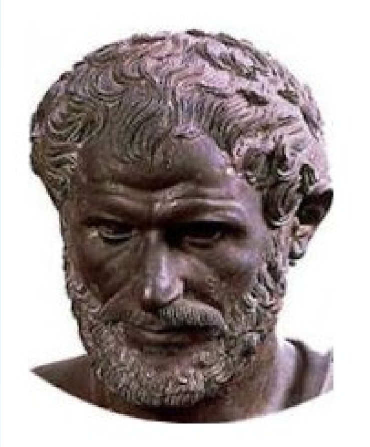
History of the Word "Energy"



The word “energy” comes from the Greek “*enérgeia*”.

Developed by **Aristotle** (384 BC − 322 BC), *enérgeia* has no direct translation to English, although it is frequently described as “being at work”.

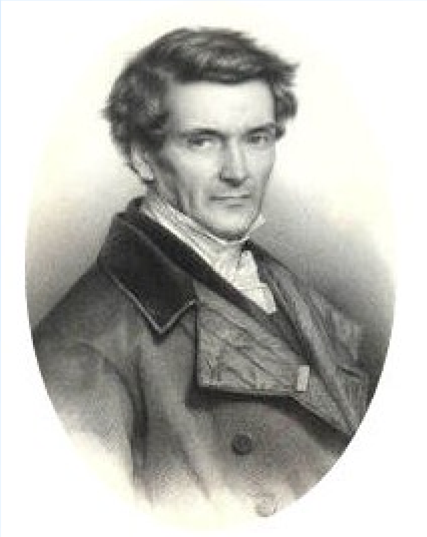
Although the term English “energy” acquired its current definition (meaning the quantitative property that must be transferred to an object to perform work or heat the object) in the 19^{th} century, the ideas behind the concept began forming at the end of the 17^{th} century, when the term was first used in English to refer to “power”.

By 1686, **Gottfried Wilhelm von Leibniz** (1646 − 1716), had developed the concepts that correspond to our current understanding of kinetic and potential mechanical energy.

However, he didn't use the term "energy".

Thomas Young (1773 − 1829) first introduced the word "energy" to the field of physics in 1800, but the word did not gain popularity.

Thomas Young later established the wave nature of light through interference experiments.



The related term "work" was defined
in 1828/29 by
Gustave Gaspard de Coriolis
(1792 − 1843),
pictured on the left, and
Jean-Victor Poncelet (1788 − 1867),
pictured on the right.

Between 1842 and 1847, Julius Robert von Mayer, James Prescott Joule, and Hermann Ludwig Ferdinand von Helmholtz discovered and formulated the basics of what we refer to today as the law of conservation of energy:

Energy cannot be created or destroyed; it can only be transformed from one form to another.

Instead of the word "energy", however, they used the terms "living force", "tensional force" or "fall-force".

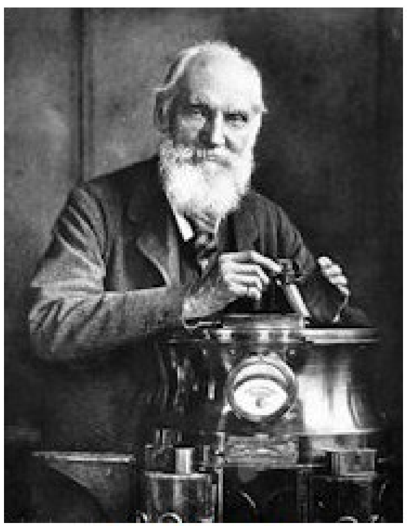
Julius Robert von Mayer (1814 – 1878)

James Prescott Joule (1818 – 1889)

Hermann von Helmholtz (1821 – 1894)

In 1851 − 1852, William Thomson (Lord Kelvin) and William J. M. Rankine began to use the word “energy” to denote any kind of “force” across all branches of science.

Finally, in 1905, Albert Einstein established the general equivalence of energy and mass with his theory of relativity. From there, the concept of “energy” was generalized into the form used today.



Lord Kelvin
(1824 – 1907)

William J. M. Rankine
(1820 – 1872)

Albert Einstein
(1879 – 1955)

Alongside scientific usage, however, the concept of "energy” has entered common speech in ways that are often confusing and contradictory. Everyday expressions such as “energy production” or “renewable energy” contradict the energy conservation law which, as we recall, asserts that energy cannot be created or destroyed. The scientific definition of energy by the law of energy conservation also does not do much to help us understand expressions like “an energetic person”.

For an everyday working definition of "energy", we might look back to Aristotle for inspiration. Stated simply, he said:

Energy is a condition that describes the capacity to do work.

Dictionary definition of energy

Many dictionaries may define energy as the capacity to do work. Here, the word "work" should be understood in its general sense, it may include mechanical, thermal, and radiative functions all together.

One **key property** of energy is given by the first law of thermal dynamics: Energy cannot be created or destroyed; it is only transformed from one form to another. So, in the context of energy resources, we really mean those kinds of energy that can readily be converted to human-usable forms (e.g., mechanical work, heat, or light, electricity, etc.). Therefore, the process of energy conversion becomes critical, so does the **conversion efficiency**.

Forms of energy:

Mechanical (Kinetic) Energy (Work): Energy involved in relative mass movements, e.g., a pendulum in motion, rotating wheel or shaft, etc.

Gravitational Energy (Mechanical energy in stored form): Because of gravitational force, matters at different elevations possess different potential energy.

Potential Energy = [Mass] [Acceleration (due to gravity)] [Height]

Thermal Energy (Heat)**:** Energy involved in temperature changes or heat transfers.

Heat = [Mass] [Heat Capacity] [Temperature Difference]

Heat Capacity = energy used per unit of temperature change per unit of mass

Electromagnetic Energy (Radiation): Energy in the form of "light" both visible and invisible (e.g., solar energy). All radiation has this relationship:

Speed of light = [Wavelength] [Frequency]

= 299 792 458 m/s in vacuum

Nuclear Energy: energy released from nuclear reactions by converting mass to energy, according to this Einstein's equation:

Energy = [Mass] [(Speed of light)^2]

Chemical Energy: energy involved in chemical reactions (e.g., fire, photosynthesis).

Electric(al) Energy: energy involved in electron movement.

Classification of Energy (by Archie W. Culp)

1. **Transitional:** energy in motion, energy which crosses system boundaries.
   - electrical current
   - work
   - heat
   - electromagnetic radiation

2. **Stored:** energy which has a mass, a position in a force field, etc.
   - electrical potential (voltage) storage mechanisms: capacitor, inductor, superconductor, . . .
   - gravitational potential (potential energy in engineering thermodynamics) storage mechanisms: water tower, hydraulic dam, raised weight, . . .

Classification of Energy (by Culp)

2. Stored (Cont.): energy which has a mass, a position in a force field, etc.

- inertial potential (kinetic energy in engineering thermodynamics) storage mechanisms: flywheel, fluid inertia, mass in motion, . . .
- Fluid compression (flow energy or boundary work in thermodynamics) storage mechanisms: gas cylinder, propane tank, piston-cylinder, . . .
- chemical potential: (internal energy, enthalpy in thermodynamics) storage mechanisms: batteries, coal, petroleum, hydrogen, glucose, . . .
- thermal: (sensible & latent heat) storage mechanisms: mass, phase-change material (PCM),
- Nuclear potential: (part of internal energy in thermodynamics)

Transitional and stored energy are distinguished by whether or not an energy flux crosses a real or imaginary surface. This is typically the energy we associate with work and power. For example, current flow is a form of electrical energy and would represent a transitional type. In contrast voltage, which is electrical potential expressed in volts, is a type of stored energy.

There is often confusion between energy and devices which convert or store energy. For example, when asked to define kinetic energy, many times you will hear kinetic energy defined as a flywheel. Flywheels are simply a device that store a type of mechanical energy. Similarly, batteries are a device which store a type of chemical energy.

Energy Forms:

- Electrical
- Electromagnetic
- Chemical
- Nuclear
- Mechanical
- Thermal

Energy Forms and Units	Energy Type		Conversion
	Transitional	Stored	
Electrical power: W, kW, MW power-time: Wh, kWh	Electrical current Units of Amperes [A]	Electrostatic field Inductive field	• Easy & efficient conversion to mechanical and thermal energy • Easy, but less efficient conversion to electromagnetic and chemical energy

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Electromagnetic energy: eV, MeV	**Electromagnetic radiation**	**-**	• **Easy to convert from, but generally inefficient** • **Photosynthesis is most common conversion process** • **No known stored form (could it be nuclear?)**

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Electromagnetic energy: eV, MeV	Electromagnetic radiation	-	• Easy to convert from, but generally inefficient • Photosynthesis is most common conversion process • No known stored form (could it be nuclear?)
Chemical **energy/mass: kJ/kg** **energy/mole: kJ/kmol**	**-**	**Chemical potential** **(+) exothermic** **(−) endothermic**	• **Easily converted to thermal, electrical and mechanical energy** • **There is no known transitional form**

Energy Forms and Units	Energy Type		Conversion
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Chemical energy/mass: kJ/kg energy/mole: kJ/kmol	-	Chemical potential (+) exothermic (−) endothermic	• Easily converted to thermal, electrical and mechanical energy • There is no known transitional form
Nuclear **energy: MeV**	**-**	**Atomic mass**	• **Easily converted to mechanical energy, then into thermal energy** • **No known transitional form (could it be electromagnetic?)**

Energy Forms and Units	Energy Type		Conversion
	Transitional	Stored	
Mechanical energy: J, kJ power: hp, W, kW	work	Potential energy Position in force field • gravitational • inertial • compressed fluid • elastic-strain • magnetic field	• Easily converted to other forms of energy

Energy Forms and Units	Energy Type		Conversion
	Transitional	Stored	
Mechanical energy: J, kJ power: hp, W, kW	work	Potential energy Position in force field • gravitational • inertial • compressed fluid • elastic-strain • magnetic field	• Easily converted to other forms of energy
Thermal energy: J, kJ power: W, kW	**heat**	**Sensible heat Latent heat**	• **Inefficient conversion to mechanical and electrical energy** • **Conversion limited by 2nd law of thermodynamics** • **All other forms are easily converted into thermal energy** • **Thermal energy can be stored in everything**

Conversion of Energy

An energy conversion device converts one form of energy into another. It is an important element of progress of society. The development of energy conversion devices through time can be used as a gauge in the history of civilization (From: L.R. Radovic 2003. Energy and Fuels in Society. McGraw-Hill):

James Watt's steam engine invented in the year 1765 marked the real beginning of the industrial revolution. Similarly, nuclear reactors (or nuclear bombs) got us to the "nuclear age“. Both made a significant difference in energy conversion by human beings.

