UNIVERSITY OF ICELAND
SCHOOL OF ENGINEERING AND NATURAL SCIENCES

FACULTY OF INDUSTRIAL ENGINEERING,
MECHANICAL ENGINEERING AND COMPUTER SCIENCE

Varmahagfræði -hvað er það?

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GEORG –Rannsóknaklasi í jarðhita

3. málstofa af sex í málstofuröðinni: Frá gufu til gjaldeyris

Feasibility

- Estimation of income
  - Net power
  - Generator power
- Estimation of cost
  - Don’nt forget the wells
  - Investment (+ NPV of parasitic power)
  - Depreciation
  - O&M

The goal

- Make a mathematical model of a power plant
- Be able to estimate net and parasitic power
- Be able to make a rough cost estimate
- Be able to make an estimate of the feasibility

Cost of power generation

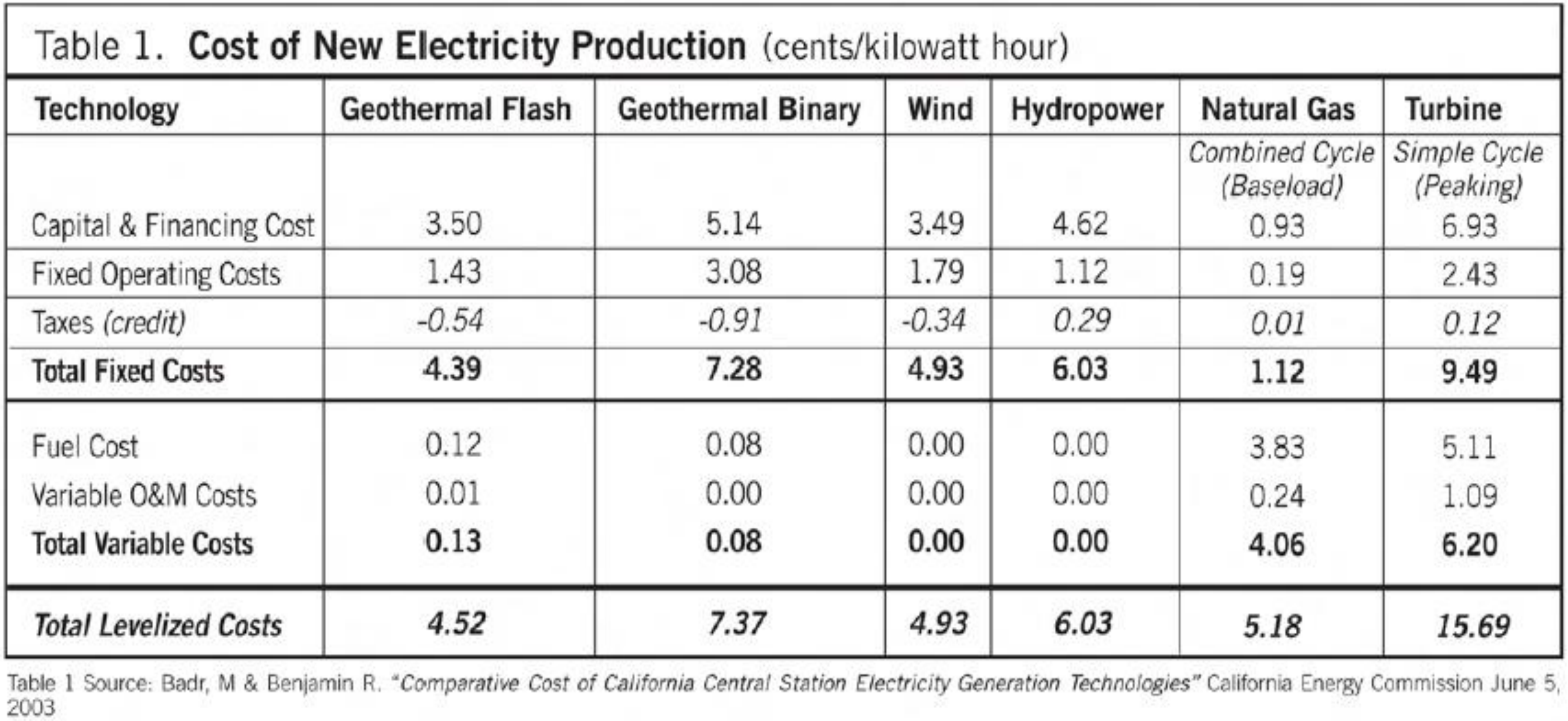


Table 1. **Cost of New Electricity Production** (cents/kilowatt hour)

