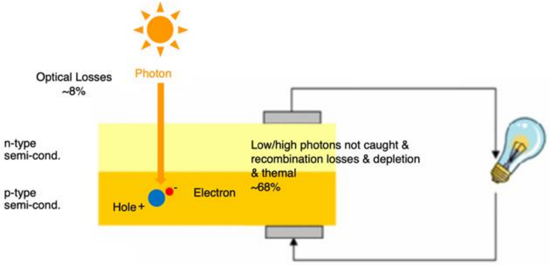
Emerging Technologies
PV – Working Principle of PV

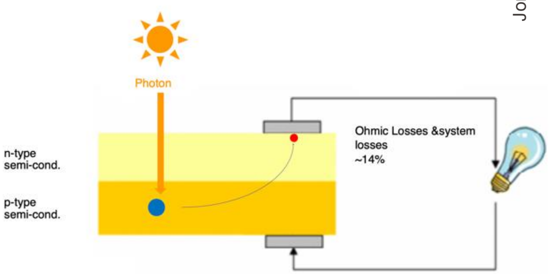


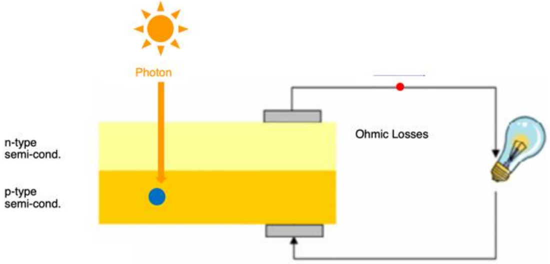
- Mechanism;
  - Incident photons excite electrons in the semiconductor, creating electron-hole pairs.
  - A p-n junction separates these charges, driving current in an external circuit.
- Semiconductor Dynamics:
  - Photons with energy > bandgap are absorbed.
  - Doping enhances carrier concentration:
    - n-type: Adds electrons.
    - p-type: Adds holes.

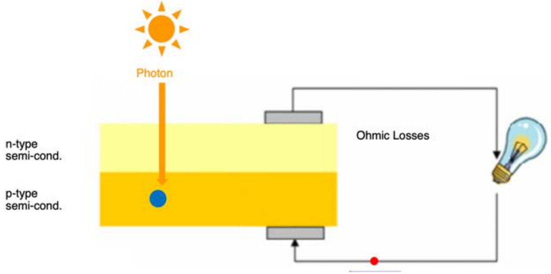
Emerging Technologies
PV – Working Principle of PV

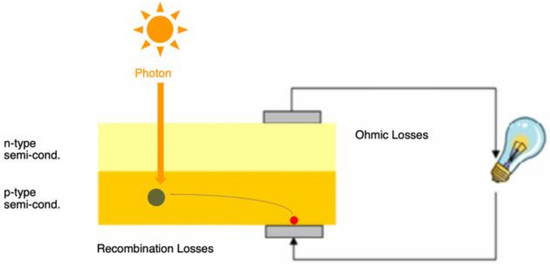


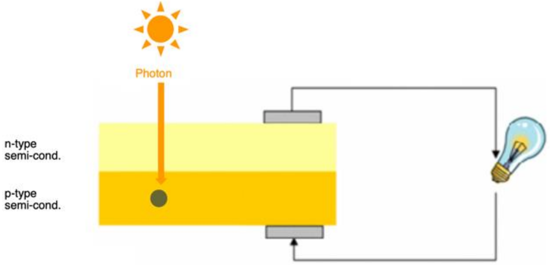












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Working Principle Solar PV

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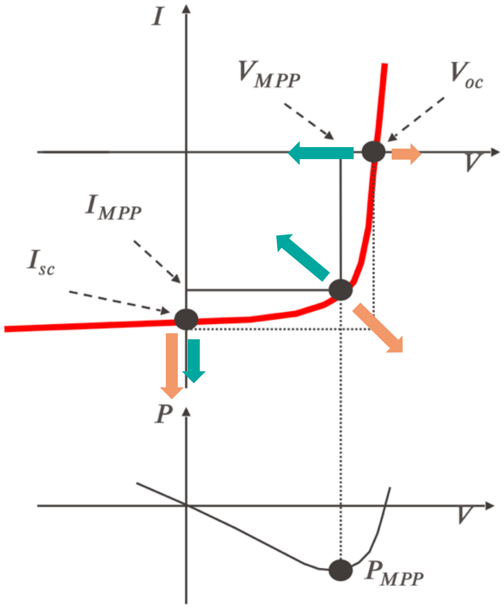
Emerging Technologies
PV – Equations and Energy Balance

Irradiance effect:

$Irr \uparrow \quad \rightarrow \quad I_{SC} \uparrow, V_{OC} \uparrow \quad \rightarrow P_{MPP} \uparrow$

Temperature effect:

$T \uparrow \quad \rightarrow \quad I_{SC} \uparrow, V_{OC} \downarrow \quad \rightarrow P_{MPP} \downarrow$



- Photon Energy: $E_{Photon} = \frac{hc}{\lambda}$
- Charge Carrier Generation: $G = I_{Photon} \cdot \alpha$, where α is absorption coefficient.
- Power Output:
  - $P = IV$,
  - max power at $P_{max} = I_{max}V_{max}$
  - efficiency defined as: $\eta = \frac{P_{incident}}{P_{max}}$
- Thermal Effects: Efficiency decreases with increasing temperature due to reductions in open-circuit voltage.
- Practical Metrics:
  - Standard Test Conditions (STC): 25°C, 1000 W/m², AM1.5G.
  - Fill Factor (FF): $FF = \frac{I_{MPP}V_{MPP}}{I_{sc}V_{OC}}$

Emerging Technologies

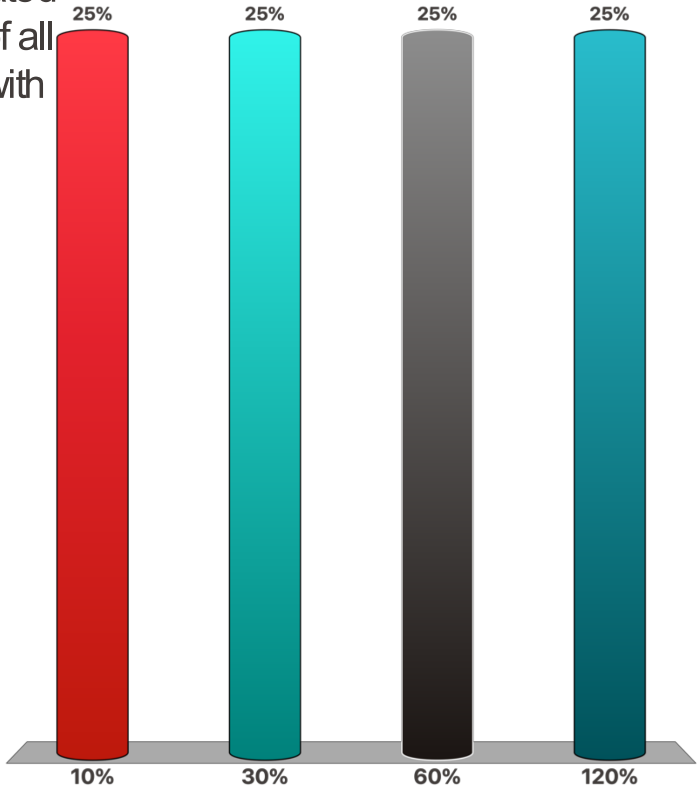
PV – Rule of thumb (1000)

- 1000 W of PV at 1000 CHF/kW
- Exposed to 1000 h/year under 1000 W/m^2 irradiance
- Results to
  - 1000 kWh/year
  - At a cost of 1000 CHF

PV example

Switzerland's annual electricity demand is approximately 60 TWh.
If the total available roof area in Switzerland is estimated at 1 000 million m², what fraction (as a percentage) of all available roof area must be approximately covered with PV panels?

