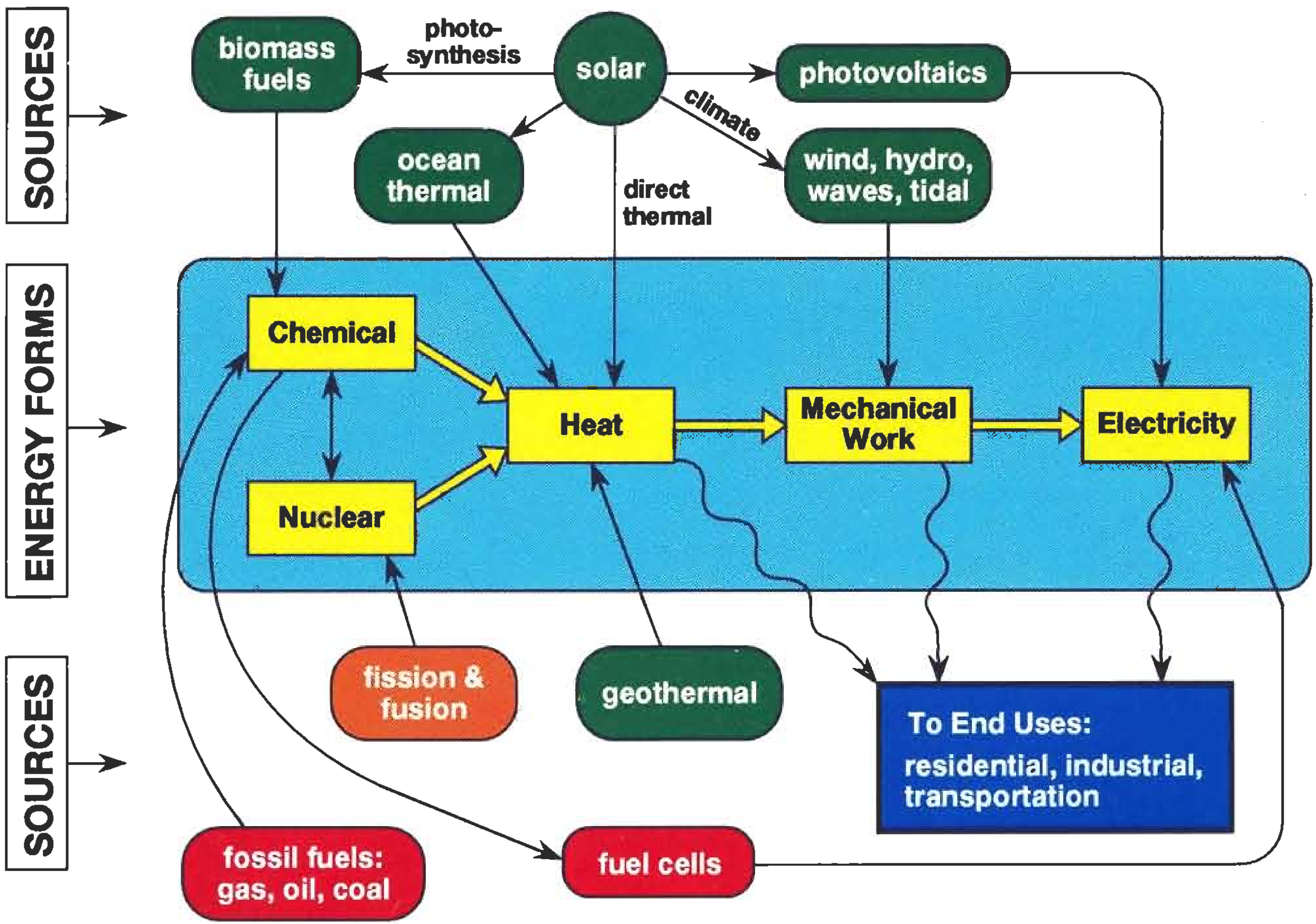
Thermodynamics and Efficiency Analysis
Toolbox 6
Sustainable Energy

