ENE 101: Introduction to Energy Engineering

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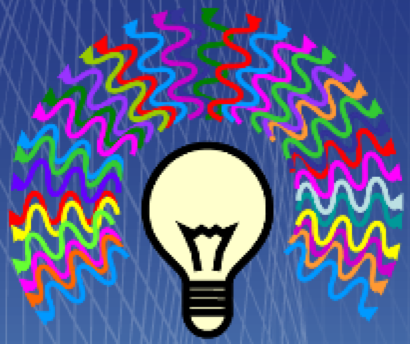


Week 6: Energy consumption and conversion

Energy Conversion Engineering

Energy conversion engineering (or heat-power engineering, as it was called prior to the Second World War), has been one of the **central themes** in the development of the engineering profession.

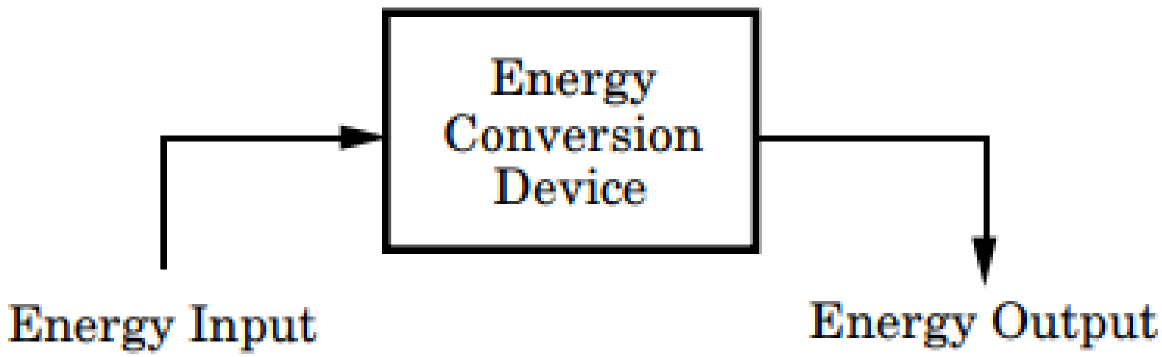
It is concerned with the transformation of energy from **sources** such as fossil and nuclear fuels and the sun into **conveniently used forms** such as electrical energy, rotational and propulsive energy, and heating and cooling.

Energy Conversion Devices and Their Efficiency

A device is a piece of equipment that serves a specific purpose. **An energy conversion device converts one form of energy into another.** It is an important element of progress of society. In fact, one can discuss the history of civilization in terms of **landmarks in the development of energy conversion devices**, as illustrated below:

Landmark Event	*Approximate Date*
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.

Schematic representation of an energy conversion device.



Energy Output = Energy Input (1st Law)

Useful Energy Output Energy Input (2nd Law)

The efficiency of an energy conversion device is a **quantitative expression** of this balance between energy input and energy output. It is defined as follows:

$$\text{Device efficiency} = \frac{\text{Useful energy output}}{\text{Energy input}}$$

The key word in the above definition is ‘**useful**’. The first law of thermodynamics tells us that energy is conserved in all its transformations. So the ratio of energy output to energy input is always unity, or 100%.

The meaning of the word ‘useful’ depends on the **purpose of the device**. For example, if the device is an electric heater, the useful energy output is heat, and the energy input is electricity. Electricity is converted to heat. Heat is also obtained from electricity in a light bulb, as we well know. But this is not the useful energy obtained from a light bulb; the purpose of a light bulb is to convert electricity into light.

