Energy Transfer and Conversion Methods

MIT 10.391J/22.811J/ESD.166J/11.371J/1.818J/3.564J/2.65J

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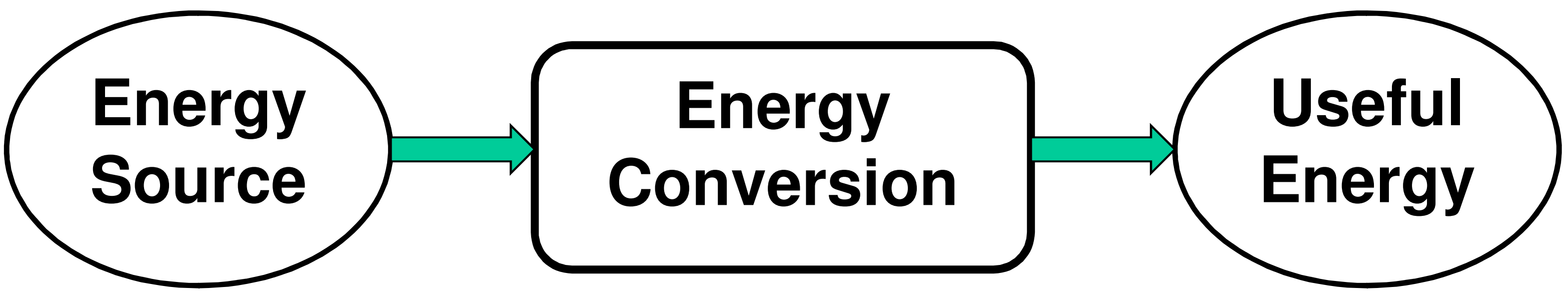
Mission of this Session

- Introduce the importance and challenges of Energy Conversion
  - Diffuse energy sources
  - Thermodynamic limits
  - Rate processes

Energy Conversion

- Energy Conversion is the process of changing energy from one form to another



Historic Energy Conversion Sequences

- Biomass → heat (esp. cooking)
- Solar → heat, dry clothes, dry food
  - Solar is still main light source, no need for conversion
  - Solar is source of biomass, wind, hydro, etc.
- Biomass → farm animals → horsepower, food

Later, people also did these conversions:

- Coal → heat
- Hydro → milling flour, running machinery
- Wind → pump water

Modern Energy Conversion Sequences

Heating of Buildings:

- Gas, oil, biomass → heat
- Solar → heat

Electricity Generation:

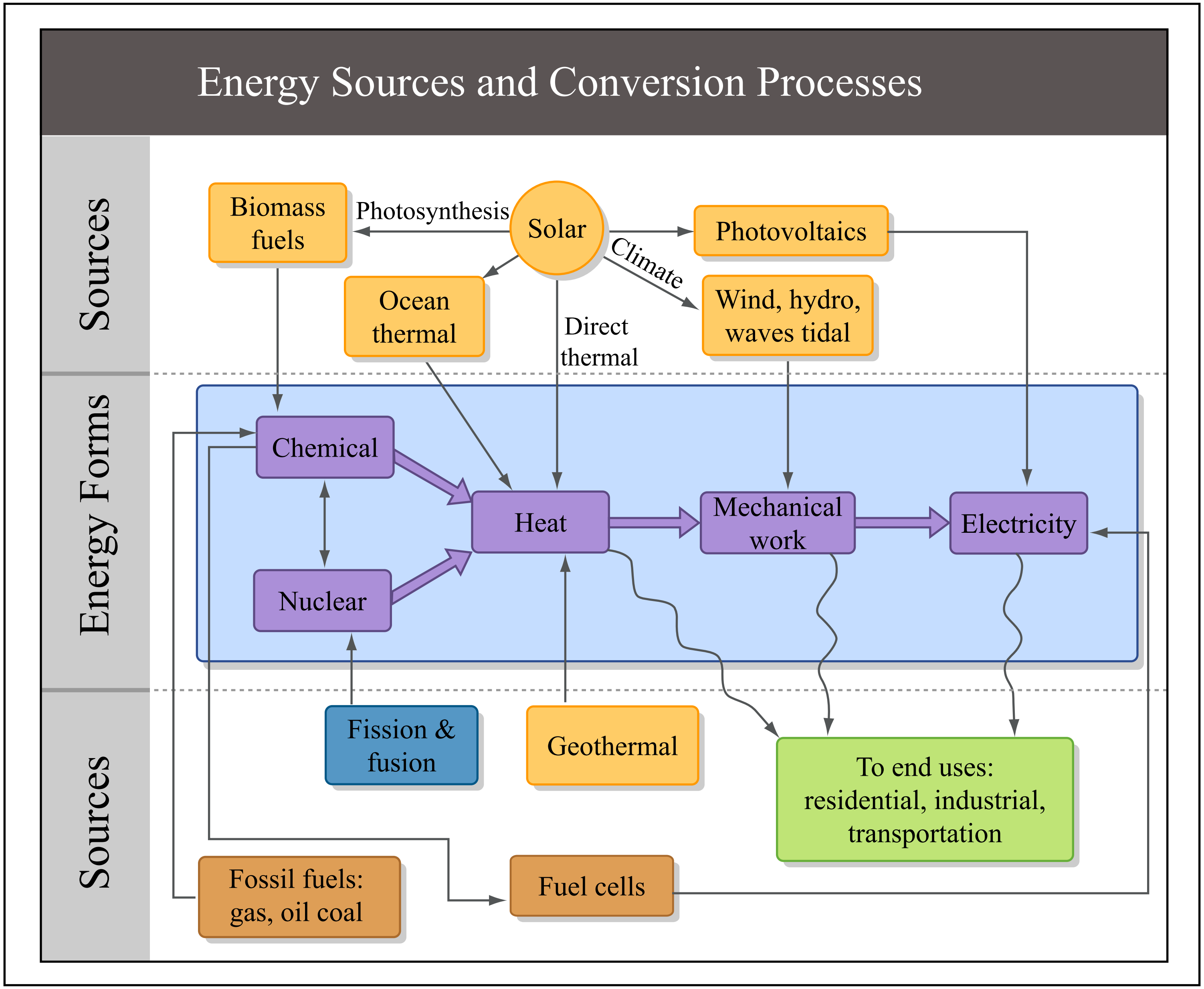
- Coal, gas, nuclear → heat → mechanical → electricity
- Hydro → mechanical → electricity
- Wind → mechanical → electricity
- Solar → Electricity

Transportation:

- Oil → gasoline, diesel, jet fuel → heat → mechanical
- Biomass → ethanol → heat → mechanical
- Fuel cell cars: Gas → hydrogen → electricity → mechanical
- Hybrid cars: Gasoline → mechanical → electricity → battery → electricity → mechanical

Energy Sources

Type of Energy	**Examples**
Potential Energy	Hydro
Kinetic Energy	Wind, Tidal
Thermal Energy	Geothermal, Ocean Thermal
Radiant Energy	Solar
Chemical Energy	Oil, Coal, Gas, Biomass
Nuclear Energy	Uranium, Thorium



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Scales of energy flows

cell phone	2 W
laptop computer	10 W
human body (2000 Calorie diet)	100 W
1 horsepower	750 W
hair dryer	1,500 W
automobile	130,000 W
1 wind turbine	2,000,000 W (2 MW)
757 jet plane	5,000,000 W (5 MW)
Large power plant	1,000,000,000 W (1 GW)
Global energy use	15,000,000,000,000 W (15 TW)
Global heat accumulation	816,000,000,000,000 W (816 TW)
Global renewable energy flow	9E16 W (90,000 TW)

