Friday September 26
Senaatszaal, Aula
9:30 – 10:00 am – Lekenpraatje
10:00 – 11:00 am – Defense
~11:30 am Reception

Chang Yu
Eco-transformation of industrial parks in China
71

http://is.gd/ChinaEIP

Marian Chertow
http://environment.yale.edu/profile/chertow
Thermodynamic Entropy ≠ Information Entropy

I thought of calling it 'information', but the word was overly used, so I decided to call it 'uncertainty'.

You should call it entropy, for two reasons.

In the first place your uncertainty function has been used in statistical mechanics under that name, so it already has a name.

In the second place, and more important, nobody knows what entropy really is, so in a debate you will always have the advantage.

https://en.wikipedia.org/wiki/Entropy
https://en.wikipedia.org/wiki/Claude_Shannon
\[ \Delta S = \frac{\Delta Q}{T} \]
\[ \Delta S = \frac{\Delta Q}{T} \quad \Delta S = \frac{\text{(Joules)}}{(\text{Kelvin})} \]

\[ c_p = 4.186 \frac{J}{g \cdot K} \]

\[ \Delta S = m c_p \ln \left( \frac{T}{T_0} \right) \quad \Delta S \propto c_p \]
Table I: List of Several Sets of Fundamental Equations among the Four State Variables and the Four Thermodynamic Potentials in Classical Thermodynamics.

Definitions of Variables and Potentials

\begin{align*}
T &= \text{temperature} \\
P &= \text{pressure} \\
v &= \text{temperature} \\
h &= \text{internal energy} \\
v &= \text{entropy} \\
f &= \text{Helmholtz free energy} \\
g &= \text{Gibbs free energy}
\end{align*}

Definitions of \(F, H,\) and \(G\) from \(U\) (Legendre Transforms)

\begin{align*}
F &= U - TS \\
H &= U + PV \\
G &= H - TS = U + PV - TS = F + PV
\end{align*}

Differential Equations for \(U, F, H,\) and \(G\)

\begin{align*}
dU &= T \, dS - P \, dv \\
dF &= -S \, dT - P \, dv \\
dH &= T \, dS + V \, dp \\
dG &= -S \, dT + V \, dp
\end{align*}

Equations to Compute Variables \(T, P, V,\) and \(S\)

\begin{align*}
T &= \left(\frac{\partial H}{\partial S}\right)_P = \left(\frac{\partial U}{\partial S}\right)_V = \left(\frac{\partial F}{\partial S}\right)_T \\
V &= \left(\frac{\partial H}{\partial P}\right)_T = \left(\frac{\partial G}{\partial P}\right)_T \\
S &= -\left(\frac{\partial F}{\partial T}\right)_P = -\left(\frac{\partial G}{\partial T}\right)_P
\end{align*}

Maxwell Equations

\begin{align*}
\frac{dV}{dT} &= \left(\frac{\partial S}{\partial V}\right)_T \\
\frac{dS}{dT} &= \left(\frac{\partial V}{\partial T}\right)_S
\end{align*}

Differential Equations for \(U, F, H,\) and \(G\) with Variable Amounts of Matter

\begin{align*}
dU &= T \, dS - P \, dv + \Sigma n_i \, dn_i \\
dF &= -S \, dT - P \, dv + \Sigma n_i \, dn_i \\
dH &= T \, dS + V \, dp + \Sigma n_i \, dn_i \\
dG &= -S \, dT + V \, dp + \Sigma n_i \, dn_i
\end{align*}

Figure 1. Comparison of the new scheme based on (b) with the Max Born square (a). The Born square (a) was used in several textbooks to help recall thermodynamic equations that relate four thermodynamic variables (temperature \(T\), pressure \(P\), volume \(V\), and entropy \(S\)) and four thermodynamic potentials (internal energy \(U\), Helmholtz free energy \(F\), enthalpy \(H\), and Gibbs free energy \(G\)). The new double-square scheme (b) significantly simplifies the procedures to recall several sets of thermodynamic equations.

Figure 2. Scheme to recall the Legendre transforms that define the Helmholtz free energy \(F\), enthalpy \(H\), and Gibbs free energy \(G\) from the internal energy \(U\).