Landmarks in the development of energy conversion devices	
Emergence of man	4,000,000 B.C.
Emergence of human civilization	5000 B.C.
Development of the water wheel	350 A.D.
Development of the windmill	950 A.D.
Invention of the cannon	1318 A.D.
Development of first atmospheric steam engine (Newcomen)	1712 A.D.
Development of modern steam engine (Watt)	1765 A.D.
Development of high-pressure steam engine (Trevithick)	1802 A.D.
Development of the automobile engine (Daimler)	1884 A.D.
Operation of first nuclear power plant	1954 A.D.

Some Significant Events in the History of Energy Conversion		
	Development of water wheel	350
	Development of windmill	950
	Invention of the cannon	1318
Giovanni Branca	Impulse steam turbine proposal	1629
Thomas Newcomen	Atmospheric engine using steam (first widely used heat engine)	1700
James Watt	Separate steam condenser idea;	1765
	and first Boulton and Watt condensing steam engine	1775
John Barber	Gas turbine ideas and patent	1791
Benjamin Thompson (Count Rumford)	Observed conversion of mechanical energy to heat while boring cannon	1798
Robert Fulton	First commercial steamboat	1807
Robert Stirling	Stirling engine	1816

N. L. Sadi Carnot	Principles for an ideal heat engine (foundations of thermodynamics)	1824
Michael Faraday	First electric current generator	1831
Robert Mayer	Equivalence of heat and work	1842
James Joule	Basic ideas of the First Law of Thermodynamics;	1847
	and measured the mechanical equivalent of heat	1849
Rudolph Clausius	Second Law of Thermodynamics	1850
William Thompson (Lord Kelvin)	Alternate form of the Second Law of Thermodynamics	1851
Etienne Lenoir	Internal combustion engine without mechanical compression	1860
A. Beau de Rochas	Four-stroke cycle internal combustion engine concept	1862
James C. Maxwell	Mathematical principles of electromagnetics	1865

Niklaus Otto	Four-stroke cycle internal combustion engine	1876
Charles Parsons	Multistage, axial-flow reaction steam turbine	1884
Thomas Edison	Pearl Street steam-engine-driven electrical power plant	1884
C.G.P. de Laval	Impulse steam turbine with convergent-divergent nozzle	1889
Rudolph Diesel	Compression ignition engine	1892
	First hydroelectric power at Niagara Falls	1895
Albert Einstein	Mass-energy equivalence	1905
Ernst Schrodinger	Quantum wave mechanics	1926
Frank Whittle	Turbojet engine patent application;	1930
	and first jet engine static test	1937
Otto Hahn	Discovery of nuclear fission	1938
Hans von Ohain	First turbojet engine flight	1939

J. Ackeret, C. Keller	Closed-cycle gas turbine electric power generation	1939
Enrico Fermi	Nuclear fission demonstration at the University of Chicago	1942
Felix Wankel	Rotary internal combustion engine	1954
	Production of electricity via nuclear fission by a utility at Shippingport, Pennsylvania	1957
NASA	Rocket-powered landing of man on the moon	1969
Electricité de France	Superphénix 1200-MW fast breeder reactor - first grid power	1986

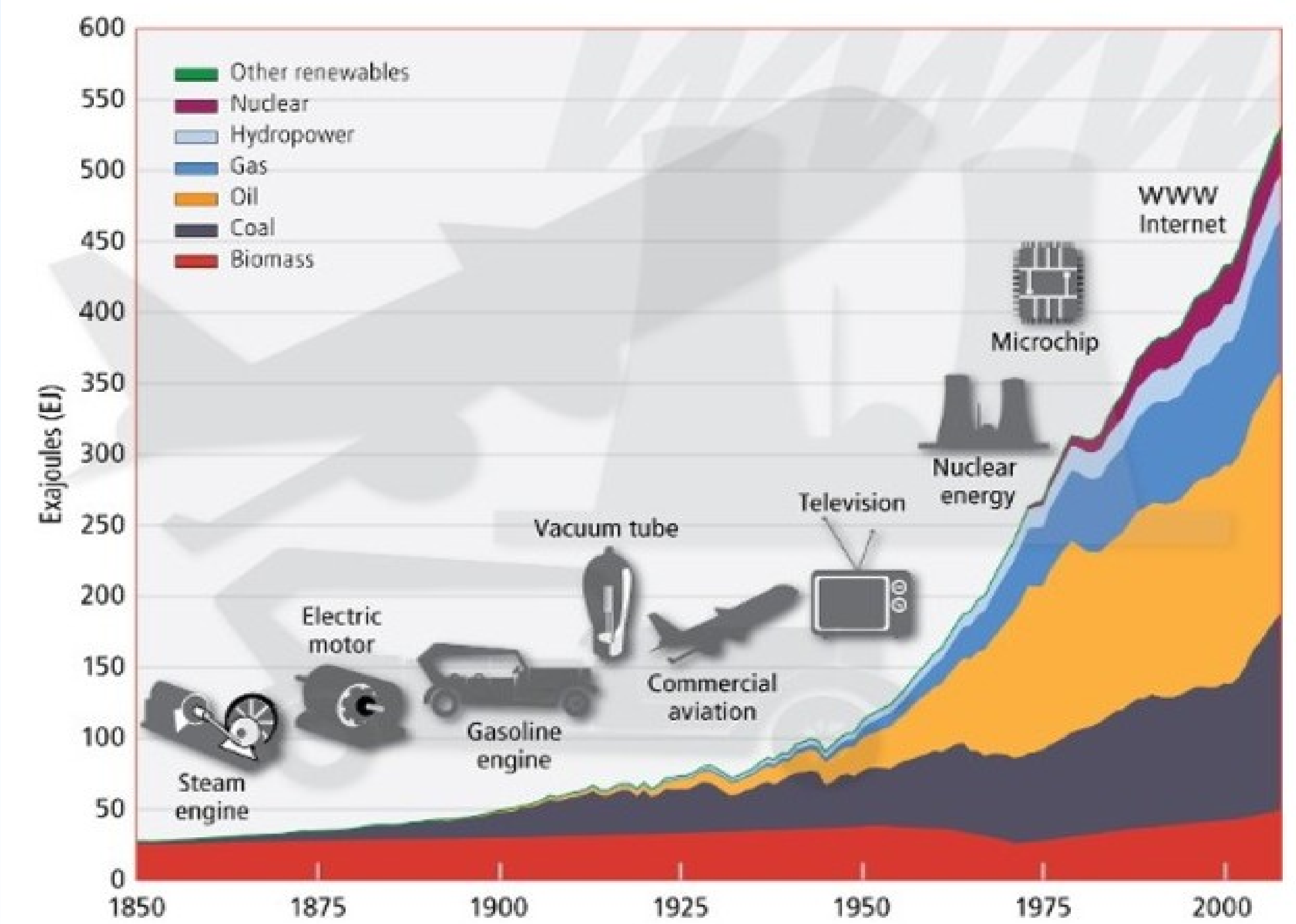
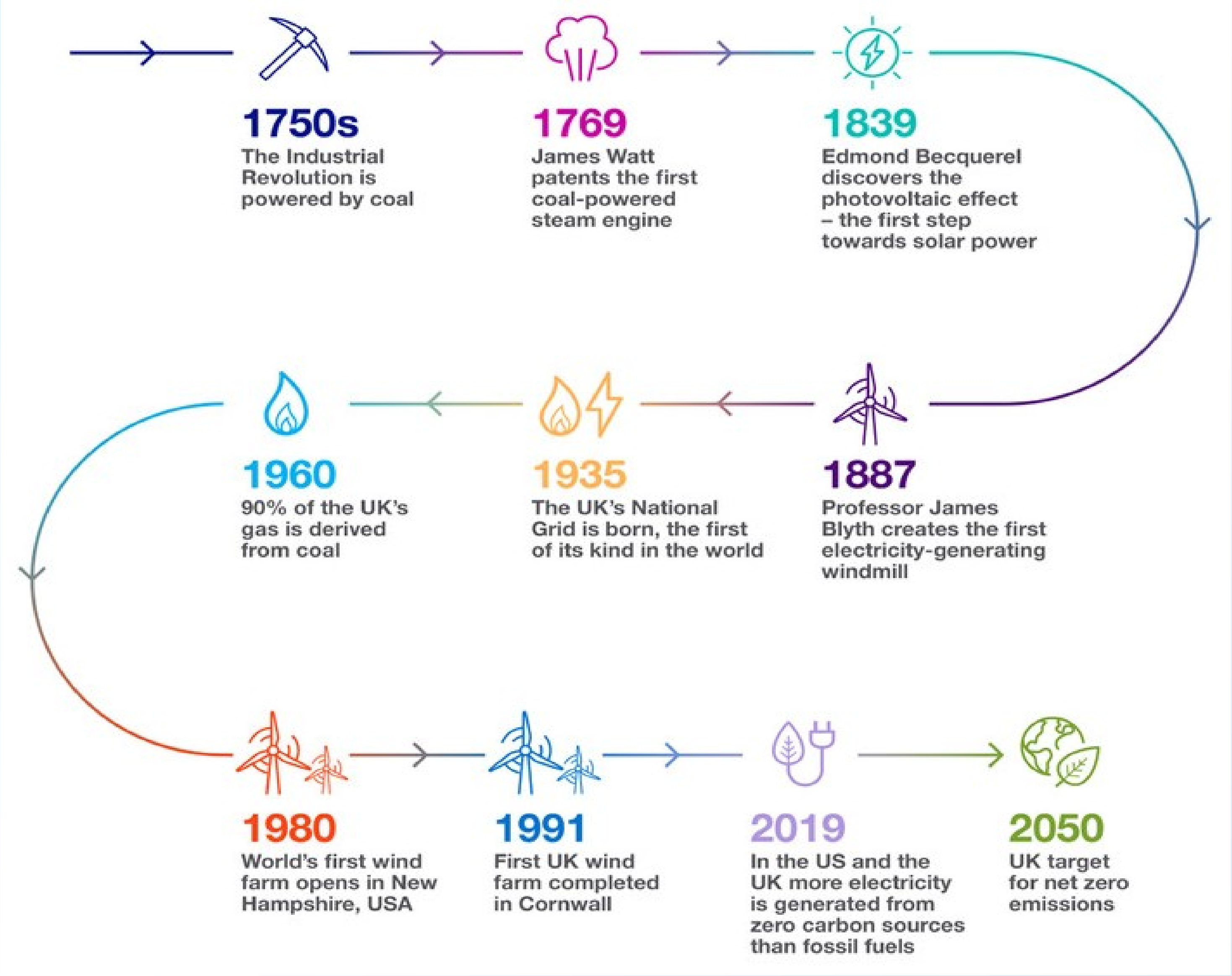


Figure 8: World energy use has increased exponentially over the past 165 years with 80% being derived from fossil fuels (1 Exajoule = 1018 Joules). Advances in technologies define advances in life-styles over time.