- Energy chains and overall versus individual efficiencies
- Playing by the rules
    - First Law – energy conservation
    - Second Law - entropy generation- irreversibility,
    - Availability and exergy concepts –max/min work
- Power generation via heat to work cycles
    - Rankine (steam and other prime movers)
    - Brayton
    - Combined cycles

ENERGY SOURCES AND CONVERSION PROCESSES



Performance Metrics for Energy Systems

Heat Transfer Efficiency
(1st Law)

$$\eta_h = \frac{Q_{out}}{Q_{in}} \equiv 1 - \frac{Q_{loss}}{Q_{in}}$$

Cycle Efficiency
(2nd Law)

$$\eta_c \equiv \frac{W_{net}}{Q_H}$$

Utilization Efficiency
(2nd Law/Exergy or availability-based)

$$\eta_u = \frac{W_{net}}{W_{max}} = \frac{\sum_i W_i}{\Delta \underline{B}}$$

Sustainability Efficiency
(couples heat and work flows)

$$\eta_s = \frac{\sum_i W_i + \sum_k \eta^*_{c,k} Q_{H,k}}{W_{max}}$$

Energy chains and efficiencies

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

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

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

for example for batteries:

$$\eta_{battery} = \eta_{rev,\max}\eta_{rx}\eta_{voltage\,losses}$$

$$\eta_{rev,\max} = \Delta G_{rx} / \Delta H_{fuel} = -nF\varepsilon / \Delta H_{fuel}$$

$$\Delta G_{rx} = -n_e F\varepsilon = \varepsilon^o - \frac{RT}{n_e F}\ln\left[\prod_{i\,species}(a_i)^{\nu_i}\right]$$

or for compressed air energy storage (CAES):

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

Energy Conservation and the First Law of Thermodynamics

- System and surroundings
- Heat and work interactions – path dependent effects (δ)
- Mass flow effects
- First Law -- conservation of energy

$$\Delta \underline{E} = Q + W + \sum H_{in} m_{in} - \sum H_{out} m_{out}$$

or

$$d\underline{E} = \delta Q + \delta W + \sum H_{in} \delta m_{in} - \sum H_{out} \delta m_{out}$$

where

$\underline{E}$ = *total energy of the system*

Q = *net heat effect at system boundary*

W = *net work effect at system boundary*

$H_{in,\ out}$ = *enthalpy of incoming or outgoing stream*

$m_{in,\ out}$ = *mass of the incoming or outgoing stream*

- Steady state versus transient -- $d\underline{E}/dt = 0$ and dm/dt

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Source: Figure 4.6 in Tester, J. W., and M. Modell. *Thermodynamics and its Applications*. 3rd ed. Englewood Cliffs, NJ: Prentice Hall, 1996.

Energy and Enthalpy

- Energy E – contains the internal energy U of the system as well as other contributions eg. KE due to inertial velocity effects, PE due to body force effects such as gravity or electrostatic

- For simple systems, that is those without inertial or body force effects –

$$E = U$$

- Enthalpy H -- contains the energy content E and mass flow (PV) work of the stream and is usually defined as

$$H \equiv U + PV$$

Entropy and the Second Law

- Provides directionality for natural processes
  - heat flows from a hot to a cold body
  - rivers flow down hill

- Describes in mathematical terms the maximum amount of heat that can be converted into work

- Introduces the concept of entropy and defines it as the ratio of a reversible heat interaction to its temperature

$$dS = \delta Q/T$$

Entropy and the Second Law

- Describes the maximum efficiency of a reversible Carnot heat engine in terms of heat source and heat sink temperatures