Figure 3. Scheme to obtain the differential equations of the thermodynamic potentials \((U, F, H,\) and \(G)\) that are the core of thermodynamic relations.

Figure 4. Scheme to obtain the quantity of one variable from the partial differential of a thermodynamic potential with respect to the conjugate variable.

Equation (Figure 2a). Similarly, the curve in Figure 2b gives \(U - ST = F\). The minus sign in front of \(ST\) is due to the fact that the arrow points downward from \(S\) to \(T\). Figures 2c and 2d give \(H - ST = G\) and \(F + VP = G\). In fact, all of the arrows can be drawn backward, and the equations still work—just remember to use a minus sign when the arrow passing along the diagonal of the inner square is pointing downward.

To obtain the differential of a potential, for example \(dU\), draw two curved arrows toward the potential \(U\) from the two far ends of the inner square, that is, \(P\) and \(T\), crossing the inner square diagonally, as shown in Figure 3a. These two curved arrows give \(+T \, dS - P \, dv\), thus \(dU = T \, dS - P \, dv\). The variables \((S\) and \(V))\) close to the potential \((U)\) are with differentials. The positive or negative sign in front of each term is simply determined by the upward or downward direction of the arrow crossing along the diagonal of the inner square. In the same fashion, Figures 3b–3d provide \(dG = -S \, dT + V \, dp\), \(dF = -S \, dT + P \, dv\), and \(dH = T \, dS + V \, dp\).

One can also find the quantity for each of the variables from the partial differential of a potential with respect to the conjugate variable.
Entropy

- Energy of any type disperses from being localized to becoming spread out, if it is not constrained.
- Dispersal of energy from hot to cold areas
- Conversion of energy only possible if total entropy increases $\Delta S > 0$
Entropy

- Entropy is the quantitative measure of a kind of spontaneous process: how much energy has flowed from being localized to becoming more widely spread out (at a specific temperature).
- Entropy change measures the dispersal of energy: how much energy is spread out in a particular process, or how widely spread out it becomes (at a specific temperature).
Entropy, Statistical Mechanics, & Microstates

- Entropy not exactly disorder
  - Not really clean versus dirty room
- Measure of states available

\[
\Delta S = \frac{\Delta Q}{T}
\]

\[
\Delta S = k_B \log \Omega
\]

https://en.wikipedia.org/wiki/Rudolf_Clausius
https://en.wikipedia.org/wiki/Ludwig_Boltzmann
Entropy

• Can't measure the exact state of molecules (total heat), so use entropy as macro state variable
• Thermodynamic equilibrium is maximum entropy
• Entropy represents the diversity of internal movement of a system
• Can decrease entropy of isolated system, but overall is increased
Entropy

\[ \Delta S = \frac{\Delta Q}{T} \]
Stretching

$$\Delta S = \frac{\Delta Q}{T}$$
Contraction

\[ \Delta S = \frac{\Delta Q}{T} \]
Isothermal or Adiabatic?
Stretching

\[ \downarrow \Delta S = \frac{\Delta Q}{T} \uparrow \]

Entropy Decreases

The environment (you) does work on the system

Contraction

\[ \uparrow \Delta S = \frac{\Delta Q}{T} \downarrow \]

Entropy Increases

The system does work on the environment

\[ \Delta S > 0 \]

\[ \Delta S = k_B \log \Omega \]
Entropy Resources

- MIT OpenCourseWare Entropy
  - https://www.youtube.com/watch?v=870y6GUKbwc
- http://physics.ucsd.edu/do-the-math/2013/05/elusive-entropy/
- http://www.science20.com/train_thought/blog/entropy_not_disorder-75081
Entropy Change, Same Energy

\[ \Delta S \gg 0 \]

System time = \( t_0 \)

System Boundary

Cement truck at time = \( t_0 \)

System time = \( t_f \)

Cement truck in a non usable state, Dispersed into the environment

Mass and energy are conserved

http://dsc.discovery.com/tv/mythbusters/
Exergy

- Maximum useful work (Joules) possible during a process that brings the system into equilibrium
- Energy available to be used
- Exergy = 0 at equilibrium
- Measure of “energy quality”
Quality of Energy (1 kWh ≠ 1 kWh)

http://www.flickr.com/photos/27089900@N00/2834643153/
https://en.wikipedia.org/wiki/Automotive_battery
Exergy value of Work

