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

A G E N D A

Overview of Energy Technologies

Heat Cycles

Emerging Technologies

Infrastructure

Overview of Technologies
What is an Energy Conversion Technology?

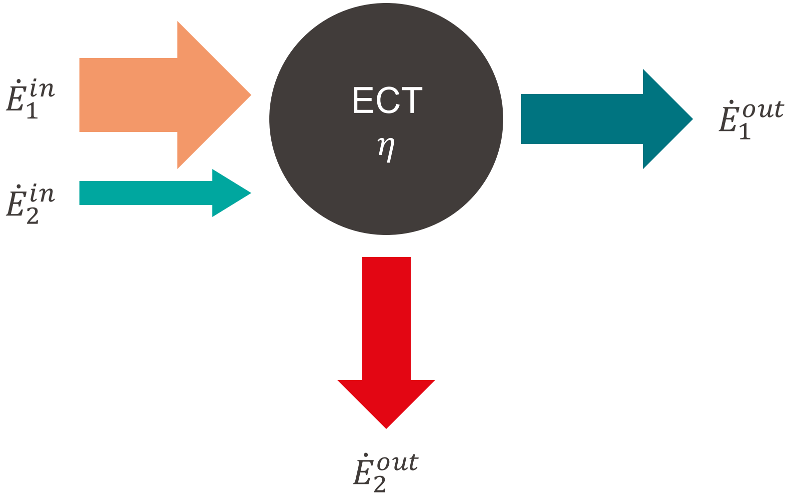
Energy conversion technology refers to any system that **converts energy** from one form to another. Energy comes in different forms, including heat, work and motion. Moreover, energy can be in the form of nuclear, chemical, elastic, gravitational, or radiant energy. All of these can be converted into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

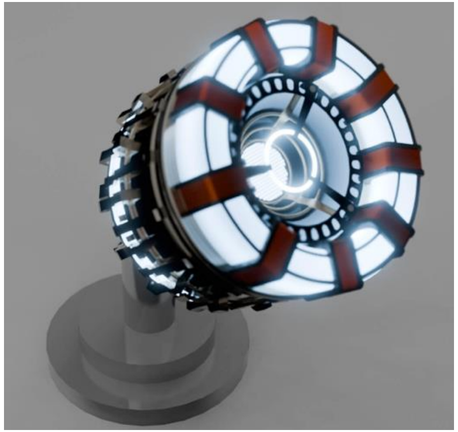
Tony Stark's Iron Man suit is designed to fly continuously for 100 years using its chest arc reactor. The reactor holds only 5 kg of an ultra-dense fuel. In flight mode, the suit draws a constant power of 2 MW, but due to conversion losses, only 70% of the fuel's energy is converted into useful work. 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?

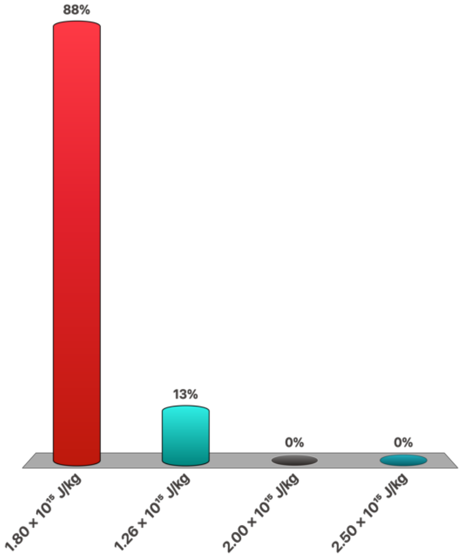
A. 1.80×10^{15} J/kg

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:
- $E_{fuel} = \frac{E_{fuel}}{\eta} = \frac{6.312 \cdot 10^{15}}{0.70} \approx 9.017 \times 10^{15}$ J