1750s
The Industrial Revolution is powered by coal
1769
James Watt patents the first coal-powered steam engine
1839
Edmond Becquerel discovers the photovoltaic effect – the first step towards solar power
1887
Professor James Blyth creates the first electricity-generating windmill
1935
The UK's National Grid is born, the first of its kind in the world
1960
90% of the UK's gas is derived from coal
1980
World's first wind farm opens in New Hampshire, USA
1991
First UK wind farm completed in Cornwall
2019
In the US and the UK more electricity is generated from zero carbon sources than fossil fuels
2050
UK target for net zero emissions

The first law of thermodynamics broadly states that energy is neither destroyed or created, which implies that there are no losses when converting from one form of energy to other forms. All forms of energy, however, are not of equal **worth**.

Electrical and chemical energy are high value commodities, while thermal energy is often of low or no value. Thermal energy associated with temperatures around 100 to 200 °C is often referred to as "**low-grade** heat" because this energy is difficult to convert to anything useful.

Conversion Processes:

Direct: Single-step conversion process

- photovoltaics: electromagnetic $\longrightarrow$ electrical
- batteries: chemical $\longleftrightarrow$ electrical
- thermoelectric coolers (TEC): thermal $\longleftrightarrow$ electrical
- piezoelectric: mechanical $\longleftrightarrow$ electrical

Indirect: Multi-step conversion process

- Diesel cycle (gas): chemical ⟶ thermal ⟶ mechanical ⟶ mechanical
- Rankine cycle (liquid-vapor), steam turbine:

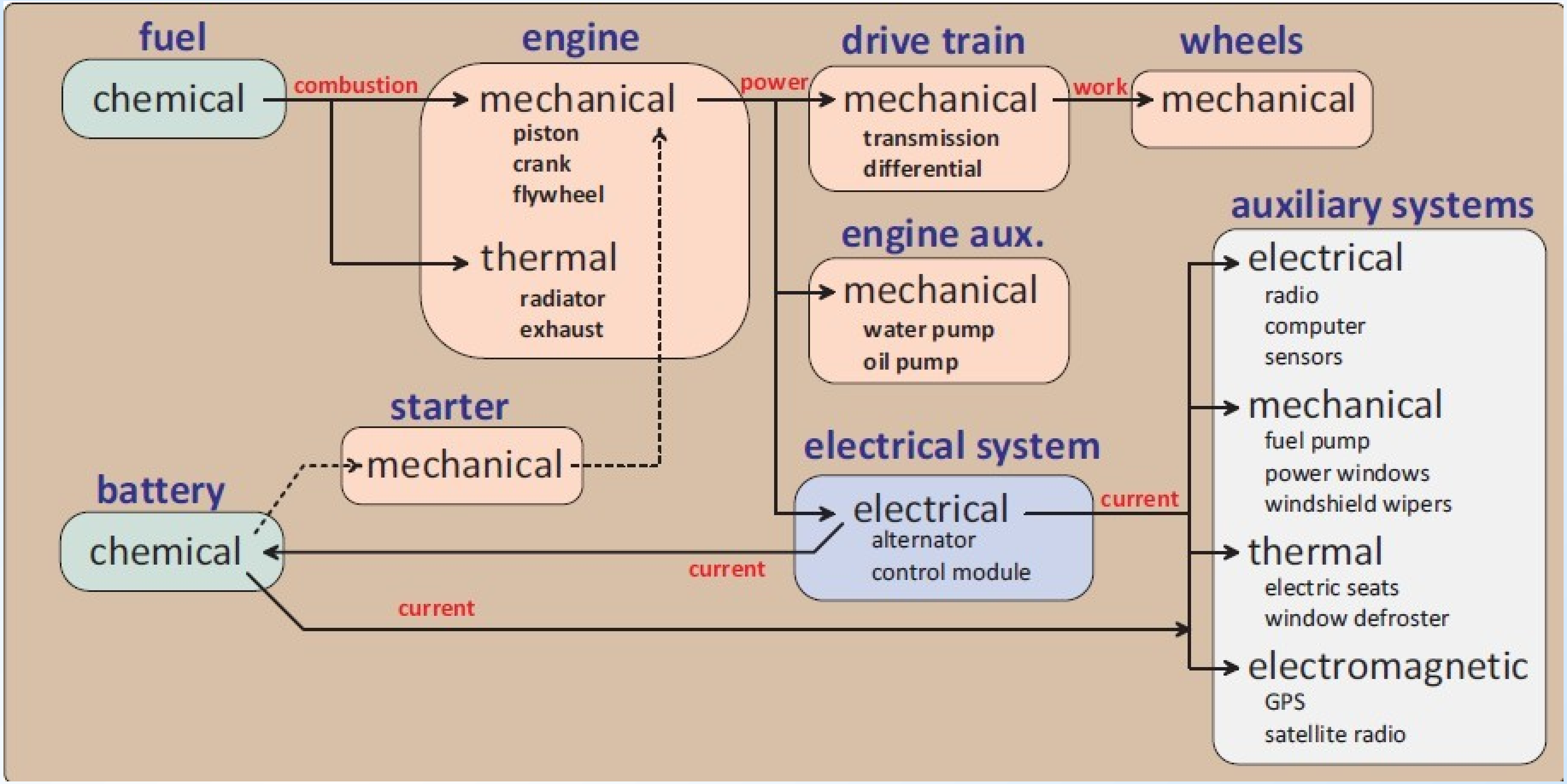
$$\left.\begin{array}{c}\text{chemical}\\ \text{nuclear}\\ \text{solar}\\ \text{geothermal}\end{array}\right\} \longrightarrow \text{thermal} \longrightarrow \text{mechanical} \longrightarrow \text{electrical}$$

- Brayton cycle (gas), gas turbine, turbojets:

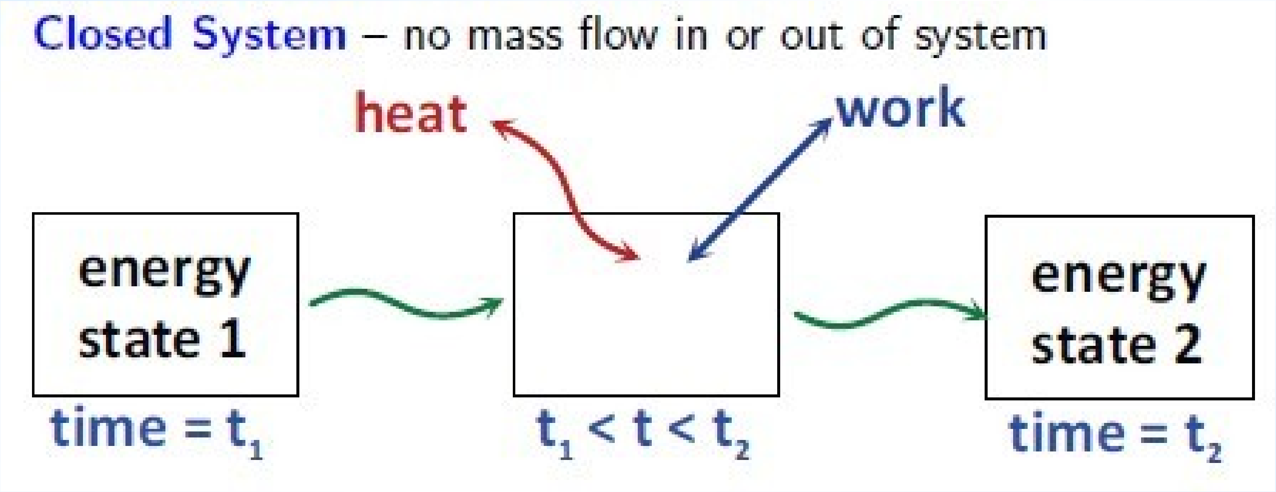
$$\left.\begin{array}{c}\text{chemical}\\ \text{nuclear}\\ \text{solar}\end{array}\right\} \longrightarrow \text{thermal} \longrightarrow \text{mechanical} \longrightarrow \text{electrical}$$

- $$\left(\begin{array}{c}\text{wind turbine}\\ \text{wave energy}\\ \text{tidal energy}\end{array}\right) \text{mechanical} \longrightarrow \text{mechanical} \longrightarrow \text{mechanical} \longrightarrow \text{electrical}$$