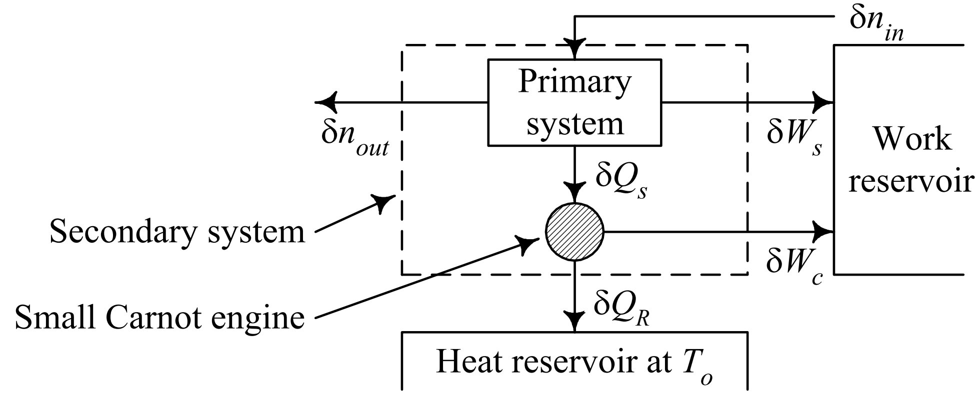
$$\eta_{\mathbf{Carnot}} = \eta_{\mathbf{thermal}} = \text{Max work produced / heat supplied}$$

$$\eta_c = (T(\text{hot}) - T(\text{cold})) \,/\, T(\text{hot})$$

- For all reversible processes the total entropy is conserved
- For all real processes the total entropy increases and often is associated with increased levels of molecular disorder – e.g. a mixture of two components versus two pure components or a gas versus a liquid or solid phase
- Entropy is in practice tends toward a maximum --- its change provides a measure of the degradation of work producing potential

Ideal maximum work – availability or exergy

Consider a fully reversible process with no dissipative effects – that is all work is transferred without loss and all heat is transferred using an ideal Carnot process to generate additional work, The resulting maximum work is given by



$$\Delta B \equiv H_{out} - H_{in} - T_o\left(S_{out} - S_{in}\right) = \Delta H - T_o \Delta S$$

Clearly, the availability *B* is a state function in the strictest mathematical sense so the maximum (or minimum) work associated with any steady state process is also independent of the path.

Availability or Exergy

- Yields the maximum work producing potential or the minimum work requirement of a process
- Allows evaluation and quantitative comparison of options in a sustainability context

$$\Delta B = change\ in\ availability\ or\ exergy$$

$$= \text{max}imum\ work\ output\ or\ \text{min}imum\ work\ input$$

$$\Delta B \equiv \left[\Delta H - T_o\ \Delta S\right]\Big|_{Tout,Pout}^{Tin,Pin}$$

$$normally\ T_{out}, P_{out} = ambient\ or\ dead\ state\ condition = T_o, P_o$$

Playing by the rules

- The 1st and 2nd Laws of thermodynamics are relevant
  - 1st Law – energy is conserved
  - 2nd Law – all real processes are irreversible
- Heat and electric power are not the same
- Conversion efficiency does not have a single definition
- All parts of the system must work – fuel and energy converters, control and monitoring sub systems, and the interconnection