A. 10%
B. 30%
C. 60%
D. Something else



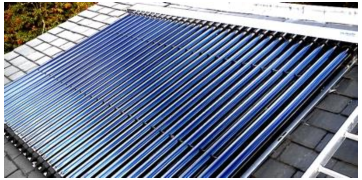
Emerging Technologies
Other Solar Applications

Solar energy

Photoconversion
$\eta = 25\%$

Electricity

Thermalisation
$\eta = 50\%$

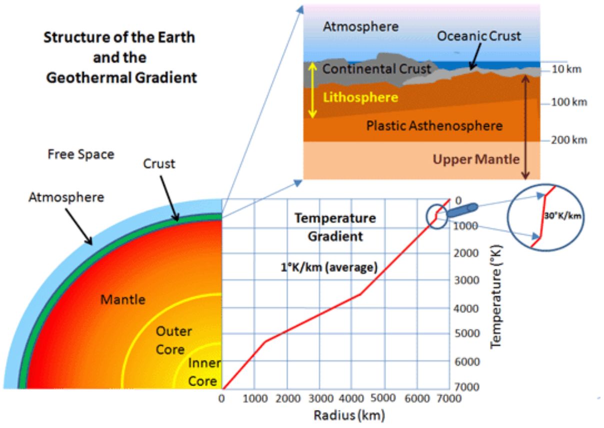


Heat

Thermochemical Reaction
$\eta = 12\%$

Fuels

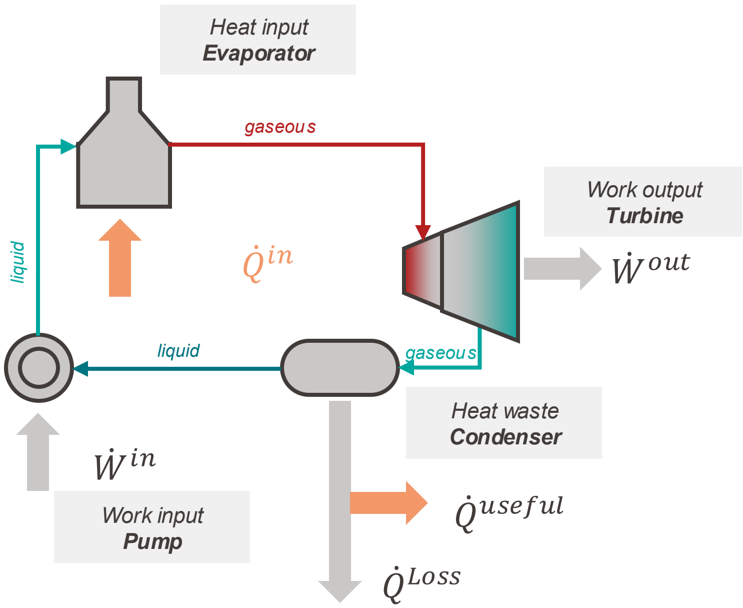
Emerging Technologies
Geothermal - Fundamentals



- Origin: Heat from Earth's formation and radioactive decay.
- Geothermal Gradient:
  - Average global increase of 20-30 K/km
  - Switzerland: ~30K/m
  - Anomalies (up to 100 K/km in volcanic regions).
- Potential:
  - Worldwide geothermal heat flux: ~50-60 mW/m².
  - Theoretical power potential: ~1% of global electricity needs.
  - Swiss geothermal flux:
    - ~65 mW/m²,
    - maximum of 4 TWh-el annually
      ~7% of national electricity needs
- Sustainability:
  - Renewable but requires careful management; over-extraction can deplete reservoirs (very very veeeeery slowly).

Emerging Technologies

Geothermal - Applications

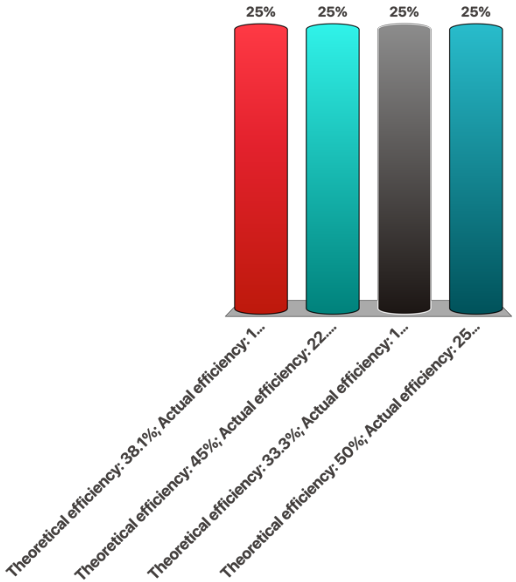


- **Direct Heat Uses:**
  - **Ground source** heat pumps for heating/cooling (5-20°C at shallow depths).
  - **Industrial/agricultural heating** (20-100°C) and district heating systems.
  - *Examples*: Lötschberg tunnel (CH) for sturgeon farming, geothermal sidewalks in Oregon (US).
- **Electricity Production:**
  - **Dry Steam**: Vapor from reservoirs drives turbines (e.g., The Geysers, USA).
  - **Flash Steam**: Uses pressurized hot water, with 30-40% flashing to steam.
  - **Binary Cycles**: Secondary working fluids like ORC/Kalina enable usage of lower temperature sources (70-90°C).
- **Combined Heat and Power (CHP):**
  - Integration of district heating with electricity generation improves efficiency.

Geothermal Example

A geothermal power plant is designed to operate on a binary cycle that exploits heat from a geothermal reservoir. The reservoir provides water at 200 °C while the plant uses ambient cooling water at 20 °C (293 K).

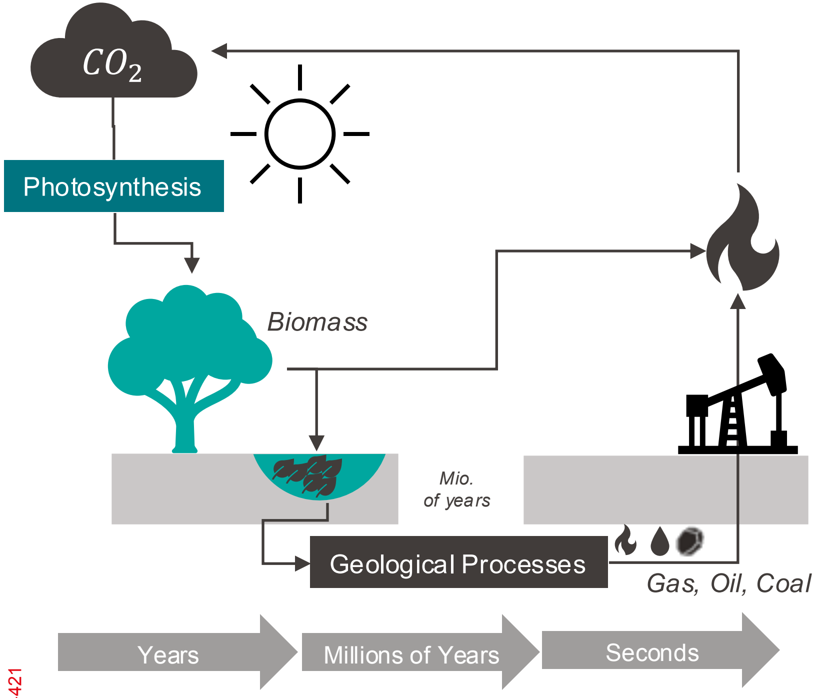
a) Calculate the theoretical (Carnot) efficiency of the power cycle
b) In practice, irreversibilities reduce the performance so that the actual electrical efficiency is only 50% of the Carnot efficiency. Determine the actual electrical efficiency.
c) If the geothermal reservoir supplies 100 MW of thermal power, what is the expected electrical power output of the plant?