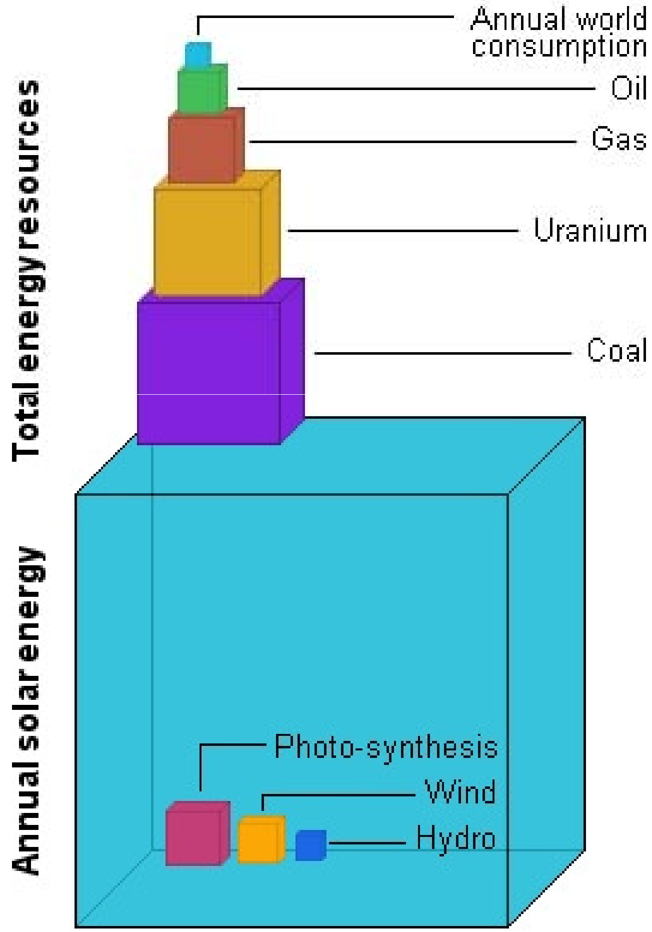
Energy versus Power

Energy E (in BTU, joules(J) or cal)
Power $P = dE/dt$ (BTU/hr, Watts(W))
1 Watt = 1 Joule/Second

Heat Flows versus Work

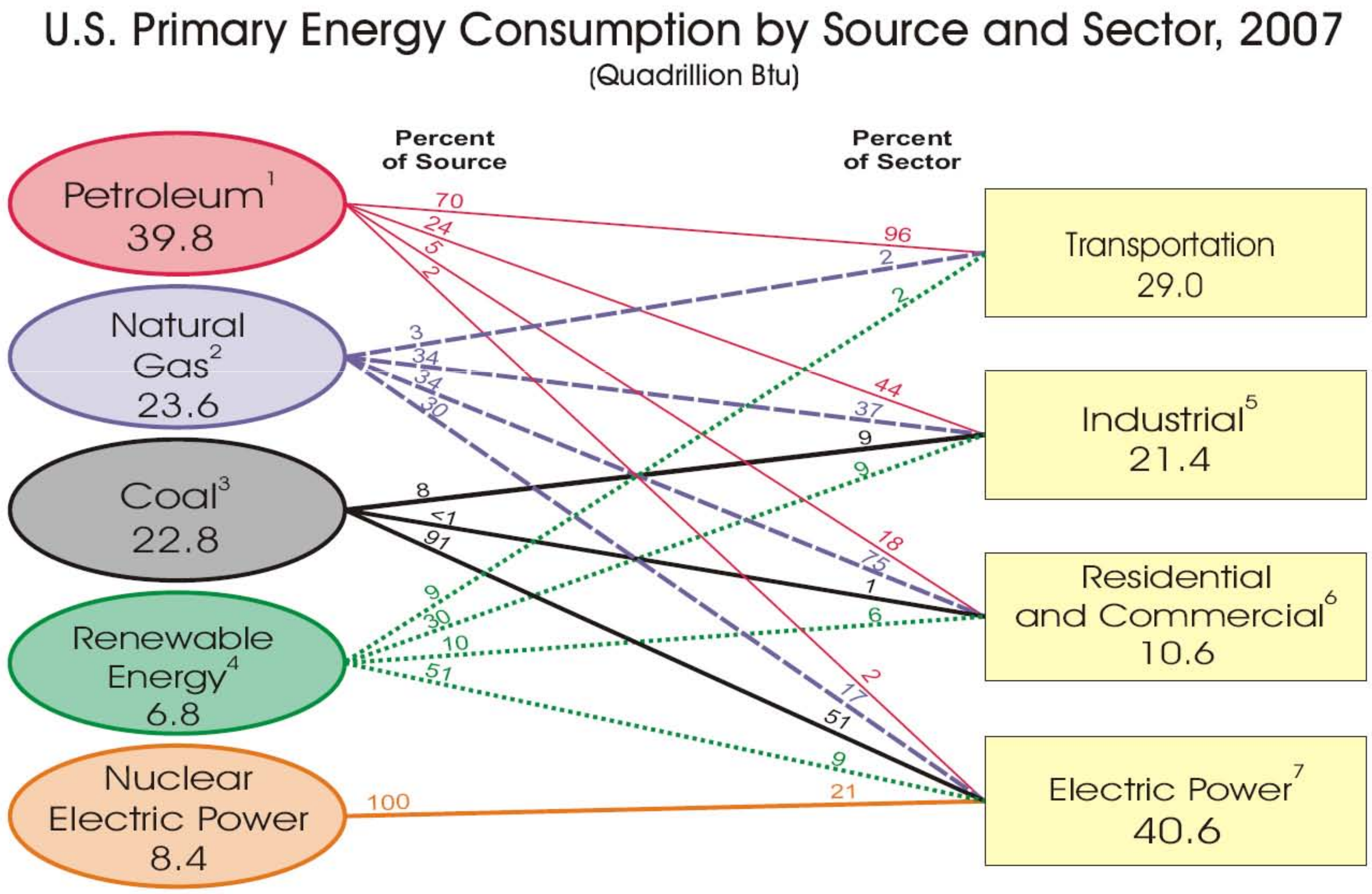
Energy per time can be used to describe heat flow and work but to distinguish between these energy flows we use notation:
thermal – t or th and electric – e
MW_{th} and MW_e

Order of Magnitude of Energy Resources



Source: World Energy Council

Energy Supply – USA Sources



Source: Energy Information Administration, Annual Energy Review 2007

Important Metrics

Energy Sources

- Specific Energy (MJ/kg)
- Energy Density (MJ/L)
- Phase
- Impurities
- Cost

Conversion Method

- Conversion Efficiency
- Form of energy product
- CO_2 generation
- Water usage
- Land usage
- Cost