Technology	**Geothermal Flash**	**Geothermal Binary**	**Wind**	**Hydropower**	**Natural Gas**	**Turbine**
					Combined Cycle (Baseload)	*Simple Cycle (Peaking)*
Capital & Financing Cost	3.50	5.14	3.49	4.62	0.93	6.93
Fixed Operating Costs	1.43	3.08	1.79	1.12	0.19	2.43
Taxes *(credit)*	*-0.54*	*-0.91*	*-0.34*	*0.29*	*0.01*	*0.12*
Total Fixed Costs	**4.39**	**7.28**	**4.93**	**6.03**	**1.12**	**9.49**
Fuel Cost	0.12	0.08	0.00	0.00	3.83	5.11
Variable O&M Costs	0.01	0.00	0.00	0.00	0.24	1.09
Total Variable Costs	**0.13**	**0.08**	**0.00**	**0.00**	**4.06**	**6.20**
Total Levelized Costs	***4.52***	***7.37***	***4.93***	***6.03***	***5.18***	***15.69***

Table 1 Source: Badr, M & Benjamin R. *"Comparative Cost of California Central Station Electricity Generation Technologies"* California Energy Commission June 5, 2003

http://www.geocollaborative.org/publications/Geothermal_Energy_Technologies_and_Costs.pdf