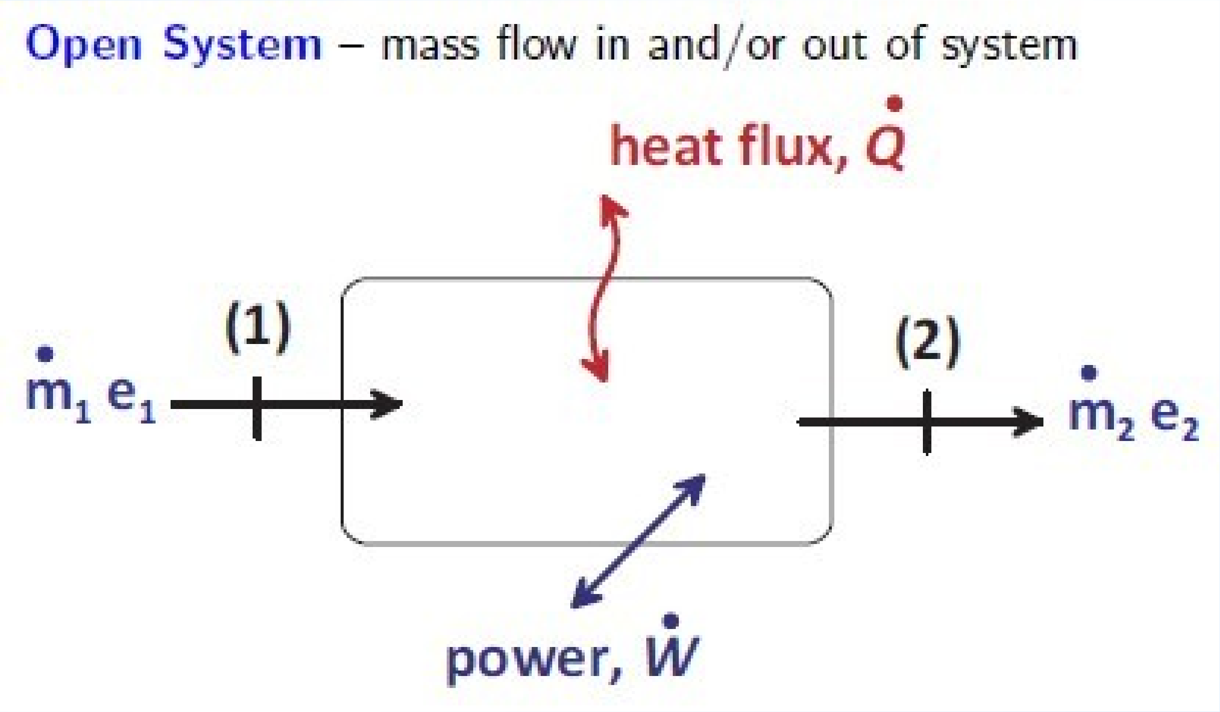
Energy flow in an Internal Combustion Engine Vehicle



Energy Balance



Energy Balance



For a steady-state, open system:

$$\Delta Q - \Delta W = \Delta E = (E_p + E_k + E_i + E_f)|_{out} - (E_p + E_k + E_i + E_f)|_{in}$$

ΔQ: heat **into** system

ΔW: work **produced** by system

ΔE: change in system energy

E_p: potential energy $= mzg/g_c$

E_k: kinetic energy $= mV^2/2g_c$

E_i: internal energy $= mu$

E_f: flow energy $= P\forall = mP/\rho$

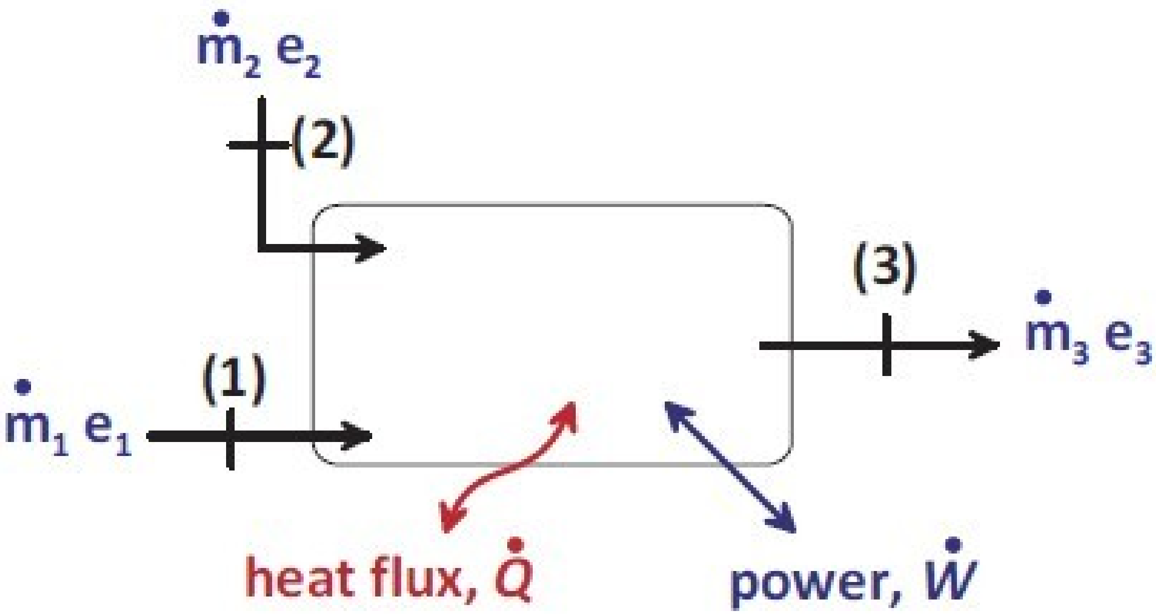
This is the first law of thermodynamics as applied to the working fluid, which is really

Change in Transitional Energy = Change in Stored Energy

First Law of Thermodynamics

Steady, rate form of the 1st Law:

$$\sum \dot{Q} - \sum \dot{W} = \sum_{out} \dot{m}e - \sum_{in} \dot{m}e$$



Note that heat, Q, and work, W, is not the same as useful heat and work.

Also note the sign convention for heat and work

Energy and Oxygen Consumption Rates for an average 76 kg male

Activity	Energy consumption in watts	Oxygen consumption in liters O2/min
Sleeping	83	0.24
Sitting at rest	120	0.34
Standing relaxed	125	0.36
Sitting in class	210	0.60
Walking (5 km/h)	280	0.80
Cycling (13–18 km/h)	400	1.14
Shivering	425	1.21
Playing tennis	440	1.26
Swimming breaststroke	475	1.36
Ice skating (14.5 km/h)	545	1.56
Climbing stairs (116/min)	685	1.96
Cycling (21 km/h)	700	2.00
Running cross-country	740	2.12
Playing basketball	800	2.28
Cycling, professional racer	1855	5.30
Sprinting	2415	6.90

Efficiency is the (often measurable) ability to avoid wasting

- materials,
- energy,
- efforts,
- money,
- and time

in doing something or in producing a desired result.

In a more general sense, it is the ability to do things well, successfully, and without waste.

In more mathematical or scientific terms, it signifies the level of performance that uses the least amount of inputs to achieve the highest amount of output.

Efficiency of Energy Conversion

combustion: $\eta = \frac{Q}{\mathrm{HV}} \equiv \frac{\text{heat released}}{\text{heating value of fuel}}$

heat pump: $\mathrm{COP} \equiv \frac{Q_H}{W_C} \equiv \frac{\text{heat into hot reservoir}}{\text{compressor work}}$

refrigeration: $\mathrm{COP} \equiv \frac{Q_C}{W_C} \equiv \frac{\text{heat from cold reservoir}}{\text{compressor work}}$

alternator: $\eta \equiv \frac{\dot{W}_e}{\dot{W}_m} \equiv \frac{\text{electrical energy out}}{\text{mechanical energy in}}$

Efficiency of Energy Conversion

battery: $\eta = \dfrac{\dot{W}_e}{\dot{W}_c} \equiv \dfrac{\text{electrical energy out}}{\text{chemical energy in}}$

IC engine: $\eta = \dfrac{\dot{W}_m}{\dot{W}_c} \equiv \dfrac{\text{mechanical energy out}}{\text{chemical energy in}}$

automotive transmission: $\eta = \dfrac{\dot{W}_m}{\dot{W}_m} \equiv \dfrac{\text{mechanical energy out}}{\text{mechanical energy in}}$

electrical transmission: $\eta = \dfrac{\dot{W}_e}{\dot{W}_e} \equiv \dfrac{\text{electrical energy out}}{\text{electrical energy in}}$

Example 1

An electric commuter vehicle uses a 24-hp electric motor and is to have a photovoltaic array on the roof to charge the batteries both while moving and parked. The average solar flux is 650 W_{em}/m^2. The commute is one hour each way and the vehicle is parked for 8 hours. Thus, for each hour of operation, you estimate that the vehicle will be parked for 4 hours during daylight hours. The overall electromagnetic-to-electrical-to-mechanical energy conversion efficiency is 13 % and the storage efficiency of the batteries is 60 %. Determine the area of the solar array required to provide sufficient energy for the commute.

The effective solar power with energy storage per hour of operation is:

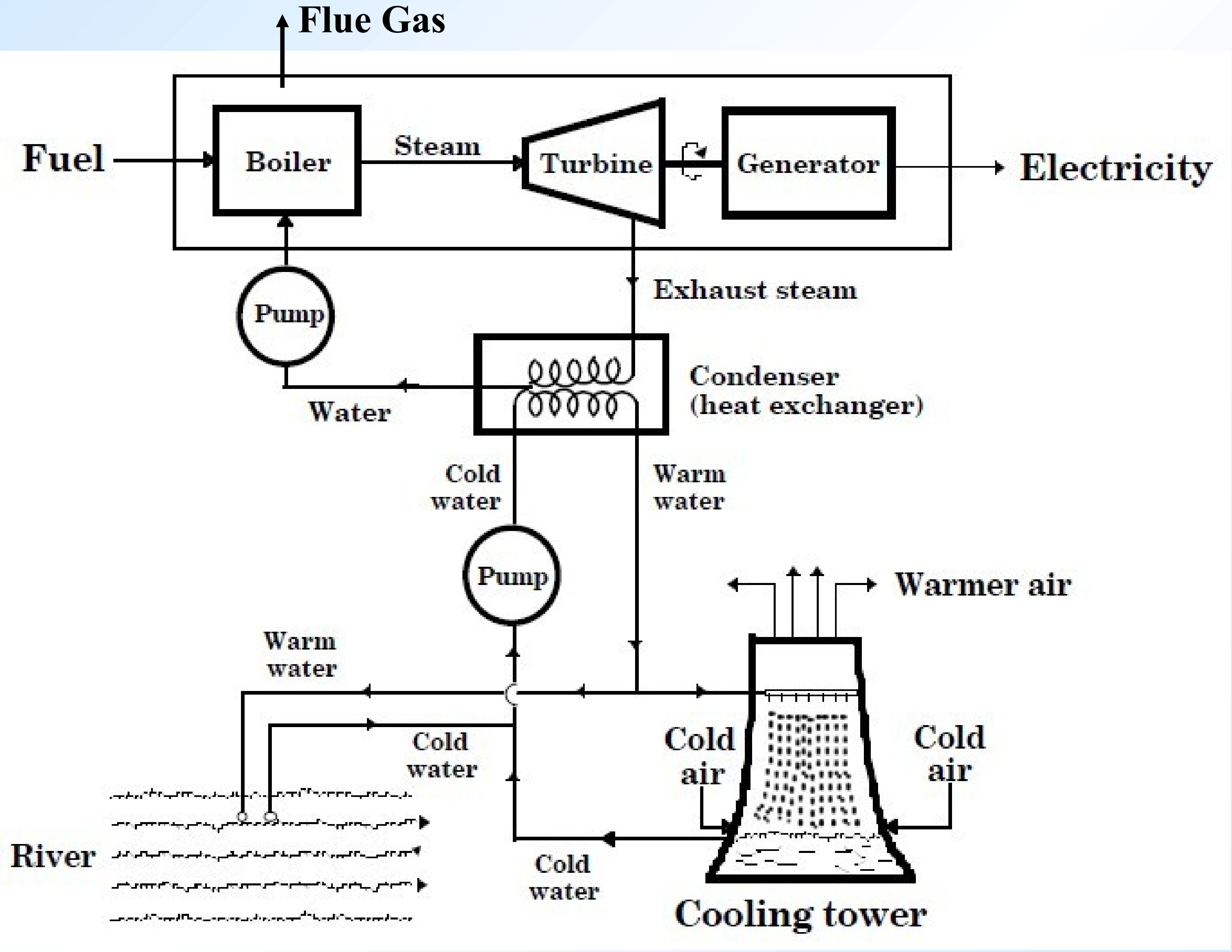
$$\frac{650\ W_{em}}{m^2}\left[\frac{1\ hr + \left(0.60\ \frac{W_{e,out}}{W_{e,in}}\right)(4\ hr)}{1\ hr}\right] = 2210\ W_{em}/m^2$$

The required area of solar array required to generate 24 hp_{em}:

$$\left(24\ hp_{em}\right)\left(\frac{745.7\ W_{em}}{hp_{em}}\right)\left(\frac{m^2}{2210\ W_{em}}\right) = 8.1\ m^2$$

This area, 8 m^2, is required to collect 24 hp worth of electromagnetic energy during 1 hour of driving and 4 hours parked. The conversion of the electromagnetic energy to mechanical energy (motion of vehicle) is 13 %. Thus, the area required to generate 24 hp_m from 650 W_{em}/m^2 is:

$$8.1\ m^2 \left(\frac{W_{em}}{0.13\ W_{em}} \right) = 62.3\ m^2$$


Flue Gas
Fuel
Boiler
Steam
Turbine
Generator
Electricity
Exhaust steam
Pump
Condenser
(heat exchanger)
Water
Cold
water
Warm
water
Pump
Warmer air
Warm
water
Cold
water
Cold
air
Cold
air
River
Cold
water
Cooling tower

Efficiency in Electrical Power Generation

Common terms used to describe efficiency in electrical power generation industry

Power density → power per unit volume kW/m^3

Specific power → power per unit mass kW/kg

Electric power output → power x time kW_eh

Rated power → power output of a plant at nominal operating conditions

Performance Factors:

Heat Rate (HR): Thermal energy required to produce 1 kWh of electricity, Btu_{th}/kW_eh

$$3412 \text{ Btu} = 1 \text{ kW}_{th}\text{h}$$

Thermal Efficiency $\eta_{th} = \dfrac{\text{electrical energy produced}}{\text{thermal energy consumed}}$ of the cycle $\dfrac{kW_e}{kW_{th}}$

Overall Efficiency $\eta_{total} = \dfrac{\text{electrical energy produced}}{\text{chemical energy input}} = \dfrac{kW_e}{\text{heating value of the fuel}}$

Capacity Factor (CF) = $\dfrac{\text{average power}}{\text{rated power}}$ per a specific time period

The Capacity Factor is the ratio of “the electrical energy produced by a generating unit for a given period of time" to “the electrical energy that could have been produced at continuous rated-power operation during the same period."

$$\textbf{Load Factor} = \frac{\text{average power}}{\text{maximum power}} \text{ per a specific time period}$$

Availability Factor = fraction of time period that power generation system is available

$$\textbf{Unit Fuel Cost} = \frac{\text{(fuel cost) (heat rate of plant)}}{\text{efficiency}}$$

Example 2

A coal burning power plant produces a net power of 300 MW_e with a heat rate of 10 663 Btu_{th}/kW_eh. The heating value of coal is 12 040 Btu/lb_m. The gravimetric air-fuel ratio is calculated to be 12 kg air / kg fuel.

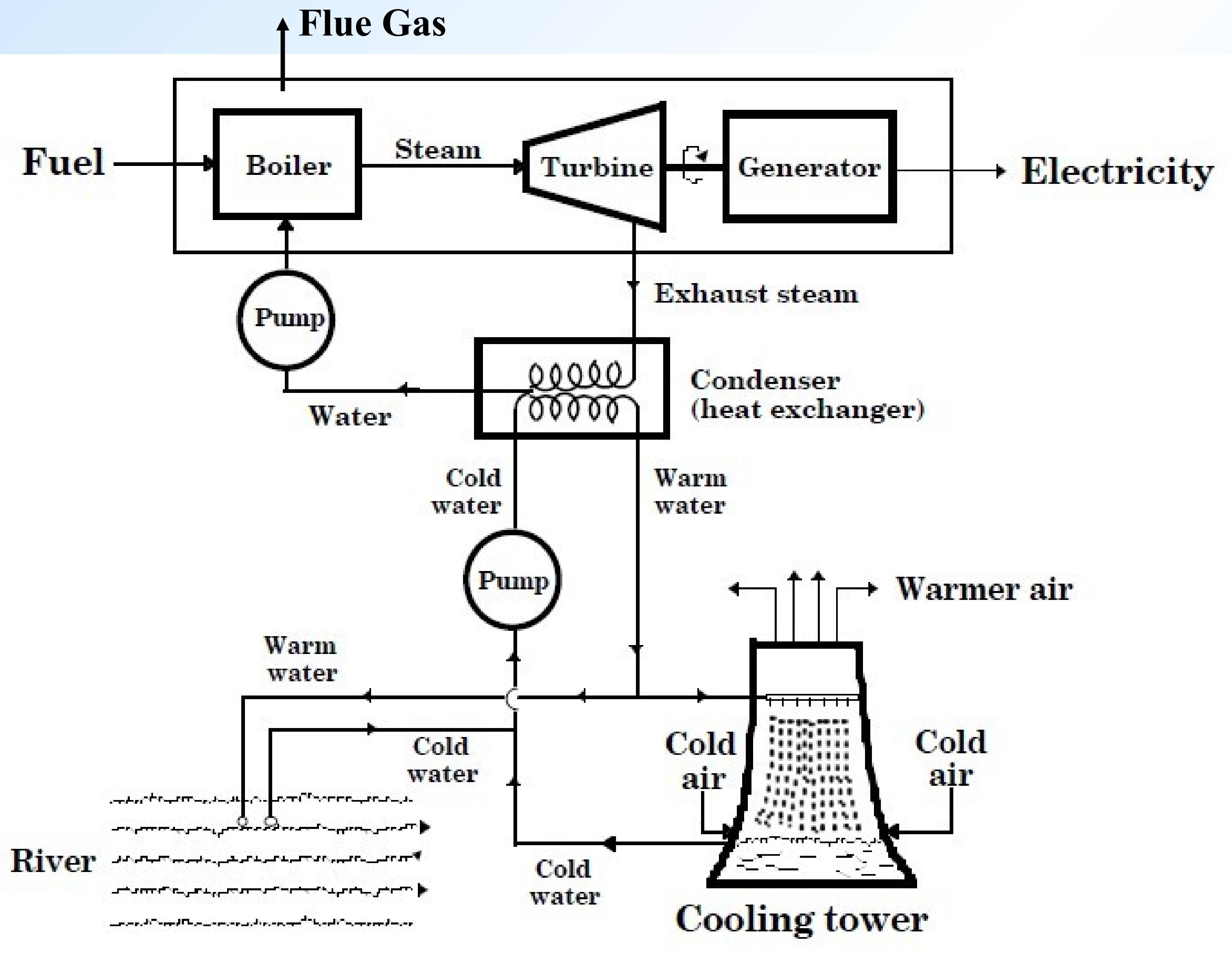
(a) What is the thermal efficiency of the plant?

