IPESE
Industrial Process and
Energy Systems Engineering

École Polytechnique
Fédérale de Lausanne

Exergy analysis and process design

De l'utilisation de l'exergie pour optimiser le design des procédés

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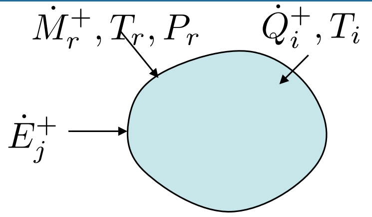
Content

- What is exergy ?
- Exergy efficiency of a process
- Analysing process unit operations & interconnectivity
- Process integration & exergy
- Process design & exergy
- Conclusions

Open system : without accumulation : Energy and entropy balances



First principle: energy balance

Nothing is lost - nothing is created, everything is transformed

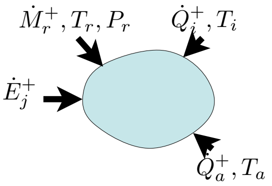
$$\sum_j \dot{E}_j^+ + \sum_i \dot{Q}_i^+ + \sum_r \dot{M}_r^+ h_r(T_r, P_r, X_r) \qquad = 0$$

Second principle: entropy balance

The entropy of an isolated system tends to increase

$$dS = \sum_i \frac{\dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ s_r(T_r, P_r, X_r) \qquad \geq 0$$

Notion of exergy



1st principle: energy balance

$$\sum \dot{E}_j^+ + \sum \dot{Q}_i^+ + \sum \dot{M}_r^+ h_r(T_r, P_r, X_r) + \dot{Q}_a^+ = 0 \qquad \textbf{(1)}$$

2nd principle: entropy balance

$$dS = \sum_i \frac{\dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ s_r(T_r, P_r, X_r) + \frac{\dot{Q}_a^+}{T_a} \geq 0$$

$$\Rightarrow T_a dS = \sum_i \frac{T_a \dot{Q}_i^+}{T_i} + \sum_r \dot{M}_r^+ T_a s_r(T_r, P_r, X_r) + \dot{Q}_a^+ \geq 0 \qquad \textbf{(2)}$$

(1) - (2)
$$\sum_j \dot{E}_j^+ + \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r) \leq 0$$

then
$$\sum_j \dot{E}_j^- \leq \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r)$$

therefore
$$E_{max}^- = \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{T_i}) + \sum_r \dot{M}_r^+ (h_r - T_a s_r)$$
→ Exergy = max work

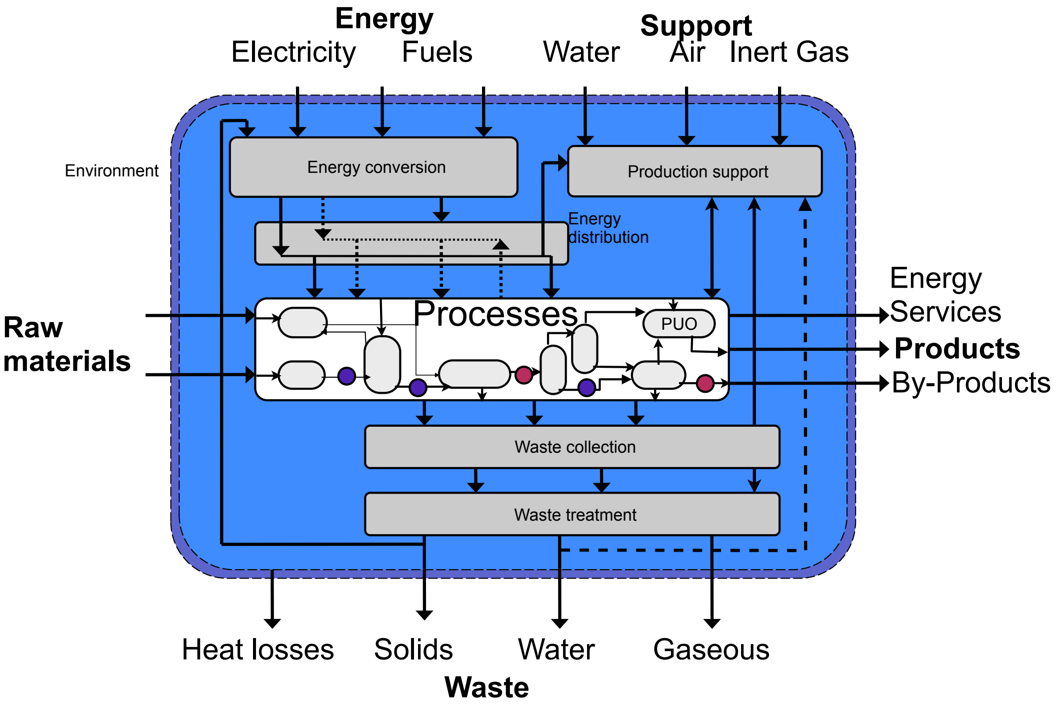
$$\dot{L} = \dot{E}_{max}^- - \sum_j \dot{E}_j^- \geq 0$$
→ Exergy loss
=> wrt max work

exergy is sometime name availability (of work), exergy loss is the loss of the capacity to produce work, the energy is not lost.

Definition of exergy

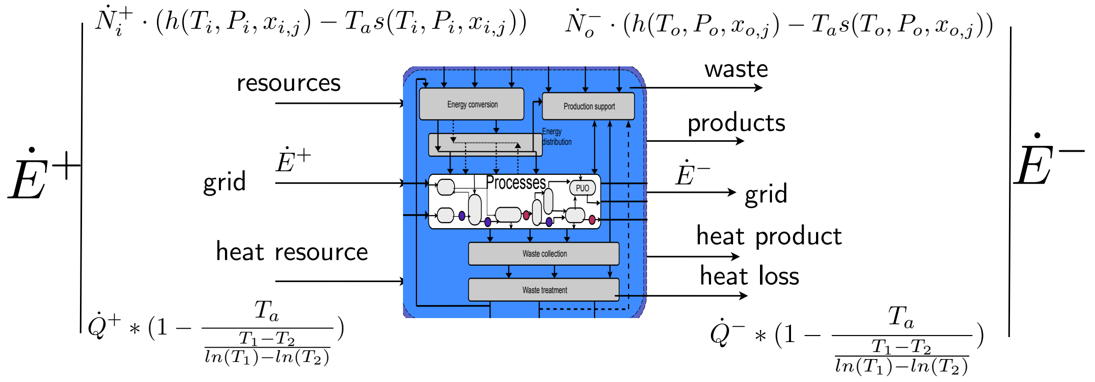
The exergy is the amount of work that can be produced by converting any thermodynamic states by using reversible transformations that exchange only with the ambiant conditions (Ta, Xi, P)

Production process



Energy
Electricity
Fuels
Water
Support
Air
Inert Gas
Environment
Energy conversion
Production support
Energy distribution
Raw materials
Processes
PUO
Energy Services
Products
By-Products
Waste collection
Waste treatment
Heat losses
Solids
Water
Gaseous
Waste

exergy balance of a process



$\dot{N}_i^+ \cdot (h(T_i, P_i, x_{i,j}) - T_a s(T_i, P_i, x_{i,j}))$ $\quad \dot{N}_o^- \cdot (h(T_o, P_o, x_{o,j}) - T_a s(T_o, P_o, x_{o,j}))$

$\dot{E}^+$

resources

grid $\dot{E}^+$

heat resource

$\dot{Q}^+ * (1 - \frac{T_a}{\frac{T_1 - T_2}{ln(T_1) - ln(T_2)}})$

waste

products

$\dot{E}^-$ grid

heat product

heat loss

$\dot{Q}^- * (1 - \frac{T_a}{\frac{T_1 - T_2}{ln(T_1) - ln(T_2)}})$

$\dot{E}^-$

Heat Mass Work

$$\dot{L} = \sum_i \dot{Q}_i^+ (1 - \frac{T_a}{\tilde{T}_i}) + \sum_{r=resources} \dot{N}_r^+ (h_r - T_a s_r) - \sum_{p=products} \dot{N}_p^- (h_p - T_a s_p) + \sum_j \dot{E}_j^+$$

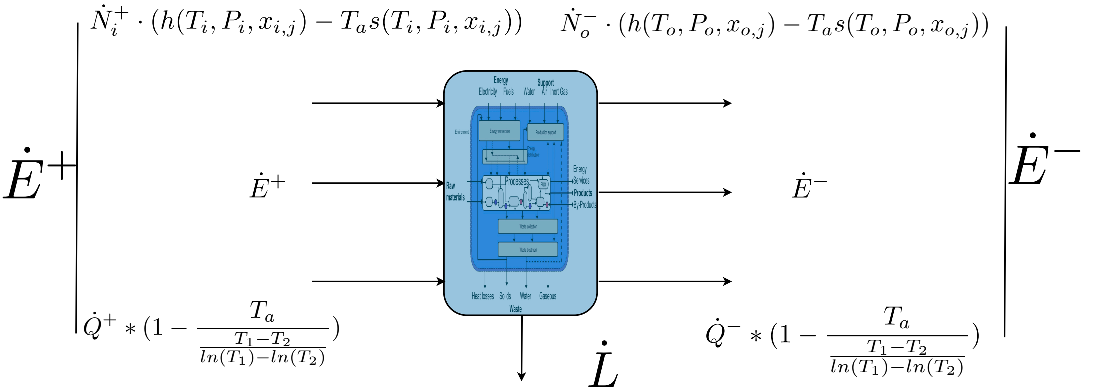
$$\dot{L} = \dot{L}_{process} + \sum_{h=HeatLoss} \dot{Q}_h^- (1 - \frac{T_a}{\tilde{T}_h}) + \sum_{w=Waste} \dot{N}_w^- (h_w - T_a s_w)$$

Heat Mass

$^+$ means positive when entering

Exergetic efficiency of a process

$$\eta = \frac{\dot{E}^-(delivered)}{\dot{E}^+(consumed)} = \frac{\dot{E}^+ - \dot{L}}{\dot{E}^+} = 1 - \frac{\dot{L}}{\dot{E}^+}$$