A. Theoretical efficiency: 38.1%; Actual efficiency: 19.1%; Electrical output: 19.1 MW
B. Theoretical efficiency: 45%; Actual efficiency: 22.5%; Electrical output: 22.5 MW
C. Theoretical efficiency: 33.3%; Actual efficiency: 16.7%; Electrical output: 16.7 MW
D. Theoretical efficiency: 50%; Actual efficiency: 25%; Electrical output: 25 MW

Emerging Technologies

Biomass - Fundamentals and Biomass Potential

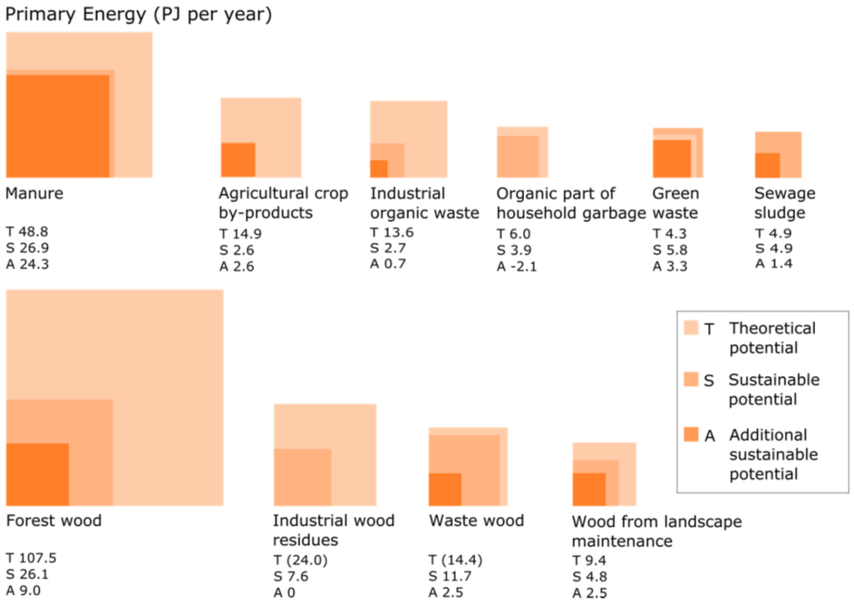


- Definition:
  - *Biomass is organic material derived from plants or animals, storing solar energy via photosynthesis.*
- Photosynthesis Equation:
  - $CO_2 + 6H_2O + \text{Light Energy} \rightarrow C_6H_{12}O_6 + 6O_2$
- Theoretical Efficiency:
  - Photosynthesis captures only ~0.6% of solar energy as biomass, with a maximum efficiency of ~3% for C_3 plants and ~5% for C_4 plants.
- Sustainable Potential:
  - Global: ~270 EJ/year (~50% global energy needs).
  - Real yields are lower due to land use and practical limitations.

Biomass Potentials in Switzerland

Biomass potentials have been collected based on Thees et al. (2017)[1] for all 10 identified biomass types and defined as follows:

Theoretical potential: the energy contained in the biomass available.
Sustainable potential: the amount that can be used for energy purposes, after deduction of environmental and techno-economical restrictions.
Already used potential: the amount already used for energy purposes.



Additional sustainable potential: the extra amount that can be used supplementary for energy purposes.

Additional sustainable = Theoretical – Restrictions – Already Used

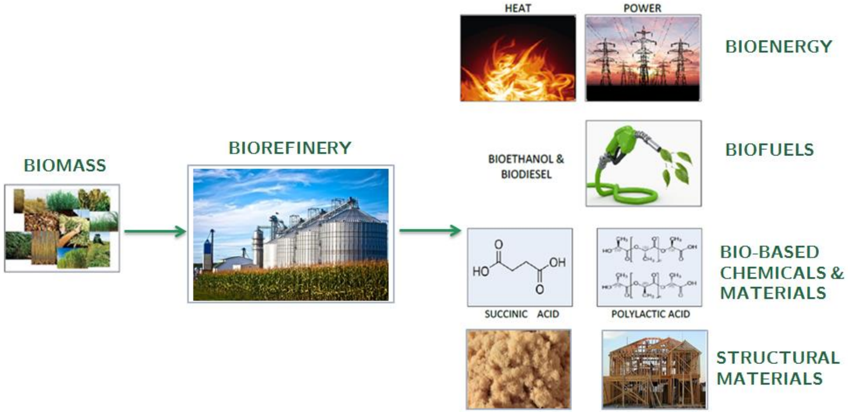
[1]O. Thees, V. Burg, M. Erni, G. Bowman, R. Lemm, Biomassenpotenziale der Schweiz für die energetische Nutzung, WSL Berichte, Heft 57, 2017.

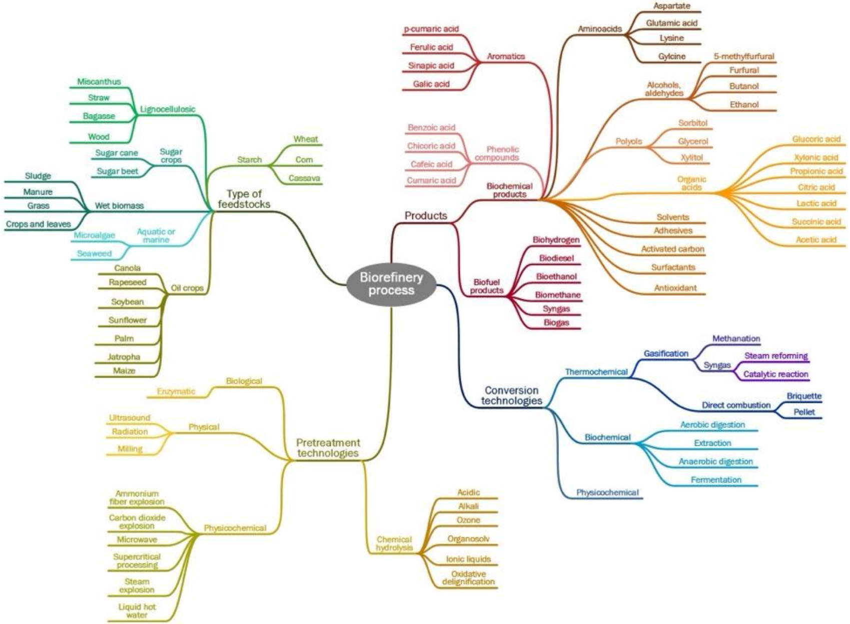
Emerging Technologies
Biomass – Energy Conversion Pathways

- **Thermochemical** Processes:
  - **Combustion**: Direct burning for heat and electricity.
    - Efficiency: ~85% (heat), ~30-45% (electricity).
  - **Gasification**: Produces syngas (CO, H_2, CH_4) for power or fuels.
    - Key Reaction: $C + H_2O \rightarrow CO + H_2$
  - **Pyrolysis**: Produces bio-oil, syngas, and charcoal at 400–700°C.
    - Yields: 360 kg oil, 200 kg gas, and 330 kg charcoal per 1 ton of wood.
- **Biochemical** Processes:
  - **Fermentation**: Converts sugars to ethanol.
    - Yield: 1 kg glucose → 0.5 L ethanol (70% efficiency).
  - **Anaerobic Digestion**: Organic matter → Biogas (CH_4, CO_2).
    - Efficiency: 65 m³ biogas/day for 3 tons of manure.