- Exergy = maximum work possible
- Exergy value = Energy value for:
  - Kinetic energy
  - Potential energy
  - Electrical energy
Quality of Energy

• Electricity 100% quality
• Electricity > hot water > warm water > cold water
Exergy value of Heat

\[ E = W_{max} = Q \left( 1 - \frac{T_C}{T_H} \right) \]
Quality of Energy

- Energy = usable part (Exergy) + unusable part

Quality means not all energy can be converted into work
Energy vs. Exergy

Another way to think of it

- Exergy – What is consumed
- Entropy – What is disposed of

http://www.lowex.net/guidebook/index.html
Causes of Exergy Losses

- Changes in pressure, temperature, concentration, chemical potential
- The greater the driving force, the greater the exergy losses
- The smaller the driving force, the smaller the exergy losses
Quality Losses

- Natural Gas → Water Boiler → Heat
- Petrol → Car → Transport
- Crude Oil → Refinery → Petrochemicals

Quality of energy is constantly lost
Less loss of quality means...

- More efficient use of
  - Fuel
  - Energy
  - Money
Example - A warm bath

- 20 C room
- 1 bucket = 10kg H₂O
- 2 buckets of cold water (20 C) +
- 2 buckets of hot water (60 C) =
- 4 buckets of 40 C water

<table>
<thead>
<tr>
<th></th>
<th>Energy (kJ/bucket)</th>
<th>Exergy (kJ/bucket)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot water (60 C)</td>
<td>2511</td>
<td>105</td>
</tr>
<tr>
<td>Warm water (40 C)</td>
<td>1675</td>
<td>28</td>
</tr>
<tr>
<td>Cold water (20 C)</td>
<td>839</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
(\text{Enthalpy}) \quad H = U + PV
\]

\[
(\text{Internal Energy}) \quad U = mc_pT
\]
Example - A warm bath

- 20 C room
- 2 buckets of cold water (20 C) +
- 2 buckets of hot water (60 C) =
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Percent Available Energy at $T_h$ for 20C Environment

Available energy as a percent of total energy vs. Temperature (°C)

Delft University of Technology
Energy & Exergy Efficiency

Energy efficiency \( \eta_{en} \) = \( \frac{\text{Energy output}}{\text{Energy input}} \) = \eta_{en} = \frac{W_{out}}{Q_{in}}

Exergy efficiency \( \eta_{ex} \) = \( \frac{\text{Exergy output}}{\text{Exergy input}} \) = \eta_{ex} = \frac{E_{out}}{E_{in}}
Exergy Factor

• Ratio between exergy and energy of transformed heat

\[
\text{Exergy factor} = \frac{\text{Exergy}}{\text{Energy}} = \frac{E}{Q}
\]

\[
E_{\text{heat}} = Q \left(1 - \frac{T_0}{T}\right)
\]

\[
\frac{E}{Q} = \left| \frac{T - T_0}{T} \right| \quad \text{(environment)}
\]

\[
\frac{E}{Q} = \left| 1 - \frac{T_0}{T - T_0} \log \frac{T}{T_0} \right| \quad \text{(body)}
\]

\[
Q = mc_p \Delta T
\]
Exercise

Estimate the energy efficiency of an oil furnace when the exergy efficiency is 3%.

The exergy factors for in and out flows are 0.9 and 0.04 respectively.

\[
\text{Exergy efficiency} = \frac{\text{Exergy output}}{\text{Exergy input}} = \eta_{ex} = \frac{E_{out}}{E_{in}}
\]

\[
\text{Energy efficiency} = \frac{\text{Energy output}}{\text{Energy input}} = \eta_{en} = \frac{Q_{out}}{Q_{in}}
\]

\[
\text{Exergy factor} = \frac{\text{Exergy}}{\text{Energy}} = \frac{E}{Q}
\]

\[
\frac{E_{in}}{Q_{in}} = 0.9 \quad Q_{in} = \frac{E_{in}}{0.9}
\]

\[
\frac{E_{out}}{Q_{out}} = 0.04 \quad Q_{out} = \frac{E_{out}}{0.04}
\]
Exercise