3. Energy Density Calculation:

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

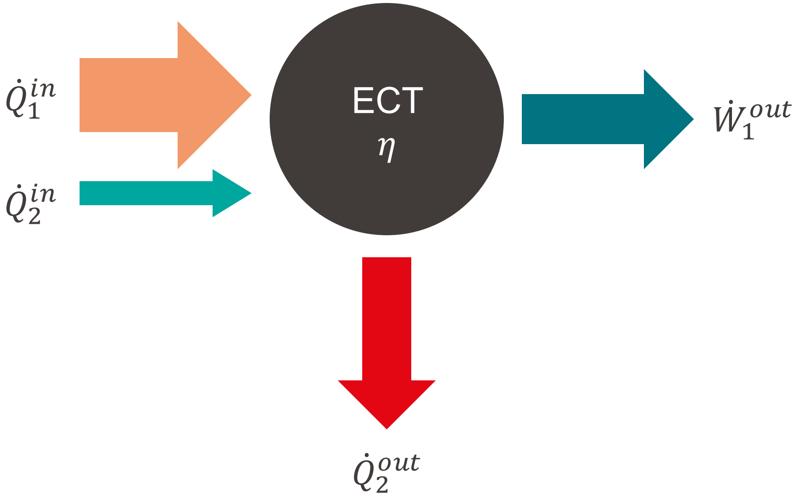
$$E = mc^2$$

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

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

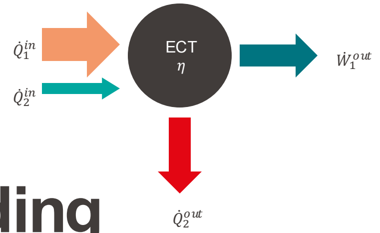
$$\oint \frac{\delta Q}{T} \leq 0$$

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

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



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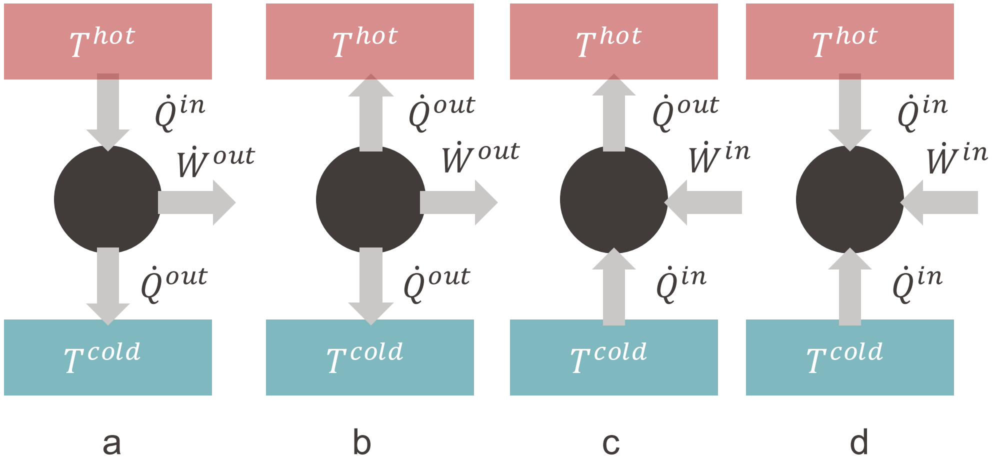
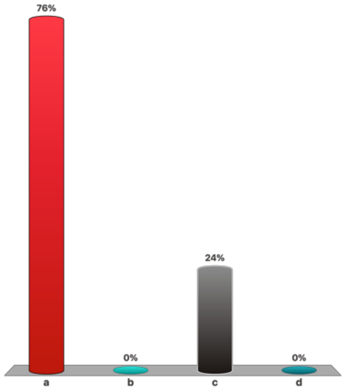
Which of these conversions is feasible according to the 1st and 2nd law?



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



Overview of Technologies

What is an Energy Conversion Technology? – 2nd law

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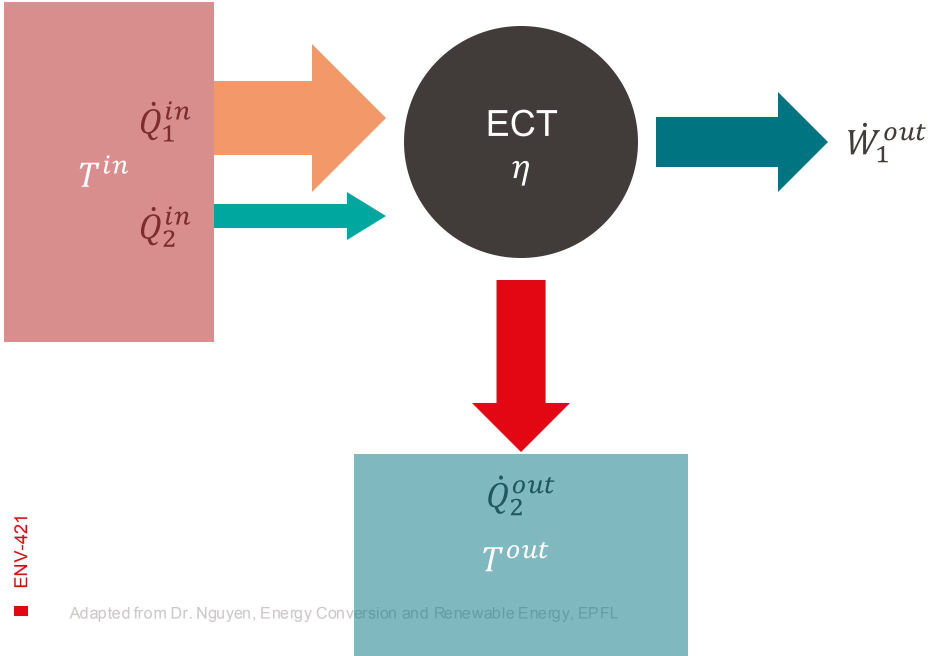

- Carnot

  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

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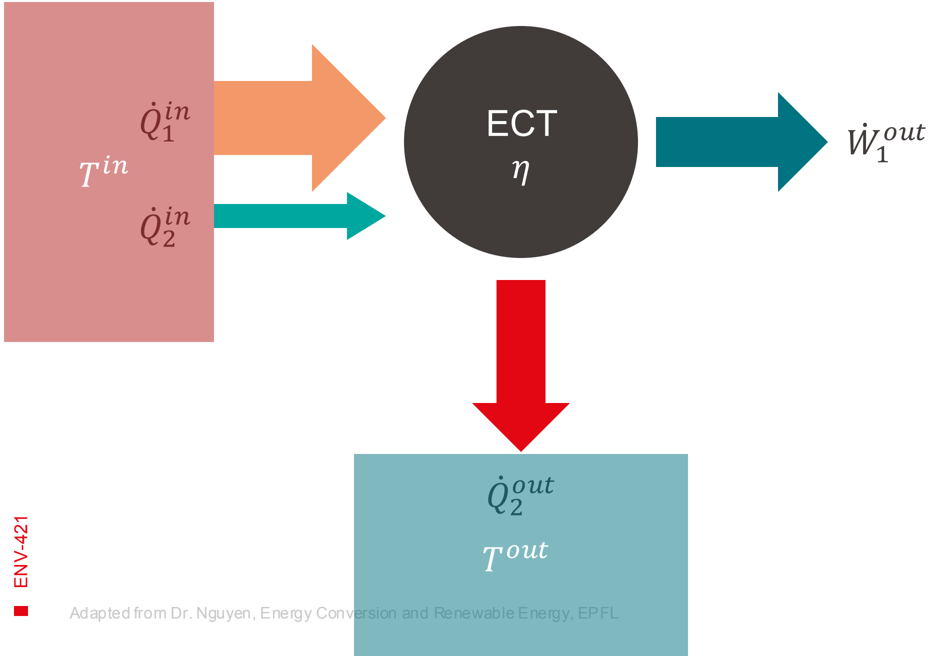