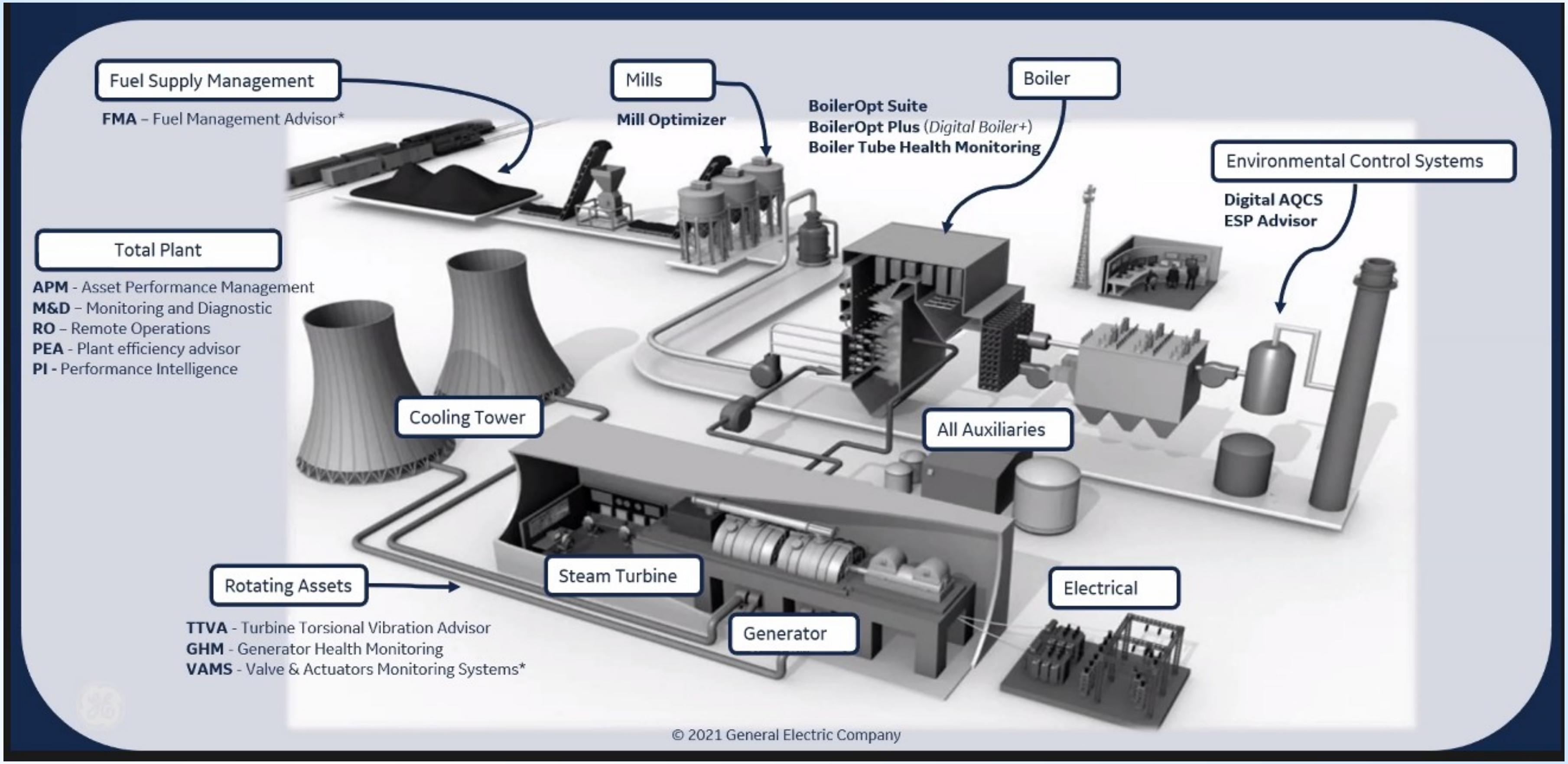
(b) How much fuel is consumed in 24 hours?

(c) What is the air flow rate?

See «odtuclass» for Unit Systems and Conversion Factors

Distinguish betwen thermal efficiency and overall (total) efficiency of a PP.


Flue Gas
Fuel
Boiler
Steam
Turbine
Generator
Electricity
Pump
Exhaust steam
Condenser
(heat exchanger)
Water
Cold water
Warm water
Pump
Warmer air
Warm water
Cold water
Cold air
Cold air
River
Cold water
Cooling tower


Fuel Supply Management
FMA – Fuel Management Advisor*
Mills
Mill Optimizer
Boiler
BoilerOpt Suite
BoilerOpt Plus (Digital Boiler+)
Boiler Tube Health Monitoring
Environmental Control Systems
Digital AQCS
ESP Advisor
Total Plant
APM - Asset Performance Management
M&D – Monitoring and Diagnostic
RO – Remote Operations
PEA - Plant efficiency advisor
PI - Performance Intelligence
Cooling Tower
All Auxiliaries
Rotating Assets
Steam Turbine
Electrical
Generator
TTVA - Turbine Torsional Vibration Advisor
GHM - Generator Health Monitoring
VAMS - Valve & Actuators Monitoring Systems*
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Use the definition of heat rate:

$$\eta_{th} = \frac{3412}{\text{Heat Rate}} = \frac{3412\ \text{Btu}_{th}/\text{kW}_{th}.\text{hr}}{10633\ \text{Btu}_{th}/\text{kW}_{th}.\text{hr}} = 0.32\ \text{kW}_e/\text{kW}_{th}$$

The amount of fuel consumed is proportional to the heat input

$$\dot{Q}_{in} = \frac{\dot{W}_{out}}{\eta_{th}} = \frac{300\ \text{MW}_e}{0.32\ \text{MW}_e/\text{MW}_{th}} = 937.5\ \text{MW}_{th} = (\dot{m}_{coal})\ (\text{HV})$$

$$\dot{m}_{coal} = \frac{937.5\ \text{MW}_{th}}{28000\ \text{kJ/kg}} = \frac{(937.5\ \text{MW}_{th})\ (\text{J.s}^{-1}/\text{W}}{28\ 10^6\ \text{J/kg}} = 33.48\ \text{kg/s}$$

$$\frac{m_{coal}}{\text{day}} = 2.86\ 10^6\ \text{kg/day}$$

The air flow rate is determined from the air-fuel ratio:

$$\dot{m}_{air} = (\dot{m}_{coal})\ (AF) = (33.48\ kg_{coal}/s)\left(\frac{12\ kg_{air}}{kg_{coal}}\right) = 401.8\ kg_{air}/s$$

Carnot Efficiency

The Carnot efficiency is the maximum efficiency of any thermodynamic power cycle. This includes gasoline engines (Otto cycle), gas turbines (Bryton cycle), steam turbine plants (Rankine cycle), and Stirling engines. The conversion efficiency of any cyclic process converting thermal energy to mechanical energy is limited by the Carnot efficiency.