Estimate the energy efficiency of an oil furnace when the exergy efficiency is 3%.
The exergy factors for in and out flows are 0.9 and 0.04 respectively

\[
\text{Energy efficiency} = \frac{\text{Energy output}}{\text{Energy input}} = \eta_{en} = \frac{Q_{out}}{Q_{in}}
\]

\[
Q_{in} = \frac{E_{in}}{0.9}
\]

\[
Q_{out} = \frac{E_{out}}{0.04}
\]

\[
\eta_{en} = \frac{Q_{out}}{Q_{in}} = \frac{\frac{E_{out}}{0.04}}{\frac{E_{in}}{0.9}}
\]
Exercise

Estimate the energy efficiency of an oil furnace when the exergy efficiency is 3%.

The exergy factors for in and out flows are 0.9 and 0.04 respectively.

\[
\text{Energy efficiency} = \frac{\text{Energy output}}{\text{Energy input}} = \eta_{en} = \frac{Q_{out}}{Q_{in}}
\]

\[
\eta_{en} = \frac{Q_{out}}{Q_{in}} = \frac{E_{out}}{0.04} = \frac{E_{in}}{0.9}
\]

\[
\text{Exergy efficiency} = \frac{\text{Exergy output}}{\text{Exergy input}} = \eta_{ex} = \frac{E_{out}}{E_{in}}
\]

\[
\eta_{ex} = \frac{E_{out}}{E_{in}} = 0.03 \quad E_{out} = 0.03 \cdot E_{in}
\]

Estimate the energy efficiency of an oil furnace when the exergy efficiency is 3%.
The exergy factors for in and out flows are 0.9 and 0.04 respectively

\[ \eta_{en} = \frac{Q_{out}}{Q_{in}} = \frac{E_{out} \cdot 0.04}{E_{in} \cdot 0.9} \]

\[ E_{out} = 0.03 \cdot E_{in} \]

\[ \eta_{en} = \frac{Q_{out}}{Q_{in}} = \frac{0.03 \cdot E_{in} \cdot 0.9}{0.04 \cdot E_{in}} = 0.675 \]
Exergy Factors

\[ \frac{E}{Q} = \left| \frac{T - T_0}{T} \right| \quad \text{(Reservoir)} \]

\[ \frac{E}{Q} = \left| 1 - \frac{T_0}{T - T_0} \log \frac{T}{T_0} \right| \quad \text{(Body)} \]

Exergy Factor versus Temperature, Environment = 20°C

\[ T_0 = 20^\circ C \]
Exergy Factors

\[ \frac{E}{Q} = \left\{ \frac{T - T_0}{T} \right\} \quad (\text{Reservoir}) \quad \frac{E}{Q} = \left\{ 1 - \frac{T_0}{T - T_0} \log \frac{T}{T_0} \right\} \quad (\text{Body}) \]

Exergy Factor versus Temperature, Environment = 20°C

Heat Pump | Heat Engine
---|---

**Equation:**

\[ \frac{E}{Q} = \frac{\text{Usable Energy}}{\text{Energy of Transferred Heat}} \]
Heat Pumps

\[ 1 \, kW_{\text{elec}} = 1 \, kW_{\text{heat}} \]

\[ 1 \, kW_{\text{elec}} = 2 \text{ to } 4.9 \, kW_{\text{heat}} \]

https://commons.wikimedia.org/wiki/File:Carbon_heater.jpg
Heat Engines vs. Heat Pumps

Heat Engine

\[ W = Q_H - Q_C \]

\[ \eta = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = \frac{T_H - T_C}{T_H} = 1 - \frac{T_C}{T_H} \]

Heat Pump

\[ Q_H = Q_C + W \]

\[ \eta = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C} \]
Coefficient of Performance (COP)