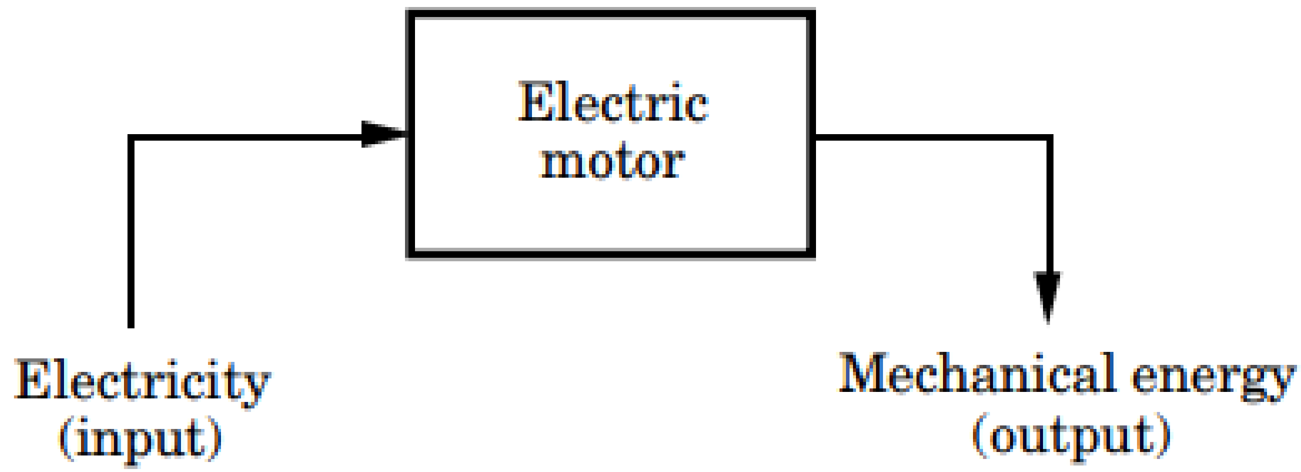


FIGURE 4-2. Energy conversion in an electric motor (electric-to-mechanical).

Illustration 4-1. An electric motor consumes 100 watts (W) of electricity to obtain 90 watts of mechanical power. Determine its efficiency (E).

Solution.

Because power is the rate of energy utilization, efficiency can also be expressed as a power ratio. The time units cancel out, and we have

$$\text{Efficiency} = \frac{\text{Useful energy output}}{\text{Energy input}} = \frac{\text{Useful power output}}{\text{Power input}}$$

Therefore, the efficiency of this electric motor is:

$$E = \frac{\text{Mechanical energy (power) output}}{\text{Electric energy (power) input}} =$$

$$= \frac{90\ \text{W}}{100\ \text{W}} = \frac{90\ \frac{\text{J}}{\text{s}}}{100\ \frac{\text{J}}{\text{s}}} = \frac{90\ \text{J}}{100\ \text{J}} = 0.9 = 90\%$$

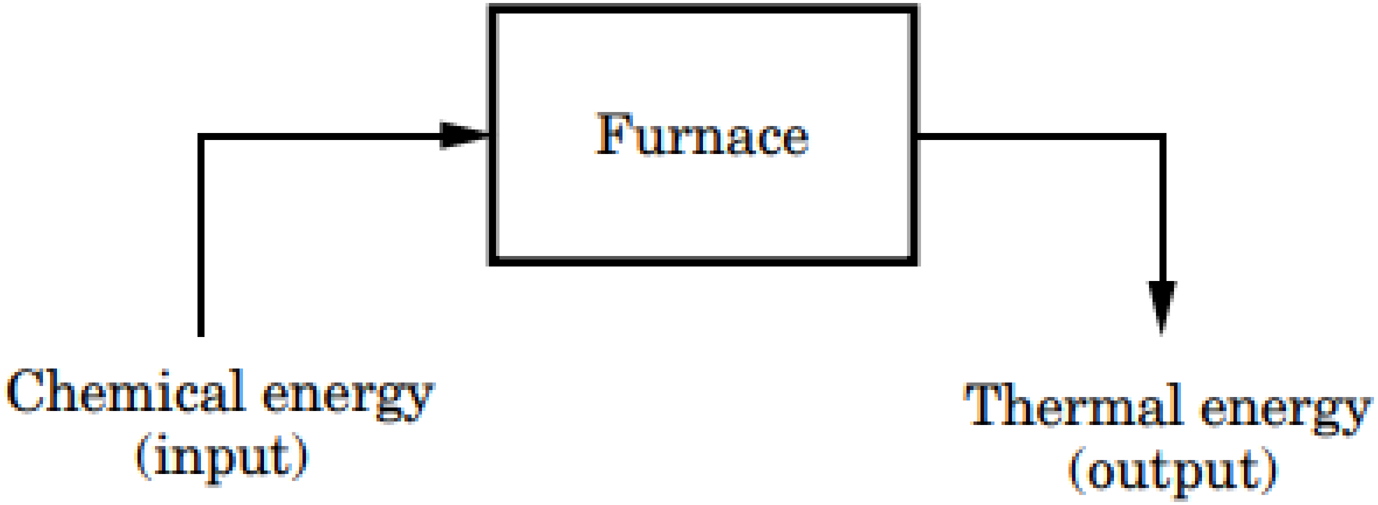


FIGURE 4-3. Energy conversion in a furnace (chemical-to-thermal).