The concept of the biorefinery
using biomass as source of carbon, energy and structure

- **variety** of feedstocks, technologies, products/functions
- **choice** between biofuels, biochemicals and bioenergy
- **maximize** the use of **biogenic carbon**
- closing **energy balance** with only renewable energy





Biomass conversion technologies

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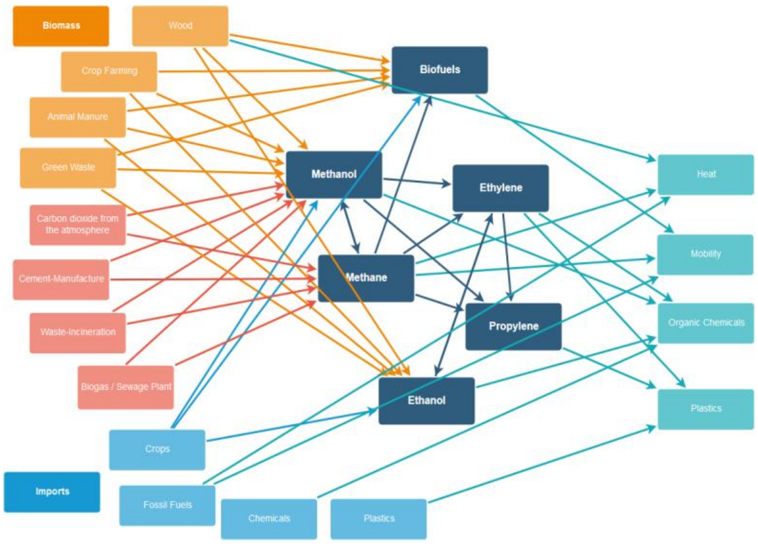
Biomass to X:

- Pyrolysis
- Gasification/HTG
- Anaerobic digestion
- Fischer-Tropsch
- Biomass to ethanol
- Methanol synthesis
- Alcohols to jetfuel

CO_2-to-X:

- Ethylene/propylene synthesis
- Benzene
- Xylene
- Acetic acid
- DME
- Bio-SNG
- Plastics from chemicals (i.e. PE, PP, HDPE, PS, PVC)



Chemicals processing to fuels and products

- …

Emerging Technologies
Biomass – Challenges and Applications

- Advantages:
  - Renewable, carbon-neutral, versatile (heat, electricity, transport fuels).
- Challenges:
  - Low energy density ($1\,\frac{\mathrm{W}}{\mathrm{m}^2}$), land competition, and seasonal availability.
- Applications:
  - Electricity: Biomass CHP (Combined Heat and Power) systems.
  - Transport: Ethanol in gasoline (5-24% blends), biodiesel as a diesel substitute.
  - Industrial Use: Residual heat, chemicals, and fertilizers from bio-refineries.

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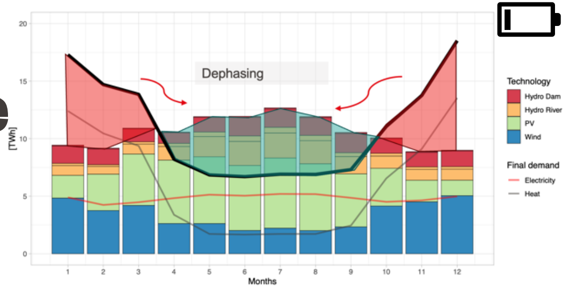
AGENDA

Infrastructure

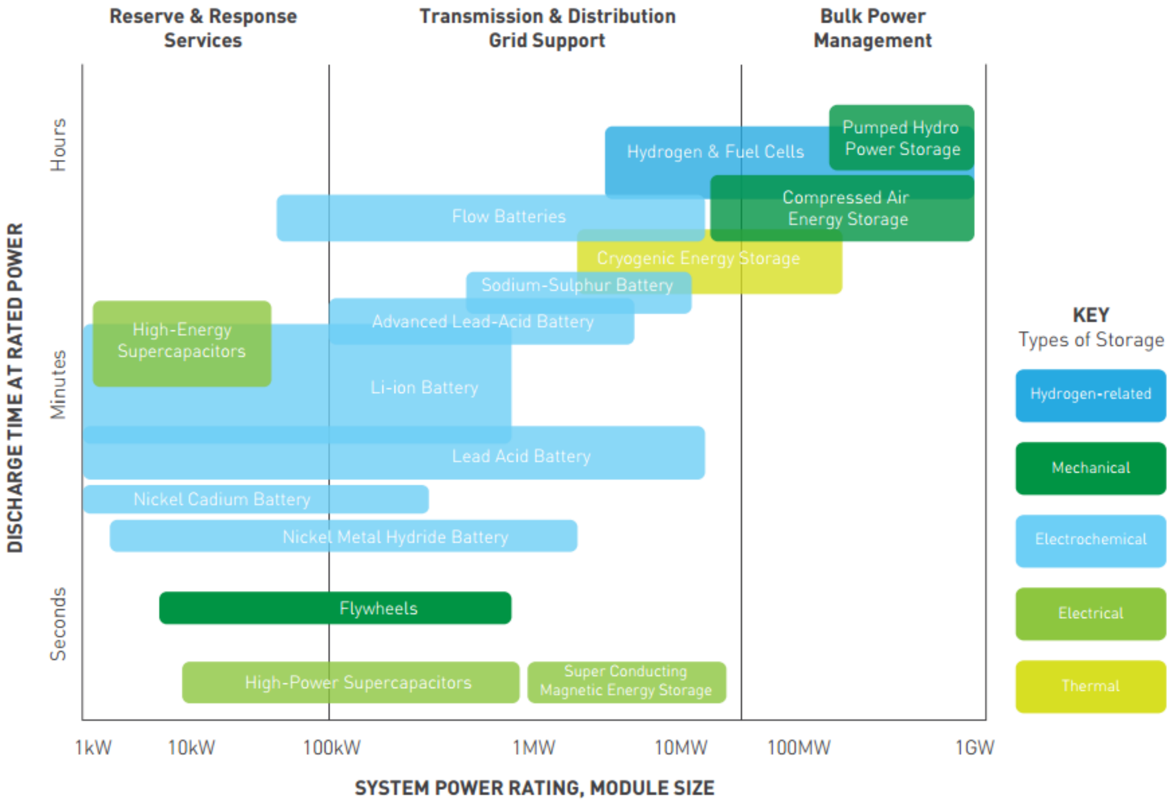
Storage – Fundamentals and Needs for Storage



- **Definition:**
  Energy storage enables the decoupling of energy supply and demand, addressing **temporal** and **spatial** mismatches.
- **Importance:**
  - Balances the variability of renewable energy sources like solar and wind.
  - Supports grid stability by peak shaving and managing seasonal demand shifts.
  - Enhances energy efficiency and reduces reliance on fossil fuels as storage.
- **Key Metrics:**
  - Efficiency (η):
    Fraction of stored energy recovered during discharge: $\eta = \frac{\text{Energy output}}{\text{Energy input}} = \eta_{in} \cdot \eta_{out}$
    - Example: For pumped hydro:
      $$\eta_{PH} = \eta_{pumping} \cdot \eta_{turbining} = 90\% \cdot 92\% = 83\%$$
  - Energy Density (e):
    Energy stored per unit volume or mass (e.g., kWh/m³ or Wh/kg).
  - Power Density (p):
    Rate at which stored energy can be delivered (e.g., W/kg or W/m³).