$\dot{N}_i^+ \cdot (h(T_i, P_i, x_{i,j}) - T_a s(T_i, P_i, x_{i,j}))$ $\quad \dot{N}_o^- \cdot (h(T_o, P_o, x_{o,j}) - T_a s(T_o, P_o, x_{o,j}))$

$\dot{E}^+$ $\quad \dot{E}^+$ $\quad \dot{E}^-$ $\quad \dot{E}^-$

$\dot{Q}^+ * (1 - \frac{T_a}{\frac{T_1 - T_2}{ln(T_1) - ln(T_2)}})$

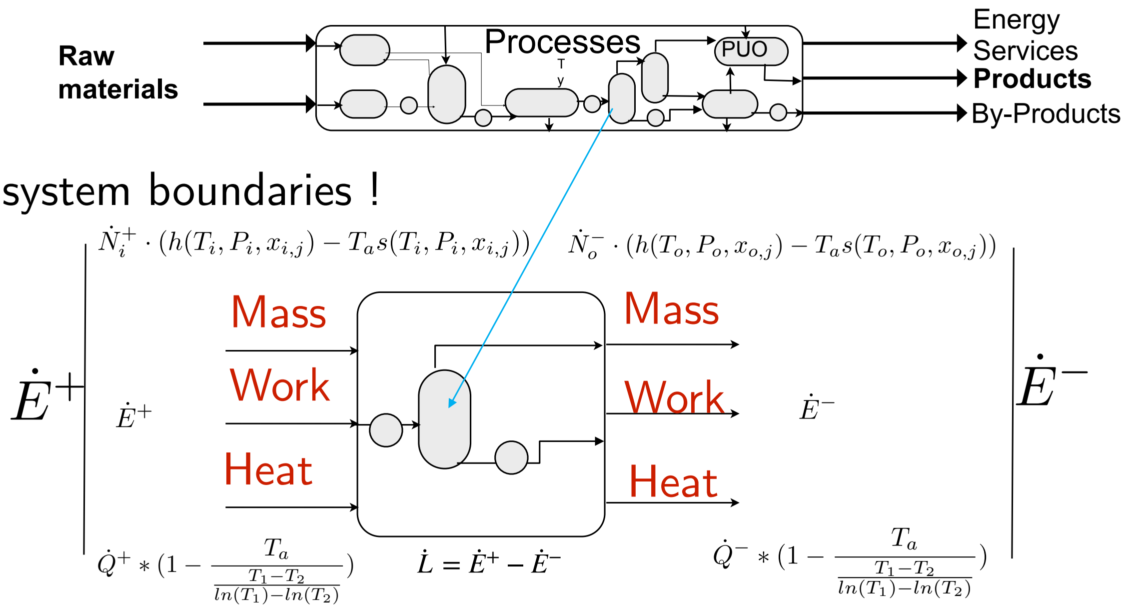
$\dot{L}$

$\dot{Q}^- * (1 - \frac{T_a}{\frac{T_1 - T_2}{ln(T_1) - ln(T_2)}})$

Note : could be lost if released in the environment!

Losses = Exergy in - Exergy out (i.e. used)

In a process, process units exchange mass, heat and work



New system boundaries !

$\dot{N}_i^+ \cdot (h(T_i, P_i, x_{i,j}) - T_a s(T_i, P_i, x_{i,j}))$ $\dot{N}_o^- \cdot (h(T_o, P_o, x_{o,j}) - T_a s(T_o, P_o, x_{o,j}))$

$\dot{E}^+$ $\dot{E}^+$ $\dot{E}^-$ $\dot{E}^-$

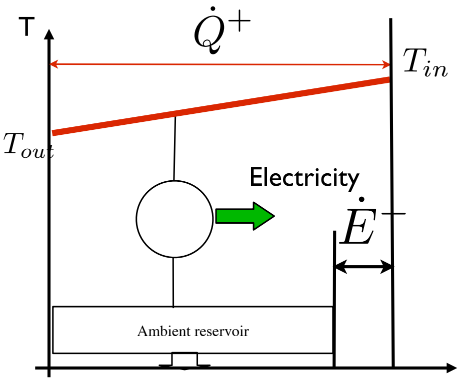
$\dot{Q}^+ * (1 - \frac{T_a}{\frac{T_1 - T_2}{ln(T_1) - ln(T_2)}})$ $\dot{L} = \dot{E}^+ - \dot{E}^-$ $\dot{Q}^- * (1 - \frac{T_a}{\frac{T_1 - T_2}{ln(T_1) - ln(T_2)}})$

Process units exchanges have an exergetic value

Exchanges take place inside the system

The exergy value of a hot stream (heat delivery)

Above the ambiance, a hot stream delivers exergy and balances with the environment

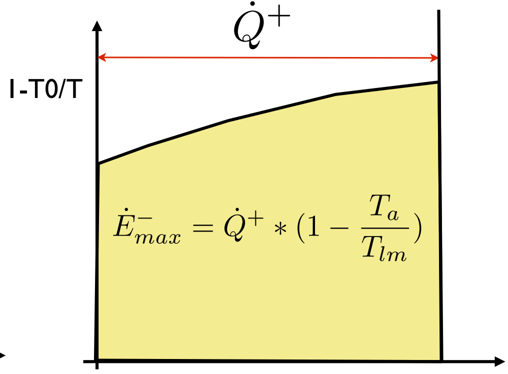


$$\dot{Q}_a^- = \dot{Q}^+ - \dot{E}^-$$

$$\dot{E}^- = \eta_{Carnot} \cdot \dot{E}_{max}^-$$

$$\eta_{Carnot} \simeq 0.55$$

Carnot composite curve



$$\dot{E}_{max}^- = \dot{Q}^+ * (1 - \frac{T_a}{T_{lm}})$$

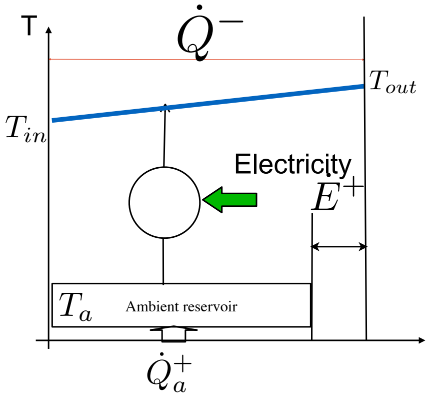
$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

When cp = constant

The exergy value of a cold stream : heat consumption

above the ambience : A cold stream requires exergy and balances with the environment

$$\dot{Q}^{-} = \dot{Q}_a^{+} + \dot{E}^{+}$$



Heat from the environment

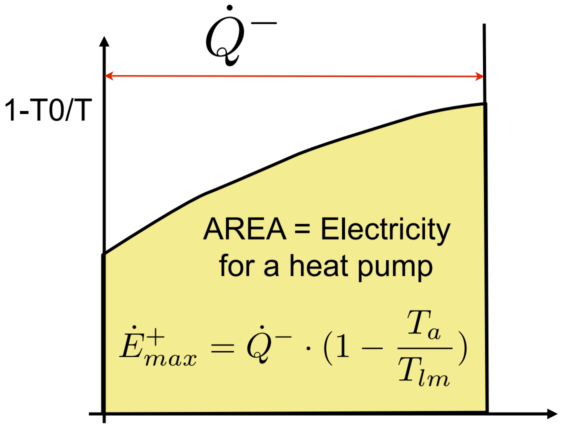
$$\dot{E}^{+}_{min} = \dot{Q}^{-} * (1 - \frac{T_a}{T_{lm}})$$

$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

$$\dot{E}^{+} = \frac{\dot{E}^{+}_{min}}{\eta_{Carnot}}$$

$$\eta_{Carnot} \simeq 0.55$$

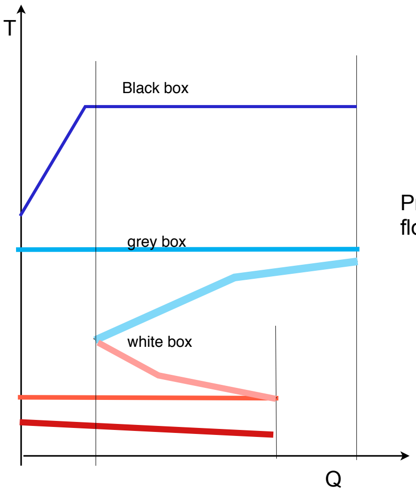
Carnot composite curve

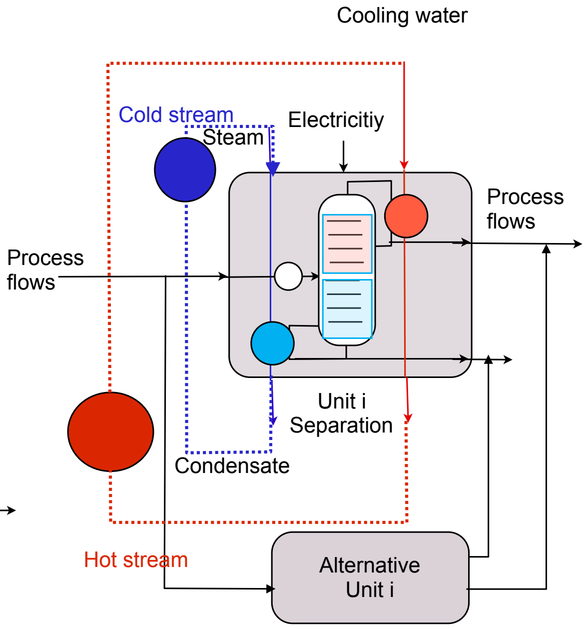


$$\dot{E}^{+}_{max} = \dot{Q}^{-} \cdot (1 - \frac{T_a}{T_{lm}})$$

$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$

Defining Unit Operation heat exchange interfaces

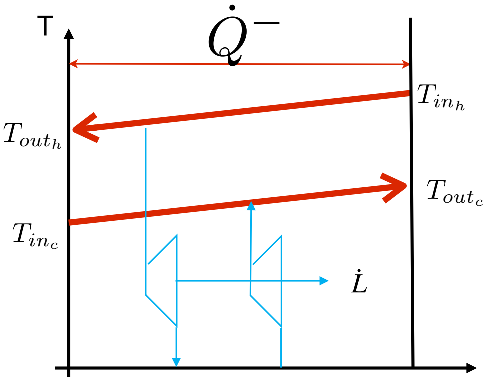




Heat recovery and exergy

$$\dot{E}^{+}_{max} = \dot{Q}^{-} \cdot (1 - \frac{T_a}{T_{lm}})$$

$$T_{lm} = \frac{T_{in} - T_{out}}{ln(T_{in}) - ln(T_{out})}$$



$$\dot{L} = \dot{Q}^{-} * (1 - \frac{T_a}{T_{h_{lm}}}) - \dot{Q}^{-} * (1 - \frac{T_a}{T_{c_{lm}}})$$