- Assume 100% of input work converted to heat
- (Overall) thermal energy not created, but moved around

\[
\eta = \frac{Q_H}{W} = \frac{Q_H}{Q_H - Q_C} = \frac{T_H}{T_H - T_C}
\]
Works backwards too

\[ COP_{heating} = \frac{\Delta Q_{\text{hot}}}{\Delta W} \leq \frac{T_{\text{hot}}}{T_{\text{hot}} - T_{\text{cool}}} \]

\[ COP_{cooling} = \frac{\Delta Q_{\text{cool}}}{\Delta W} \leq \frac{T_{\text{cool}}}{T_{\text{hot}} - T_{\text{cool}}} \]
Options for Heat & Electricity

http://www.withouthotair.com/c21/page_149.shtml
Options for Heat & Electricity

http://www.withouthotair.com/c21/page_150.shtml
Ground Source vs. Air Source Heat Pumps

http://www.withouthotair.com/c21/page_152.shtml
Remember this?

http://www.iea.org/Sankey/index.html
What to do with this?

- Power another planet
- Solve our energy problems
- ...
- ...

http://www.iea.org/Sankey/index.html
Let's build an industrial scale hot tub!

E.On Maasvlakte units 1,2 & 3
E.On Maasvlakte units 1, 2 & 3

- $2 \times 520 \text{ MW}_{\text{elec}}$ @ 40% efficiency
  - $2600 \text{ MW} = 1040 \text{ MW}_{\text{elec}} + 1560 \text{ MW}_{\text{heat}}$
- $1 \times 1100 \text{ MW}_{\text{elec}}$ @ 46% efficiency
  - $2391 \text{ MW} = 1100 \text{ MW}_{\text{elec}} + 1291 \text{ MW}_{\text{heat}}$

$2.85 \text{ GW}_{\text{heat}}$

$2.14 \text{ GW}_{\text{elec}} / 5 \text{ GW}_{\text{total}} = 42.8\% \text{ efficiency}$
Let's heat up a hot tub...

But how big should/can it be?

\[ Q_{\text{total}} = Q_{\text{surface}} + Q_{\text{heat-up}} \]
Let's heat up a hot tub...

But how big should/can it be?

We know this

\[ Q_{total} = Q_{surface} + Q_{heat-up} \]

We can figure this out

Assume:

\[ Q_{heat-up} \gg Q_{surface} \]

...and heat up occurs within a completely isolated container

http://www.engineeringtoolbox.com/swimming-pool-heating-d_878.html
Temperature of heat transfer

Energy input required for phase changes in 1 g of water

- **Ice**
  - Heat of Fusion: $\frac{334}{g}$ J g$^{-1}$ C$^{-1}$

- **Specific Heat Capacity**
  - Water: $\frac{4.186}{g}$ J g$^{-1}$ C$^{-1}$

- **Vaporization**
  - Heat of Vaporization: $\frac{2260}{g}$ J g$^{-1}$

- **Steam**
  - $\frac{2.08}{g}$ J g$^{-1}$ C$^{-1}$

Temperature (°C)

Energy added in Joules
Very Awesome Hot Tub Design

1 m

x m

x m

x m
We're only willing to wait 24 hours for it to heat up...

Our energy budget:

\[ 2.85 \text{ GW}h_{\text{heat}} \cdot \frac{3.6e12 J}{1 \text{ GW}h} \cdot 24 \text{ hours} = 2.4624e14 J \quad \text{(Delivered over 24 hours)} \]

We need to heat it up from 10 C to 38 C

\[
2.4624e11 kJ \cdot \frac{1}{4.186 \frac{kJ}{kg \cdot K}} \cdot \frac{1}{(311 \text{ K} - 283 \text{ K})} = 2,100,880,486 \text{ kg}
\]
We're only willing to wait 24 hours for it to heat up...

$$2.4624 \times 10^7 J \cdot \frac{1 kg \cdot K}{4.186 \frac{kJ}{J}} \cdot \frac{1}{(311 \frac{K}{K} - 283 \frac{K}{K})} = 2,100,880,486 \text{ kg}$$

$$1000 \text{ kg} H_2O = 1 m^3$$

$$2,100,880,486 \text{ kg} = 2,100,880 \text{ m}^3$$

length of one side = $\sqrt{2,100,880 m^2} = 1450 m$

$1 m^2$ per person = 2,100,880 people to invite
A Remarkable Coincidence (?)
Mount Storm Power Station - 1.6 Gwe, 4.9 km²
Is this sustainable?