Infrastructure

Storage – Classification of Energy Storage Technologies



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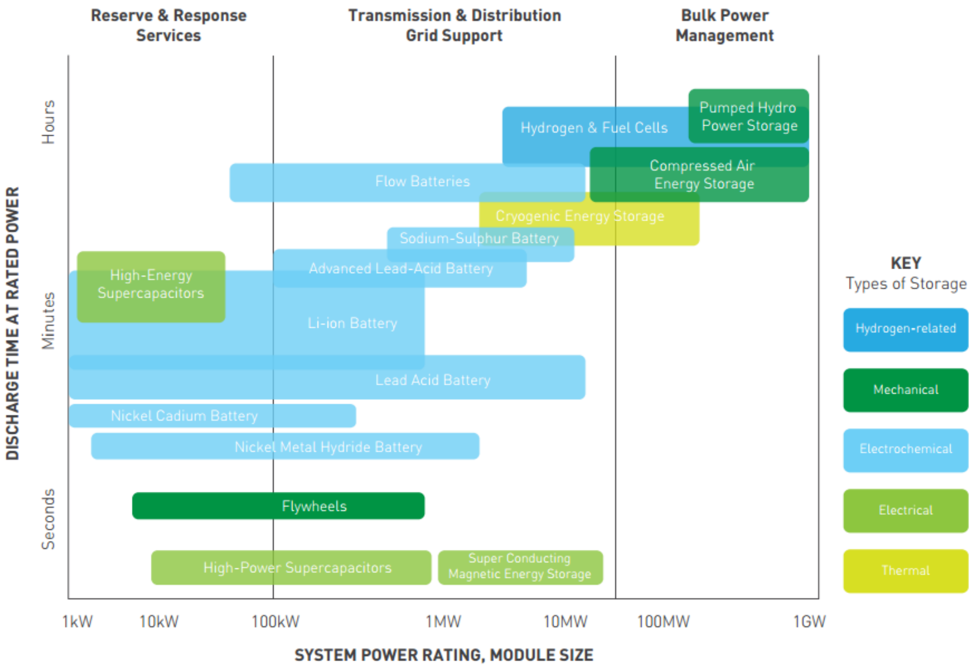
Infrastructure

Storage – Classification of Energy Storage Technologies



Mechanical Storage:

- Pumped Hydro:
  - Efficiency: 70-85%.
  - Energy Density: $0.01 \frac{\text{MJ}}{\text{m}^3}/\text{m}$
  - Example: Nant-de-Drance $E = mgh = 10^9 \cdot 9{,}8 \cdot 2225 = 2.18\ \text{GWh}$
  - Applications: Large-scale storage for renewable energy.
- Compressed Air Energy Storage (CAES):
  - Efficiency: 27-70%.
  - Energy Density: $15\ \text{MJ}/\text{m}^3$
  - Example: Stored in caverns or salt domes.
- Flywheels:
  - Efficiency: ~90%.
  - Energy Density: $240 - 950\ \text{MJ}/\text{m}^3$
  - Equation for stored energy: $$E = \frac{1}{2} I\omega^2$$ where I is the moment of inertia and ω is the angular velocity.

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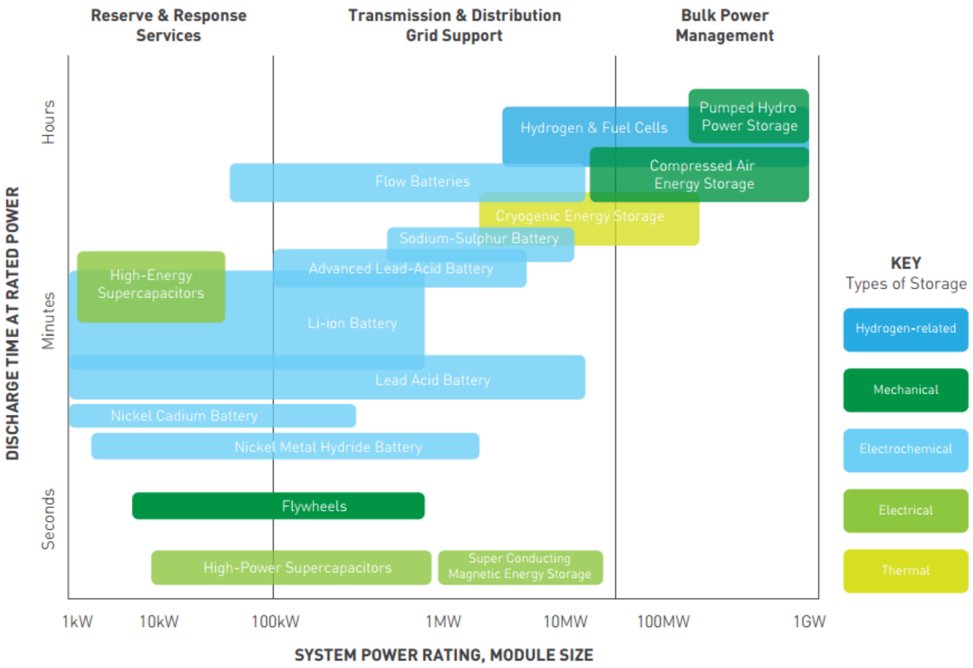
Infrastructure
Storage – Classification of Energy Storage Technologies

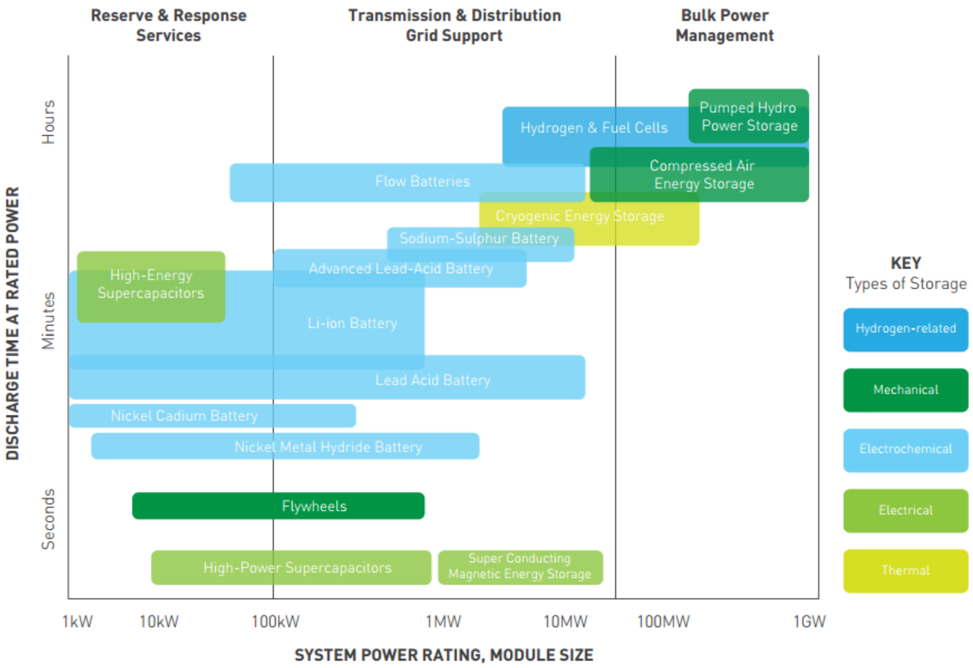


Thermal Storage:

- Sensible Heat: $Q = mc\Delta T$
  Energy stored by changing the temperature of a material
  - Example: Water tanks, molten salts.
- Latent Heat:
  Energy stored during a phase change (e.g., solid to liquid)
  - $Q = mL$
  - where L is the latent heat of fusion.