The exergy lost in the heat exchanger is the amount of work that can not be produced any more (lost) when the heat exchange is realised. It corresponds to the power that could be produced if one installs an infinite number of perfect Rankine cycles between the hot and the cold streams of the heat exchanger

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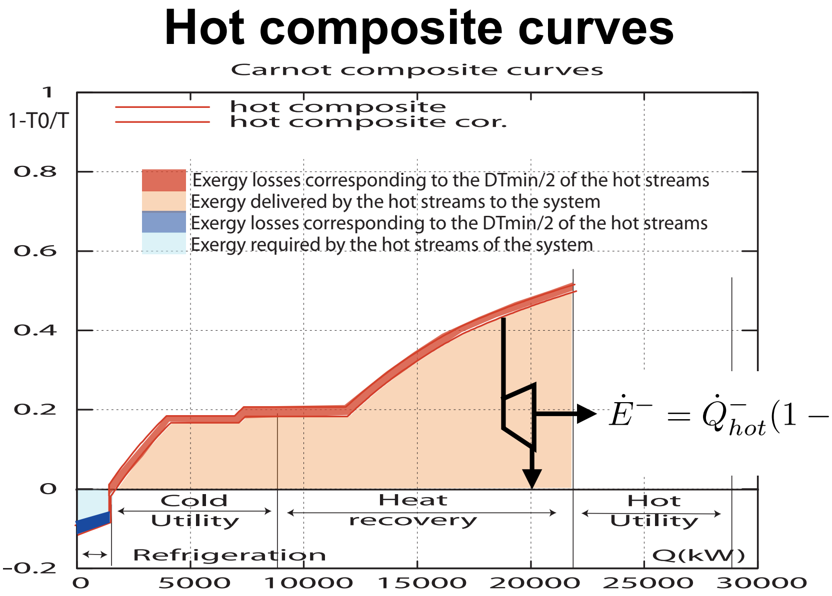
Carnot composite curves of a process



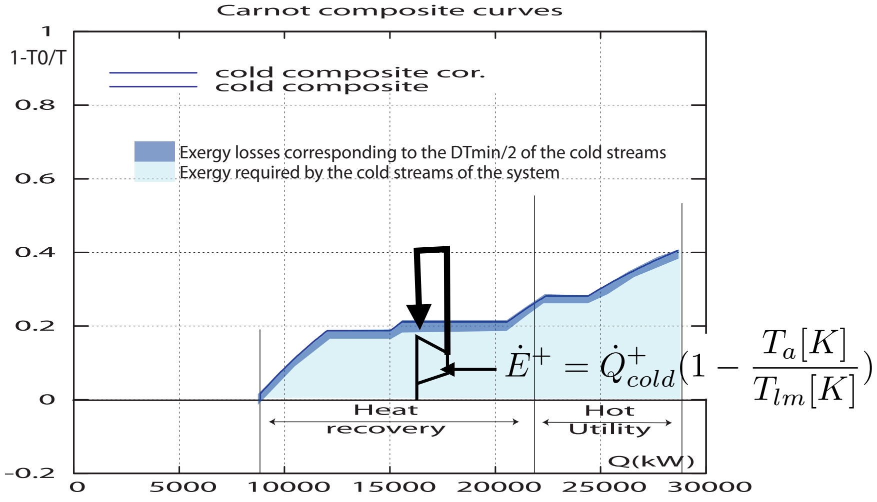
$$\dot{E}^{-} = \dot{Q}^{-}_{hot}(1 - \frac{T_a[K]}{T_{lm}[K]})$$

This is the exergy made available by all the hot streams in the

Marechal, François, and Daniel Favrat. "Combined exergy and pinch analysis for the optimal integration of energy conversion technologies." *18th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems.* 2005.

Carnot composite curves of the process

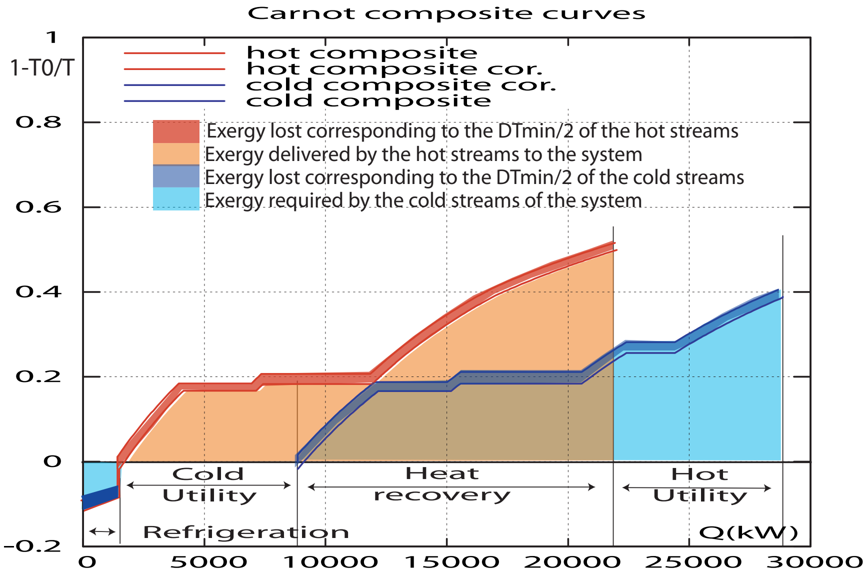
Cold composite curves



$$\dot{E}^{+} = \dot{Q}^{+}_{cold}(1 - \frac{T_a[K]}{T_{lm}[K]})$$

Marechal, François, and Daniel Favrat. "Combined exergy and pinch analysis for the optimal integration of energy conversion technologies." *18th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems.* 2005.

Carnot composite curves and heat recovery

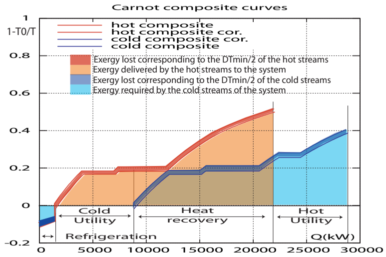


Marechal, François, and Daniel Favrat. "Combined exergy and pinch analysis for the optimal integration of energy conversion technologies." *18th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems.* 2005.

Exergy value of the heat transfer in the process

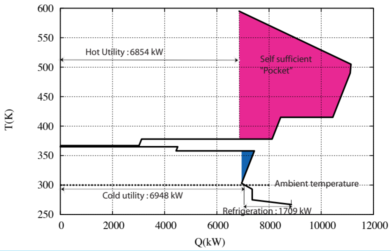
Exergy of the hot and cold process composite curves

	Energy	Exergy Total	Exergy $\Delta T_{min} corrected$	Name
Hot streams [kW]	20291.0	5521.4	5352.4	$\dot{E}q_{hot_a}$
below T_0 [kW]	1709.0	131.5	151.2	$\dot{E}q_{hot_r}$
Cold streams[kW]	20197.0	4599.3	4650.1	$\dot{E}q_{cold_a}$
below T_0 [kW]	0.0	0.0	0.0	$\dot{E}q_{cold_r}$
ΔT_{min} losses [kW]	-		381.2	
Balance [kW]	1803.0	+790.0	+409.0	



Heat recovery

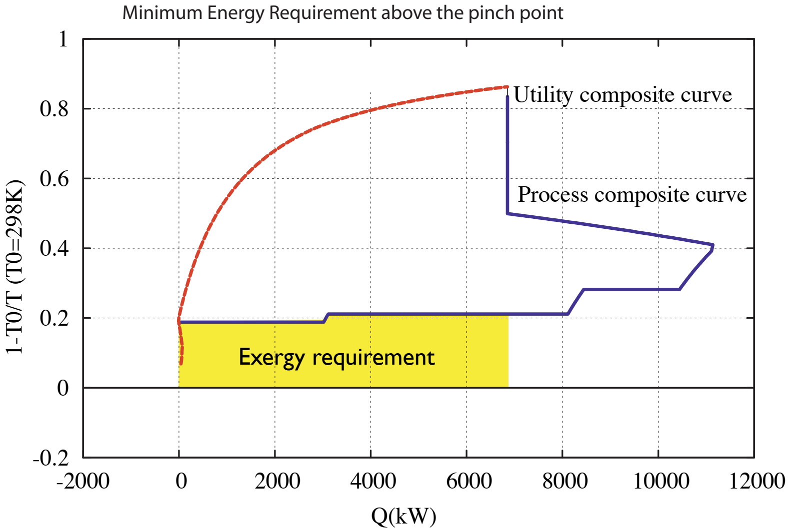
	Energy	Exergy
Heating (kW)	+6854	+567
Cooling (kW)	-6948	- 1269
Refrigeration (kW)	+1709	+ 157



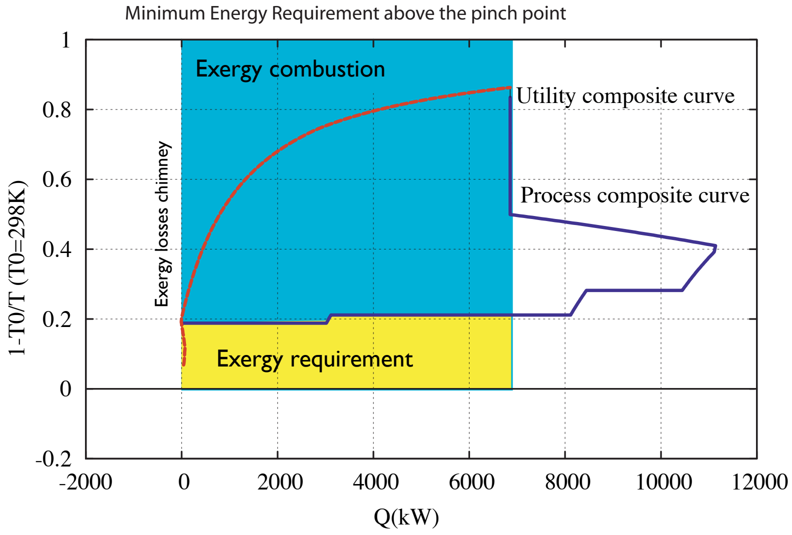
Marechal, François, and Daniel Favrat. "Combined exergy and pinch analysis for the optimal integration of energy conversion technologies." *18th International conference on efficiency, cost, optimization, simulation and environmental impact of energy systems.* 2005.