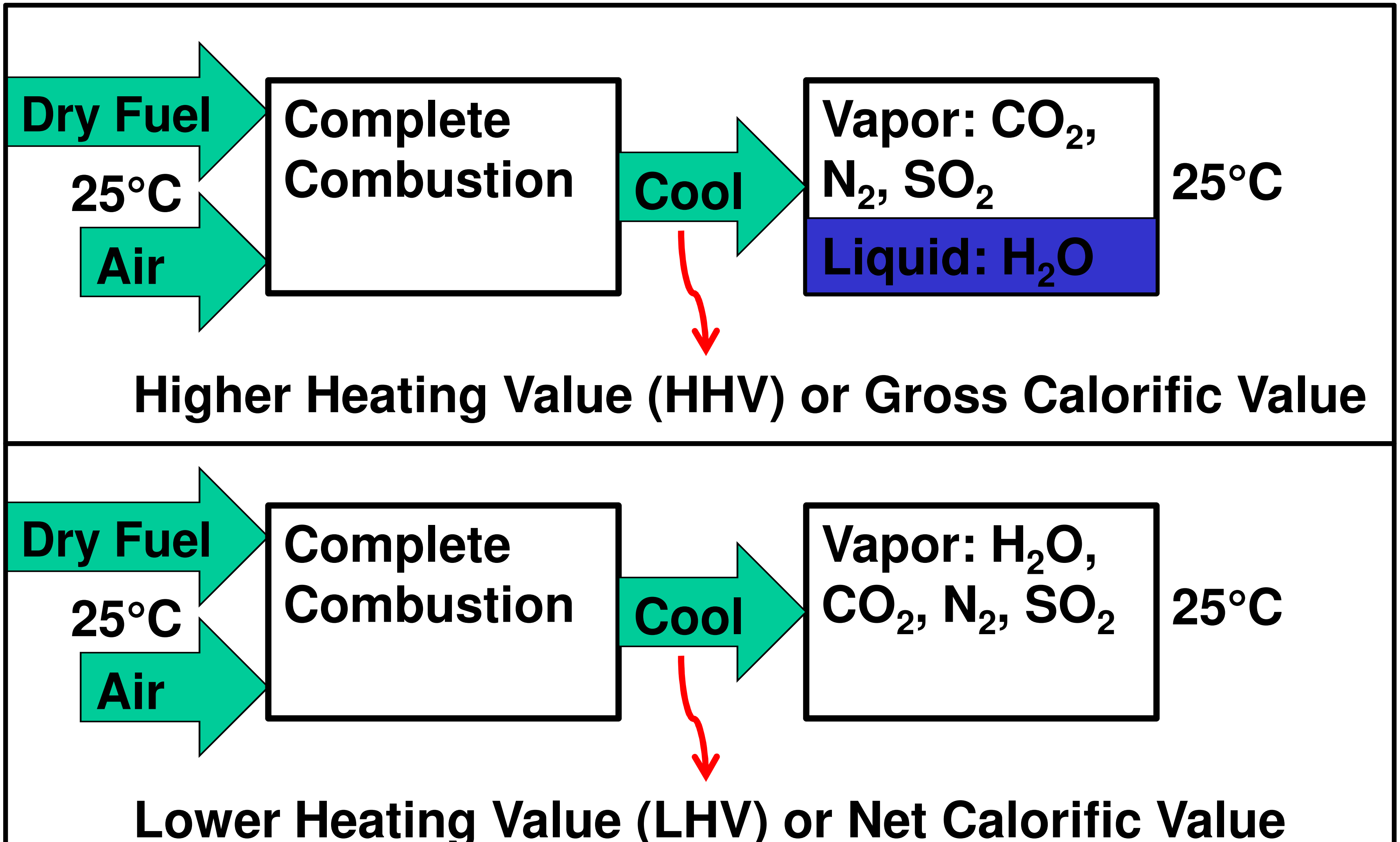
Typical Specific Energy Values

Fuel	Higher Heating Value (MJ/kg)
Hydrogen	141.8
Methane	55.5
Gasoline	47.3
Diesel	44.8
Bituminous coal	31.0
Lignite	25.1
Douglas Fir Wood	20.4
Corn Stover	17.8
Bagasse	17.3
Wheat Straw	17.0
Animal Waste	13.4
Sewage Sludge	4.7

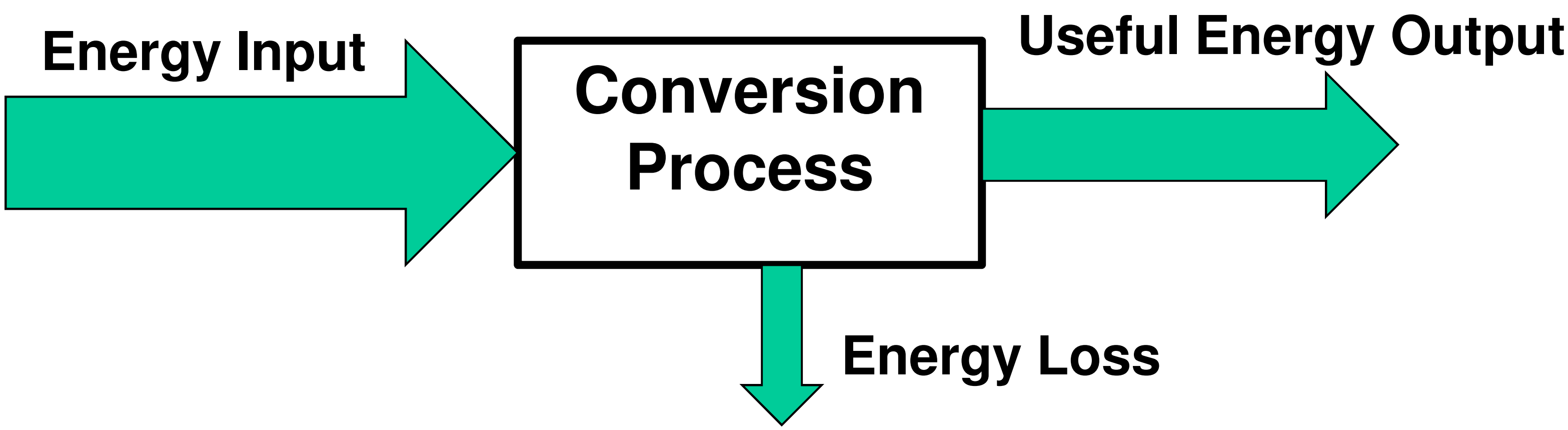
Channiwala, et al. 2002 and NIST Chemistry WebBook

Energy Content of Fuels

Energy content of fuel is characterized by the heat produced by burning



Key Metric: Conversion Efficiency

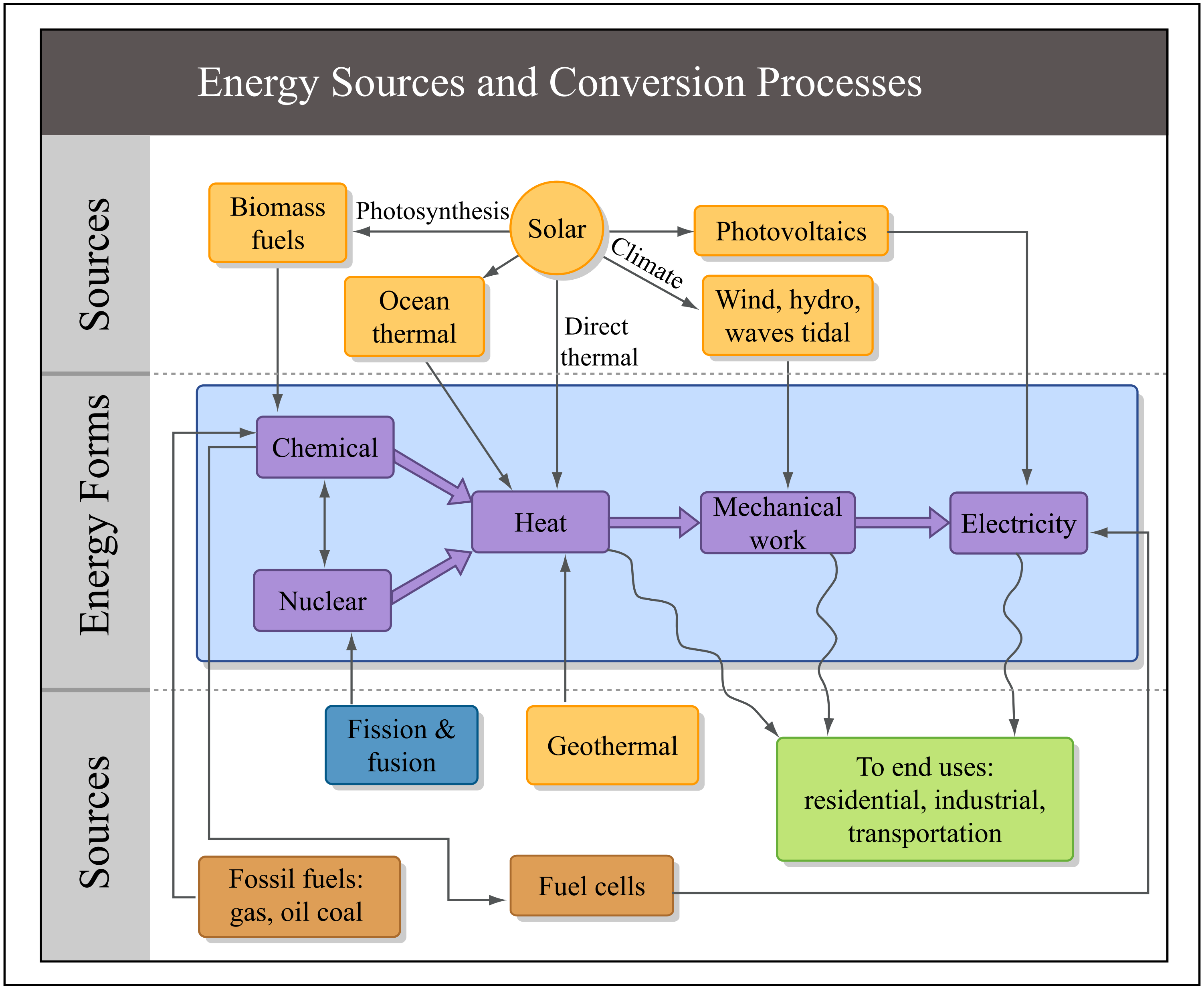


- When producing work (mechanical or electricity):