Consider three cases

Case 1 – Central station generator

Case 2 – DER fuel cell system

Case 3 – DER CHP microturbine + geothermal heat pump

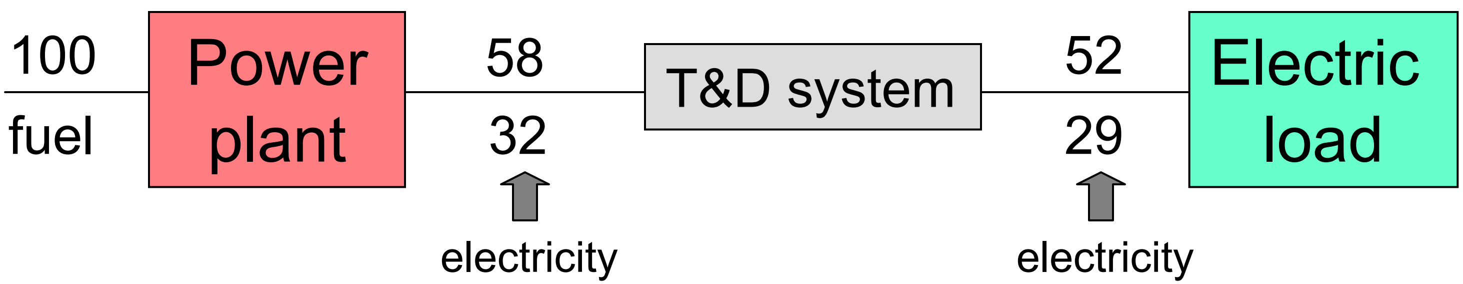
Define efficiency as

♒🕓 **output/input = (energy utilized) / (energy content of fuel used)**

Basis = 100 units of chemical energy in fuel

Case 1 – Central station generator

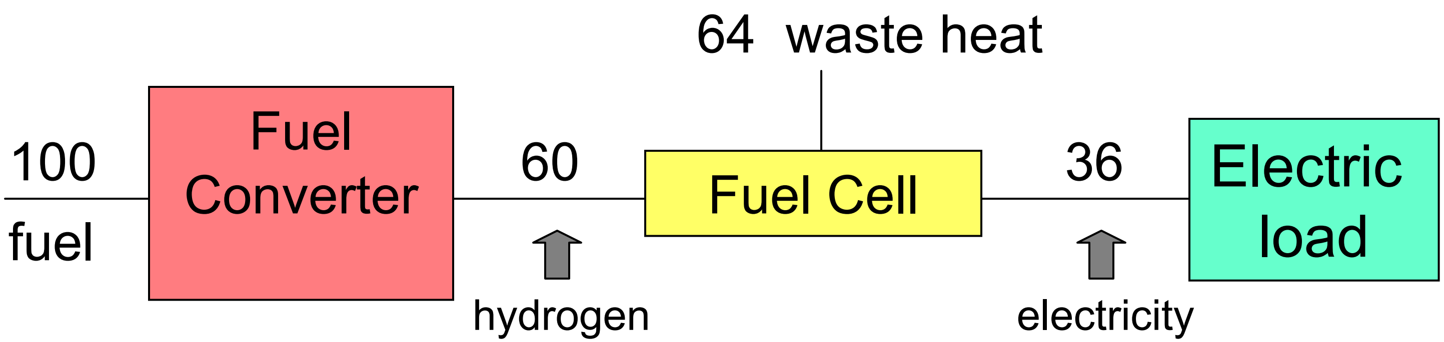
State of the art vs system average performance