Exergy requirement above the pinch

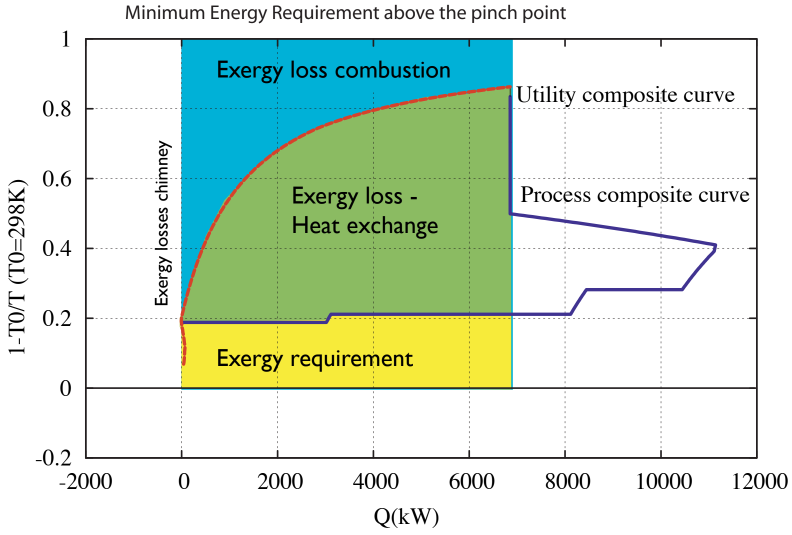
	Energy	Exergy
Heating (kW)	+6854	+567
Cooling (kW)	-6948	- 1269
Refrigeration (kW)	+1709	+ 157



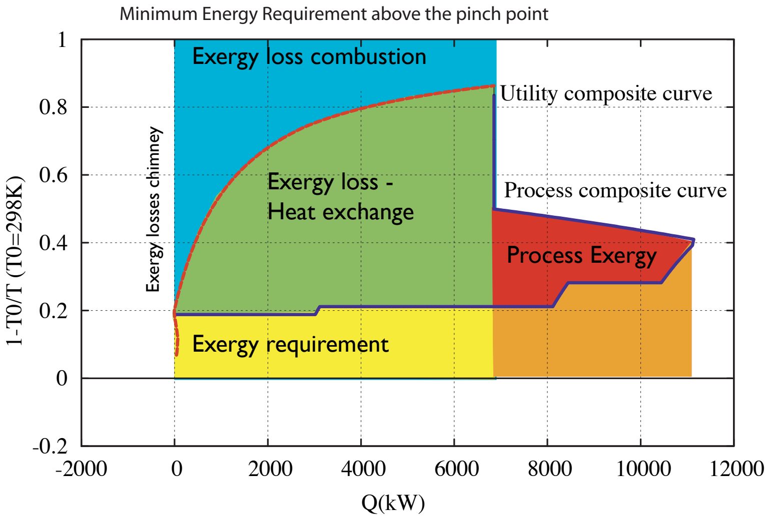
Exergy by combustion



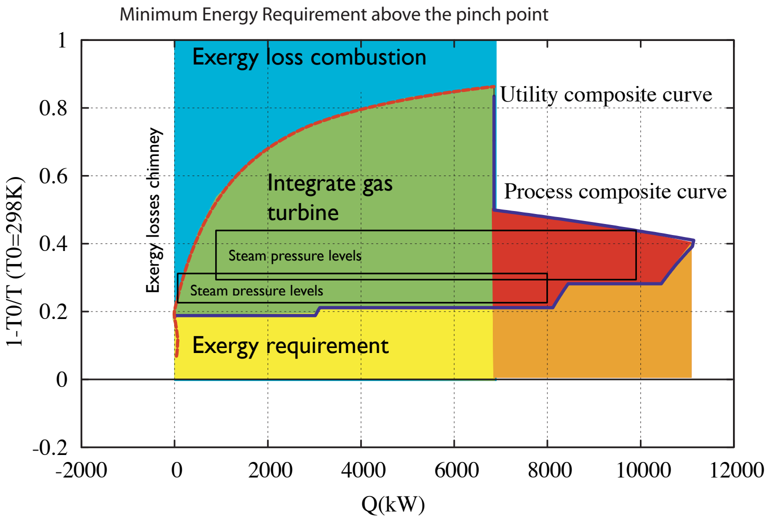
Exergy composite Heat exchange losses



Carnot composite -self-sufficient pockets

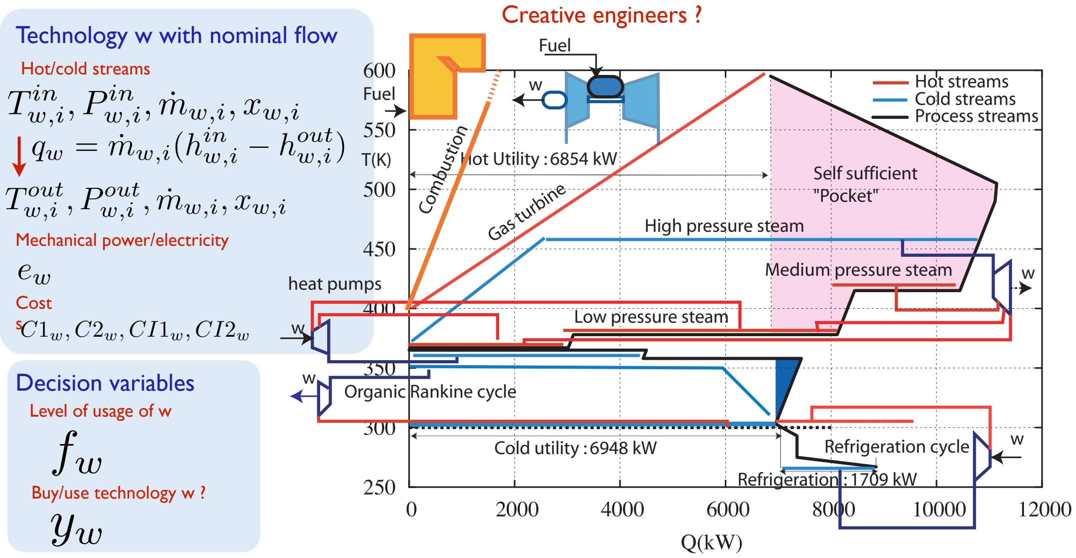


Carnot composite - suggestions to convert the exergy



What is the best way to close the energy balance with the energy resources that we buy ?

Integration of the energy conversion system



Technology w with nominal flow

Hot/cold streams

$T^{in}_{w,i}, P^{in}_{w,i}, \dot{m}_{w,i}, x_{w,i}$

$\downarrow q_w = \dot{m}_{w,i}(h^{in}_{w,i} - h^{out}_{w,i})$

$T^{out}_{w,i}, P^{out}_{w,i}, \dot{m}_{w,i}, x_{w,i}$

Mechanical power/electricity

e_w

Cost

$C1_w, C2_w, CI1_w, CI2_w$

Decision variables

Level of usage of w

f_w

Buy/use technology w ?

y_w

Energy conversion units with unknown flowrates

Mixed integer linear programming formulation of the process integration

Operating cost

$$\min_{R_r, y_w, f_w, E^+, E^-} \left(\sum_{w=1}^{n_w} C2_w f_w + C_{el^+} E^+ - C_{el^-} E^-\right) * t + \sum_{w=1}^{n_w} C1_w y_w + \frac{1}{\tau}\left(\sum_{w=1}^{n_w} (CI1_w y_w + CI2_w f_w)\right)$$

Fixed maintenance

Investment

Subject to : Heat cascade constraints

$$\sum_{w=1}^{n_w} f_w q_{w,r} + \sum_{s=1}^{n_s} Q_{s,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1, ..., n_r$$

Feasibility $$R_r \geq 0 \qquad \forall r = 1, ..., n_r; R_{n_r+1} = 0; R_1 = 0 \qquad E^+ \geq 0; E^- \geq 0$$

Electricity consumption

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c \geq 0$$

Electricity production

$$\sum_{w=1}^{n_w} f_w e_w + E^+ - E_c - E^- = 0$$

Energy conversion Technology selection

$$fmin_w y_w \leq f_w \leq fmax_w y_w \qquad y_w \in \{0, 1\}$$

Maréchal, François, and Boris Kalitventzeff. "Process integration: Selection of the optimal utility system." *Computers & Chemical Engineering* 22 (1998): S149-S156.