  η = Work Output / Energy Input

- When producing energy carriers (diesel, hydrogen):

  η = Energy Content of Product / Energy Input



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Conversion Efficiencies

Conversion	Type	Efficiencies
Natural Gas Furnace	Chemical $\rightarrow$ Heat	90-96%
Internal combustion engine	Chemical $\rightarrow$ Mechanical	15-25%
Power Plant Boilers	Chemical $\rightarrow$ Heat	90-98%
Steam Turbines	Heat $\rightarrow$ Mechanical	40-45%
Electricity Generator	Mechanical $\rightarrow$ Electricity	98-99%
Gas Turbines	Chemical $\rightarrow$ Mechanical	35-40%
Hydro	Grav. Potential $\rightarrow$ Mechanical	60-90%
Geothermal	Thermal$\rightarrow$ Mech$\rightarrow$ Electricity	6-13%
Wind	Kinetic $\rightarrow$ Mech$\rightarrow$ Electricity	30-60%
Photovoltaic Cells	Radiation $\rightarrow$ Electricity	10-15%
Ocean Thermal	Thermal$\rightarrow$ Mech$\rightarrow$ Electricity	1-3%

Source: Sustainable Energy

Overall Efficiency includes Steps Upstream & Downstream of the Energy Conversion System

A linked or connected set of energy efficiencies from extraction to use:

$$Overall\ efficiency = \eta_{overall} = \prod_{i=1}^{n} \eta_i$$

$$\eta_{overall} = \eta_{gas\ extraction}\eta_{gas\ processing}\eta_{gas\ transmission}\eta_{power\ plant}\eta_{electricity\ transmission}\eta_{distribution}\eta_{motor}$$

Key Efficiencies include:

- Fuel production
- Fuel Transport
- Transmission
- Energy Storage

for example compressed air energy storage (CAES):

$$\eta_{overall} \equiv \frac{Work\ output}{Work\ input} = \frac{W_{turbine}}{W_{compressor}} = \eta_{turbine}\eta_{compressor}$$

Energy Conversion

- Laws of Thermodynamics provide limits
- Heat and work are not the same
  - They are both energy, but..
  - …cannot convert all heat to work
- Each conversion step reduces efficiency
- Maximum work output only occurs in idealized reversible processes
- All real processes are **irreversible**
- Losses always occur to degrade the efficiency of energy conversion and reduce work/power producing potential

In other words – You can't win or even break even in the real world

Rate Processes in Energy Conversion

- Heat Transfer
- Mass Transfer
- Chemical Reactions

Fluxes of heat, material, electrons must be driven by gradients in free energy

- Fourier's law of heat conduction $q = -k\dfrac{dT}{dx}$

- Fick's law of diffusion $j = -D\dfrac{dC}{dx}$

- Fluid mechanics $Flow\,in\;\;pipe = -\dfrac{2\rho D^2}{\mu f\,\mathrm{Re}}\dfrac{dP}{dx}$

- Ohm's law of current flow $\dfrac{I}{A} = -\sigma\dfrac{dV}{dx}$

Consequence: the heat arrives at lower T, the mass arrives at lower P, the electrons arrive at lower V, etc.: "Losses"

Heat Transfer

- For heat to be transferred at an appreciable rate, a temperature difference (Δ T) is required.
  - $Q = U A \Delta T$

- The non-zero Δ T guarantees irreversibility
- As Δ T does to zero, area and cost goes to infinity

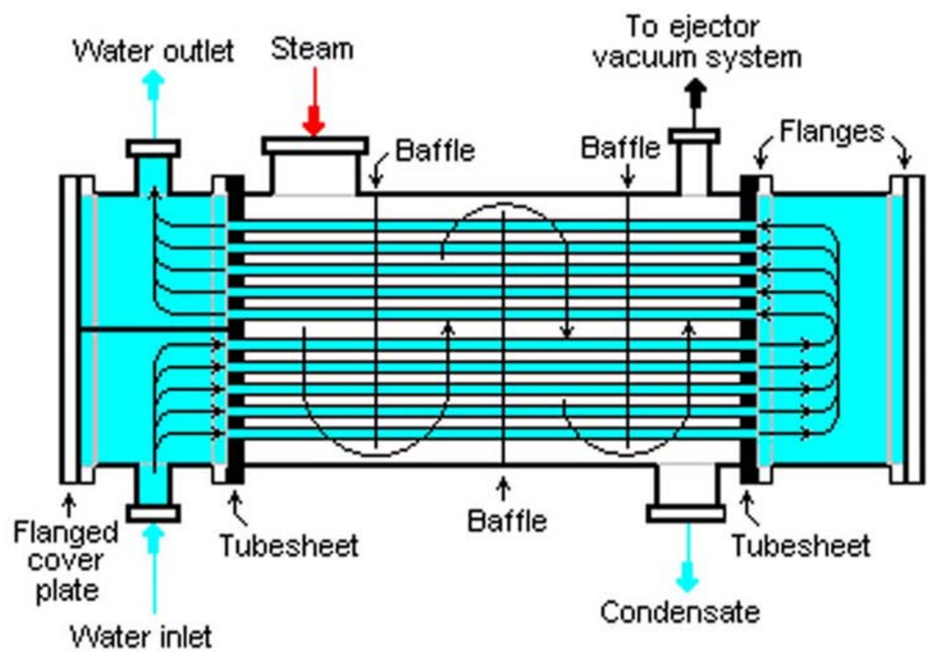


Image by Mbeychok on Wikimedia Commons.

Heat exchangers

- Many varieties of heat exchangers used in energy conversion
  - Heat recovery steam generators (HRSG)
  - Air-cooled condensers
  - Shell-and-tube exchangers
  - Plate-fin exchangers
  - Cooling Tower

Humanity's Main Energy Source: Chemical reactions

- Virtually all fossil fuels and biofuels are converted to useful energy via chemical reactions at a rate of ~13 TW
- Energy released by conversion reactions can be converted to mechanical energy or electricity
- Some reactions are used to convert a primary energy sources to more useful forms of chemically stored energy
  - Solid fossil fuels → Liquid fuels
  - Natural Gas → Hydrogen
  - Biomass → Liquid fuels

Chemical Reactions

Chemical reactions either require or release heat.

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$ ΔH_{rxn} = -890 kJ/mol

Exothermic reaction: one that gives off energy. $\Delta H_{rxn} < 0$.
Endothermic reaction: one that requires energy. $\Delta H_{rxn} > 0$.

Except in unusual situations (e.g. fuel cells, chemiluminescence) essentially all of the ΔH_{rxn} is released or supplied as heat.