- 2nd law efficiency ϵ

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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A G E N D A

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Conventional Technologies

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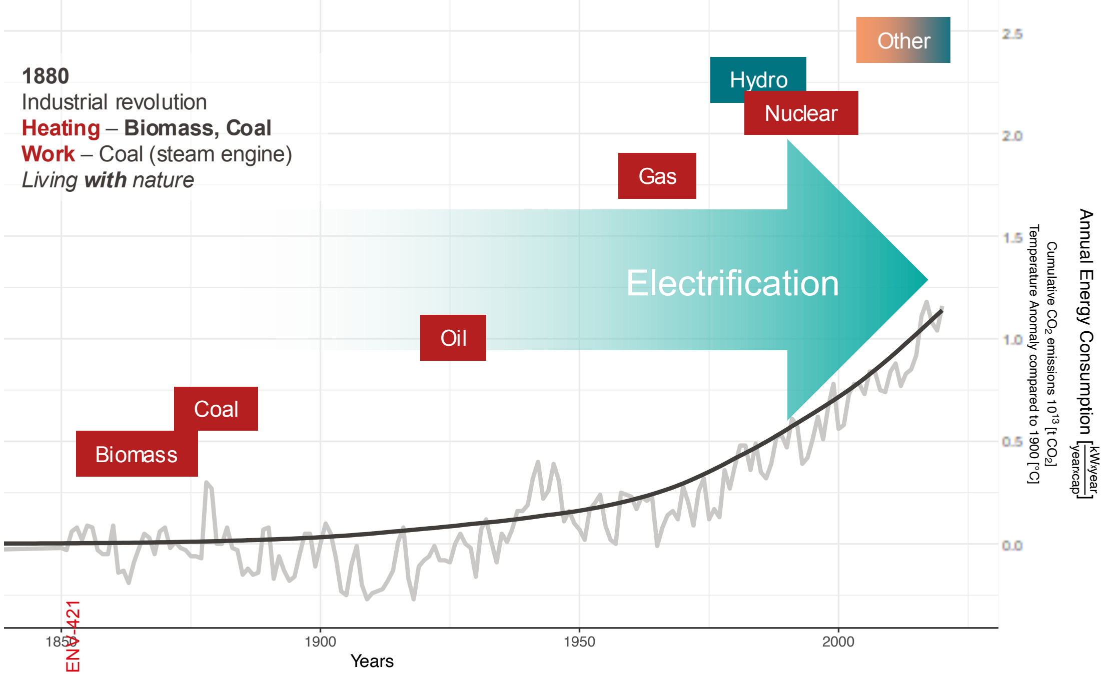
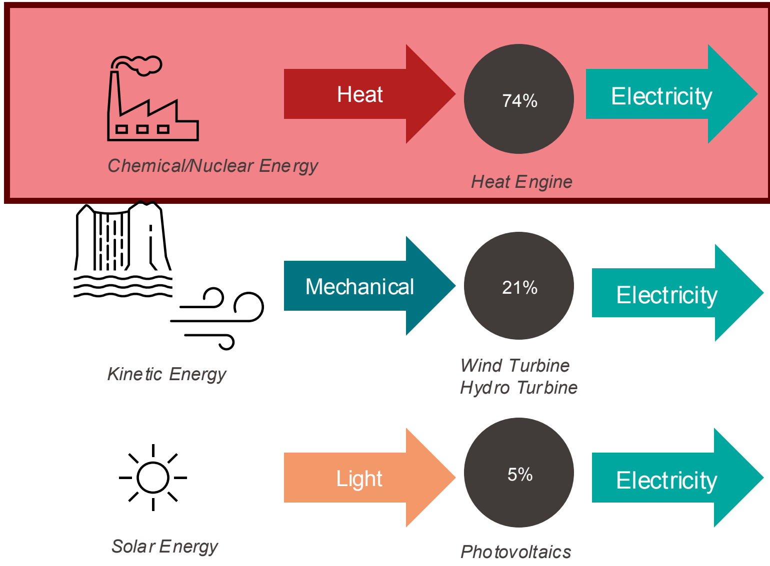
Conventional Technologies
Rankine Cycles - Heat to Electricity



Electricity production 2020



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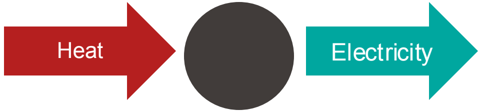
Conventional Technologies

Heat to Work



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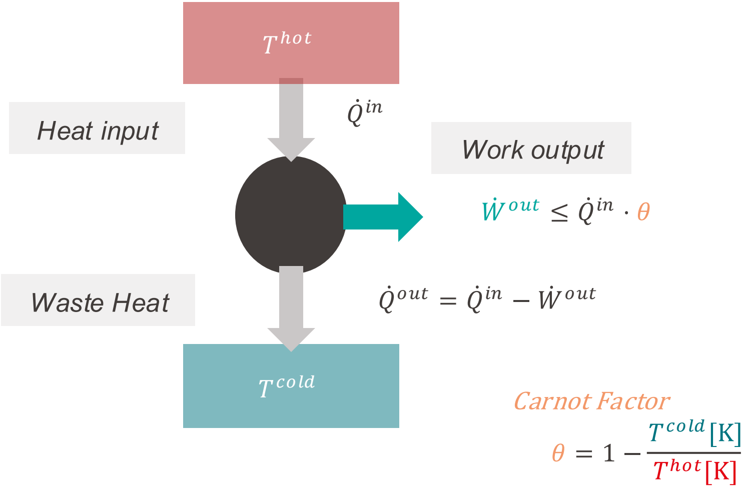

- **Definition:**
  Heat-to-power engines are systems that convert thermal energy from a heat source into mechanical work or electricity through thermal cycles.
- **Principle:**
  Transferring energy from a high-temperature fuel source to a working fluid that expands and produces work, then rejecting 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 $\theta = 1 - \frac{T^{cold}[\mathrm{K}]}{T^{hot}[\mathrm{K}]}$