Consider exergy losses

New objective function

$$\underset{\dot{R}_r, y_w, f_w}{Min} \sum_{w=1}^{n_w} \dot{L}_w = \sum_{w=1}^{n_w} (f_w * (\sum_{f=1}^{n_{fuel,w}} \dot{m}_{f,w} \Delta k_f^0 + \dot{e}_w^+ - \sum_{r=1}^{n_r} (\dot{e}q_{w,r}^-)_{\Delta T_{min}} - \dot{e}_w^-)) \quad (1)$$

– Heat exergy :

$$(\dot{e}q_{w,r}^-)_{\Delta T_{min}} = \sum_{s=1}^{ns_w} \dot{q}_{s,r}^-(1 - \frac{T_0}{T_{lmr}^*})$$

where T_{lmr}^* is the logarithmic mean temperature of interval r

$T_{lmr}^* = \frac{T_{r+1}^* - T_r^*}{ln(\frac{T_{r+1}^*}{T_r^*})}$ when $T_{r+1}^* \neq T_r^*$ and $T_{lmr}^* = T_r^*$ otherwize

– Chemical Exergy :

$$\sum_{f=1}^{n_{fuel,w}} \dot{m}_{f,w} \Delta k_f^0$$

– Work :

$\dot{e}_w^+$ IN

$\dot{e}_w^-$ Out

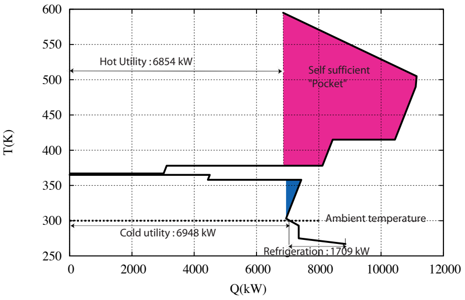
Application : the engineer creativity

Maximum energy recovery

	Energy	Exergy
Heating (kW)	+6854	+567
Cooling (kW)	-6948	- 1269
Refrigeration (kW)	+1709	+ 157

Hot utility

Boiler house : NG (44495 kJ/kg)
Air Preheating
Gas turbine : NG (el. eff = 32%)



Steam cycle

Header	P (bar)	T (K)	Comment
HP2	92	793	superheated
HP1	39	707	superheated
HPU	32	510	condensation
MPU	7.66	442	condensation
LPU	4.28	419	condensation
LPU2	2.59	402	condensation
LPU3	1.29	380	condensation
DEA	1.15	377	deaeration

Heat pumps
Fluid R123

	P_{low} (bar)	T_{low} (°K)	P_{high} (bar)	T_{high} (K)	COP -	kWe
Cycle 3	5	354	7.5	371	15	130
Cycle 2	6	361	10	384	12	323
Cycle 0	6	361	7.5	371	28	34

Refrigeration

Refrigerant	R717	Ammonia
Reference flowrate	0.1	kmol/s
Mechanical power	394	kW

	P (bar)	T_{in} (°K)	T_{out} (°K)	Q kW	$\Delta T min/2$ (°K)
Hot str.	12	340	304	2274	2
Cold str.	3	264	264	1880	2

Results of MILP optimisation

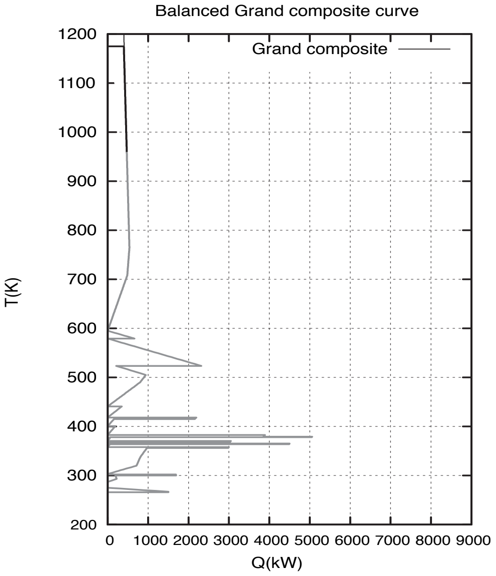
Generating multiple options

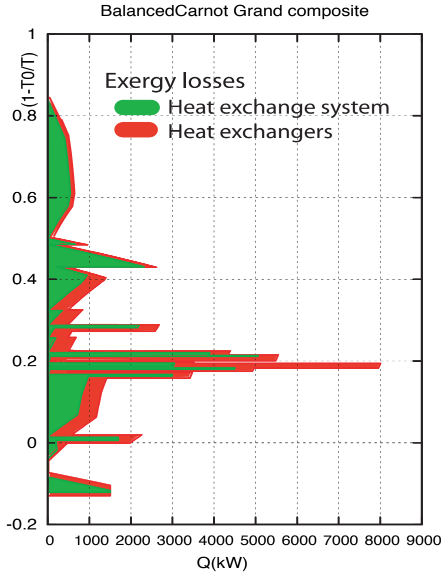
Opt	Fuel kW_{LHV}	GT kWe	CHP kWe	Cooling kW	HP kWe	
1	7071	-	-	8979	-	Comb. + frg
2	10086		2957	9006	-	Comb. + stm + frg
3	16961	5427	2262	9160	-	GT + stm + frg
4	-	-	-	2800	485	hpmp + frg
5	666	-	738	2713	496	hpmp + stm + frg

Share between heat pumps

HP1 : 34 kWe
HP2 : 323 kWe
HP3 : 129 kWe

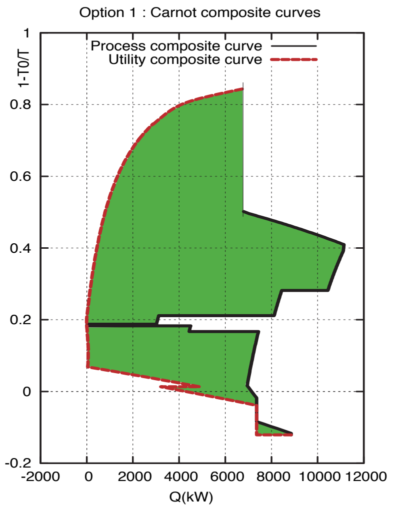
Balanced composite curves (option 5)

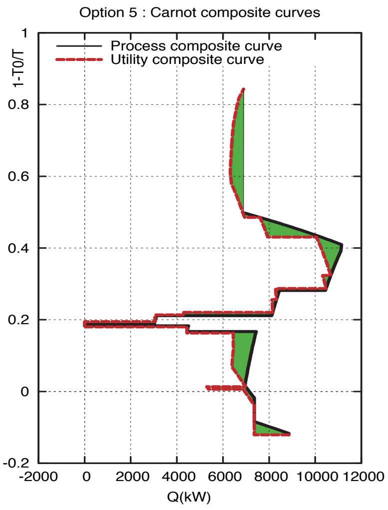




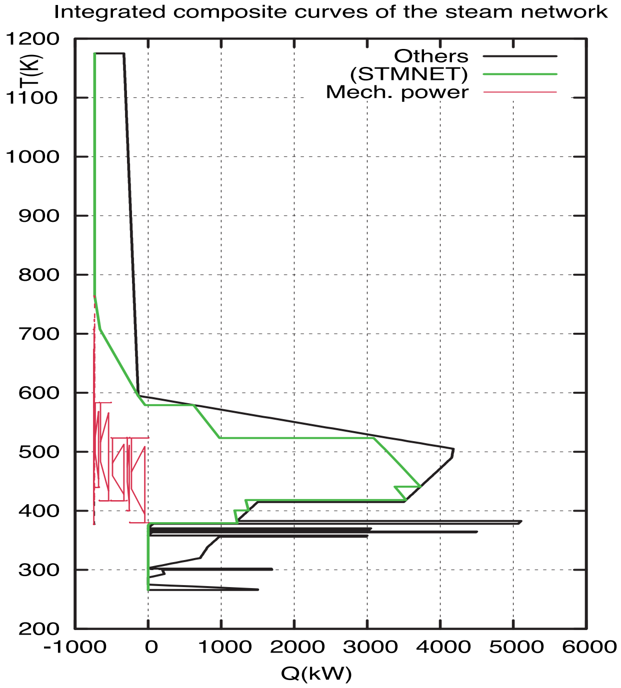
Visualising the results : Carnot composite

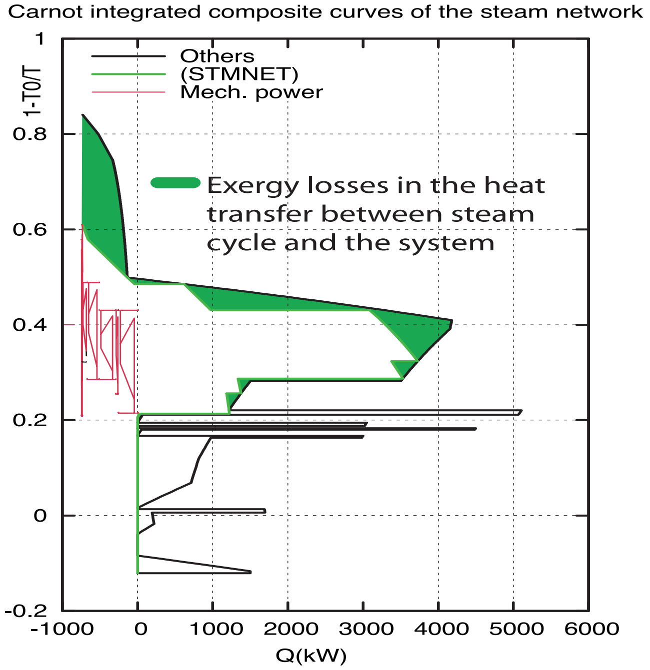
Tricks for creative engineers : reduce the green area !