Examples of Energy Conversion Reactions

Fuel combustion

- $CH_4 + 2\,O_2 = CO_2 + 2\,H_2O$ – natural gas
- $C_8H_{12} + 11\,O_2 = 8\,CO_2 + 6\,H_2O$ – gasoline
- $C_6H_{12}O_6 + 6\,O_2 = 6\,CO_2 + 6\,H_2O$ – cellulosic biomass

Hydrogen production

- $CH_4 + H_2O = CO + 3H_2$ – steam reforming of methane
- $CO + H_2O = CO_2 + H_2$ – water gas shift reaction

Hydrogen fuel cell

- $H_2 + \frac{1}{2}\,O_2 = H_2O$ + electricity + heat

N.B. These overall reactions occur through multiple steps

Gasification to Syngas

Fossil fuel or biomass → Gasifier 800 °C
Steam or oxygen → Gasifier 800 °C

Gasifier → Syngas: CO, H_2 → Electricity, CH_4, H_2, Gasoline/diesel, methanol

$$\underbrace{CH_{1.5}O_{0.67}}_{\text{wood}} + 0.33\ \underbrace{H_2O}_{\text{steam}} \rightarrow \underbrace{CO + 1.08\ H_2}_{\text{syngas}}$$

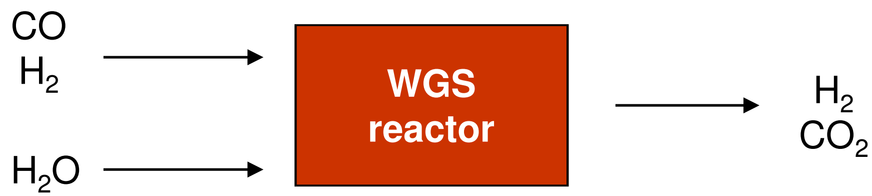
$\Delta H_r = +101$ kJ/mol
700-900 °C, 1 atm

Heat required to drive this endothermic reaction usually provided by partial oxidation with O_2

Image by Gerfriedc on Wikimedia Commons.

Source: National Renewable Energy Lab; F. Vogel, Paul Scherrer Institut, Switzerland.

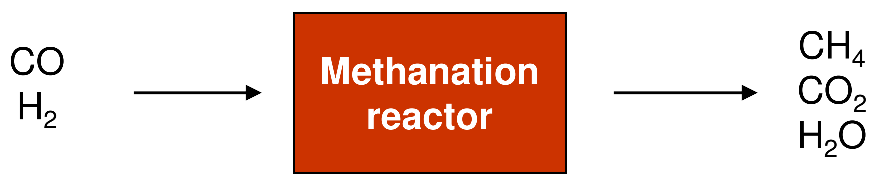
Water-gas-shift and methanation reactions



Water gas shift

$$CO + H_2O \rightarrow CO_2 + \boxed{H_2}$$

ΔH_r = -41 kJ/mol
400-500 °C, 1 atm
Iron oxide catalyst



Methanation

$$CO + 1.08\ H_2 \rightarrow \boxed{0.52\ CH_4} + 0.48\ CO_2 + 0.04\ H_2O$$

ΔH_r = -127 kJ/mol
400 °C, 10-20 atm
Ni catalyst

Source: F. Vogel, Paul Scherrer Institut, Switzerland;
& Cat Comm 4 215-221 (2003).

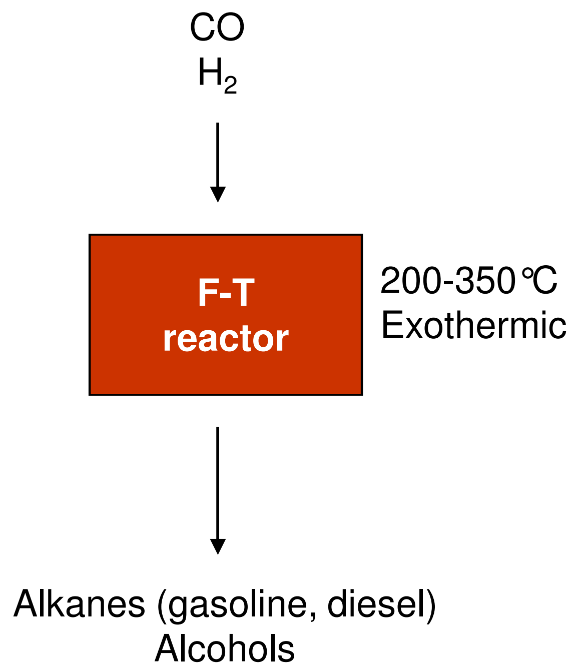
Fischer-Tropsch Reaction: Syngas to Liquid Fuels

- "Ideal" FT reaction:

$$(2n+1)\ H_2 + n\ CO \rightarrow C_nH_{2n+2} + n\ H_2O$$

- Many simultaneous reactions
  - alcohols, alkenes, etc.

- Applications:
  - Coal-to-liquids
  - Gas-to-liquids
  - Biomass-to-liquids



Rates of chemical reactions

- Chemical reaction rates are functions of the concentration of reacting species.

- Forward and Backward Reactions running simultaneously: need a free-energy difference to drive in one direction.

$$A + B \leftrightarrow C + D$$

Forward rate

$$r_f = k_f [\mathrm{A}]^{n_A} [\mathrm{B}]^{n_B}$$

Backward rate

$$r_b = k_b [\mathrm{C}]^{n_C} [\mathrm{D}]^{n_D}$$

Overall rate

$$r = k_f [\mathrm{A}]^{n_A} [\mathrm{B}]^{n_B} - k_b [\mathrm{C}]^{n_C} [\mathrm{D}]^{n_D}$$

Rate definition

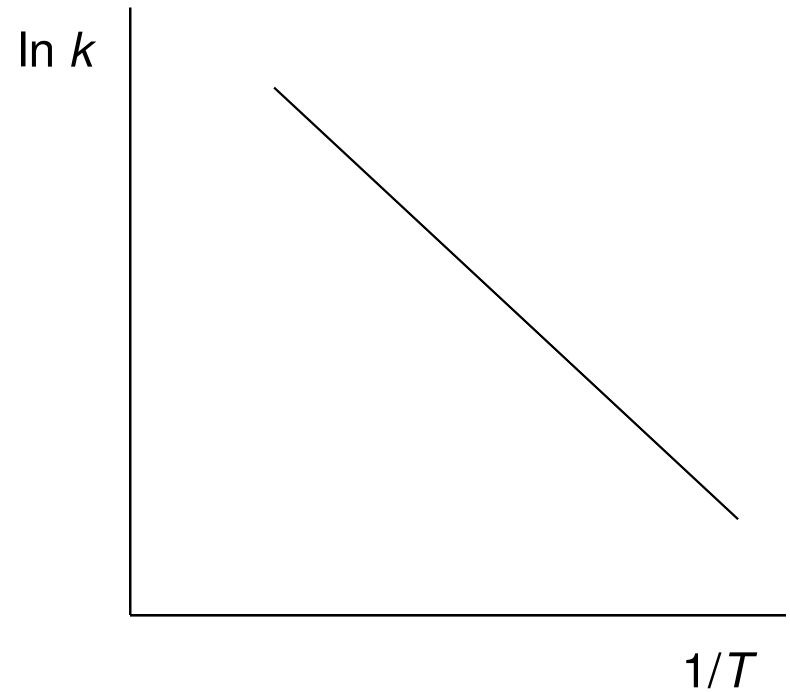
$$r \equiv -\frac{\mathrm{d[A]}}{\mathrm{dt}} = -\frac{\mathrm{d[B]}}{\mathrm{dt}} = \frac{\mathrm{d[C]}}{\mathrm{dt}} = \frac{\mathrm{d[D]}}{\mathrm{dt}}$$