FACE PALM
when even ernie thinks u r stupid
Serious and Not-So-Serious Applications

- A Happy Shrimp Farm
- Algae farms
- Heating roads in winter
- Power grid congestion management
- Energy storage in a thermal mass
- Emergency (jacuzzi) cooling reserve

Waste = Fun
Stupidity depends on your system boundaries
A bit better...
Why all the examples with fossil fuel plants?

- It's hard to get rid of them
  - Extremely long lifetimes (30 – 50 years)
- Sustainability is also about rational use of energy
- There are hybrid approaches
  - Biomass co-combustion, gasification
  - Integrated Solar Combined Cycle (ISCC)
  - Still help with Learning Effects, Economics of Scale

http://www.flickr.com/photos/ekkaia/3082853134/
The Majority of Electricity Generation


- Oil products: 241 Mtoe
- Oil: 42 Mtoe
- Coal: 2 366 Mtoe
- Natural gas: 1 118 Mtoe
- Biofuels and waste: 135 Mtoe
- Geothermal: 58 Mtoe
- Solar/Hide/wind (Solar Thermal): 43 Mtoe
- Hydro: 300 Mtoe
- Nuclear: 674 Mtoe

Power plants don't “want” fossil fuels
What a (thermal) power plant cares about

Make this really really hot

Make this really really cold

-160 C
Combined Cycle Gas Turbine (CCGT)

Integrated Gasification Combined Cycle (IGCC)

http://www.flickr.com/photos/dukeenergy/5080976897
Integrated Solar Combined Cycle (ISCC)

Ain Beni Mathar Concentrated Solar Power Plant
470 MWe total, 20 MWe from solar thermal
Dutch Greenhouses & CHP
(Cogeneration, Warmtekrachtkoppeling WKK)
Dutch Greenhouses & CHP (Cogeneration, Warmtekrachtkoppeling WKK)

- A story (sort of) about sustainability
- Increased energy efficiency, reduced CO$_2$
- Natural gas is involved :(
- Rapid diffusion of a new energy technology
- ...all embedded within a complex socio-technical system
**Combined Heat and Power**

- **Benefit:** An increase in energy efficiency from <50% to >90% (general)

*Source: Compernolle et al. (2011)*

*Source: SourceOne website.*
Combined Heat and Power

- Natural gas is the used fuel
- Not only the heat, but also the CO\textsubscript{2} is utilized (\textit{not waste})
- Two main components: heat buffer and flue gas cleaner
  - Heat buffer gives flexibility
  - Flue gas cleaner needed for CO\textsubscript{2} use
Combined Heat and Power

- (Potential) CHP installations
  - Steam and Gas (STAG) installations
  - Gas turbines
  - Gas engines used primarily in greenhouses
  - Stirling engines
  - Fuel cells
- Different sizes no standard ranges
  - CHP (> 1 MW<sub>e</sub>)
  - Mini CHP (50 kW<sub>e</sub> – 1 MW<sub>e</sub>)
  - Micro CHP (<50 kW<sub>e</sub>)
CHP (WKK) in the Netherlands

Source: Gasterra (2008)
Combined Heat and Power

- **Supplier:** GE Jenbacher
- **Model:** JMS 616 GS (3x)
- **El. cap.:** 2.4 MW per engine
- **Thermal cap.:** 2.4 MW per engine
- **Heat buffer:** 1,000 m³ per 5 hectare
- **Water:** between 90 and 30 degrees Celcius
- **Flue gas cleaner:** Codinox

Source: Gasterra (2008)
The Greenhouse Sector

Ca. 7,800 greenhouse companies in 2007

Source: CBS (2008)

Scale-up of companies

Source: ECN (2007)
The Greenhouse Sector

Source: ECN (2007)
Figures from 2009 (LEI, 2011)

- 9,729 hectare (cultivation)
- 118 PJ energy use
  - 3.74 GW avg demand
  - (not all electricity)
- 7.2 Mton CO$_2$ emission
- CHP installations:
  - 2,902 MW$_e$ on 6,147 ha
Figures from 2009 (LEI, 2011)