Carnot integrated composite curves





Exergy losses in the heat transfer between steam cycle and the system

Key performance indicator of the system

Energy efficiency

–NGCC equivalence of electricity

$$Total1 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}}(= 55\%(NGCC))$$

–EU mix for electricity

$$Total2 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}}(= 38\%(EUmix))$$

Exergy efficiency of the energy conversion

$$\eta_{ex} = \frac{\dot{E}q_{cold_a} + \dot{E}q_{hot_r} + \dot{E}^-_{grid}}{\dot{E}^+ + \dot{E}q_{cold_r} + \dot{E}q_{hot_a}} \quad \text{with} \quad \dot{E}^+ = \sum_{fuel=1}^{n_{fuels}} \dot{M}^+_{fuel} \Delta k^0_{fuel} + \dot{E}^+_{grid}$$

$$\dot{L} = (1 - \eta_{ex})(\dot{E}^+ + \dot{E}q_{cold_r} + \dot{E}q_{hot_a})$$

! Process units are sources of exergy (supply and requirements) like the energy conversion system

Results

$$Total1 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}}(= 55\%(NGCC))$$

$$Total2 = \dot{m}_{fuel} * LHV_{fuel} + \frac{(E^+ - E^-)}{\eta_{el}}(= 38\%(EUmix))$$

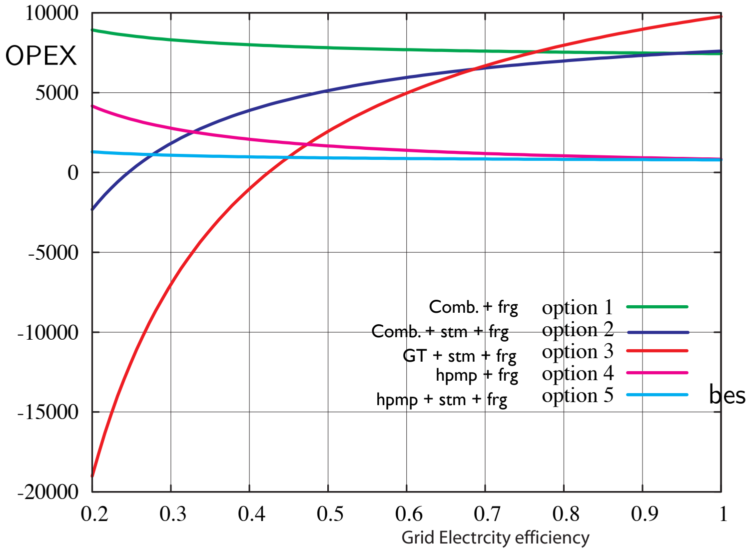
Table 9

Energy consumption and exergy efficiency of the different options

Option	Fuel	$\dot{E}^+_{grid}$	Total 1	Total 2	η_{ex}	Losses
	$[kW_{LHV}]$	[kWe]	$[kW_{LHV}]$	$[kW_{LHV}]$	%	[kW]
Comb. + frg	7071.0	371.0	7745.5	8029.7	34.9	8868.0
Comb. + stm + frg	10086.0	-2481.0	5575.1	3675.1	44.5	8830.0
GT + stm + frg	16961.0	-7195.0	3879.2	-1630.7	51.3	11197.2
hpmp + frg	0.0	832.0	1512.7	2149.9	72.4	2408.1
hpmp + stm + frg	666.0	125.0	893.3	989.0	72.6	1831.6

Exergy vs Energy cost

Exergy and costs are not always compatible



best exergy efficiency

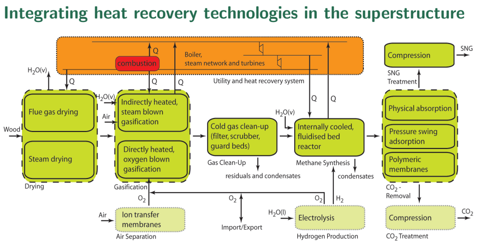
$$\frac{c_{fuel}(€/kJ)}{c^{-}_{grid}(€/kJ_e)} \qquad \frac{CO_{2_{fuel}}[kg/kJ]}{CO_{2_{grid}}[kg/kJ]}$$

Exergy and CO2 emissions are not always compatible

Process design methodology

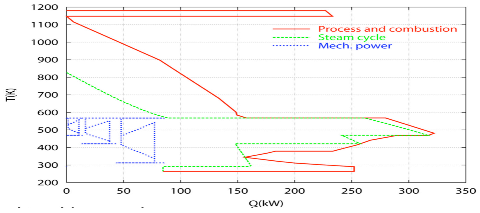
Super-Structure

- Flowsheeting models
- Process unit operation
- Process unit options
- Exchange interfaces



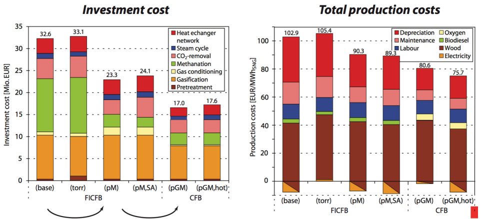
Process integration

- Energy conversion
- Heat recovery
- Energy balance

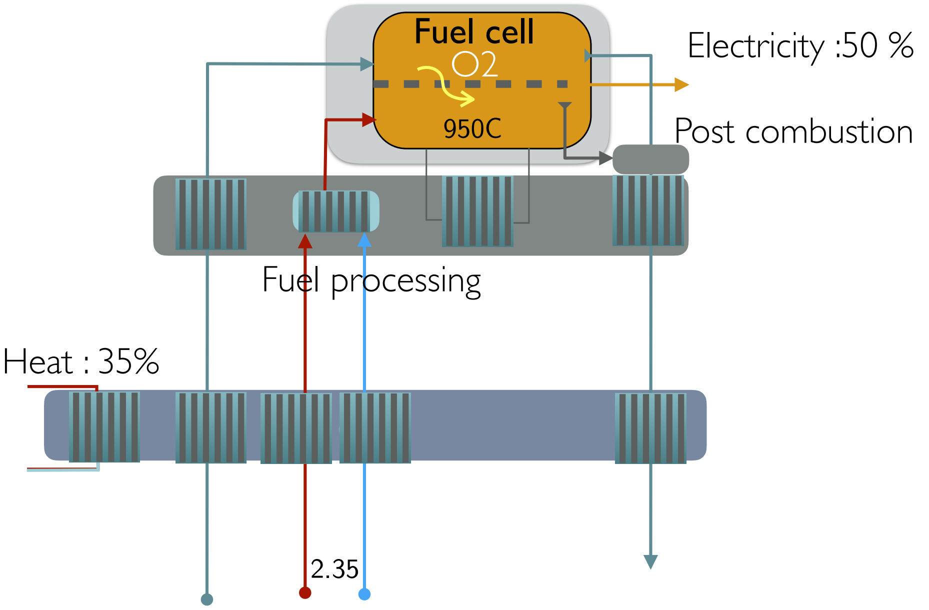


Performances

- OPEX
- CAPEX
- LCA
- Thermodynamic



Producing electricity with Fuel Cell System



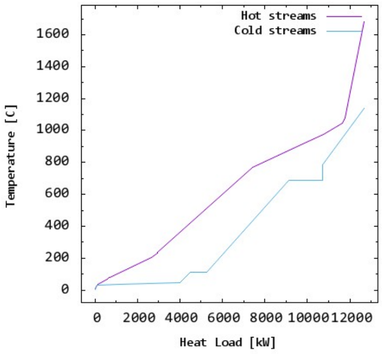
Electricity :50 %

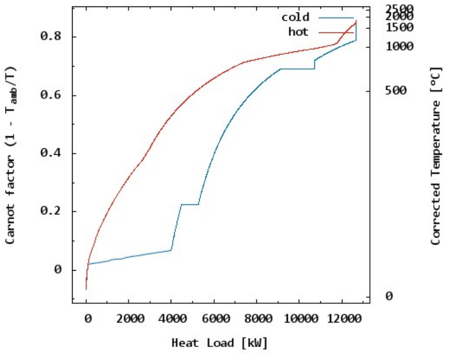
Post combustion

Fuel processing

Heat : 35%

Air CH4 H2O





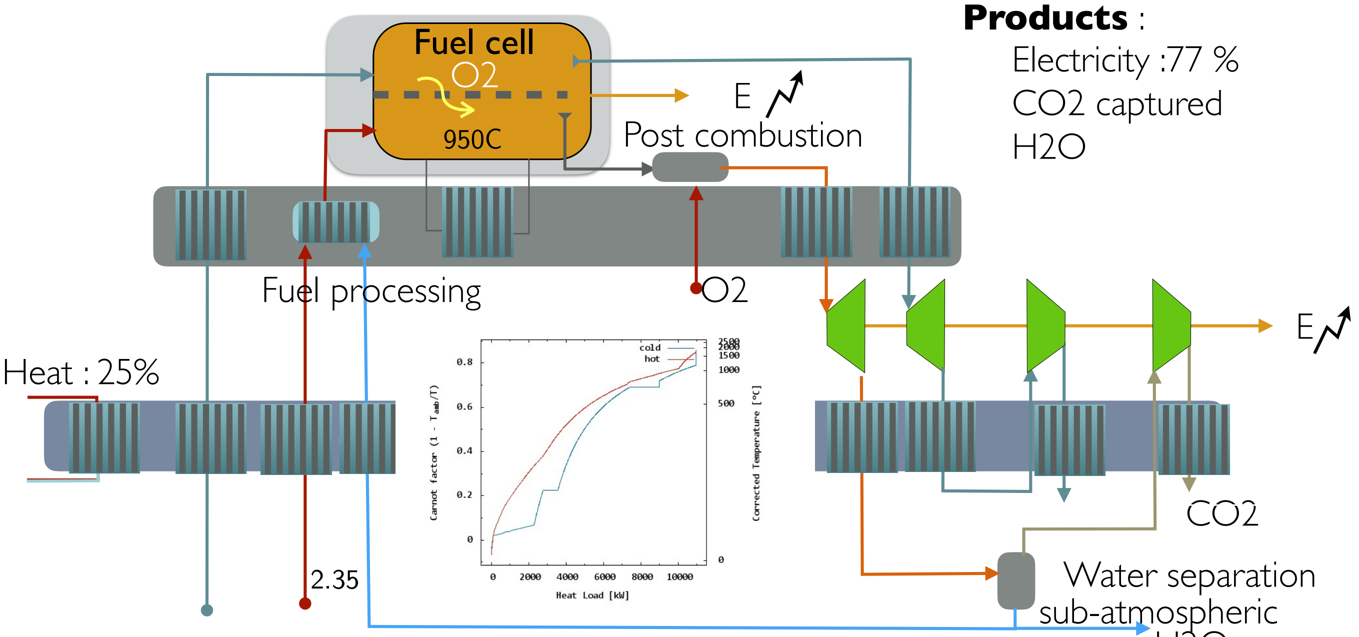
Producing electricity with Fuel Cell System

Products :