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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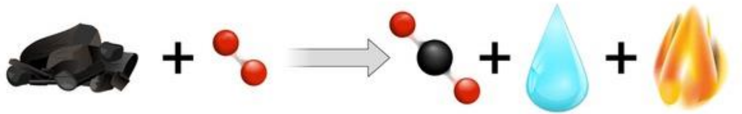

- Key Components
  - **Fuel**: Hydrocarbons (e.g., biomass, coal, oil, natural gas)
  - **Oxidizer**: Typically, atmospheric oxygen (O_2)
  - **Heat**: Initiates and sustains the reaction
- Products of Combustion
  - **Primary**: Carbon dioxide (CO_2), Water vapor (H_2O)
  - **Byproducts**:
    - **Complete 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

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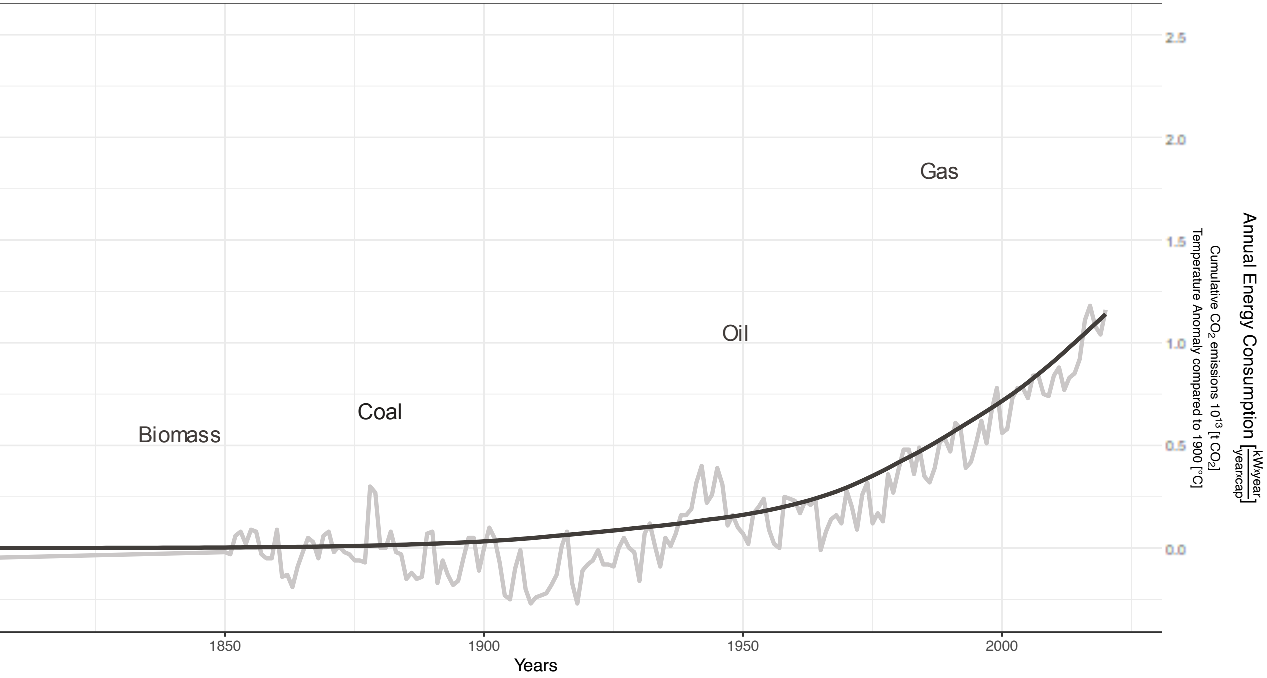
Conventional Technologies

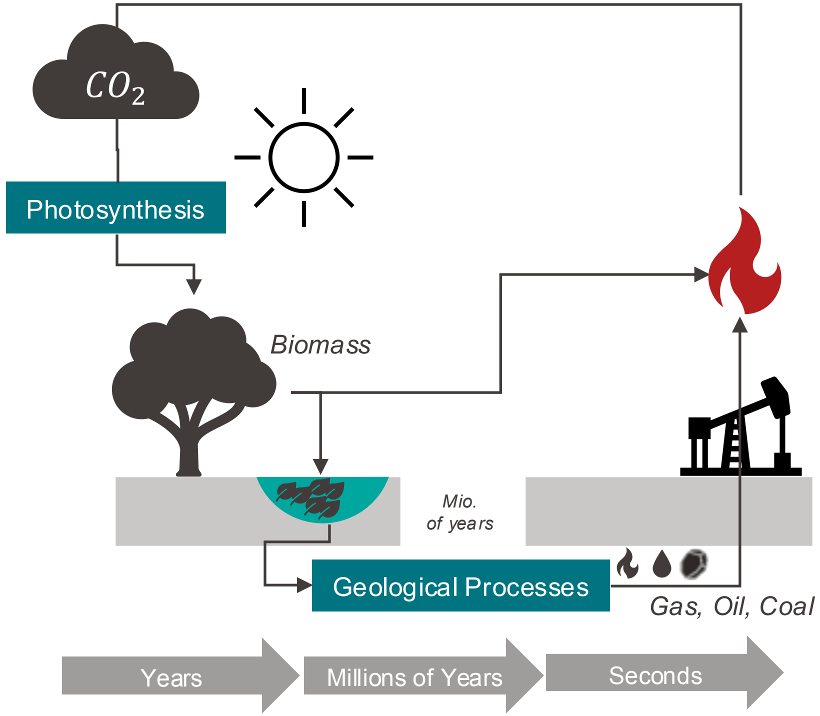
Heating – Fuel usage



- 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

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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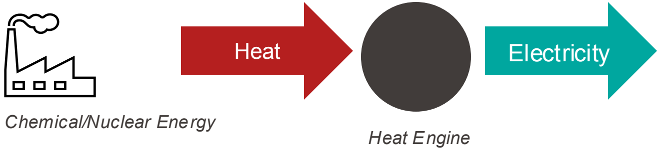
Conventional Technologies