Data from 2003 for California

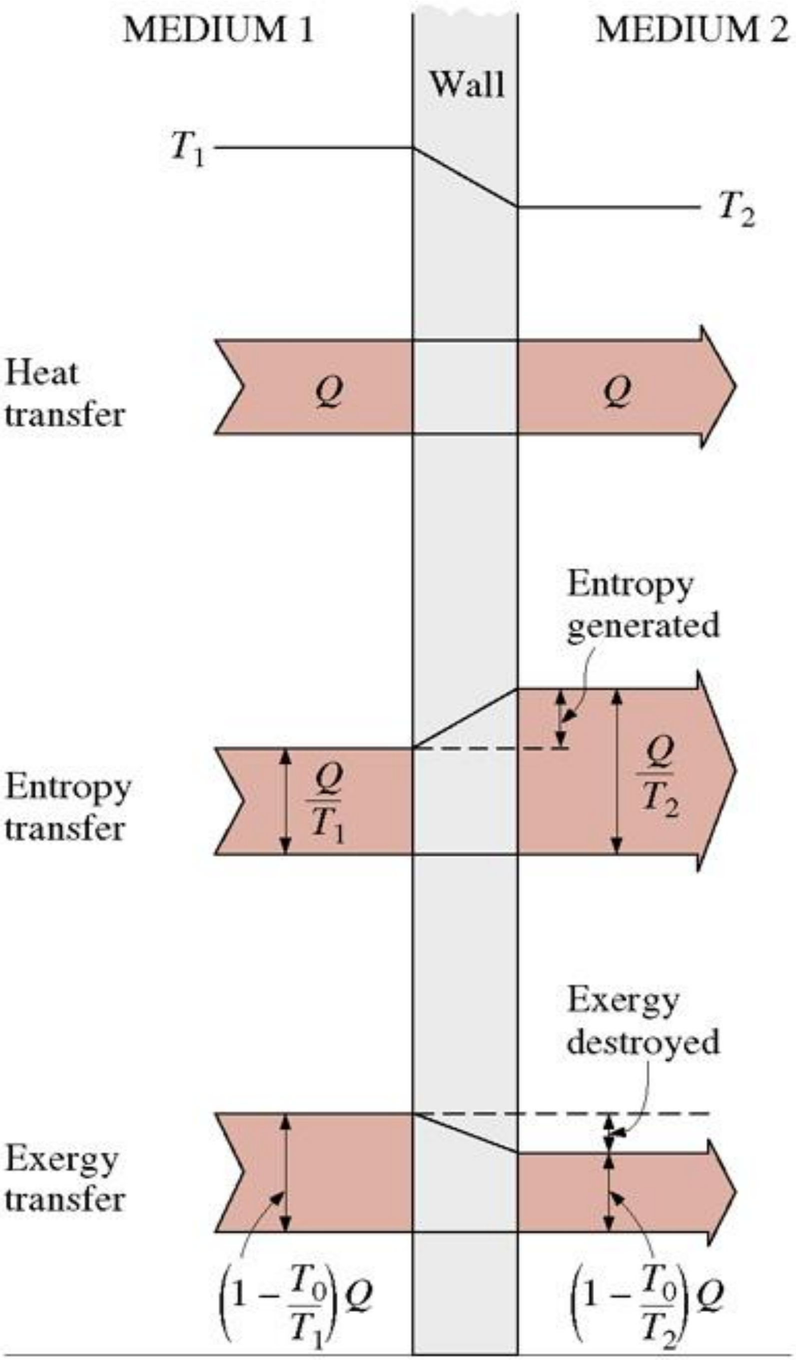
Engineering mathematics

- A mathematical model of the power plant
- Estimation of net and parasitic power
  - given well data
  - given climate
- A rough cost estimate
- An estimate of the feasibility.

Exergy and Anergy

- Exergy is energy, which can be converted without limitations
- Exergy is dependent on the definition of the environment
- Anergy is energy, which cannot be converted into exergy

Exergy
in heat flow



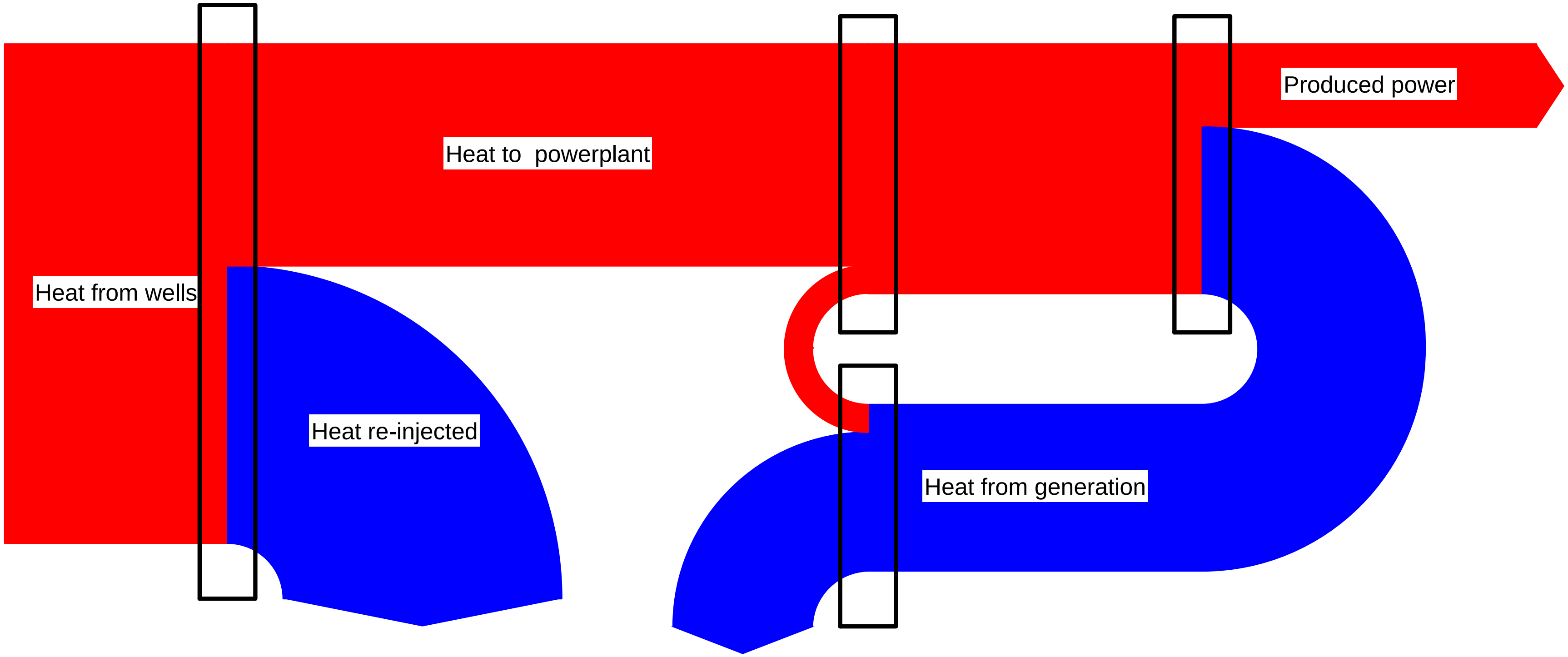
The entropy death

- Finally, the universe will be in equilibrium
- No heat flows
- Everything is in chemical equilibrium
- No wind blows
- ….