Electricity :77 %

CO2 captured

H2O



E

Post combustion

Fuel processing

O2

E

Heat : 25%

CO2

Water separation sub-atmospheric

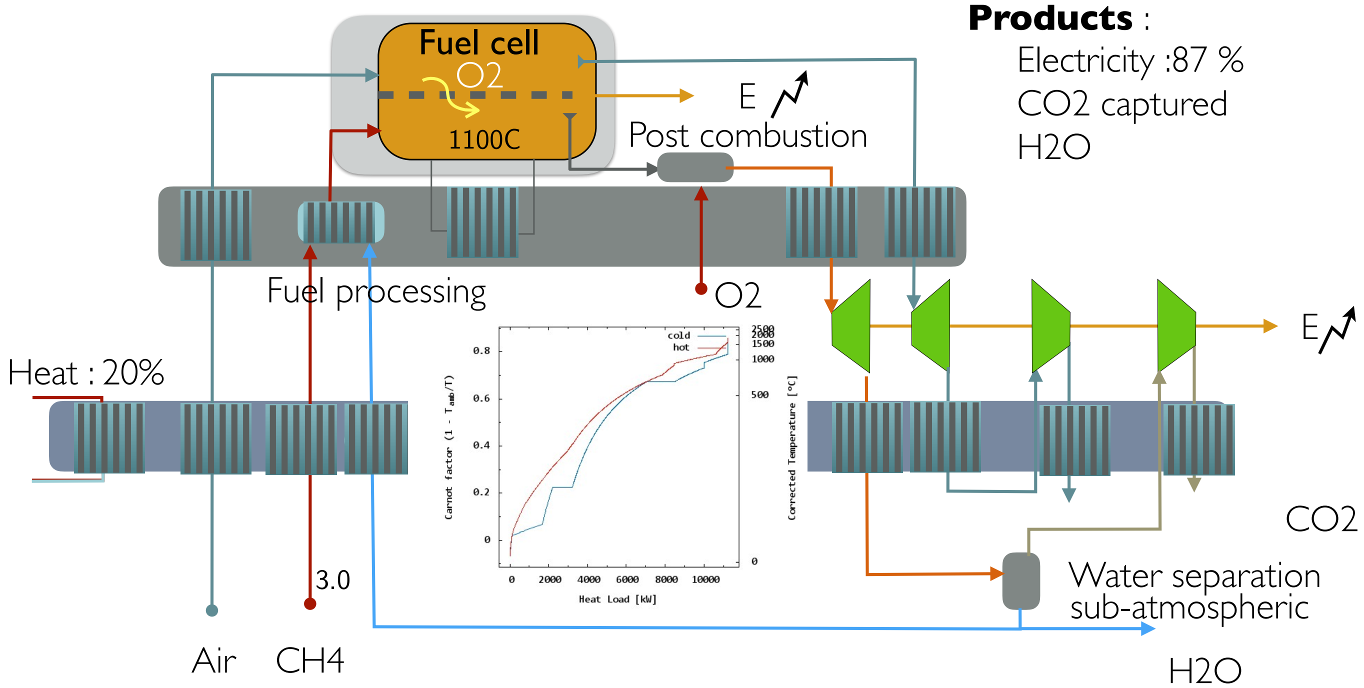
H2O

Air CH4

Facchinetti, M, Daniel Favrat, and Francois Marechal. “Sub-atmospheric Hybrid Cycle SOFC-Gas Turbine with CO2 Separation.” *PCT/IB2010/052558, 2011*.

Producing electricity with Fuel Cell System : optimised system

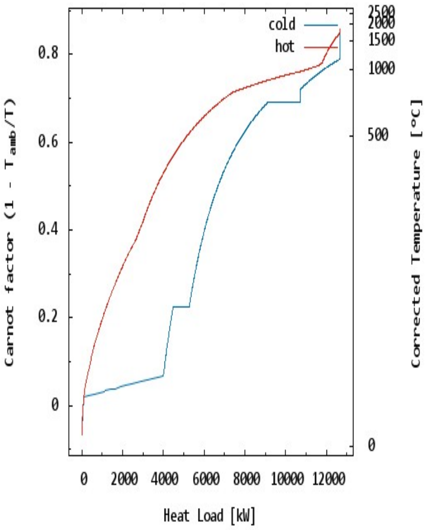
Products :
Electricity :87 %
CO2 captured
H2O



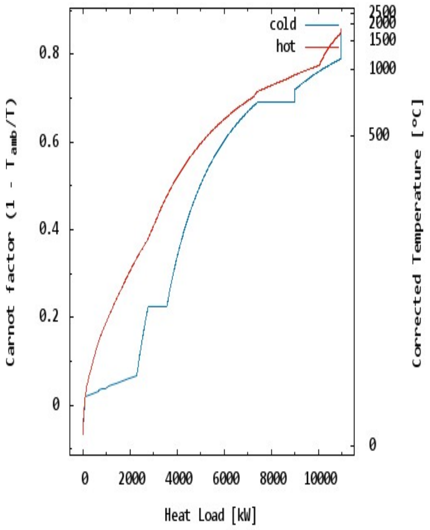
Fuel cell
O2
1100C
E
Post combustion
Fuel processing
O2
E
Heat : 20%
CO2
Water separation sub-atmospheric
3.0
Air
CH4
H2O

Fuel cell : SOFC-GT

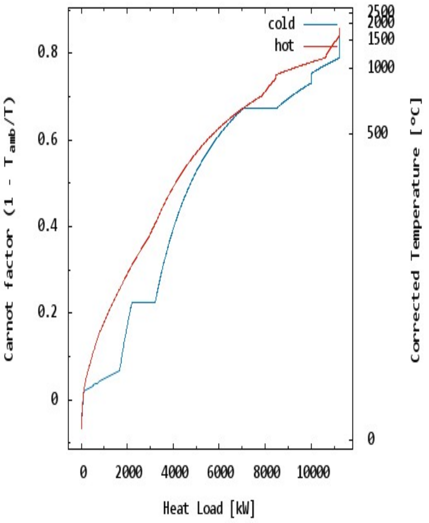
50%



77%

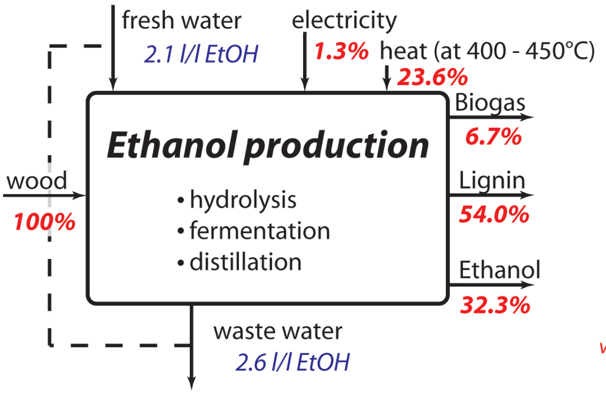


87%

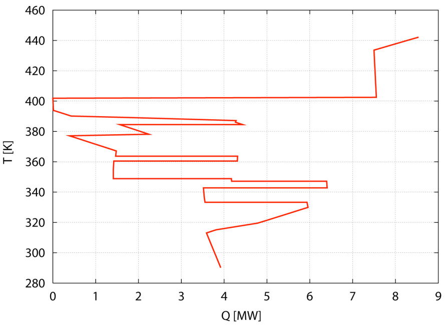


Bio-refineries : system integration

Ethanol production from lignocellulosic biomass:



values based on LHV

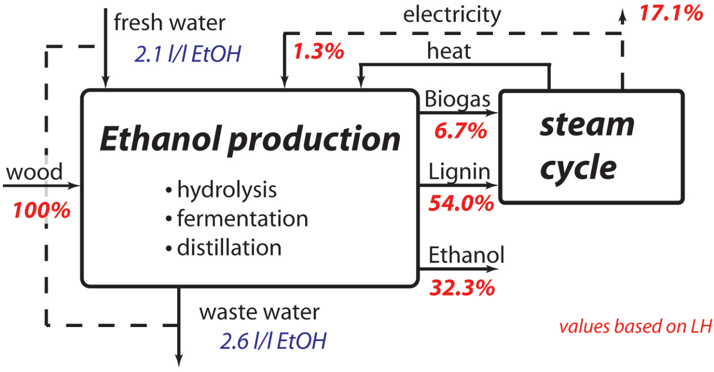


input: $58\ MW_{th,wood}$

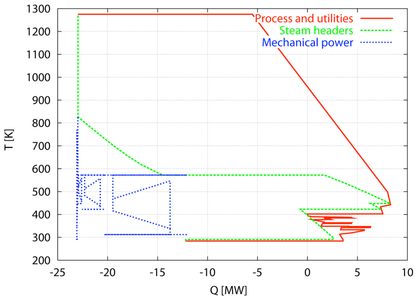
Gassner, Martin, and Francois Marechal. "Increasing efficiency of fuel ethanol production from lignocellulosic biomass by process integration." *Energy & Fuels* 27.4 (2013): 2107-2115.

Converting waste streams to satisfy the process needs : CHP

Ethanol production from lignocellulosic biomass:



values based on LHV



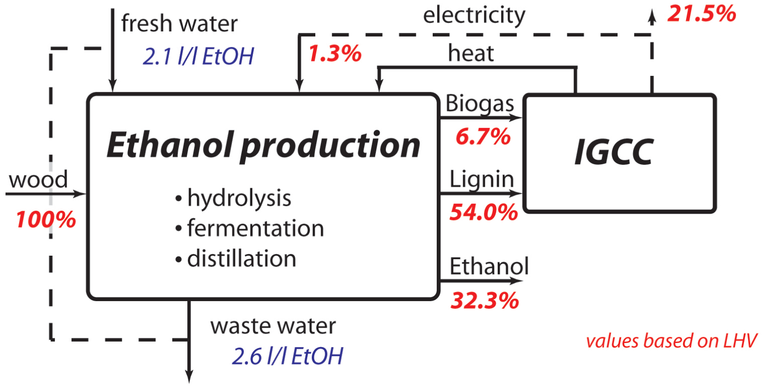
input: $58\ MW_{th,wood}$

		steam cycle
Input	wood	100 %
Output	ethanol	32.3 %
	SNG	-
	electricity	17.1 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %
total efficiency		49.4 %

Energy balance for different process integration options (without seed train, non-optimised).