Reaction rates are strong functions of temperature

$$r \propto k = A\exp\left\{\frac{-E_A}{RT}\right\}$$

- Chemical reactions generally accelerate dramatically with temperature

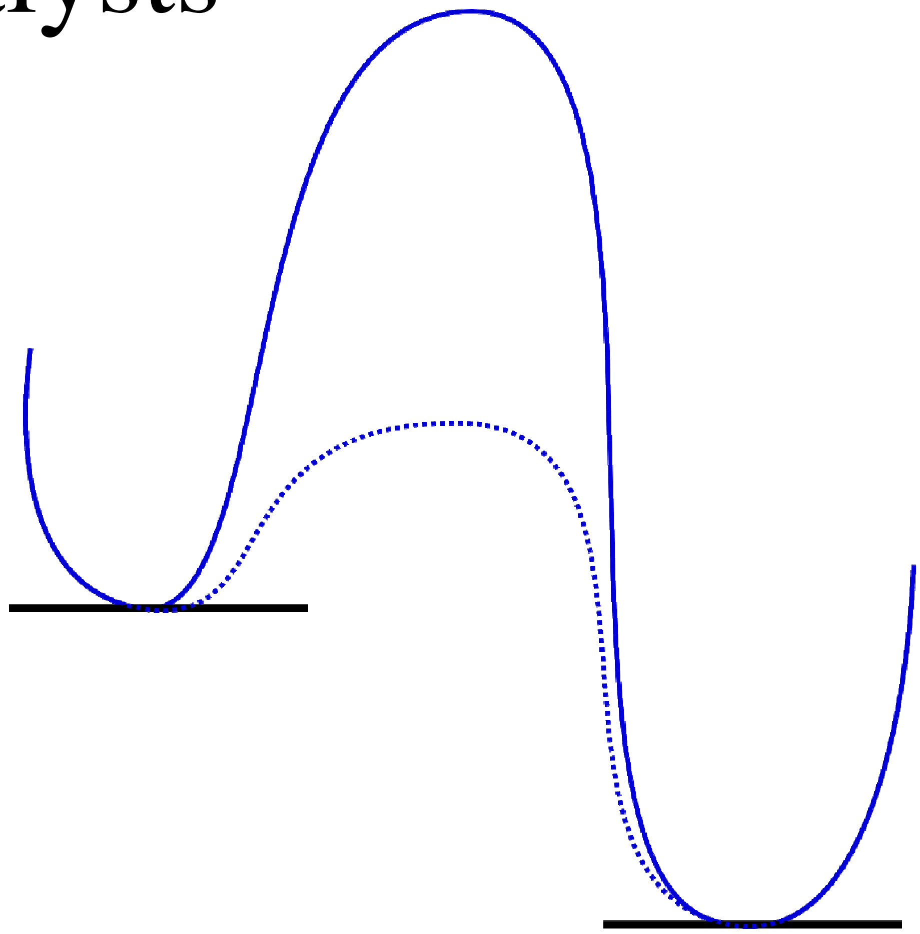
- Typical values of E_A are ~200 kJ/mol.



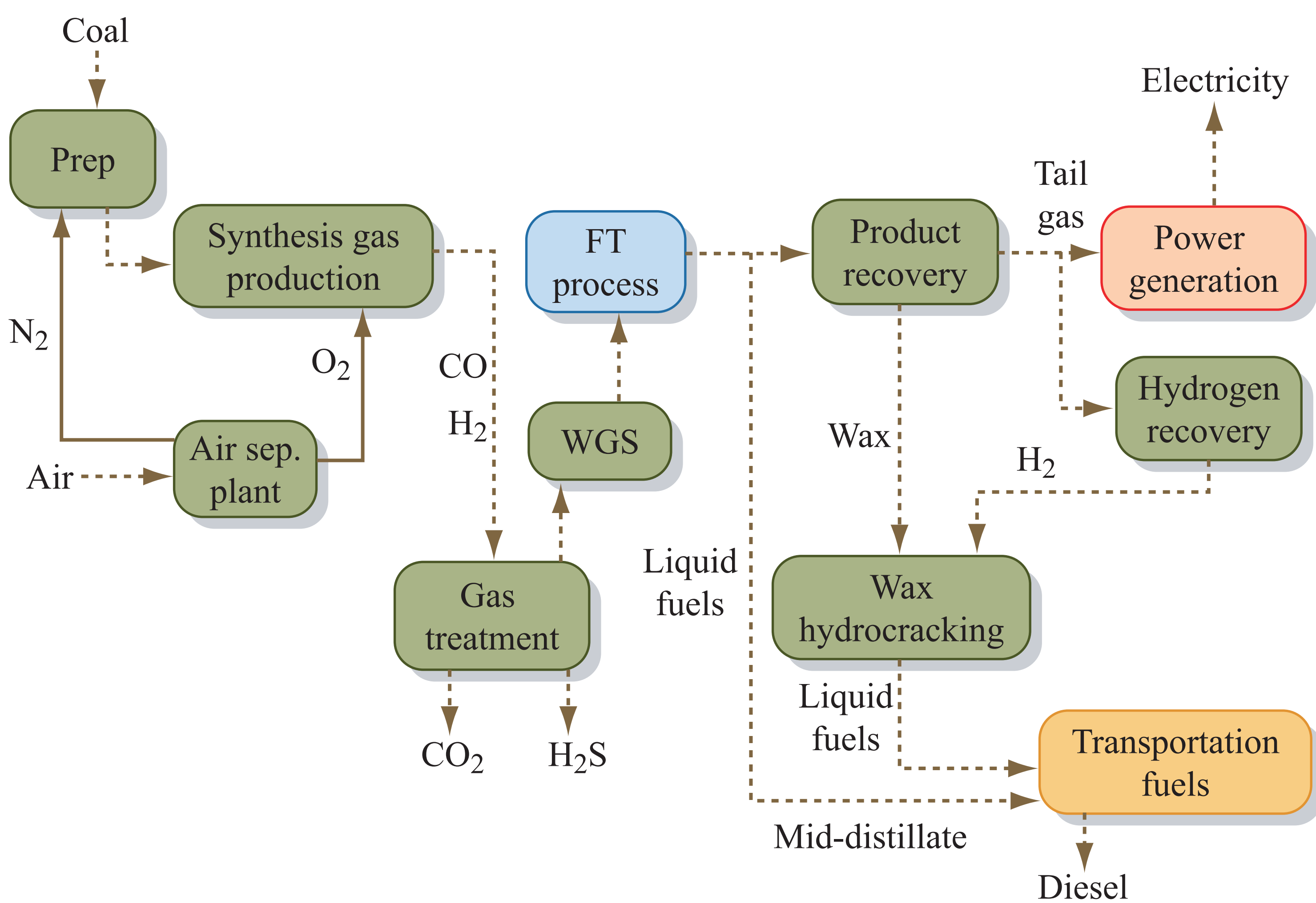
Arrhenius plot

Catalysts

- Catalysts accelerate chemical reactions.
- In mixtures with many reactions possible, catalysts can accelerate desired reactions to increase selectivity.
- Catalysts don't change the equilibrium.
- Catalysts don't change ΔH_{rxn}.