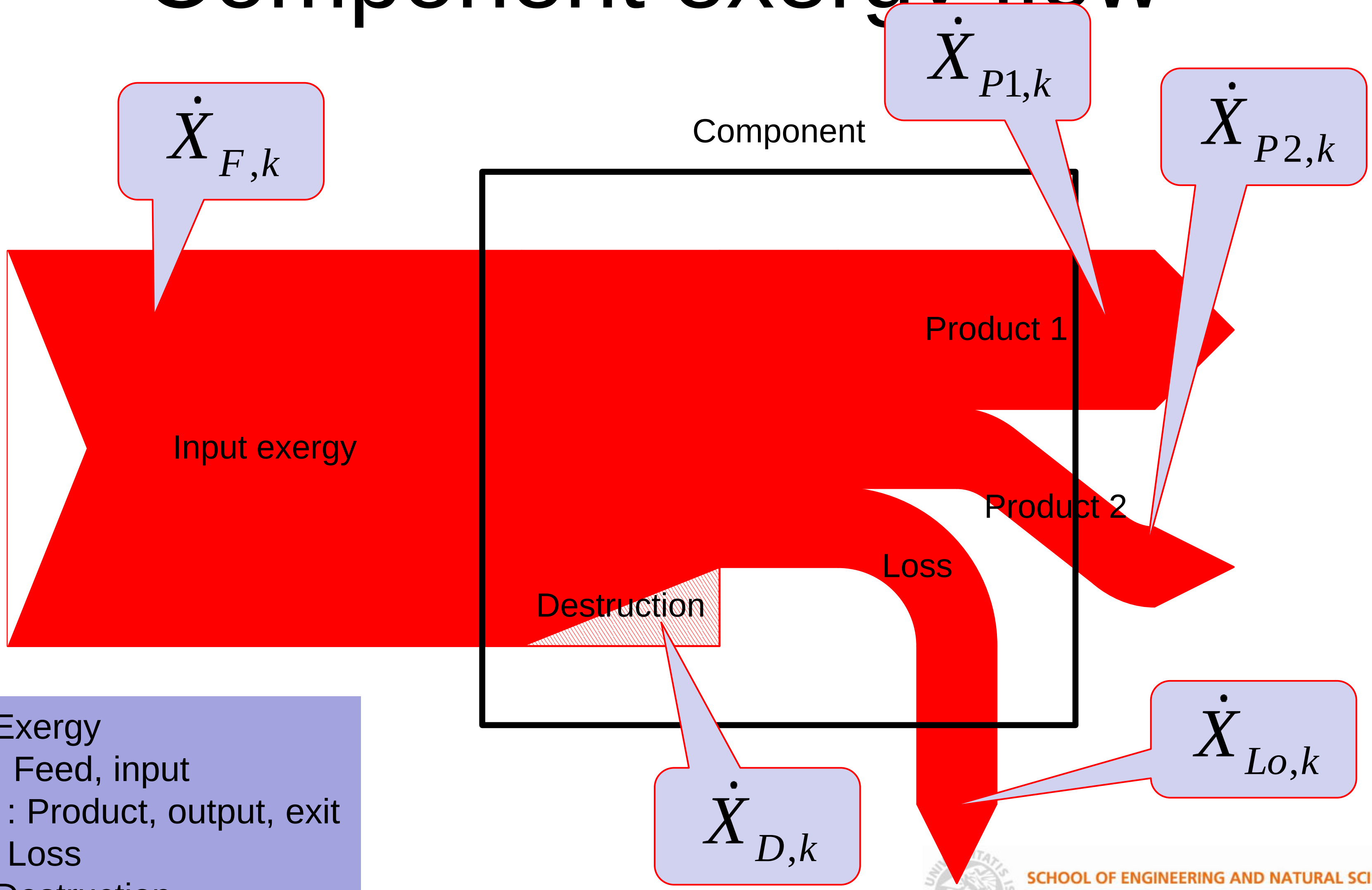
Thermoeconomics

- Only exergy has value
- Anergy has no value
  - Cost (value) flowstreams
    - Exergy cost (variable)
    - Investment cost (fixed)
  - Product value = Raw material value