η = 52/100 or 52% -- state of the art technology

or η = 29/100 or 29% -- system average

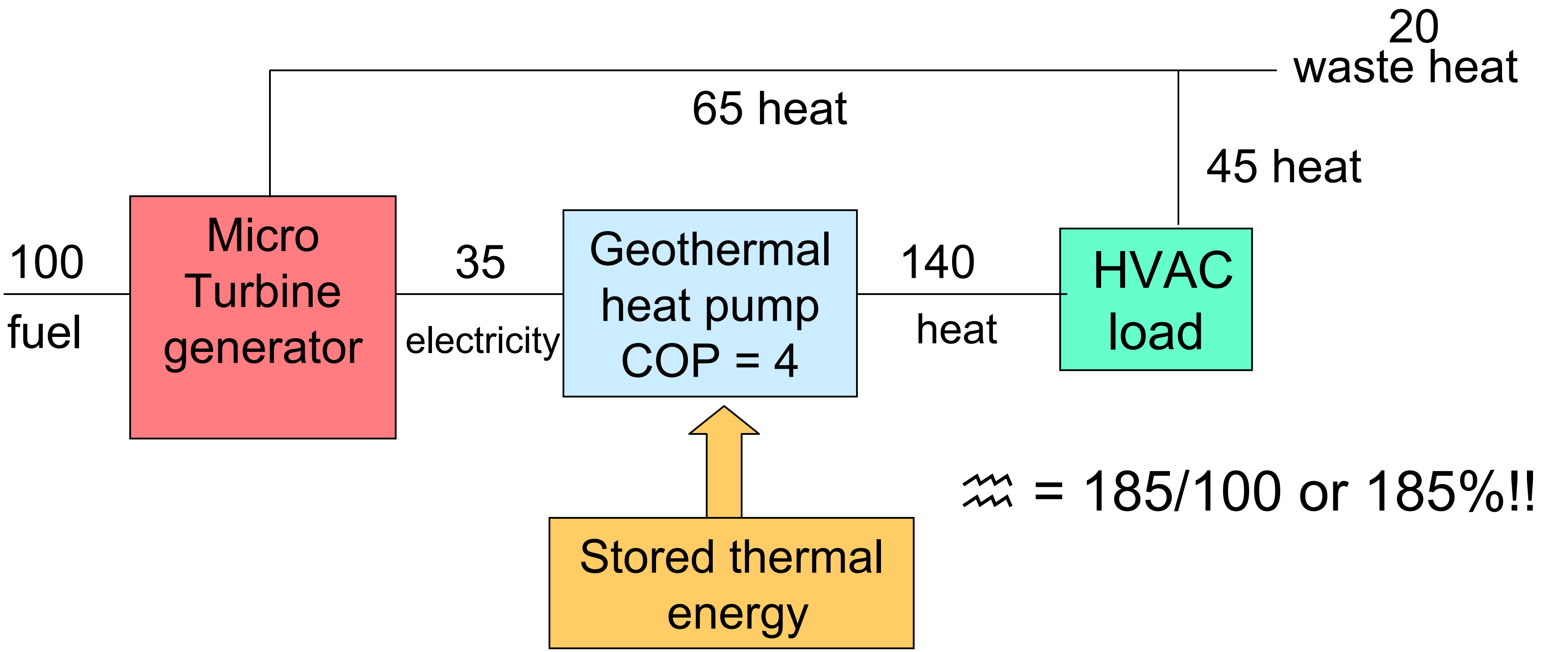
Case 2 – DER fuel cell system



η = 36/100 or 36%

DER = distributed energy resource or distributed generator

Case 3 – DER CHP microturbine + geothermal heat pump



♒ = 185/100 or 185%!!

With ♒🕒 (energy used) / (energy content of fuel)

Case 1 – Central station generator

♒ = 52 to 29 %

Case 2 – DER fuel cell system

♒ = 36 %

Case 3 – DER CHP microturbine + geothermal heat pump

♒ = 185 %

Sustainable Energy
Toolbox lecture #6

Thermodynamics and Efficiency Analysis Methods
Supplementary notes to lecture materials and Chapter 3

1. Fundamental principles
    - energy conservation and the 1st Law of thermodynamics
    - entropy production and the 2nd Law of thermodynamics
    - reversible Carnot heat engines
    - maximum work / availability / exergy concepts -- $\Delta B = \Delta H - T_o \Delta S$

2. Efficiencies
    - mechanical device efficiency for turbines and pumps
    - heat exchange efficiency
    - Carnot efficiency
    - cycle efficiency
    - fuel efficiency
    - utilization efficiency

3. Ideal cycles
    - Carnot with fixed T_H and T_C
    - Carnot with variable T_H and fixed T_C
    - Ideal Brayton with variable T_H and T_C

4. Practical power cycles
    - an approach to Carnotizing cycles
    - Rankine cycles with condensing steam or organic working fluids
        - sub and supercritical operation
        - feed water heating
        - with reheat
    - Brayton non-condensing gas turbine cycles
    - Combined gas turbine and steam Rankine cycles
    - Topping and bottoming and dual cycles
    - Otto and diesel cycles for internal combustion engines

5. Examples of power conversion using a natural gas or methane energy source
    - sub-critical Rankine cycle
    - gas turbine open Brayton cycle
    - combined gas turbine steam Rankine cycle
    - electrochemical fuel cell