Illustration 4-2. A gas furnace has an efficiency of 75%. How many BTU will it produce from 1000 BTU of natural gas.

Solution.
The function of a gas furnace is to convert the chemical energy of the gas into heat (thermal energy), as shown in Table 4-1 and illustrated in Figure 4-3.

Therefore, we have:

$$\text{Useful energy output} = [\text{Energy input}]\,[\text{Efficiency}]$$

$$= [1000\ \text{BTU (chemical energy)}]\left[\frac{75\ \text{BTU (thermal energy)}}{100\ \text{BTU (chemical energy)}}\right]$$

$$= 750\ \text{BTU (thermal energy)}$$

The concept of efficiency thus embodies both laws of thermodynamics. It reflects the quantitative equality and the qualitative difference of the various energy forms. Its understanding requires some knowledge of thermodynamics; once understood, it is only this concept – from the entire field of thermodynamics – that is necessary for understanding the principal energy issues facing society today.

TABLE 4-1
Tasks performed by common energy conversion devices

Energy Conversion Device	Energy Input	Useful Energy Output
Electric heater	Electricity	Thermal energy
Hair drier	Electricity	Thermal energy
Electric generator	Mechanical energy	Electricity
Electric motor	Electricity	Mechanical energy
Battery	Chemical energy	Electricity
Steam boiler	Chemical energy	Thermal energy
Furnace	Chemical energy	Thermal energy
Steam turbine	Thermal energy	Mechanical energy
Gas turbine	Chemical energy	Mechanical energy
Automobile engine	Chemical energy	Mechanical energy
Fluorescent lamp	Electricity	Light
Silicon solar cell	Solar energy	Electricity
Steam locomotive	Chemical	Mechanical
Incandescent lamp	Electricity	Light

Efficiency Definitions

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

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

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

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

Efficiency Definitions

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

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

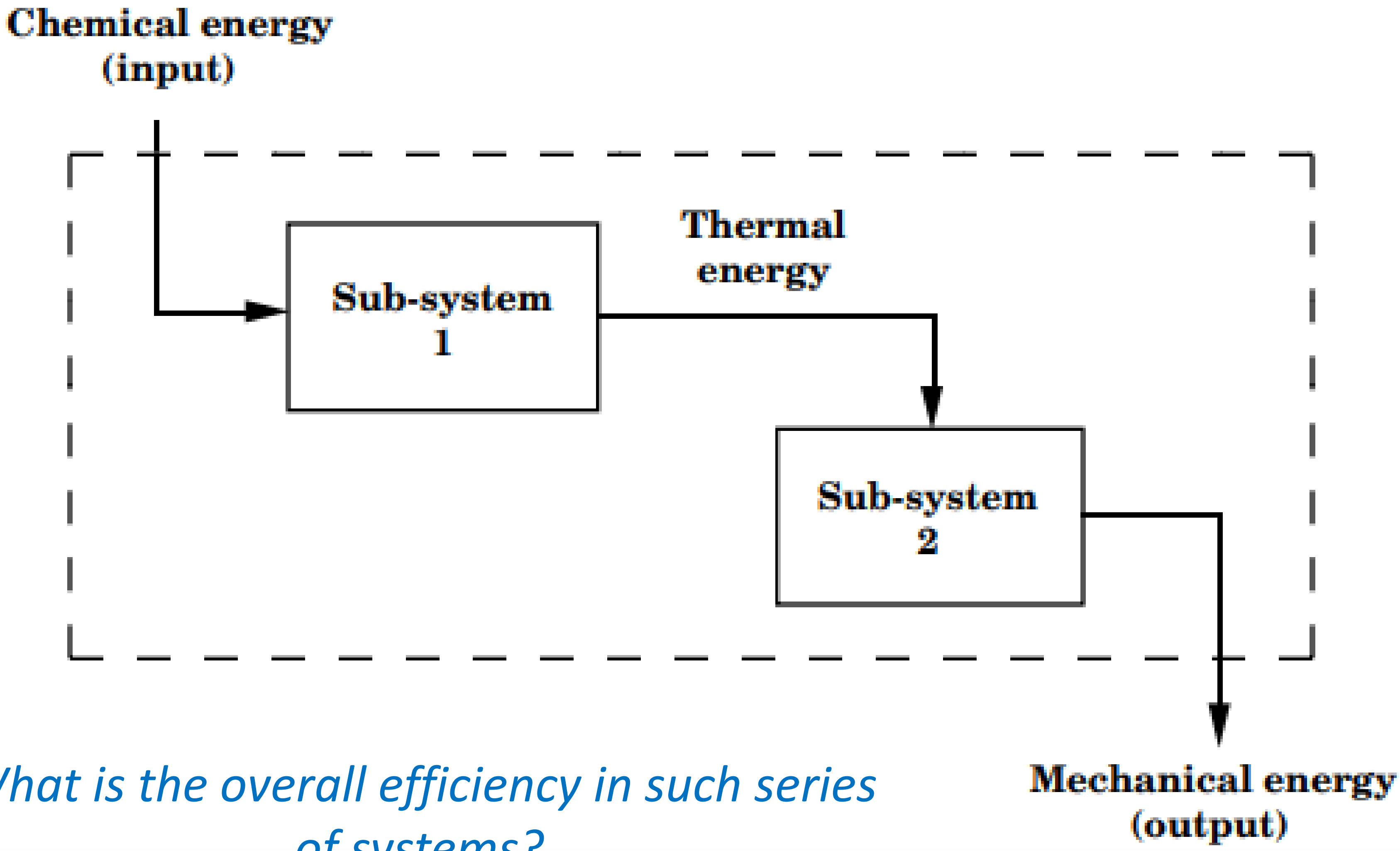
automotive transmission: $\eta = \frac{\dot{W}_m}{\dot{W}_m} \equiv \frac{\text{mechanical energy out}}{\text{mechanical energy in}}$