Power Cycles – Carnot (maximum)



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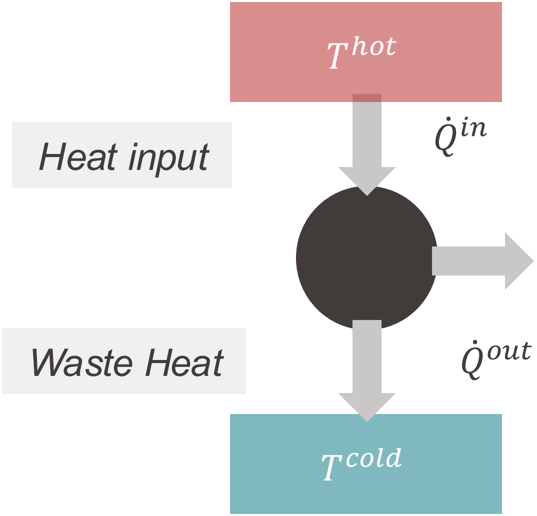
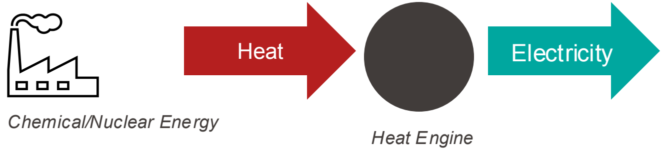


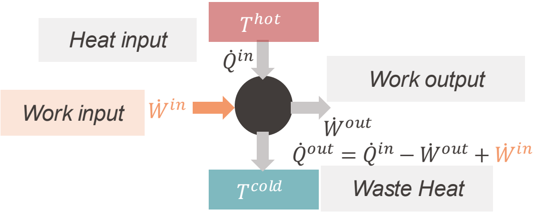
$$\dot{W}^{out} \leq \dot{Q}^{in} \cdot \theta$$

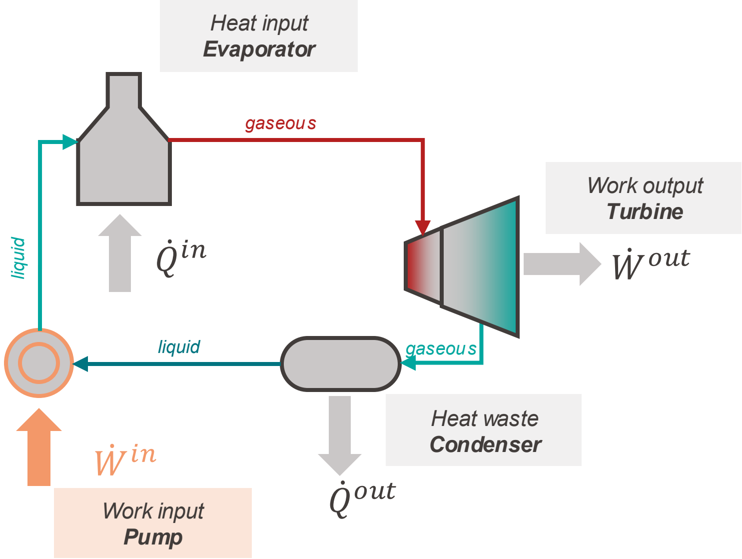
$$\dot{Q}^{out} = \dot{Q}^{in} - \dot{W}^{out}$$

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

Conventional Technologies
Power Cycles – Rankine cycle

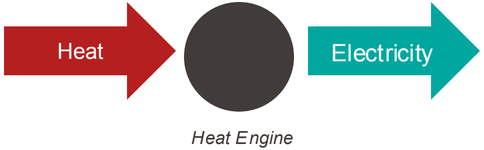


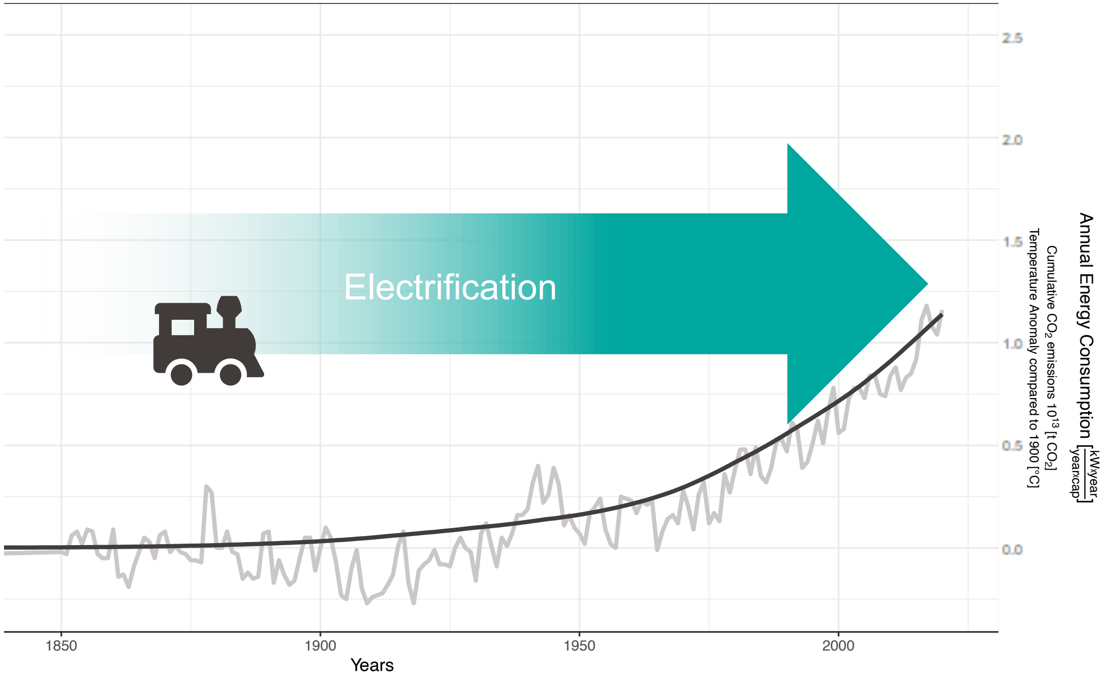




- Most used Power Cycle
- Working fluid passes through phase change (gaseous – liquid)
- 4 Steps
  1. Evaporation
     - Heat input
     - Furnace
  2. Expansion
     - Work output
     - Turbine
  3. Condenser
     - Heat waste
     - Heat exchanger
  4. Pumping
     - Work input
     - Pump