6. Heat pumps

Let's look a little deeper into heat to work cycle analysis

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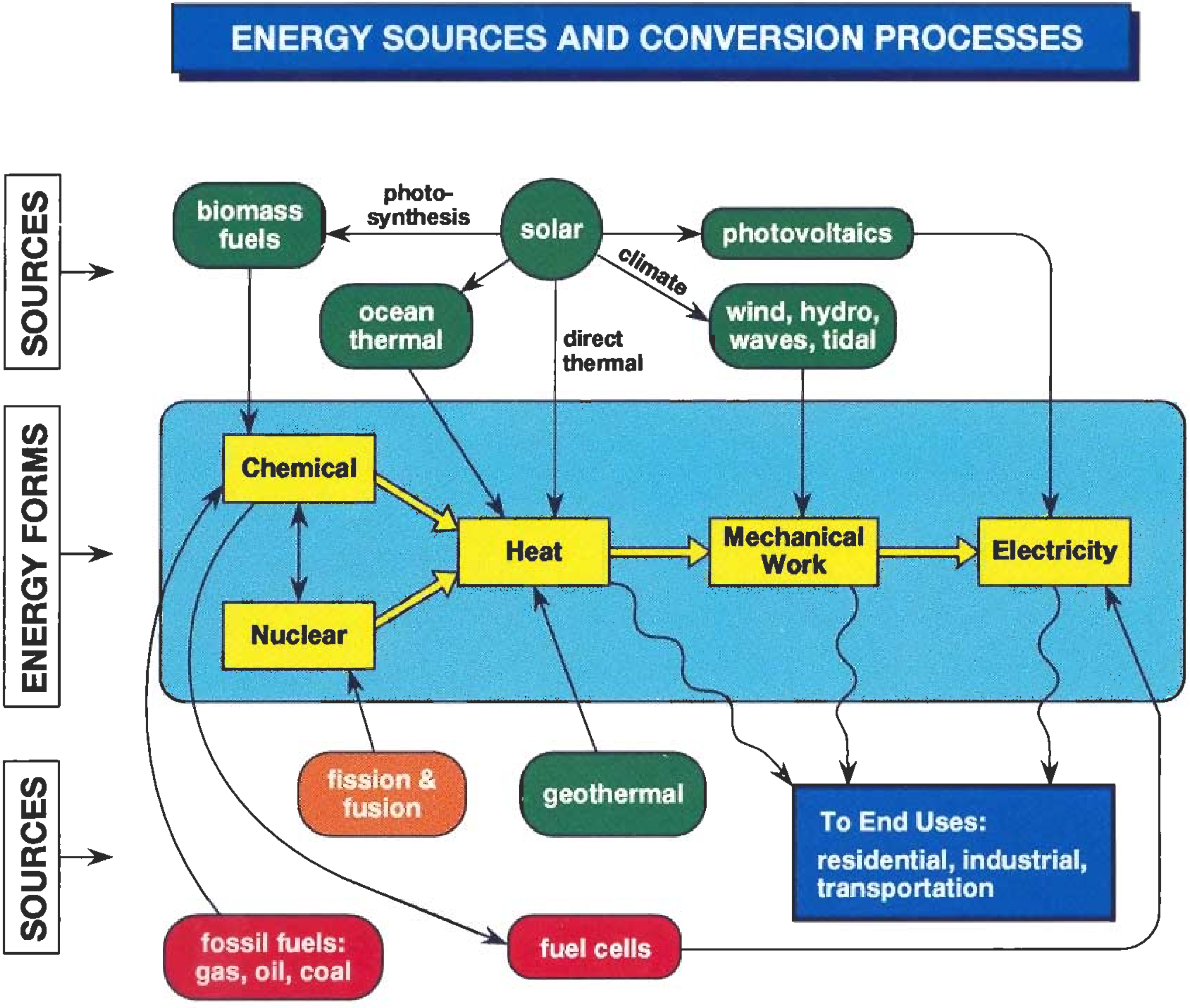
Source: Figure 14.7 in Tester, J. W., and M. Modell. *Thermodynamics and its Applications*. 3rd ed. Englewood Cliffs, NJ: Prentice Hall, 1996.