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

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

Energy conversion in a heat engine



What is the overall efficiency in such series of systems?

Illustration 4-3. Calculate the efficiency of a power plant if the efficiencies of the boiler, turbine and generator are 88, 40 and 98%, respectively.

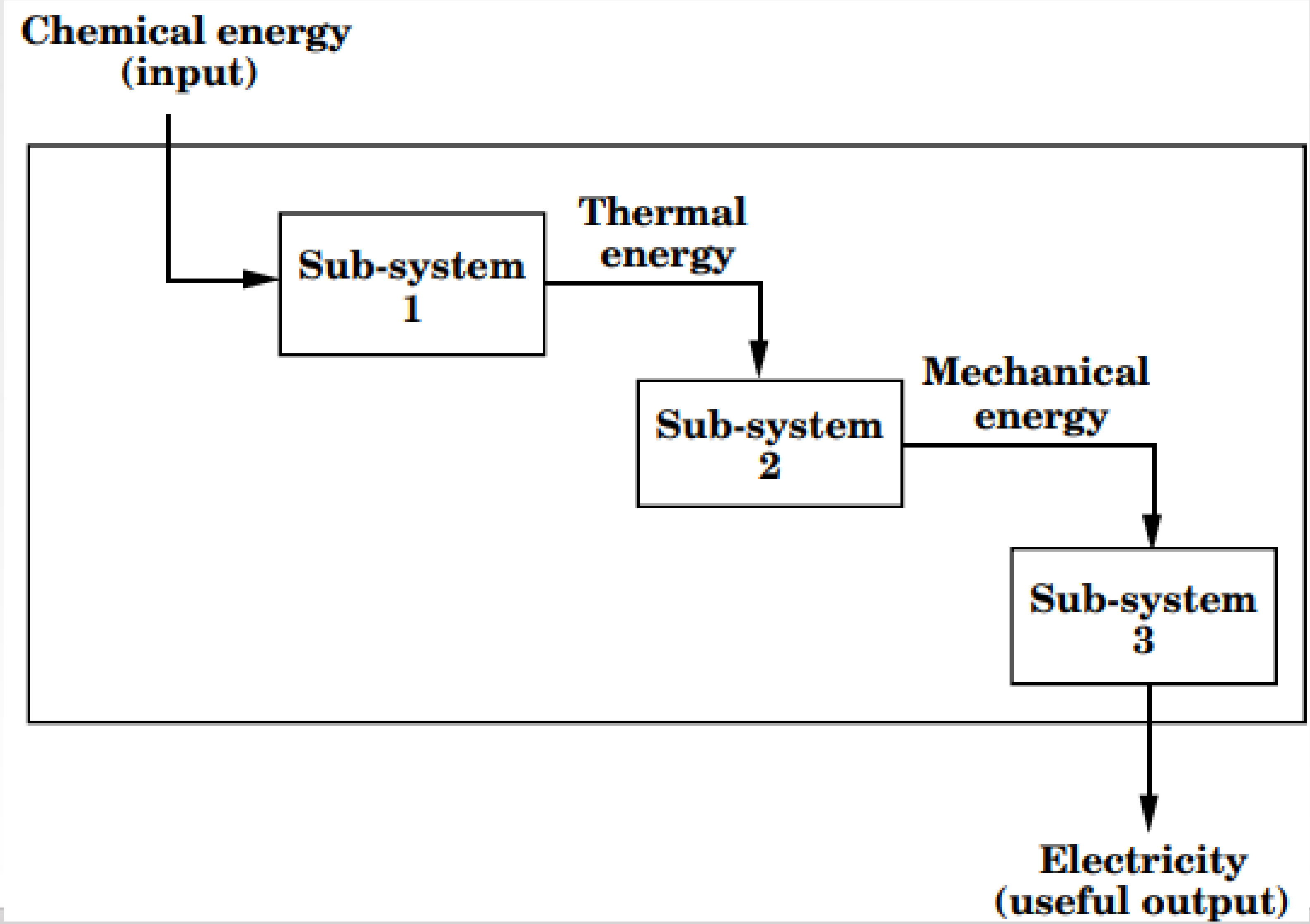
Solution.