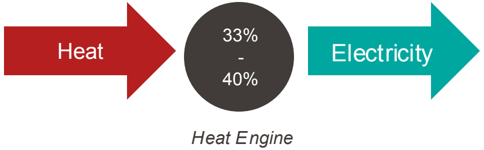
Conventional Technologies
Power Cycles – Rankine Cycles - Coal

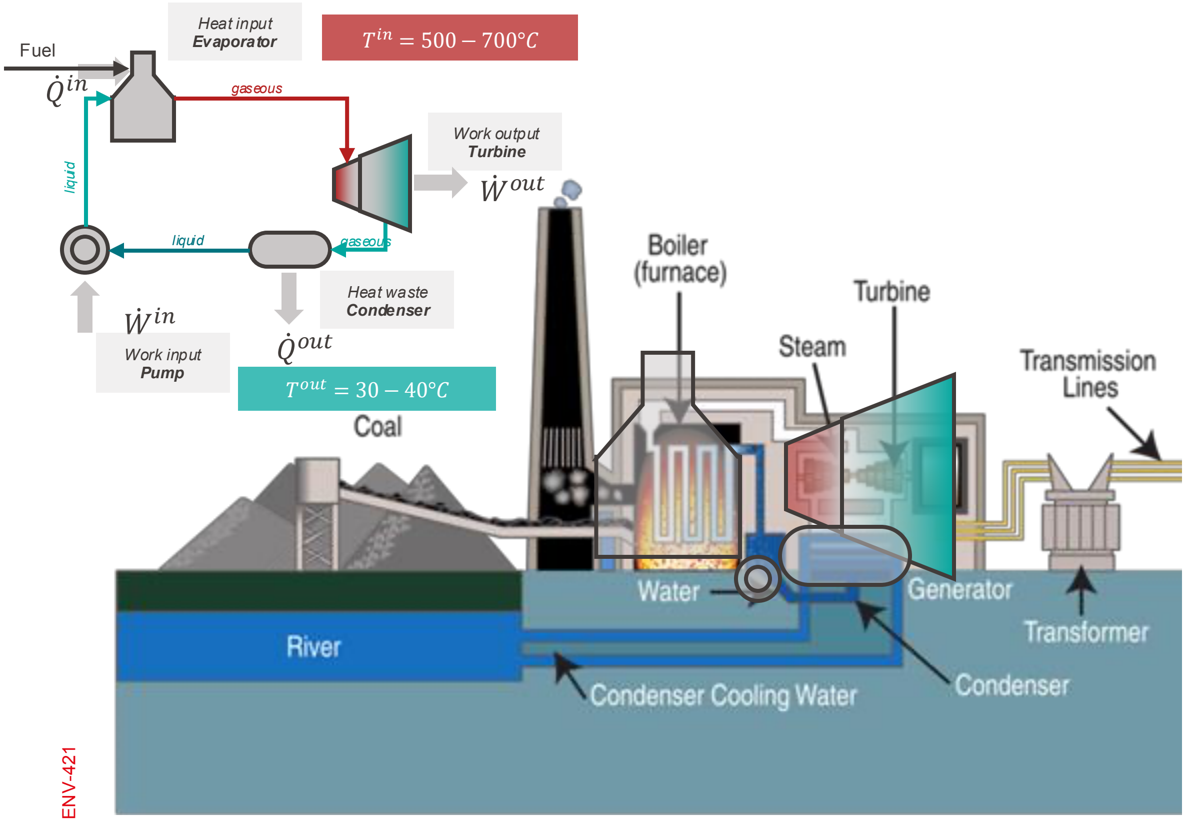




- Coal as fuel for heat
- ~40% of electricity production
  - South-Africa 94%
  - China & India 70-75%
- 9 kt/day coal for 1GW
- Operation
  - Extraction/Mining
  - Unloading
  - Pulverization
  - Combustion

Conventional Technologies
Power Cycles – Rankine Cycles - Coal





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

- Rankine Cycle
  - Evaporation
  - Expansion
  - Condensation
  - Pumping

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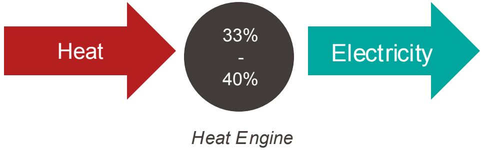
Conventional Technologies

Power Cycles – Rankine Cycles - Coal



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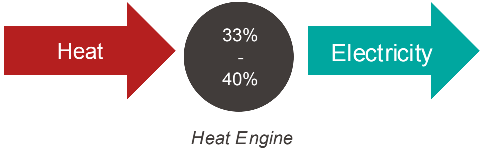
Discuss in groups what advantages/challenges are being faced with coal power-plants?