Infrastructure

Storage – Classification of Energy Storage Technologies



Electrochemical Storage (Batteries):

- Efficiency: 75-95%.
- Energy Density: $100 - 1400 \frac{\mathrm{MJ}}{\mathrm{m}^3}$ (e.g., Li-ion batteries).
- Key Equation: Stored energy depends on capacity: $E = VQ$ where V is voltage, and Q is charge in ampere-hours (Ah).

Infrastructure

Storage – Classification of Energy Storage Technologies

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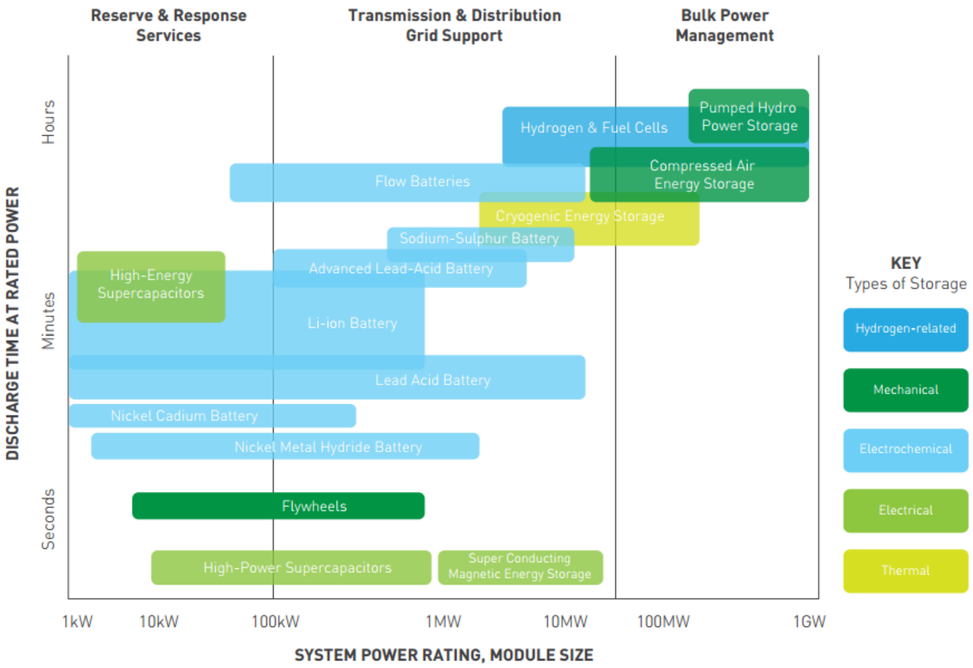


Chemical Storage:

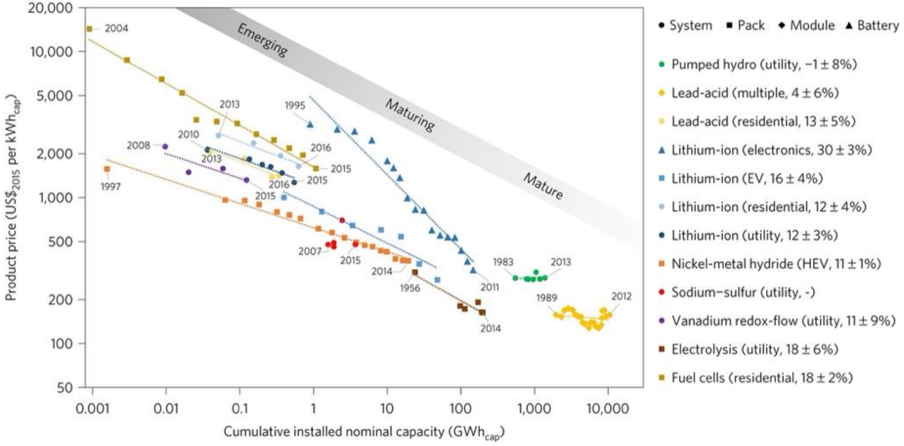
- Hydrogen production via electrolysis:
- $H_2O + \text{Electricity} \rightarrow H_2 + \frac{1}{2}O_2$
- Efficiency: 25-50%.
- Energy Density: $10\ \text{MJ/m}^3$ (hydrogen gas).

Infrastructure

Storage – Energy Storage Applications

- Applications:
  - **Short-term** (seconds to minutes):
    - Frequency regulation and load balancing.
    - Examples: Flywheels, batteries.
  - **Mid-term** (hours to days):
    - Grid stability and peak shaving.
    - Examples: Pumped hydro, compressed air.
  - **Long-term** (seasonal):
    - Seasonal heating and renewable energy integration.
    - Examples: Thermal storage, chemical fuels (e.g., hydrogen).
- Key Examples:
  - Torino Sensible Heat Storage:
    - System connects 5,000 buildings; efficiency: 80-90%.
  - Crescent Dunes Solar Plant (USA):
    - Molten salt stores energy for 10 hours, powering 75,000 homes.

Infrastructure
Storage – Advantages and Challenges

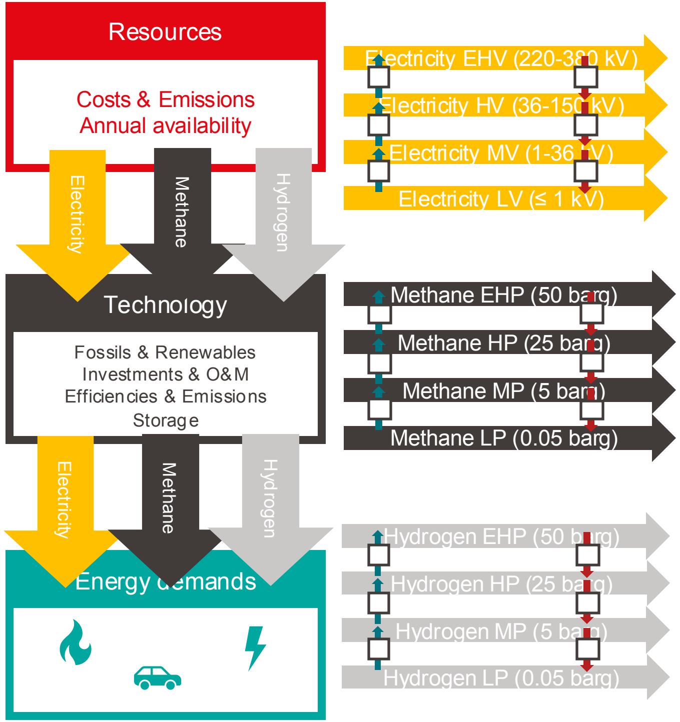


Experience curves for EES technologies.
Schmidt, O., Hawkes, A., Gambhir, A. *et al.* The future cost of electrical energy storage based on experience rates. *Nat Energy* **2**, 17110 (2017). https://doi.org/10.1038/nenergy.2017.110

- **Advantages**:
  - Enhances grid reliability and renewable integration.
  - Reduces reliance on fossil fuel-based backup systems.
  - Improves overall energy system efficiency.
- **Challenges**:
  - High Costs:
    - Example: Li-ion battery costs (~$120-250/kWh in 2023).
  - Low Energy Density:
    - Example: Flywheels: , compared to hydrogen's .
  - Environmental Concerns:
    - Land use for pumped hydro.
    - Resource extraction for Li-ion batteries (e.g., cobalt, lithium).
- **Future**
  - Market Growth:
    - Battery costs projected to decrease by 50-60% by 2030.
    - Global energy storage capacity expected to increase **tenfold** by 2050.
  - Research Focus:
    - Advanced materials for higher energy densities (e.g., solid-state batteries).
    - Hybrid systems combining thermal and electrochemical storage.
  - Policy and Deployment:
    - Incentives for large-scale storage deployment.
    - Integration into renewable energy roadmaps (e.g., IEA's 2°C Scenario).