Energy flow

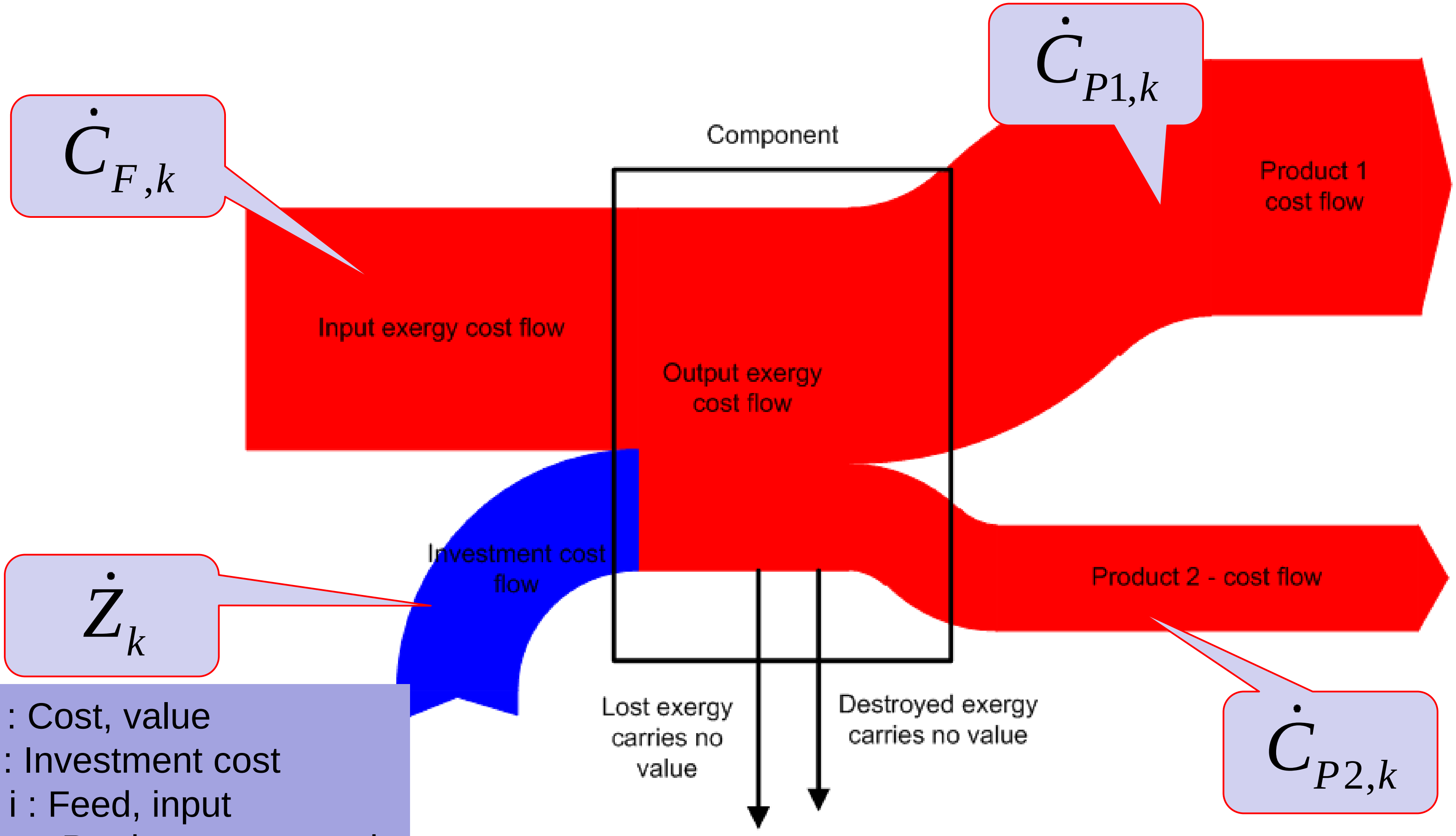

Produced power
Heat to powerplant
Heat from wells
Heat re-injected
Heat from generation

Component exergy flow



X : Exergy
F, i : Feed, input
P, e : Product, output, exit
Lo : Loss
D : Destruction
K : Number of component