PRO: CO-MINING FOR OTHER SRUFF (BÉTON), CONTRO: ECOSYSTEM DISTRUPTION
POLLUTION
LOW COST BUT COULD CAUSE SEVERE POLLUTION
EASILY SCALED UP
NO INTERMITTENCY
COST
EFFICIENCY ISSUES
LOW COST, GHG EMISSIONS
IMPURITIES
BIG INFRASTRUCTURES
RIVER HEATING
ECONOMICALLY ADVANTAGEOUS / ECOSYSTEMS POLLUTION

Conventional Technologies

Power Cycles – Rankine Cycles - Coal



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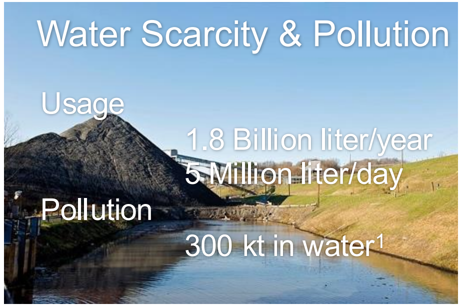
- *The impact of 1GW coal power plant*

Inquinamento sul Taj Mahal
© Wikimedia Commons: Buiobuione 2019



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
© Wikimedia Commons: CSIRO 2009

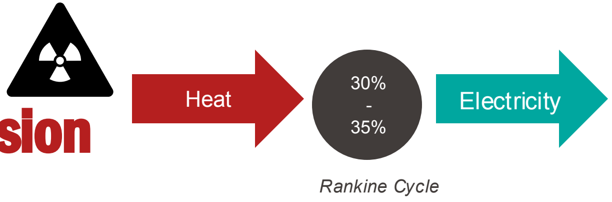
Garzweiler coal mine on April 22
© Wikimedia Commons: Sean Allup 2022

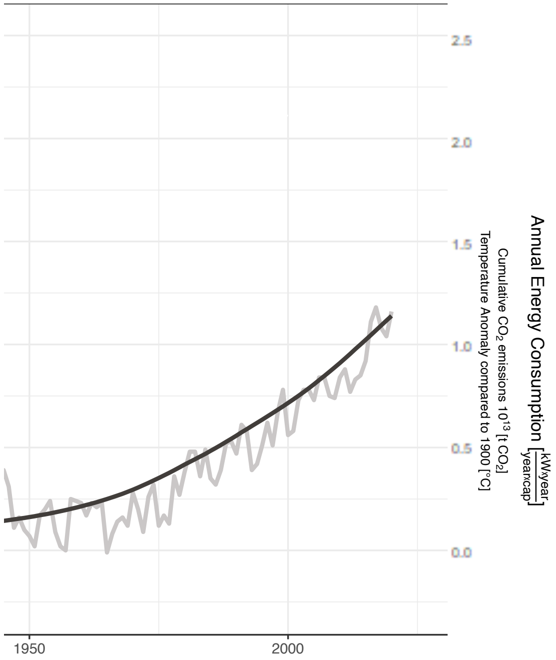
...

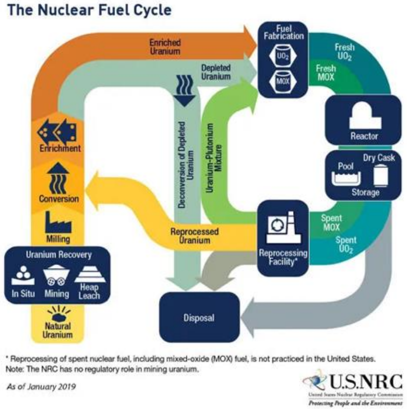
Australian National Railways 160-car train travelling south on the standard-gauge railway line from Leigh Creek coalfield and Port Augusta, South Australia
© Wikimedia Commons: Australian National Railways Commission 1987

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

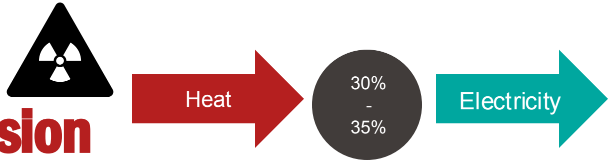






- Nuclear as Fuel for Heat
- ~10% of electricity production globally
  - France: 70%
  - USA: 20%
  - China: 10%
- 200 kg of enriched uranium per year for 1 GW
- Operation
  - Recovery/Extraction/Mining
  - Enrichment
  - Reaction
  - Reprocessing
  - Disposal