$$E_{power\ plant} = [E_{boiler}]\ [E_{turbine}]\ [E_{generator}] =$$

$$= (0.88)\ (0.40)\ (0.98) = 0.35\ (35\%)$$

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).

Energy conversion in an electric power plant.



One of the most important energy conversion systems in our modern society is the electric power plant. The chemical energy is first converted to thermal energy in the boiler; thermal energy is then converted to mechanical energy in the turbine; finally, mechanical energy is converted to electricity in the generator. System efficiency is, therefore,

$$E_{\text{power plant}} = [E_{\text{boiler}}]\,[E_{\text{turbine}}]\,[E_{\text{generator}}] =$$

$$= \left[\frac{\text{Thermal energy}}{\text{Chemical energy}}\right]\left[\frac{\text{Mechanical energy}}{\text{Thermal energy}}\right]\left[\frac{\text{Electric energy}}{\text{Mechanical energy}}\right] = \frac{\text{Electric energy}}{\text{Chemical energy}}$$

FIGURE 4-8. Energy conversion (from potential to kinetic) in a water wheel.

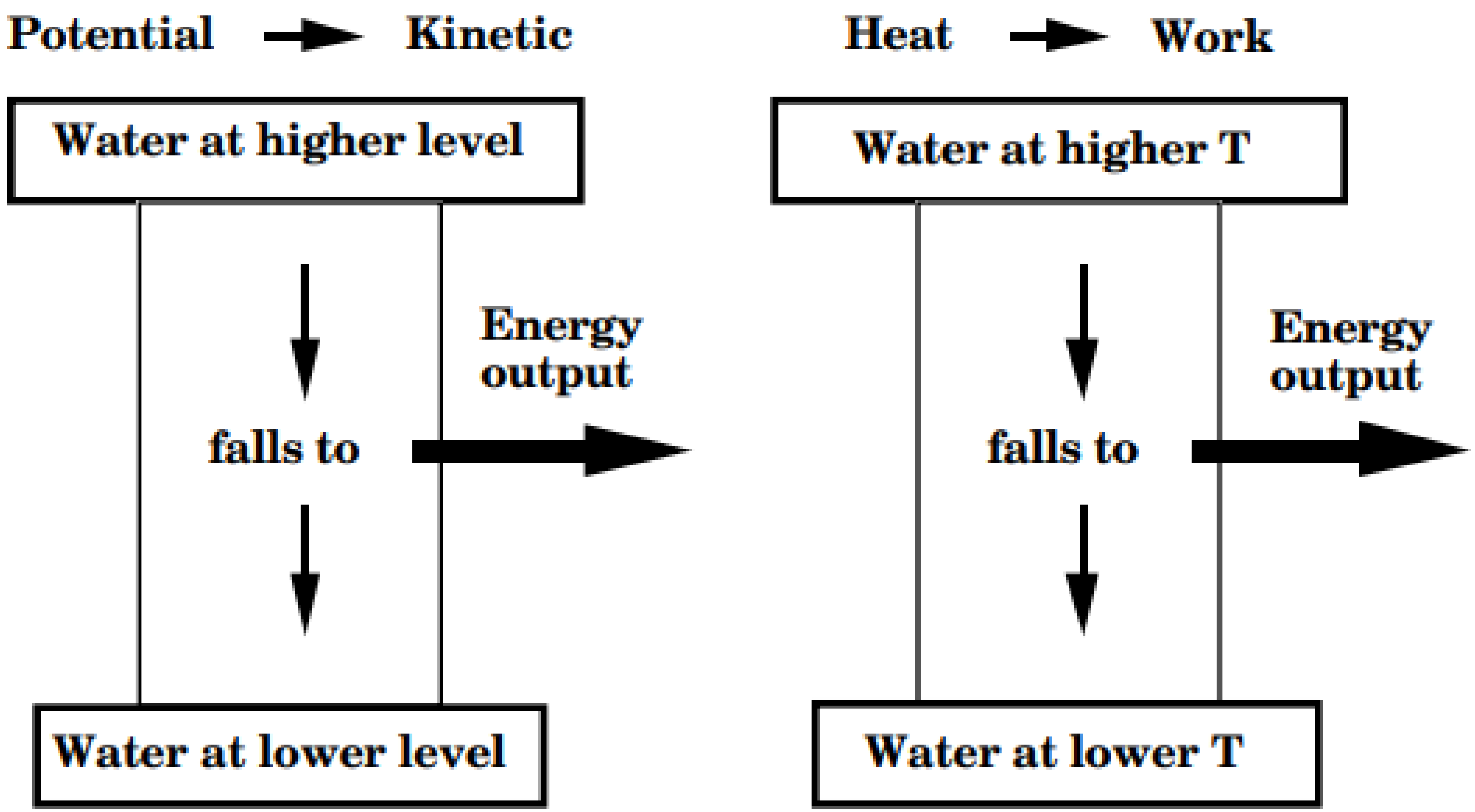


FIGURE 4-9. Analogy between energy conversion in a water wheel and a heat engine.

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

Conversion Processes

Indirect: Multi-step conversion process

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

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

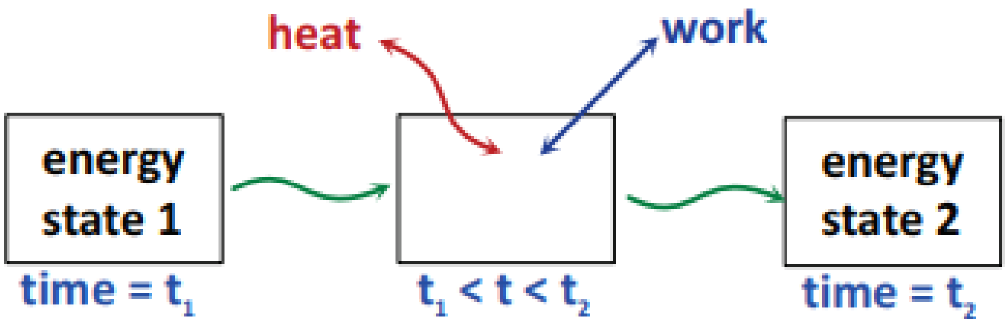
- Brayton cycle (gas), gas turbine, turbojets:

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

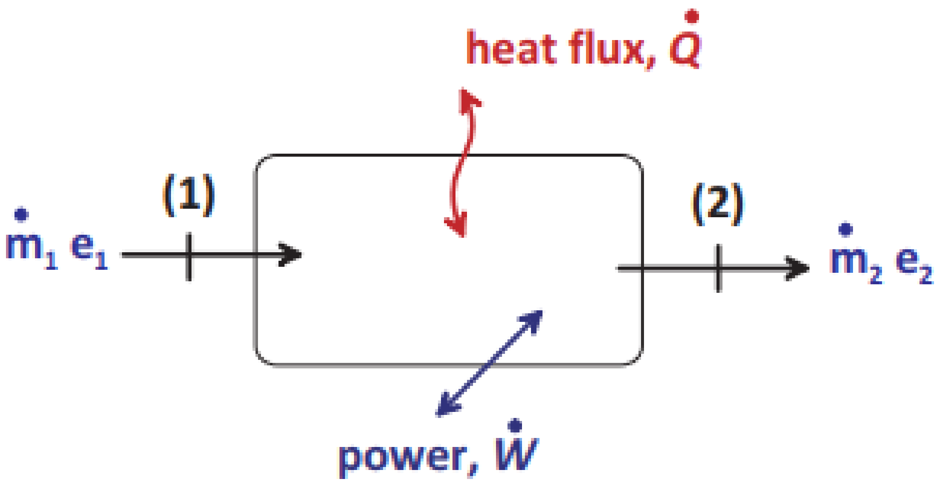
- $$\left(\begin{array}{c}\text{wind turbine}\\ \text{wave energy}\\ \text{tidal energy}\end{array}\right) \text{mechanical} \longrightarrow \text{mechanical} \longrightarrow \text{mechanical} \longrightarrow \text{electrical}$$

Energy Balance

Closed System – no mass flow in or out of system



Open System – mass flow in and/or out of system



Steady Energy Balance

For a steady-state, open system:

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

ΔQ:	heat **into** system	E_p:	potential energy $= mzg/g_c$
ΔW:	work **produced** by system	E_k:	kinetic energy $= mV^2/2g_c$
ΔE:	change in system energy	E_i:	internal energy $= mu$
		E_f:	flow energy $= P\forall = mP/\rho$

This is the first law of thermodynamics, which is really:

change in transitional energy $\Longleftrightarrow$ change in stored energy

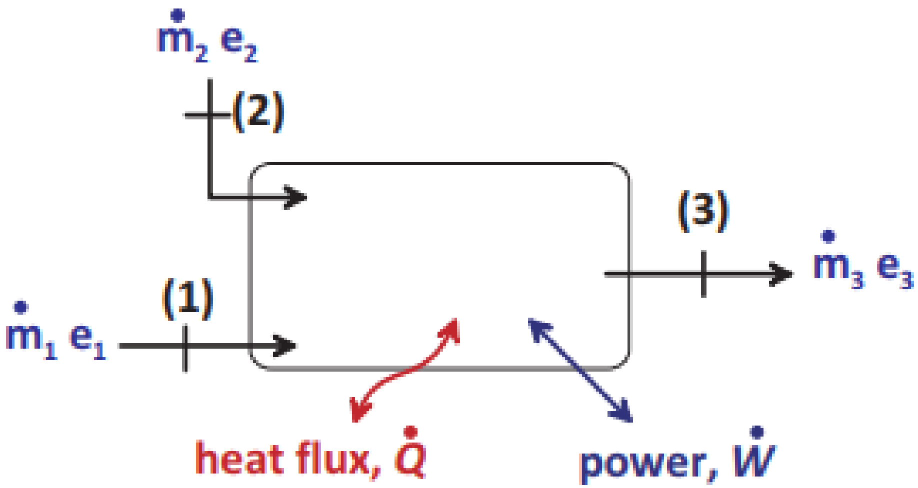
Steady implies that there is no energy or mass accumulation within the system. That is different than the exchange of energy in the mass which passes through the system. The mass which passes through may accumulate energy.

The 1st Law of Thermodynamics applies to the fluid!

First Law of Thermodynamics

Steady, rate form of the 1st Law:

$$\sum \dot{Q} - \sum \dot{W} = \sum_{\text{out}} \dot{m}e - \sum_{\text{in}} \dot{m}e \qquad (1)$$



Heat ($\dot{Q}$) & Work ($\dot{W}$)

Not the same as useful heat and work

Heat and work are balanced by changes in stored energy in the fluid.

References

Book Chapter Links:

- http://pages.mtu.edu/~jstallen/courses/MEEM4200/lectures/Part01_Energy_Introduction_2016_v11.pdf
- https://www.ems.psu.edu/~radovic/Chapter4.pdf
- http://www.personal.utulsa.edu/~kenneth-weston/chapter1.pdf
- https://www.saylor.org/content/weston_energy/Energy_Conversion.pdf

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