Thermoeconomics



C : Cost, value
Z : Investment cost
F, i : Feed, input
P, e : Product, output, exit
Lo : Loss
D : Destruction
k : Number of component

Component cost

$$\dot{Z} = \dot{Z}_{tot}^{CI} + \dot{Z}_{tot}^{OM}$$

Investment cost (value) flow [€/s, €/year]

Capital cost (value) flow [€/s, €/year]

Operation & maintenance cost (value) flow [€/s, €/year]

Cost flow balance

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}$$

Product (output)
cost (value) flow
[€/s, €/year]

Feed (input) cost
(value) flow
[€/s, €/year]

Investment cost
(value) flow
[€/s, €/year]

Unitary cost calculation

$\dot{C}_i, \dot{C}_e$: Input / output cost flow $\left[\frac{€}{s}, \frac{€}{h}\right]$

c_i, c_e : Input / output specific exergy cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{X}_i, \dot{X}_e$: Input / output exergy flow $[kW]$

$\dot{m}_i, \dot{m}_e$: Input / output mass flow $\left[\frac{kg}{s}\right]$

x_i, x_e : Input / output specific exergy $\left[\frac{kJ}{kg}\right]$

$\dot{C}_w$: Work cost flow $\left[\frac{€}{s}, \frac{€}{h}\right]$

c_w : Specific work cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{W}$: Work flow $[kW]$

$\dot{C}_q$: Heat cost flow $\left[\frac{€}{s}, \frac{€}{h}\right]$

c_q : Specific heat cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{X}_q$: Heat exergy flow $[kW]$

$$\dot{C}_i = c_i \dot{X}_i = c_i \left(\dot{m}_i x_i\right)$$

$$\dot{C}_e = c_e \dot{X}_e = c_e \left(\dot{m}_e x_e\right)$$

$$\dot{C}_w = c_w \dot{W}$$

$$\dot{C}_q = c_q \dot{X}_q$$

The k-th component

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k$$

$\dot{C}_{i,k}, \dot{C}_{e,k}$: Input / output cost flow for $\mathrm{k^{th}}$ component $\left[\frac{€}{s}, \frac{€}{h}\right]$

$\dot{C}_{w,k}$: Work cost flow for $\mathrm{k^{th}}$ component $\left[\frac{€}{s}, \frac{€}{h}\right]$

$\dot{Z}_k$: Investment cost flow for $\mathrm{k^{th}}$ component $\left[\frac{€}{s}, \frac{€}{h}\right]$

$\dot{C}_{q,k}$: Heat cost flow for $\mathrm{k^{th}}$ component $\left[\frac{€}{s}, \frac{€}{h}\right]$

$\sum_i$: Sum of all inputs

$\sum_e$: Sum of all outputs

...unitary

$$\sum_e \left(c_e \dot{X}_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{X}_{q,k} + \sum_i \left(c_i \dot{X}_i\right)_k + \dot{Z}_k$$

c_i, c_e : Input / output specific exergy cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{X}_i, \dot{X}_e$: Input / output exergy flow $[kW]$

k : Number of the components under consideration $[-]$

c_w : Specific work cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{W}$: Work flow $[kW]$

c_q : Specific heat cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{X}_q$: Heat exergy flow $[kW]$

$\dot{Z}_k$: Investment cost flow for kth component $\left[\frac{€}{s}, \frac{€}{h}\right]$

Component exergy efficiency

Component	ε, %
Separator	92.00
Vaporizer	86.90
Throttle	80.19
Turbine	77.01
Condenser	71.58
LT recuperator	63.65
HT recuperator	62.05
Pump	50.54
Plant	28.25

A sample list from analysis of a Kalina plant

$$\varepsilon = \frac{\dot{X}_P}{\dot{X}_F} = 1 - \frac{\dot{X}_D + \dot{X}_{Lo}}{\dot{X}_F}$$