Coal-to-Liquids Conversion



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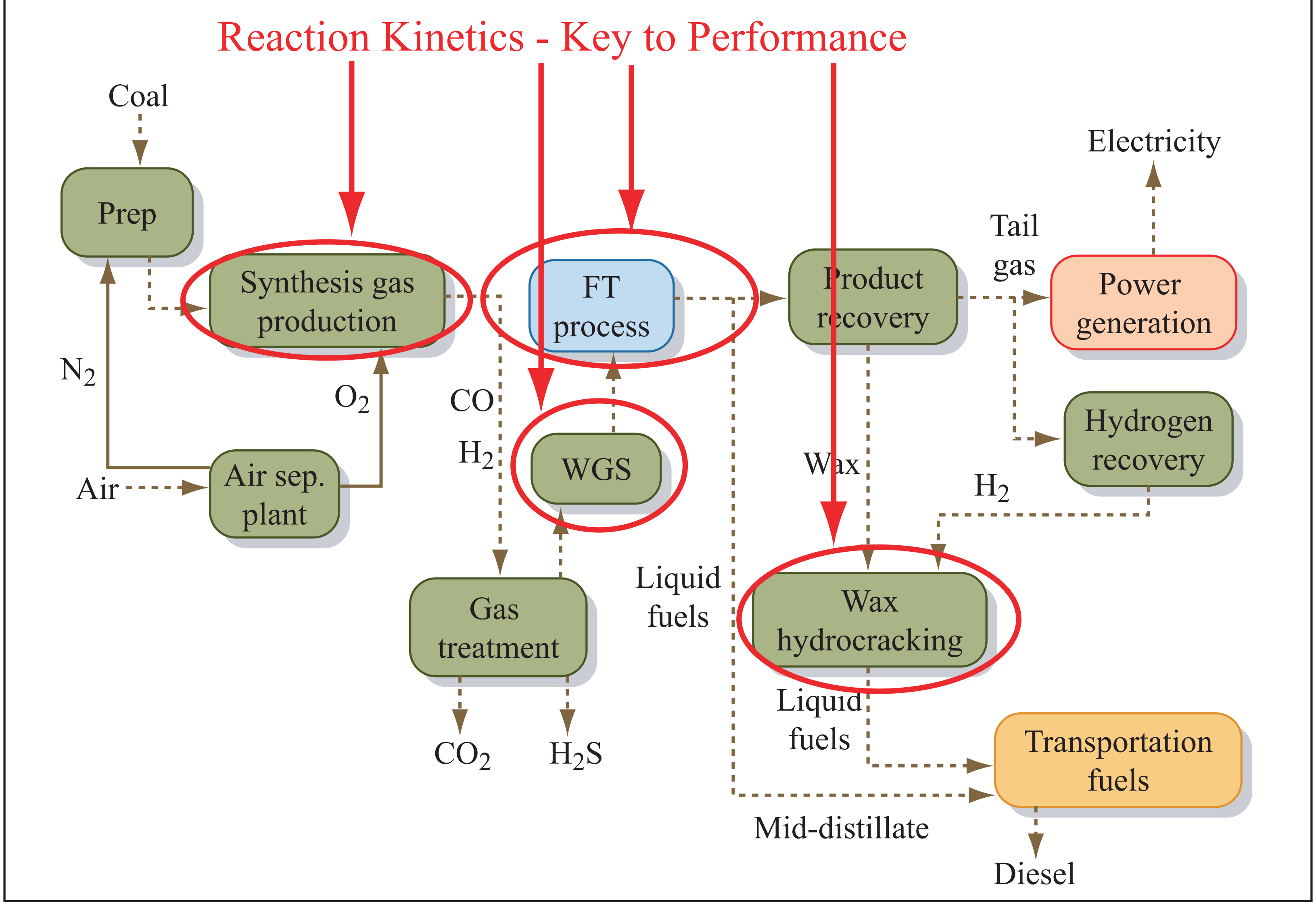
Coal-to-Liquids Conversion



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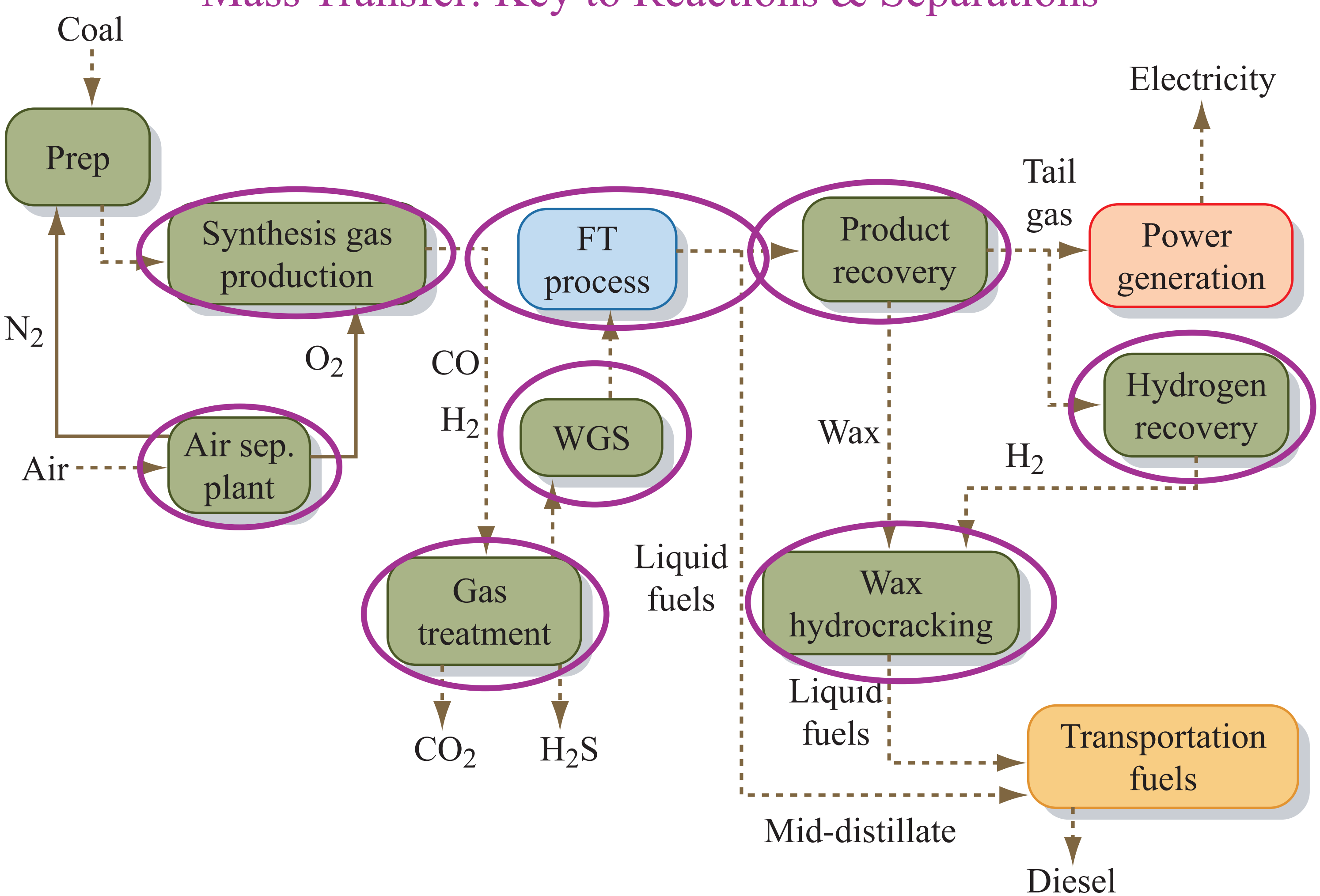
Coal-to-Liquids Conversion