Conventional Technologies
Power Cycles – Rankine Cycles – Nuclear Fission



Rankine Cycle

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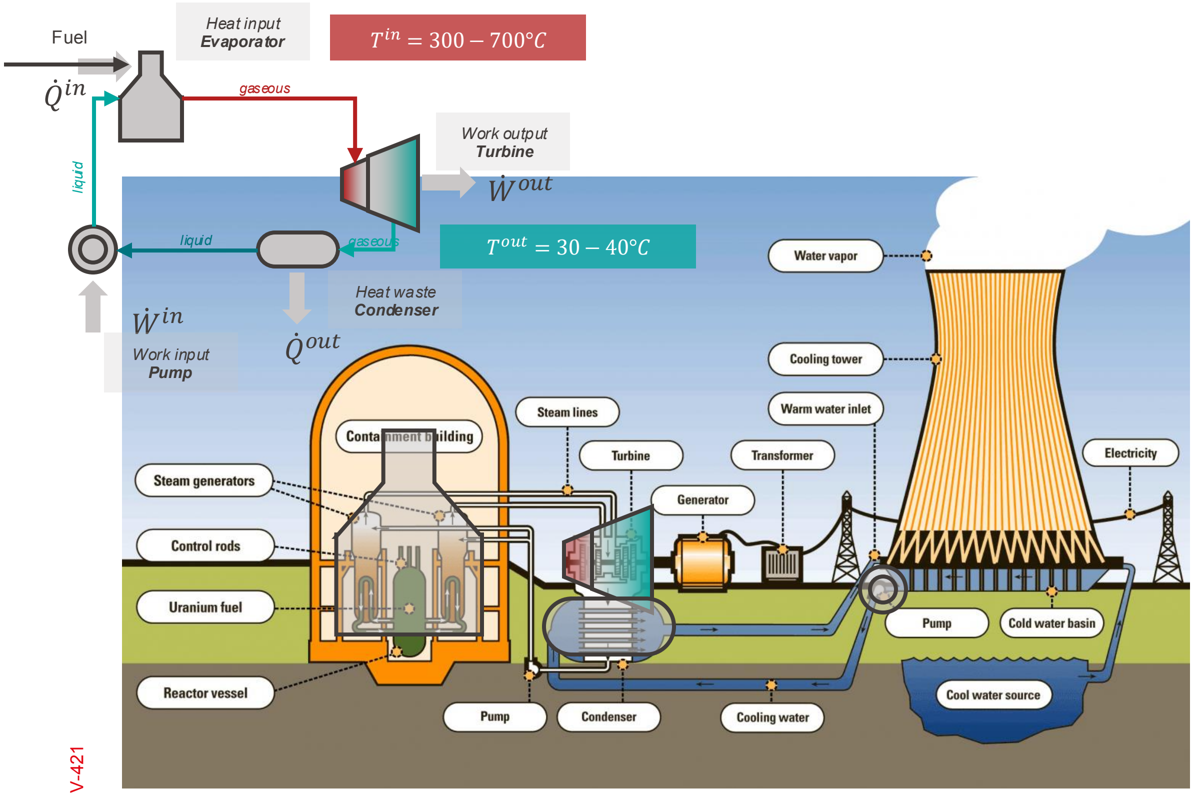
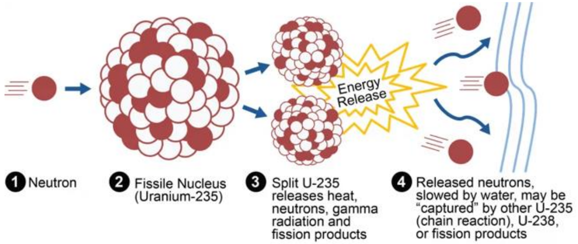


- Rankine Cycle
  - Evaporation
  - Expansion
  - Condensation
  - Pumping

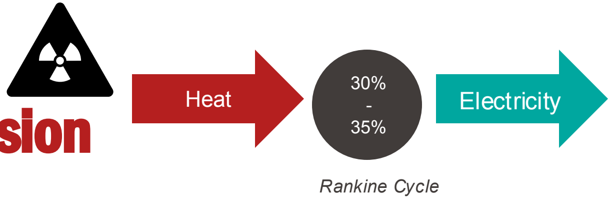


Fission of Uranium-235 in a Nuclear Reactor
©UMICH 2020

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

Conventional Technologies

Power Cycles – Rankine Cycles – Nuclear Fission



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

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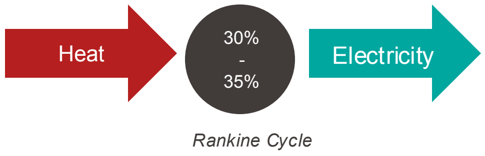
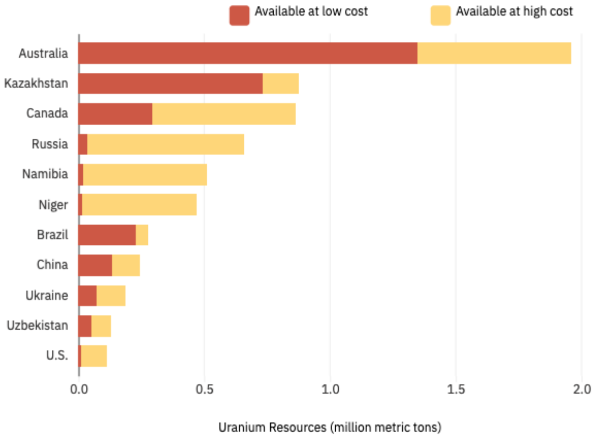
Conventional Technologies
Power Cycles – Rankine Cycles – Nuclear Fission





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

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.

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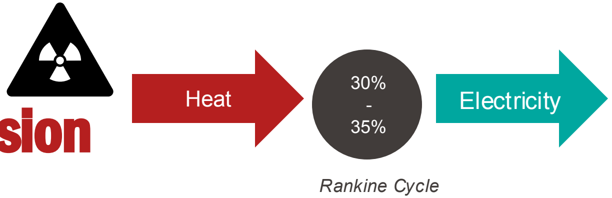

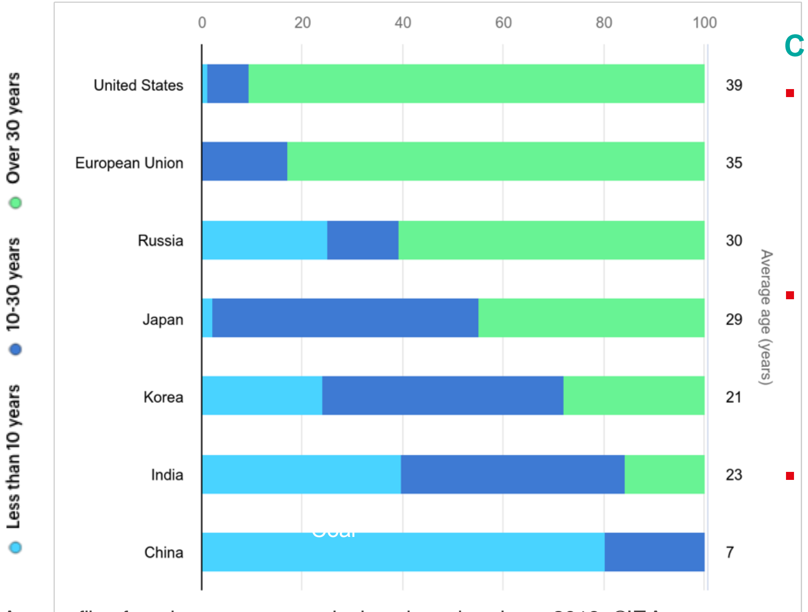

Age profile of nuclear power capacity in selected regions, 2019, ©IEA

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.