ε : Component exergy efficiency $[-]$

$\dot{X}_P$: Exergy flow of the products $[kW]$

$\dot{X}_F$: Exergy flow of the feeds (inputs) $[kW]$

$\dot{X}_D$: Exergy flow destroyed due to irreversibilities $[kW]$

$\dot{X}_{Lo}$: Exergy flow lost to the surroundings $[kW]$

Component exergy destruction ratio

Component	y_D, %
Vaporizer	6.85
Seperator	3.97
Turbine	8.84
HT recuperator	1.05
Throttle	0.10
LT recuperator	1.00
Condenser	1.56
Pump	0.67
Total destruction	24.04

$$y_D = \frac{\dot{X}_D}{\dot{X}_F}$$

y_D : Component exergy destruction ratio $[-]$

$\dot{X}_F$: Exergy flow of the feeds (inputs) $[kW]$

$\dot{X}_D$: Exergy flow destroyed due to irreversibilities $[kW]$

A sample list from analysis of a Kalina plant

Component exergy loss ratio

Component	y_{Lo}, %
Vaporizer	43.78
Condenser	3.94
Total loss	47.71

$$y_{Lo} = \frac{\dot{X}_{Lo}}{\dot{X}_F}$$

A sample list from analysis of a Kalina plant
(These are the only components
that have a loss stream)

y_{Lo} : Component exergy loss ratio $[-]$

$\dot{X}_F$: Exergy flow of the feeds (inputs) $[kW]$

$\dot{X}_{Lo}$: Exergy flow lost to the surroundings $[kW]$

Plant exergy efficiency

$$\varepsilon_{plant} = 1 - \sum_k y_{D,k} - \sum_k y_{Lo,k}$$

ε_{plant} : Plant exergy efficiency $[-]$

$y_{D,k}$: Compnent exergy destruction ratio $[-]$

$y_{Lo,k}$: Compnent exergy loss ratio $[-]$

$\sum_k$: Sum over all components

Component relative cost difference

$$r = \frac{c_P - c_F}{c_F}$$

r : Component relatice cost differenceexergy efficiency $[-]$

$\dot{X}_P$: Exergy flow of the products $[kW]$

$\dot{X}_F$: Exergy flow of the feeds (inputs) $[kW]$

$\dot{X}_D$: Exergy flow destroyed due to irreversibilities $[kW]$

$\dot{X}_{Lo}$: Exergy flow lost to the surroundings $[kW]$

$\dot{C}_F, \dot{C}_P$: Input / output cost flow $\left[\frac{€}{s}, \frac{€}{h}\right]$

c_F, c_P : Input / output specific exergy cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{Z}$: Investment cost flow $\left[\frac{€}{s}, \frac{€}{h}\right]$

$$\left.\begin{aligned} c_P &= \frac{\dot{C}_P}{\dot{X}_P} \\ c_F &= \frac{\dot{C}_F}{\dot{X}_F} \\ \dot{X}_F - \dot{X}_P &= \dot{X}_D + \dot{X}_{Lo} \\ \dot{C}_P - \dot{C}_F &= \dot{Z} \end{aligned}\right\rangle \Rightarrow \quad r = \frac{c_F(\dot{X}_D + \dot{X}_{Lo}) + \dot{Z}}{c_F \dot{X}_P}$$

Component exergoeconomic factor

$$f = \frac{\dot{Z}}{\dot{Z} + c_F\left(\dot{X}_D + \dot{X}_{Lo}\right)}$$

f : Component exergoeconomic factor $[-]$

$\dot{X}_D$: Exergy flow destroyed due to irreversibilities $[kW]$

$\dot{X}_{Lo}$: Exergy flow lost to the surroundings $[kW]$

c_F : Input (feed) specific exergy cost $\left[\frac{€}{kWh}, \frac{€}{kJ}\right]$

$\dot{Z}$: Investment cost flow $\left[\frac{€}{s}, \frac{€}{h}\right]$

Thermoeconomic ranking

Component	r_k	$f_{k,}$ %	$\dot{Z}+\dot{C}_D$ $\cdot 10^{-3}$, US$/s	$\dot{C}_D$ $\cdot 10^{-3}$, US$/s
Condenser	0	40.6	0.5	1.8
Pump	6.2	85.6	0.2	2.5
Vaporizer	2.8	18.1	2.3	3.2
Turbine	0.7	59.4	**5.1**	**9.4**
HT Recuperator	5.7	**14.8**	2.3	2.4
LT recuperator	**6.7**	38.7	2.6	2.8