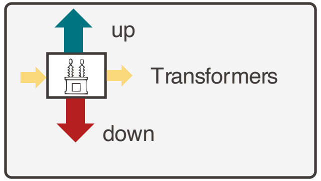
Modeling the infrastructure

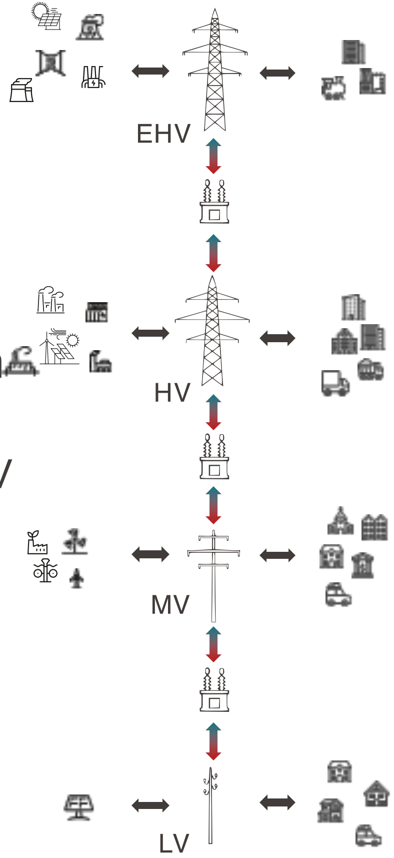
Grids as constraints of the energy system



Schematic illustration of the grid level power separation

- Energy vectors
  - Electricity
  - Methane
  - Hydrogen
- Distribution & Transmission levels
  - Electricity: LV, MV, HV, EHV
  - Gas: LP, MP, HP, EHP
- Transformers



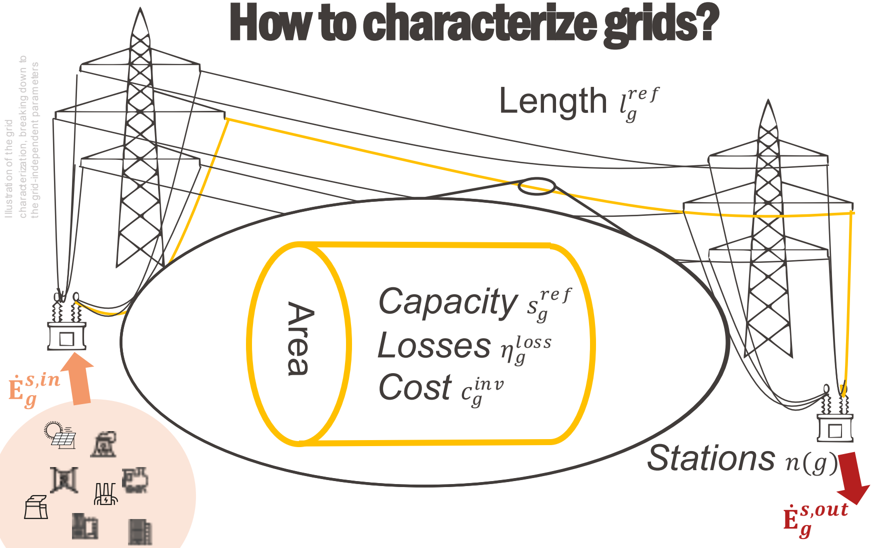


Schnidrig et al. 2023, *Assessment of the Role of infrastructure in energy system models*, Frontiers in Energy

Grids as constraints of the energy system

How to characterize grids?

Illustration of the grid characterization, breaking down to the grid-independent parameters



$$S_g = \max_t \dot{E}_g^{s,in} = \max_t \sum_T F_t(T,t) \cdot \eta_{out}(T, l(g)) \cdot \frac{1}{n(g)}$$

$$\dot{E}_g^{s,in} + \dot{E}_g^{loss} = \dot{E}_g^{s,out}$$

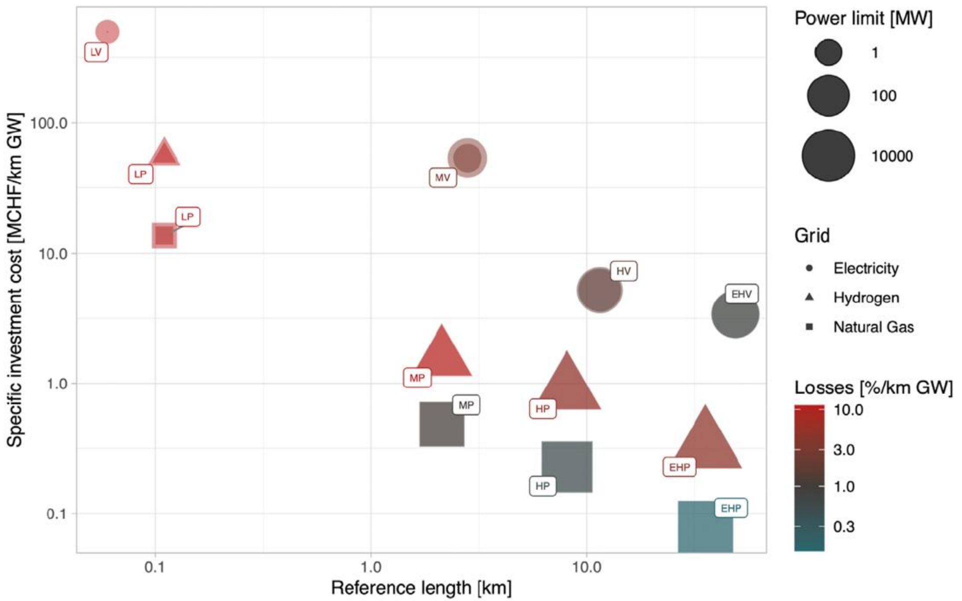
$$C_g^{inv} = S_g^{inst} \cdot c_g^{inv} \cdot l_g^{inst} \quad \forall \quad g \in \mathcal{G}$$

$$\dot{E}_g^{loss} = \eta_g^{loss} \cdot l_g^{ref} \cdot \dot{E}_g^{s}, \quad \forall \quad g \in \mathcal{G}$$

where

C_g^{inv}	:	Investment costs	[MCHF]
c_g^{inv}	:	Specific investment costs	$[\frac{MCHF}{km GW}]$
S_g^{inst}	:	Installation size	$[GW^{inst}]$
l_g^{inst}	:	Installed grid length	[km]

$\dot{E}_g^{loss}$	:	Losses	[GW]
η_g^{loss}	:	Specific losses	$[\frac{\%}{GW \cdot km}]$
l_g^{ref}	:	Grid reference length	[m]
$\dot{E}_g^{s}$	:	Power used	[GW]



Techno-economic characterization of the electrical, natural gas pressure and hydrogen network infrastructure, divided into four power levels: extra-high pressure and voltage (EH), high (H), medium (M) and low (L). The inner radius corresponds to the minimum power limit and the outer radius to the maximum power limit. case values for the average Swiss infrastructure. The specific losses $[\frac{\%_0}{GW\ km}]$ are displayed in the specific bubbles

Reference average length

The averge distance an "energytron" is travelling between two conversion/production/consumption points in Switzerland