$$\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}}$$

The temperatures must be in absolute units, Kelvin

Efficiencies of thermodynamic power cycles are typically around 30 %

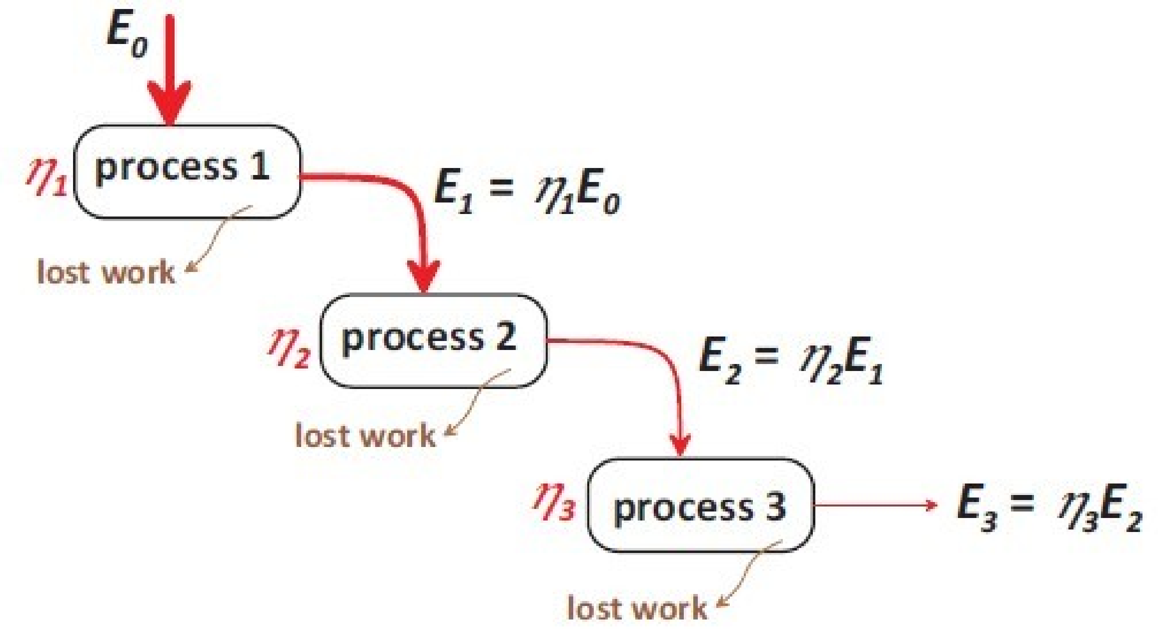
Nicolas Léonard Sadi Carnot

Frency Army Officier

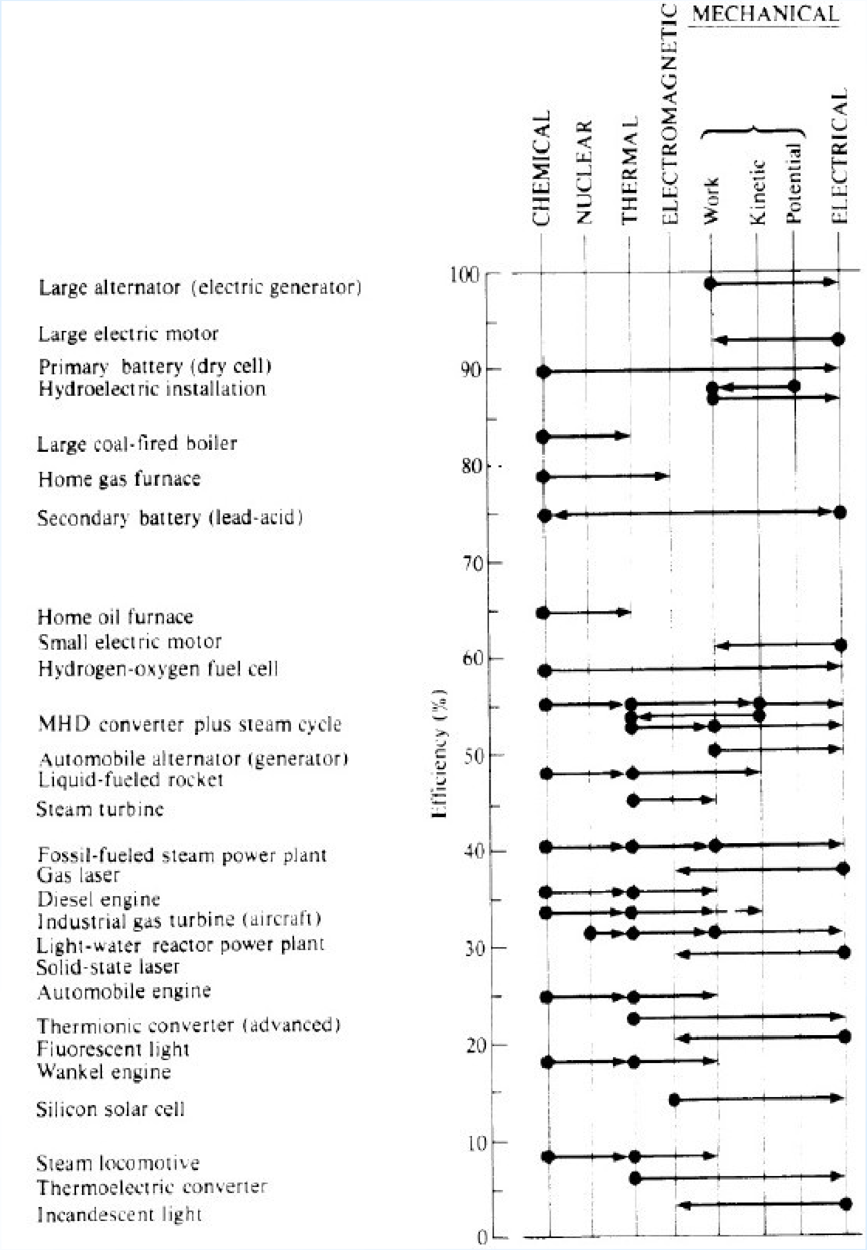
1796 - 1832

Serial Efficiency

Each time energy is converted from one form to another, there is a loss of available energy; in other words, the efficiency of energy conversion is always less than 1. In a system where there are multiple energy conversion processes occurring, the efficiencies of each subsequent conversion result in an ever decreasing net energy output.



$$E_3 = \eta_3 \ \eta_2 \ \eta_1 \ E_0$$


MECHANICAL
CHEMICAL
NUCLEAR
THERMAL
ELECTROMAGNETIC
Work
Kinetic
Potential
ELECTRICAL
Efficiency (%)
100
90
80
70
60
50
40
30
20
10
0
Large alternator (electric generator)
Large electric motor
Primary battery (dry cell)
Hydroelectric installation
Large coal-fired boiler
Home gas furnace
Secondary battery (lead-acid)
Home oil furnace
Small electric motor
Hydrogen-oxygen fuel cell
MHD converter plus steam cycle
Automobile alternator (generator)
Liquid-fueled rocket
Steam turbine
Fossil-fueled steam power plant
Gas laser
Diesel engine
Industrial gas turbine (aircraft)
Light-water reactor power plant
Solid-state laser
Automobile engine
Thermionic converter (advanced)
Fluorescent light
Wankel engine
Silicon solar cell
Steam locomotive
Thermoelectric converter
Incandescent light

Efficiencies of common energy conversion devices

Energy Conversion Device	Energy Conversion	Typical Efficiency, %
Electric heater	Electricity/Thermal	100
Hair drier	Electricity/Thermal	100
Electric generator	Mechanical/Electricity	95
Electric motor (large)	Electricity/Mechanical	90
Battery	Chemical/Electricity	90
Steam boiler (power plant)	Chemical/Thermal	85
Home gas furnace	Chemical/Thermal	85
Home oil furnace	Chemical/Thermal	65
Electric motor (small)	Electricity/Mechanical	65
Home coal furnace	Chemical/Thermal	55
Steam turbine	Thermal/Mechanical	45
Gas turbine (aircraft)	Chemical/Mechanical	35
Gas turbine (industrial)	Chemical/Mechanical	30
Automobile engine	Chemical/Mechanical	25
Fluorescent lamp	Electricity/Light	20
Silicon solar cell	Solar/Electricity	15
Steam locomotive	Chemical/Mechanical	10
Incandescent lamp	Electricity/Light	5

Example 3

You are developing a hybrid motorbike using 2-hp, 2-strike gasoline engine to drive a generator that powers an electric motor. There is a small lead acid battery used for storing energy. The thermal efficiency of the engine is 25 %. The generator is 60 % efficient.

The electric drive motor is 50 % efficient. The battery storage system is 75 % efficient.

(a) With battery system by-passed, what is the power delivered to the wheels?

(b) Power delivered using batteries?

(a)

Engine ===> Generator ===> Motor ===> Wheels

2 hp_m ===> Generator ===> $(2hp_m)\ (0.60\ hp_e/hp_m) = 1.2\ hp_e$

1.2 hp_e ===> Drive Motor ===> $(1.2\ hp_e)\ (0.50\ hp_m/hp_e) = 0.6\ hp_m$

Power Delivered to the Wheels = $(0.6\ hp_m)\ (0.7459\ kW/hp) = 0.45\ kW_m$

When starting with the fuel:

System Efficiency = $(0.25\ W_m/W_e)\ (0.60\ W_e/W_m)\ (0.5\ W_m/W_e) = 7.5\ \%\ W_m/W_c$

(b)

Engine ===> Generator ↘ Battery ↗ Motor ===> Wheels

Power Delivered to the Wheels = $(2\ hp_m)\ (0.75\ hp_{e,b}/hp_{e,b})\ (0.50\ hp_m/hp_{e,b})$

$= 0.45\ hp_m = 0.34\ kW_m$

System Efficiency = 5.6 % $W_m/W_c = 0.056$

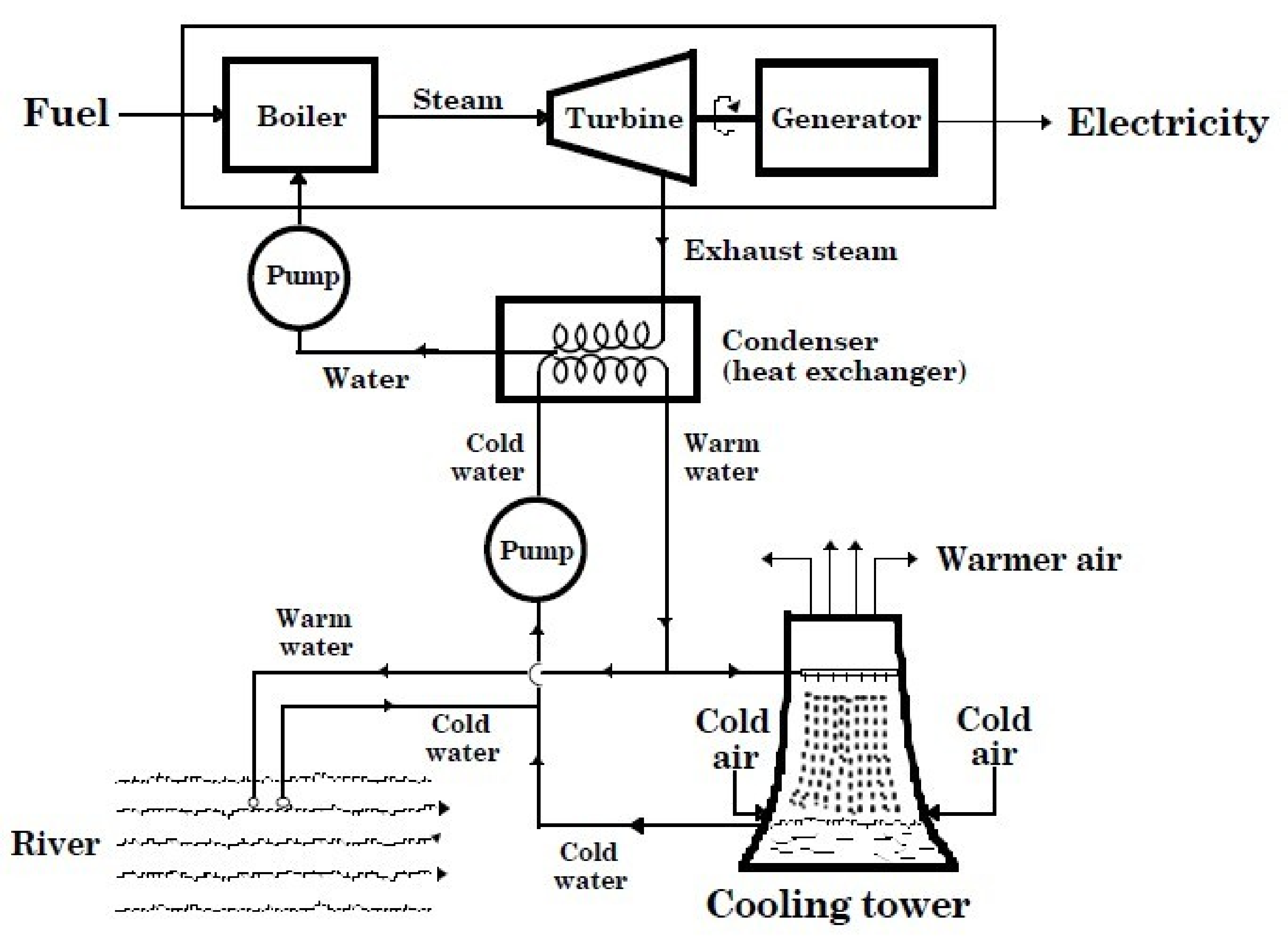
Mechanical energy out / Chemical energy in

Example 4

Calculate the efficiency of a power plant if the efficiencies of the boiler, turbine and generator are 88 %, 40 %, and 98%, respectively.

$$\eta_{pp} = \eta_{\text{boiler}} \; \eta_{\text{turbine}} \; \eta_{\text{generator}} = (0.88)\,(0.40)\,(0.98) = 0.35 \quad \text{or } 35\ \%$$

Note that the efficiency of the system is lower than any one of the efficiencies of the individual components of the system. In the case of this electric power plant, only 35% of the chemical energy input is converted to electricity. The rest is lost to the environment, mostly as heat (to keep nature happy, by satisfying the Second Law of Thermodynamics).