A sample list from analysis of a Kalina plant

Exergy of common fuels
- fuel oil

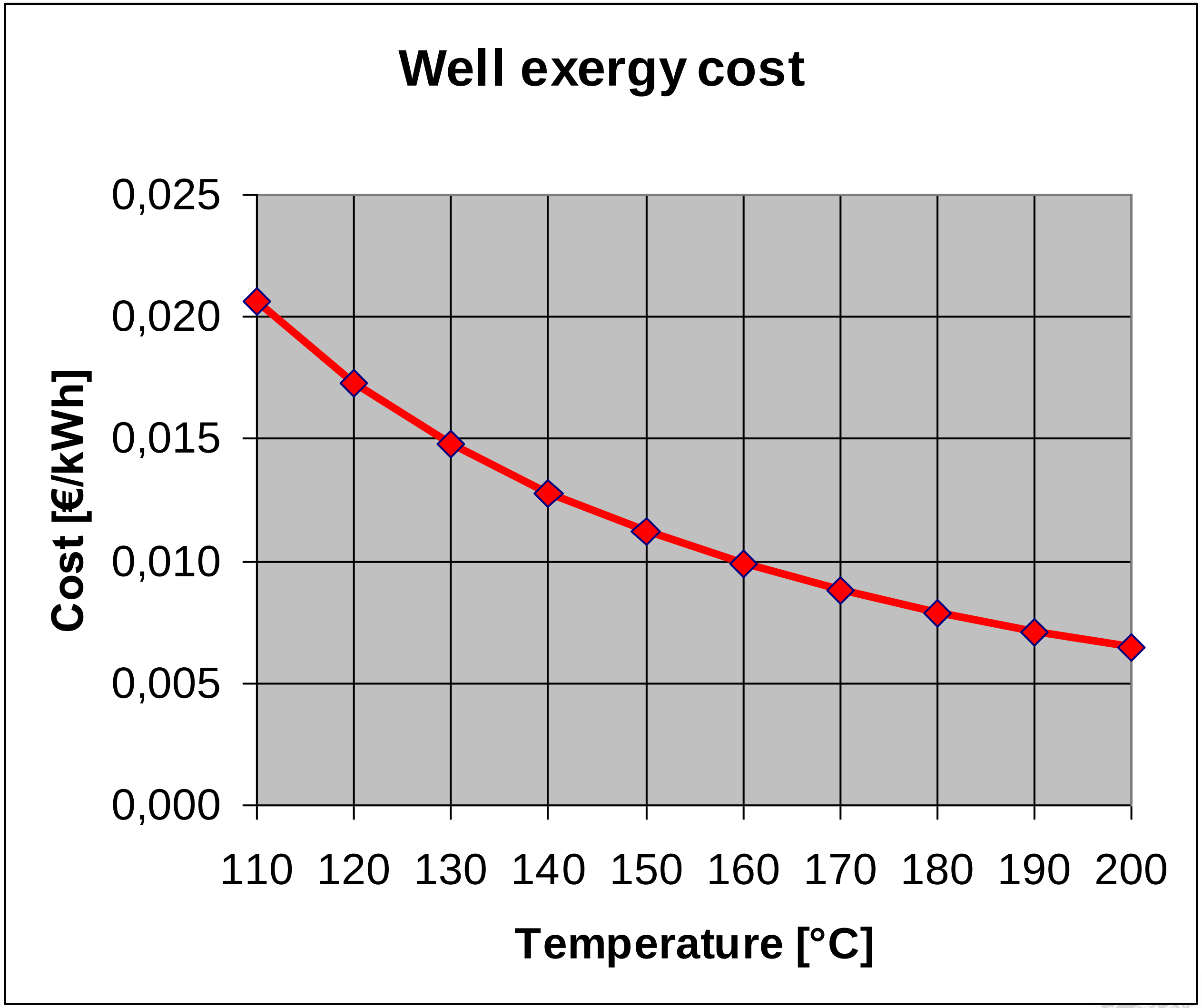
- Similar correlations exist for fuel oil

$$\frac{e_B}{H_u} = 1.065 - \frac{0.320}{H_u} \qquad 38 < H_u < 44\, MJ/kg$$

$$\frac{e_B}{H_o} = 0.905 + \frac{4.06}{H_o} \qquad 40 < H_o < 47\, MJ/kg$$

Well cost

- Assume 5 000 000€ for each well
- Two production wells, one re-injection
- Well production 150 kg/s, 120°C
- Environment at 10°C
- Assume yearly cost as 10% of investment


Well exergy cost
Cost [€/kWh]
0,025
0,020
0,015
0,010
0,005
0,000
110
120
130
140
150
160
170
180
190
200
Temperature [°C]