ENERGY SOURCES AND CONVERSION PROCESSES
SOURCES
ENERGY FORMS
SOURCES
biomass fuels
photo-synthesis
solar
photovoltaics
ocean thermal
climate
wind, hydro, waves, tidal
direct thermal
Chemical
Heat
Mechanical Work
Electricity
Nuclear
fission & fusion
geothermal
To End Uses:
residential, industrial, transportation
fossil fuels: gas, oil, coal
fuel cells

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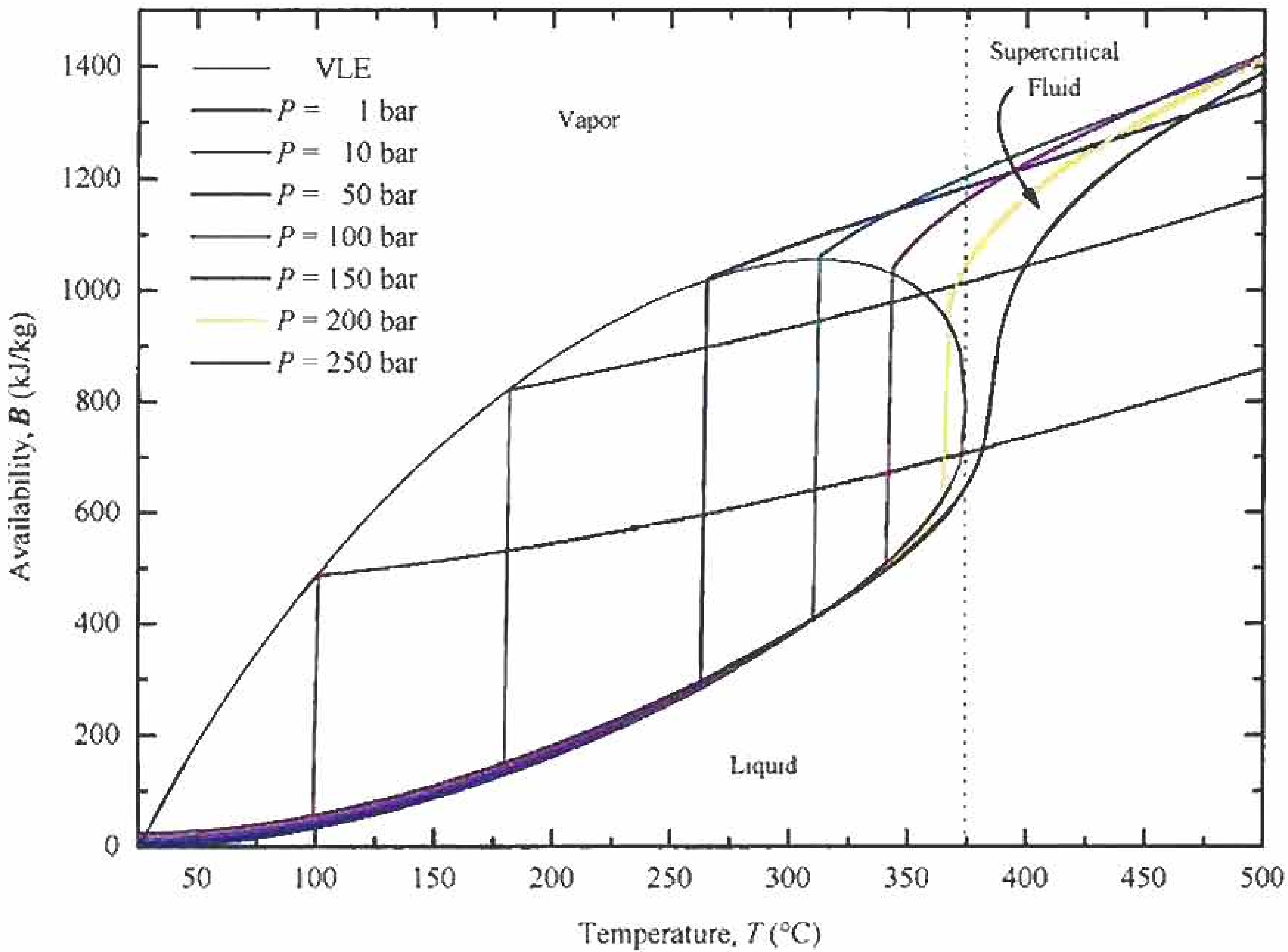
Availability Diagram for Water



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