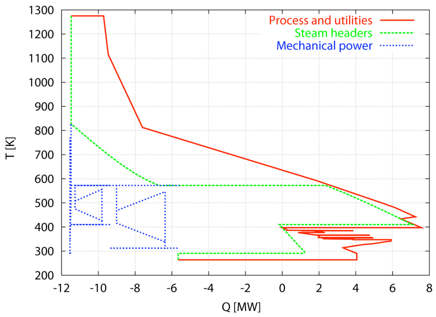
Optimised CHP + power

Ethanol production from lignocellulosic biomass:


fresh water
2.1 l/l EtOH
electricity
21.5%
1.3%
heat
Biogas
6.7%
IGCC
Ethanol production
- hydrolysis
- fermentation
- distillation

wood
100%
Lignin
54.0%
Ethanol
32.3%
waste water
2.6 l/l EtOH

values based on LHV

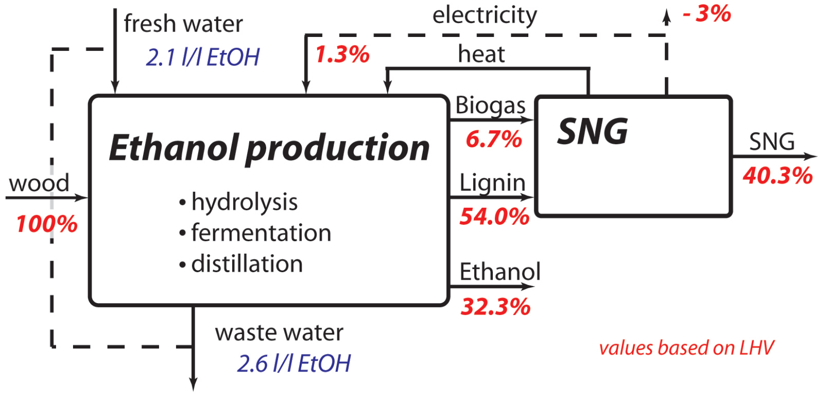


input: 58 $MW_{th,wood}$

		steam cycle	IGCC
Input	wood	100 %	100 %
Output	ethanol	32.3 %	32.3 %
	SNG	-	-
	electricity	17.1 %	21.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %
total efficiency		49.4 %	53.8 %

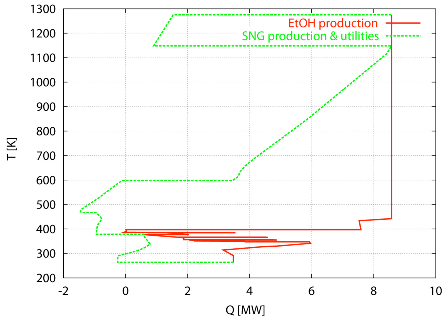
Combined heat and fuel

Ethanol production from lignocellulosic biomass:


fresh water
2.1 l/l EtOH
electricity
- 3%
1.3%
heat
Biogas
6.7%
SNG
SNG
40.3%
Ethanol production
- hydrolysis
- fermentation
- distillation

wood
100%
Lignin
54.0%
Ethanol
32.3%
waste water
2.6 l/l EtOH

values based on LHV

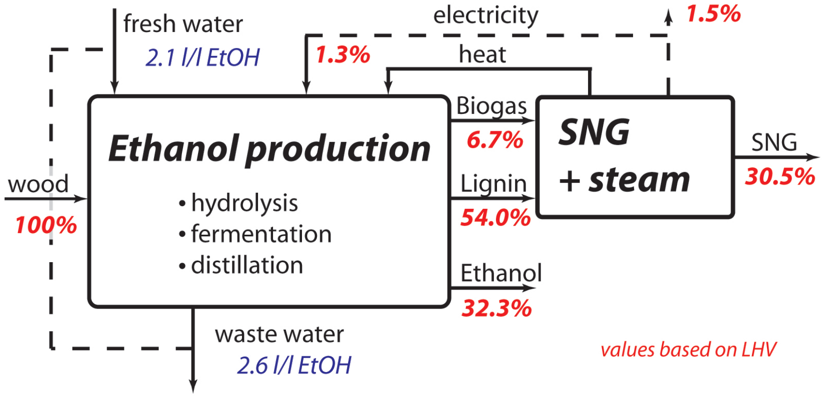


input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG
Input	wood	100 %	100 %	100 %
Output	ethanol	32.3 %	32.3 %	32.3 %
	SNG	-	-	40.3 %
	electricity	17.1 %	21.5 %	-3.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %
total efficiency		49.4 %	53.8 %	70.5 %

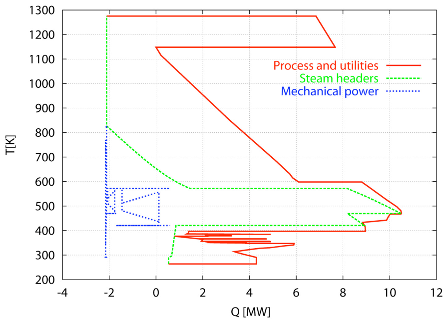
combined heat - fuel and power ?

Ethanol production from lignocellulosic biomass:


fresh water
2.1 l/l EtOH
electricity
1.5%
1.3%
heat
wood
100%
Ethanol production
- hydrolysis
- fermentation
- distillation

Biogas
6.7%
Lignin
54.0%
Ethanol
32.3%
SNG + steam
SNG
30.5%
waste water
2.6 l/l EtOH

values based on LHV

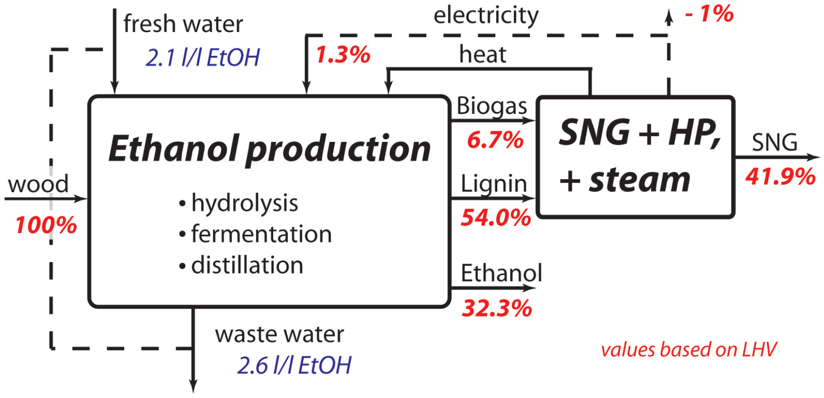


input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam
Input	wood	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %

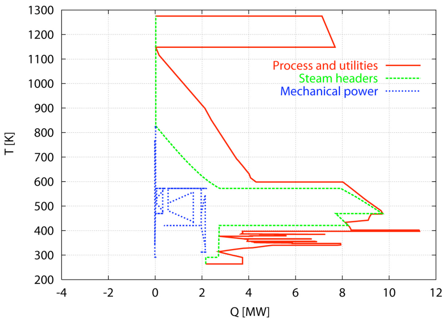
From the exergy analysis

Ethanol production from lignocellulosic biomass:


fresh water
2.1 l/l EtOH
electricity
- 1%
1.3%
heat
wood
100%
Ethanol production
- hydrolysis
- fermentation
- distillation

Biogas
6.7%
Lignin
54.0%
Ethanol
32.3%
SNG + HP, + steam
SNG
41.9%
waste water
2.6 l/l EtOH

values based on LHV

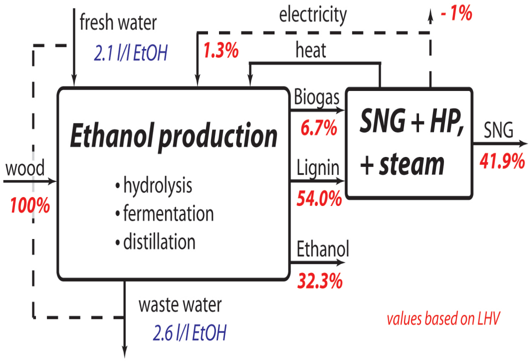


input: 58 $MW_{th,wood}$

		steam cycle	IGCC	SNG	+ steam	+ HP
Input	wood	100 %	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %	41.9 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %	-1.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %	72.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %	73.1 %

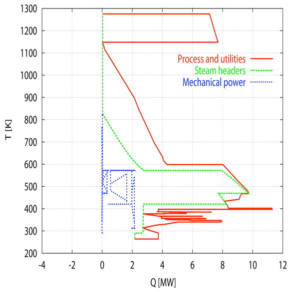
From the exergy analysis

Ethanol production from lignocellulosic biomass:



fresh water
2.1 l/l EtOH
1.3%
electricity
- 1%
heat
wood
100%
Ethanol production
- hydrolysis
- fermentation
- distillation

Biogas
6.7%
Lignin
54.0%
Ethanol
32.3%
SNG + HP, + steam
SNG
41.9%
waste water
2.6 l/l EtOH
values based on LHV



input: 58 $MW_{th,wood}$

Energy balance still holds

Extracting exergy means extracting energy

		steam cycle	IGCC	SNG	+ steam	+ HP
Input	wood	100 %	100 %	100 %	100 %	100 %
	ethanol	32.3 %	32.3 %	32.3 %	32.2 %	32.2 %
Output	SNG	-	-	40.3 %	30.5 %	41.9 %
	electricity	17.1 %	21.5 %	-3.0 %	1.5 %	-1.0 %
chem. efficiency ($\Delta\eta_{NGCC}$=55%)		62.3 %	70.0 %	67.3 %	65.3 %	72.3 %
total efficiency		49.4 %	53.8 %	70.5 %	64.2 %	73.1 %

Gassner, Martin, and Francois Marechal. "Increasing efficiency of fuel ethanol production from lignocellulosic biomass by process integration." *Energy & Fuels* 27.4 (2013): 2107-2115.

Conclusion : process design and exergy

Modeling and Optimisation techniques to design processes

- Flowsheet models
- Operating conditions
- Process integration
  - unit selection and interactions
- Exergy loss : (one of the) objective function

Exergy analysis

- Definition of process unit interfaces
- Carnot composite for the efficiency of the energy conversion
- Identify missing conversion units
- Reducing losses means changing flows

Any Question ?