Mass Transfer: Key to Reactions & Separations



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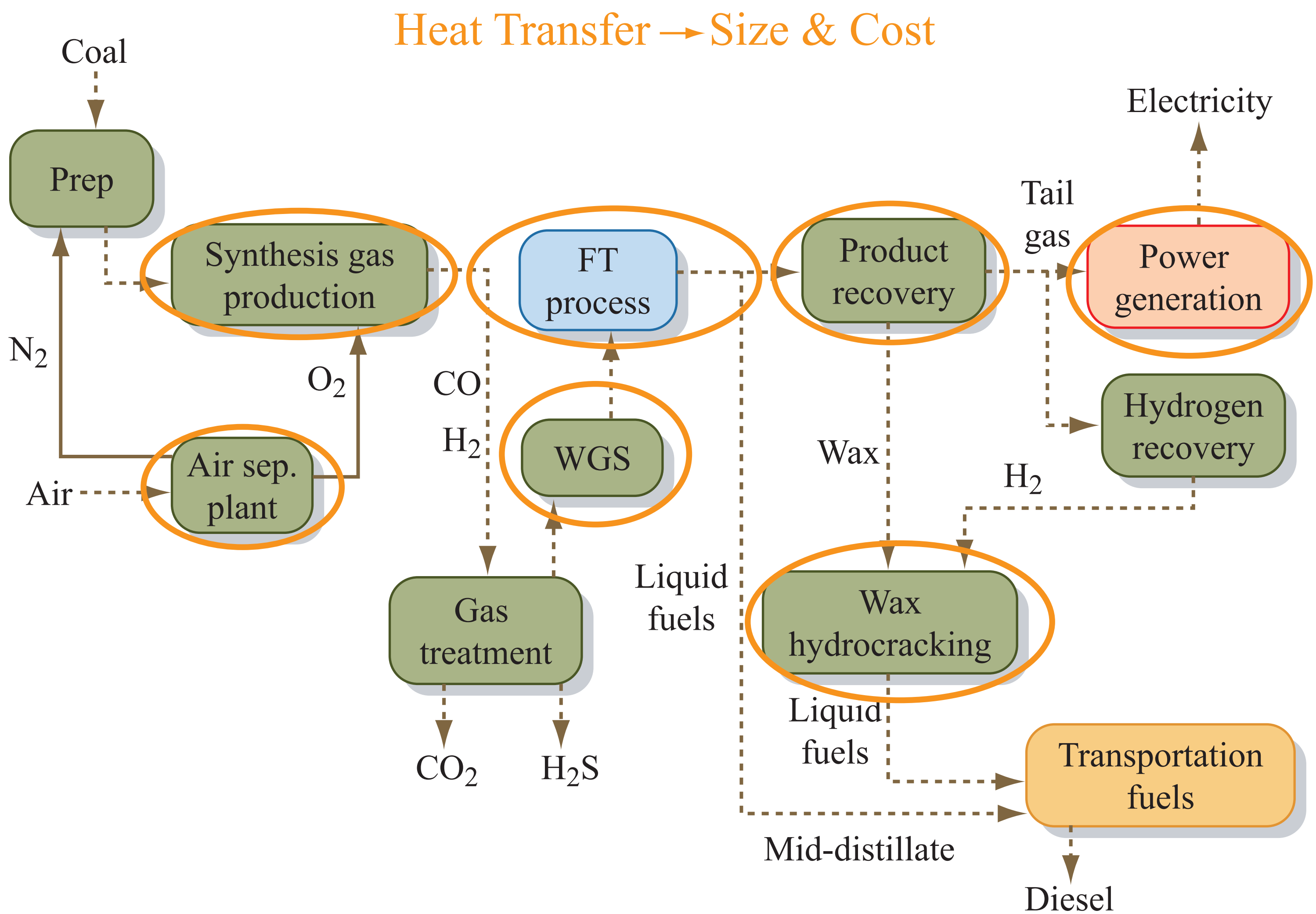

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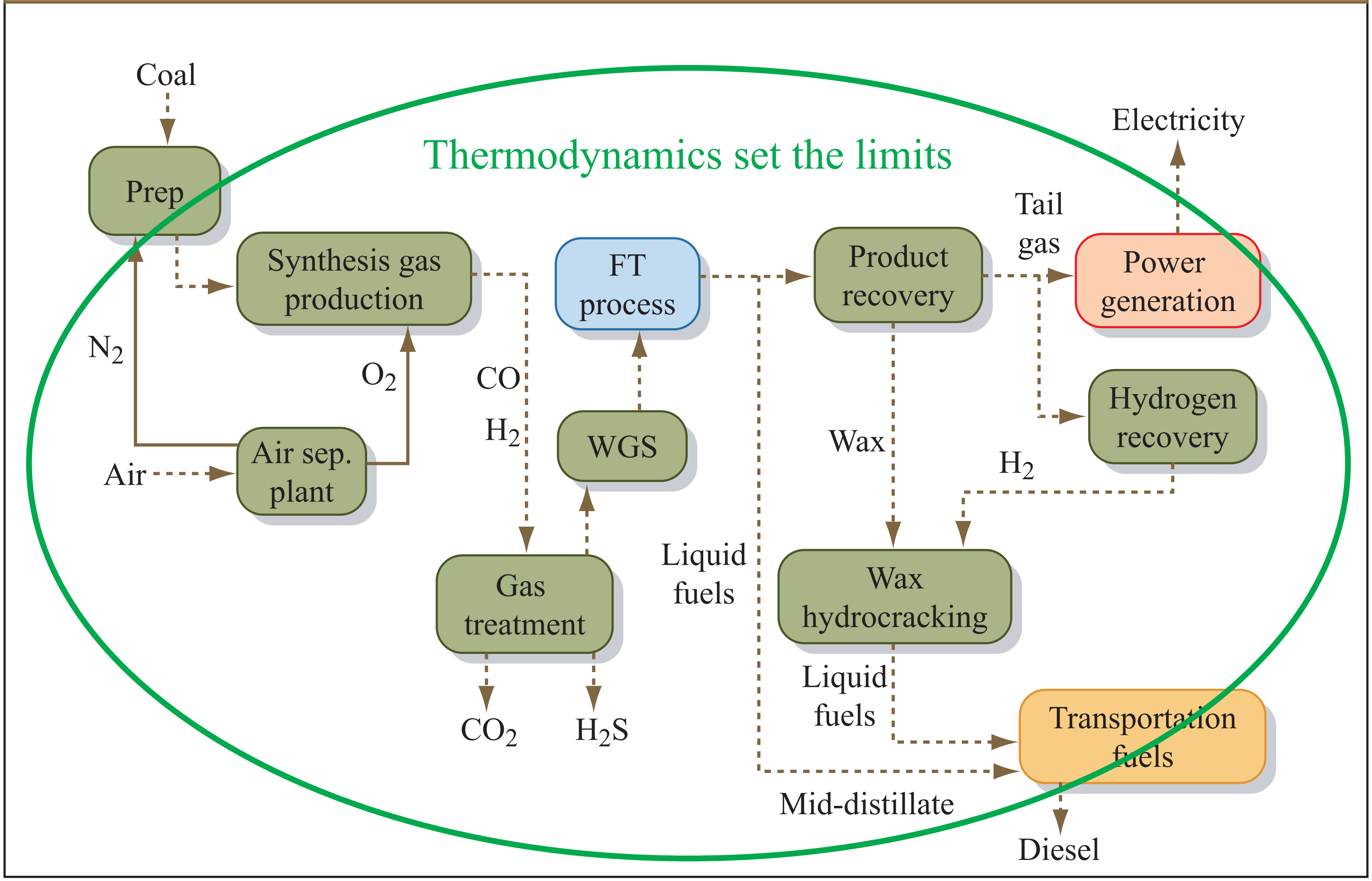

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Common Conversion Efficiency Challenges, Part 1

- Thermo Limit on Conversion of heat to work:
  - Work < Heat (1- T_{low}/T_{high})
  - Material (boiler, turbine) & emission (NO_X) limits T_{high}
  - Cooling tower (rate of evaporation, LHV) limit on T_{low}
- Difficult to precisely control chemical reactions
  - Common energy conversion strategy: just mix a fuel with air, and let the reaction run to completion.
  - Then extract work from the hot exhaust gases.
  - Usually the conversion of chemical energy to heat is irreversible: large increase in entropy.

Common Conversion Efficiency Challenges, Part 2

- Energy Resources Far From Users
  - Real security, global economy issues
  - Takes energy and money to move the resource or electricity to the users
- Convenience, Reliability, Emissions Matter
  - Solid Fuels Difficult to handle (so we don't use coal for ships any more)
  - Coal only 1/10 the price of oil
- Energy Density and Specific Energy Matters
  - Lots of land needed to collect diffuse resources like solar, wind, biomass, hydro
  - Transport costs and transport energy significant for low-energy-density fuels (e.g. natural gas, hydrogen)
- Power Density Matters
  - Energy conversion equipment is expensive, want to do a lot of conversion with small equipment: Large Fluxes required, so Large Free Energy Gradients
  - For transportation, need to carry the energy conversion equipment with you!

Remember, each conversion reduces efficiency and costs money.