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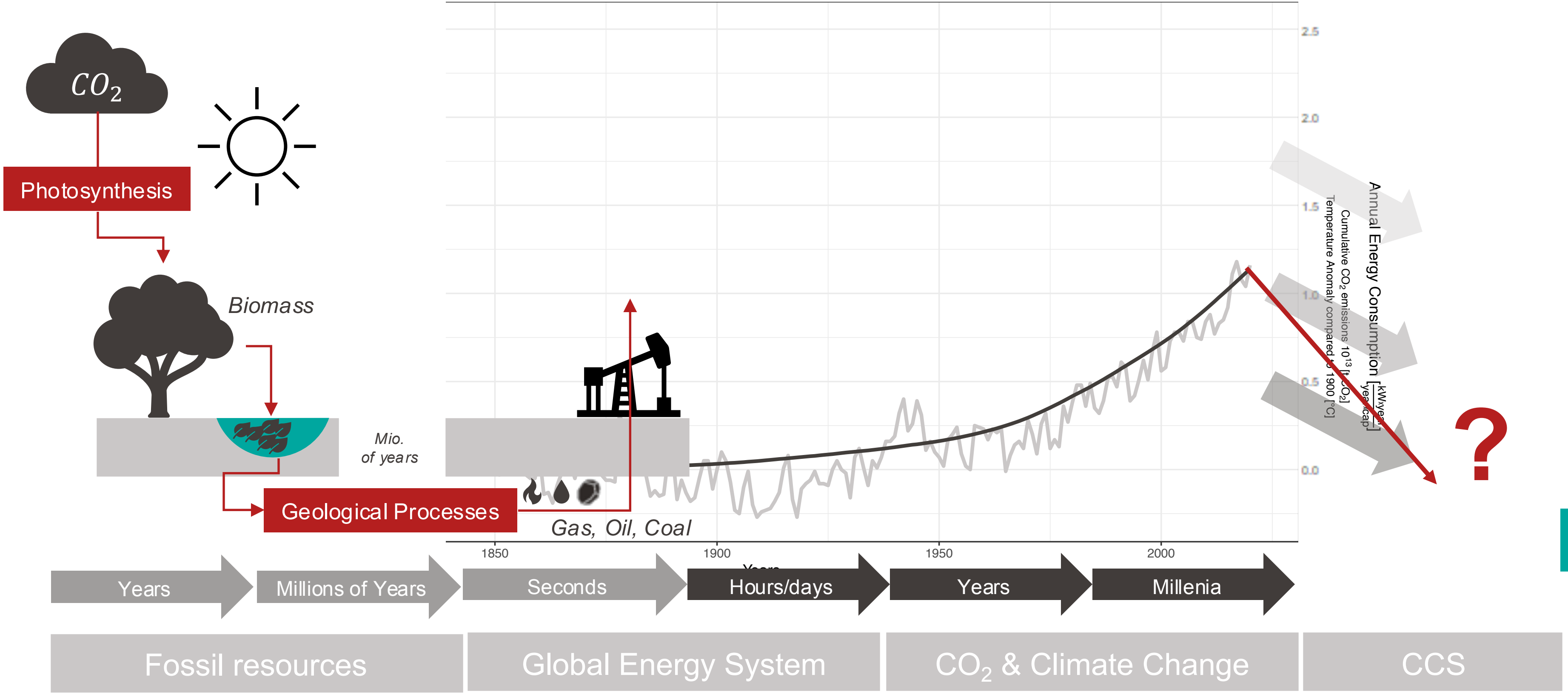
Infrastructure
Carbon Capture



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Carbon Capture - Fundamentals

- Definition:

  Carbon Capture and Sequestration (CCS) involves the capture of CO_2 emissions from industrial or energy-related processes, followed by transportation and secure underground storage to prevent atmospheric release.

- Capture Methods:
  - **Post-combustion**:
    Uses solvents (e.g., amines) to absorb CO_2 from flue gases.
  - **Pre-combustion**:
    CO_2 is separated from syngas (H_2 and CO_2) in Integrated Gasification Combined Cycle (IGCC) plants.
  - **Oxy-fuel combustion**:
    Combustion in pure oxygen produces a flue gas primarily composed of CO_2 and water, simplifying CO_2 capture.

- Energy Requirements:
  - Capture and compression of CO_2 consume 15-30% of the power plant's energy output, leading to an energy penalty:

$$\text{Energy Penalty: } \Delta E = \frac{ECCS}{E_{gross}}$$

  - For a plant producing 500 MW, with a CCS energy demand of 100 MW:

$$\Delta E = \frac{100\text{MW}}{500\text{MW}} = 20\%$$

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Carbon Capture – Transport Methods

- **Transport Methods:**
  - **Pipelines**:
    Most cost-effective for distances <1500 km. CO_2 is compressed to 8 MPa for transport, with capacities of ~20 Mt/year.
  - **Ships**:
    Economical for long distances (>1500 km), with CO_2 liquefied at 0.7 MPa for storage and transport; typical capacity: ~6 Mt/year.
  - **Trucks/Rail**:
    Limited capacity and uneconomical for large-scale applications.
- **Storage Options:**
  - **Depleted Oil/Gas Fields**:
    Often used for Enhanced Oil Recovery (EOR), utilizing CO_2 to extract additional oil.
  - **Deep Saline Aquifers**:
    CO_2 dissolves in brine and reacts to form stable carbonates.
  - **Unminable Coal Beds**:
    CO_2 adsorbs onto coal surfaces while displacing methane.
  - **Re-use**
    Use CO_2 as input product within the value-chain (plastics, synthetic fuels etc.)

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Carbon Capture – Storage Mechanisms and Capacity

- **Capture** Mechanisms:
  - Residual Trapping: CO_2 is physically trapped in pore spaces due to capillary forces.
  - Dissolution Trapping: CO_2 dissolves in formation water over time.
  - Mineral Trapping: CO_2 reacts with minerals to form stable carbonates (e.g., $CaCO_3$).
- **Storage** Capacity (estimated Global Capacity):
  - Oil/Gas Fields: 675-900 $GtCO_2$
  - Deep Saline Aquifers: 1,000-10,000 $GtCO_2$
- **Cost** Estimates:
  - Storage costs range from \$0.5-8/tCO_2, including monitoring costs of \$0.1-0.3/tCO_2.

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Carbon Capture – CO_2 utilization and Industrial Applications

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- CO_2 Utilization and **Industrial Applications**
- CO_2 as a **Resource**:
  - Enhanced Oil Recovery (EOR):

    $$\mathrm{CO_2\ injected:}\ 3.15\ t - \mathrm{CO_2}\ /\ t - \mathrm{Oil\ extracted}$$

  - Chemical Production: Methanol, urea, and polymers are produced using captured CO_2.
  - E-Fuels: CO_2 is combined with hydrogen in methanation to produce synthetic fuels:

    $$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

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Carbon Capture – Challenges and Future Potential

- **Challenges**:
  - **Energy Demand**:
    Capture and compression require ~20-30% energy penalty, reducing plant efficiency.
  - **Infrastructure Costs**:
    High initial investments for transport and storage infrastructure.
  - **Leakage Risk**:
    Long-term monitoring is necessary to ensure CO_2 remains trapped.
- **Future Potential:**
  - **Integration with Renewable Hydrogen**:
    Combining CCS with green hydrogen production (from renewable electricity) to create net-zero emission systems.
  - **Expansion of Utilization Markets**:
    Emerging applications in synthetic fuels, materials, and chemical feedstocks could offset CCS costs.
  - **Policy Support:**
    Financial incentives and stricter CO_2 emissions targets can drive CCS adoption to meet climate goals.