- 3,981 million m$^3$ natural gas use
- $\sim 50$ m$^3$ gas / m$^2$ crops (eggplants)
- 2,432 million kWh elec purchase
- 6,528 million kWh elec sale
A rapid diffusion of CHP units in the Dutch greenhouse sector occurred between 2003 and 2009 (the ‘transition period’).
Historical Description


- **End of 1970s:** CHP is already a well-known technology in the Dutch industrial sectors.
- **1974-1982:** Electricity price doubles, increasing the attractiveness for industrial companies to self-generate power.
- **1979:** The Dutch government installs a Commission on Cogeneration in the Industry.
- **1982:** Investment subsidy WIR-ET (Wet Investeringsrekening-Energietoeslag) is decisive for CHP projects.
Historical Description

- **1980s-1990s**: A stable spark spread (difference between electricity price and natural gas price) and national subsidies fuels the diffusion of CHP in Dutch industries: Electricity production from CHP increases from 10% to 30%.

- **1980s-1990s**: Flower growers with a high electricity demand (for illumination) installs CHP units to meet this demand, without a connection to the grid. This allows them to reduce their energy bill.
1989: Entry into force of the Electricity Act, enabling joint ventures between energy companies and industries.
  • Initiated by the energy companies, who install a CHP unit at the greenhouse company site
  • The produced heat is sold to the grower at a discount

1989: A feed-in tariff for electricity from industrial cogeneration is installed (from Electricity Act).

1990s: CHP is stimulated through the BSET / EIA subsidy, for investment in energy saving technologies.
Historical Description

- **1994:** A temporary moratorium on the construction of CHP units is set, as a result of a booming diffusion that depleted subsidy funds and risked large electricity generation surpluses.
- **1996:** Natural gas for CHP is exempted from ecotax.
- **1997:** The Dutch government signs the covenant Glastuinbouw en Milieu with the greenhouse sector, including energy efficiency, renewable energy and CO₂ targets.
- **1998:** The feed-in tariff is cancelled.
- **2000s:** The joint ventures become less profitable for energy companies, causing a reduction of this type of CHP units.
Historical Description

- **2002**: Opening of the electricity market for the greenhouse sector, making it possible for growers to sell electricity in the electricity market.
- **2003**: A large tomato grower makes huge profits from selling electricity.
August 2003 - Code Red

- 100 MW of spare capacity
- 99.2% capacity operating
- Peak price 2000 Euros/MWh on APX

Leiden Powerplant
83 MWe

http://www.flickr.com/photos/julesstoop/1430044918/
August 2003 – Code Red

- 100 MW of spare capacity
- Peak price 2000 Euros/MWh on APX

What if...
August 2003 - Code Red

2000 Euros/MWh
100 W average output → 0.20 Euros/hour

Historical Description

- **2001-2006**: A feed-in tariff for electricity from small CHP installations is active, to support economic viability.
- **2002-2010**: To make electricity sales more profitable, large heat buffers are installed, and CHP units are sometimes overdimensioned.
- **2005**: OCAP pipeline is put into operation, providing cheap and high-quality CO$_2$ from Shell (Pernis). This reduces the investment in and use of flue gas cleaners.
Historical Description

• **2003-2009**: A rapid and complete diffusion of CHP units by growers with warm cultivation, driven by a high spark spread.
  • **2006**: A CHP installation has become a standard investment option for greenhouses
  • **2008**: Almost 11 TWh (about 10%) of the total Dutch electricity demand is produced in the greenhouse sector
  • **2010**: 64% of the electricity produced by growers is sold
  • **2010**: Almost all warm cultivation companies have now installed a CHP unit
  • **2010**: 20% less primary fuel use and 2.4 Mton CO$_2$ reduction in the sector compared to 1990 due to CHP
• **2010**: Profitability of CHP for greenhouses has dropped to zero, caused by lower electricity prices.
Further Developments
Next Classes

- September 29th
  - Chris Davis - Biomass
  - Fokko Mulder – Renewables & Energy Storage
- October 6th – Kas Hemmes – Fuel Cells, Multi-Source Multi-Product Systems
- October 13th – Martin Rohde - Nuclear
- October 20th – Fabienne Goosens – WtE, “Waste to Other Things”
- October 27th – No class
- November 3rd – Miro Zeman - Solar