Fuel
Boiler
Steam
Turbine
Generator
Electricity
Pump
Exhaust steam
Condenser
(heat exchanger)
Water
Cold
water
Warm
water
Pump
Warmer air
Warm
water
Cold
water
Cold
air
Cold
air
River
Cold
water
Cooling tower

Example 5

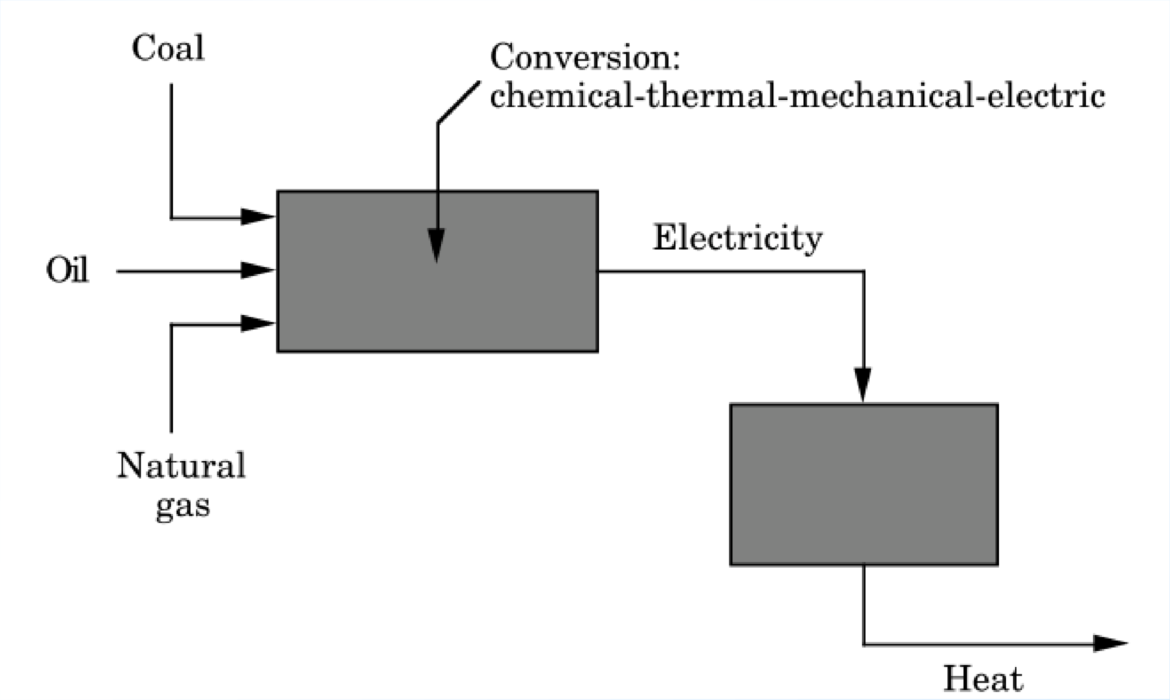
Determine the coefficient of performance of a refrigerator that consumes 800 Watts of power to remove heat at a rate of 5 Btu per second.

$$\text{COP} = \frac{\text{Useful energy output}}{\text{Energy input}} = \frac{5 \text{ Btu/s}}{800 \text{ J/s}} (1055 \text{ J/s}) = 6.6$$

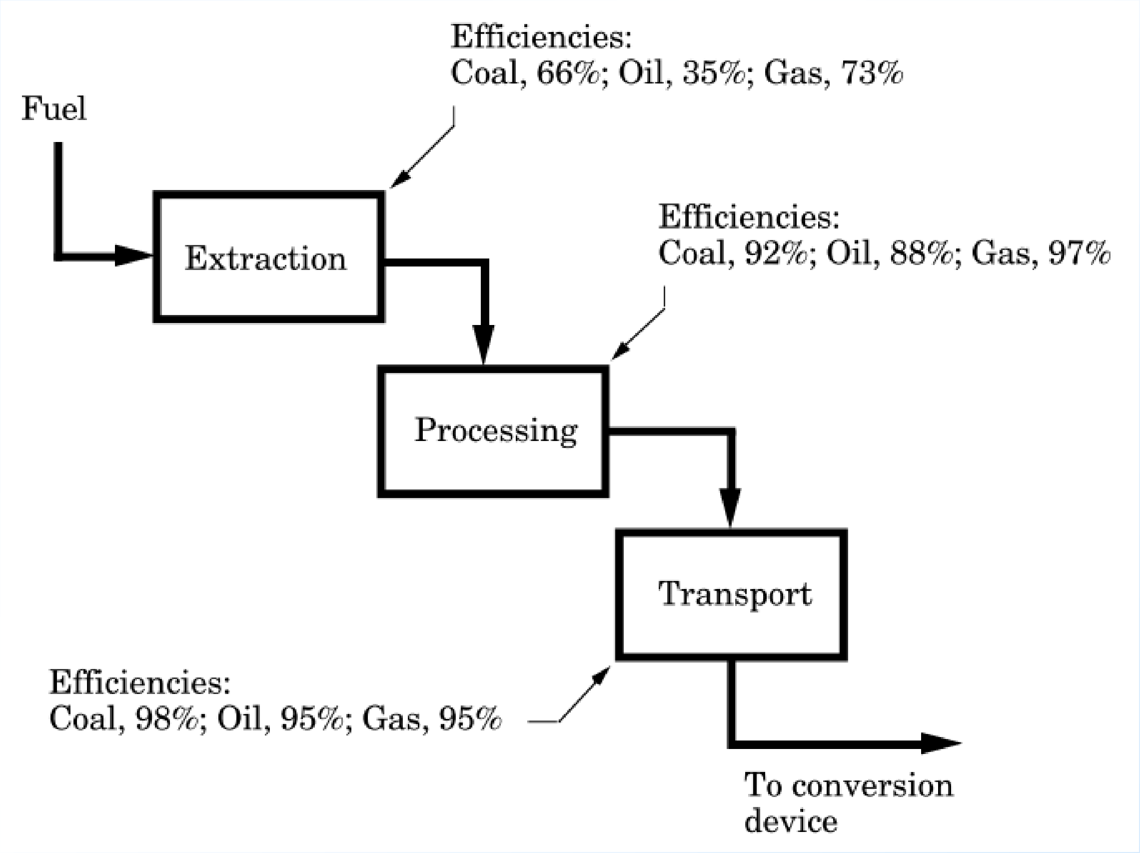
The meaning of this number is that for every watt of electric power used to drive this heat mover, 6.6 Watts of heat are delivered to the high-temperature reservoir (air in the kitchen) and 5.6 Watts are extracted from the low-temperature reservoir (refrigerator).

Comparison of Efficiencies

Let us consider the case of electric home heating using different primary energy sources. We have a common useful energy output (electric home heating), and we are evaluating the most important alternatives available as energy input (coal, petroleum and natural gas)



Now, before we can use these primary sources in a power plant, they need to be extracted from the earth, processed and transported. The efficiencies of each one of these operations are different and their estimates are shown in the Figure.



Once these fuels reach the power plant, the efficiency of conversion of their chemical energy to electricity is approximately the same, if the power plant is designed to burn that particular fuel.

Once produced at the power plant, electricity needs to be transported to our homes. The efficiency of this operation is relatively high, say, about 90%. When it reaches our homes, electricity is converted to heat at 100% efficiency because this is a conversion of low-entropy energy to high-entropy energy. So the overall (system) efficiencies for the three cases considered are calculated as follows:

$$\eta_{coal} = \eta_{extraction}\ \eta_{processing}\ \eta_{transport}\ \eta_{power\ plant}\ \eta_{transmission}\ \eta_{electric\ heater}$$

$$= (0.66)\ (0.92)\ (0.98)\ (0.35)\ (0.90)\ (1.0)$$

$$= 0.19 \quad (19\ \%)$$

$$\eta_{oil} = \eta_{extraction}\ \eta_{processing}\ \eta_{transport}\ \eta_{power\ plant}\ \eta_{transmission}\ \eta_{electric\ heater}$$

$$= (0.35)\ (0.88)\ (0.95)\ (0.35)\ (0.90)\ (1.0)$$

$$= 0.09 \quad (9\ \%)$$

$$\eta_{gas} = \eta_{extraction}\ \eta_{processing}\ \eta_{transport}\ \eta_{power\ plant}\ \eta_{transmission}\ \eta_{electric\ heater}$$

$$= (0.73)\ (0.97)\ (0.95)\ (0.35)\ (0.90)\ (1.0)$$

$$= 0.21 \quad (21\ \%)$$

These results mean that in our homes we have available only 21, 19 and 9 % of the chemical energy of natural gas, coal and petroleum, respectively. The rest is wasted.

From this simple analysis, we can reach an important conclusion about the use of coal, oil and natural gas in power plants (if the efficiencies given in the Figure are correct). Primarily because of the low thermodynamic efficiency of oil extraction (35%, compared to 66 and 73% for extraction of coal and natural gas), it makes more (technical) sense to use coal or natural gas than to use oil. This is the conclusion that a utility executive would reach if he or she were concerned about the optimum allocation of fossil fuels.

Vilfredo Pareto

1848 – 1923)

Pareto efficiency (or Pareto optimality) is an important efficiency concept in economics used to evaluate or compare different allocations of resources, named after Italian economist Vilfredo Pareto (1848–1923). An allocation of resources is Pareto efficient if it cannot be modified to increase the wellbeing of one individual without diminishing the wellbeing of any other individual. If it is possible to reallocate resources and improve the welfare of one person without harming anyone else, this reallocation is an efficiency improvement and consequently the initial allocation was not Pareto efficient.

See: https://inomics.com/terms/pareto-efficiency-1441708

See ‘’odtuclass’’ for review of **unit systems** used in energy conversion processes.

Read the article on **efficiency of energy conversion** on ‘’odtuclass’’.

Distinquish between **efficiency** and **effectiveness**. See the table of differences on ‘’odtuclass’’.

See ‘’odtuclass’’ for more problems on ‘’Introduction’’.

Efficiency refers to the ability to produce maximum output from the given input with the least waste of time, effort, money, energy and raw materials. It can be measured quantitatively by designing and attaining the input-output ratios of the company's resources like funds, energy, material, labor, etc.

Effectiveness refers to the extent to which something has been done, to achieve the targeted outcome. It means the degree of closeness of the achieved objective with the predetermined goal to examine the potency of the whole entity.

For instance, using a car is a rather effective way of transportation. But, it is not efficient at all. Very often, efficiency and effectiveness are mutually exclusive.