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DIEF Dipartimento di Ingegneria Industriale

From Exergy to Exergo-economic and Exergo-environmental analysis of renewable energy systems: intro and selected case studies

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Exergy - Definition

"Exergy is an indicator of the capacity of a system, of a matter stream flow or of an Energy interaction (heat, work, potential or kinetic energy) to produce work when interacting with the reference environment."

Work = Exergy   Heat Exergy = θ Q   Carnot Factor $\theta = 1 - T_o/T_{avS}$

Transformation Exergy (phys., steady flow): $e = (h - h_o) - T_o(s - s_o)$ kJ/kg

(+ chemical exergy for reactive processes)

$E = m\ e$ [kW]

Reference environment (Thermomechanical Equilibrium):

$T_o = 298{,}16$ K, $p_o = 101325$ Pa

Exergy Balance – Exergy Efficiency (Direct)

An exergy balance can be written separating input (+) and output (-) terms:

$$\Sigma_k W_k^- + \Sigma_i \theta_{mi} Q_i^- + \Sigma_j E_j^- = \Sigma_k W_k^+ + \Sigma_i \theta_{mi} Q_i^+ + \Sigma_j E_j^+ - \Sigma_h EXDL_h$$

$EXDL_h$ is the exergy Destruction or Loss – the balance is non-conservative because real processes are irreversible.

The exergy balance allows to define the system Exergy Efficiency; in Direct Terms:

$$\eta_{xd} = (\Sigma_k W_k^- + \Sigma_i \theta_{mi} Q_i^- + \Sigma_j E_j^-)/(\Sigma_k W_k^+ + \Sigma_i \theta_{mi} Q_i^+ + \Sigma_j E_j^+)$$

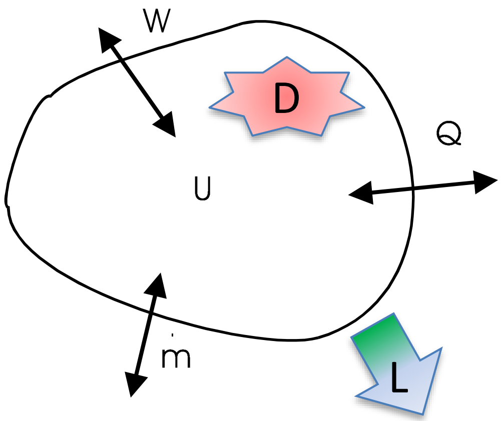
Exergy Efficiency – Indirect – System level

The exergy balance allows to formulate the exergy efficiency in Indirect Form, providing evidence for exergy destructions and losses which can be of very different nature in an energy conversion system:

$$\eta_{xi} = 1 - (\Sigma_h EXDL_{xh}) / (\Sigma_k W_k^+ + \Sigma_i \theta_{mi} Q_i^+ + \Sigma_j E_j^+)$$

Exergy Destructions D are connected to entropy generation (irreversible processes taking place in system components)

Exergy Losses L are connected to direct waste of exergy, discharged to the environment (e.g. heat or material stream)



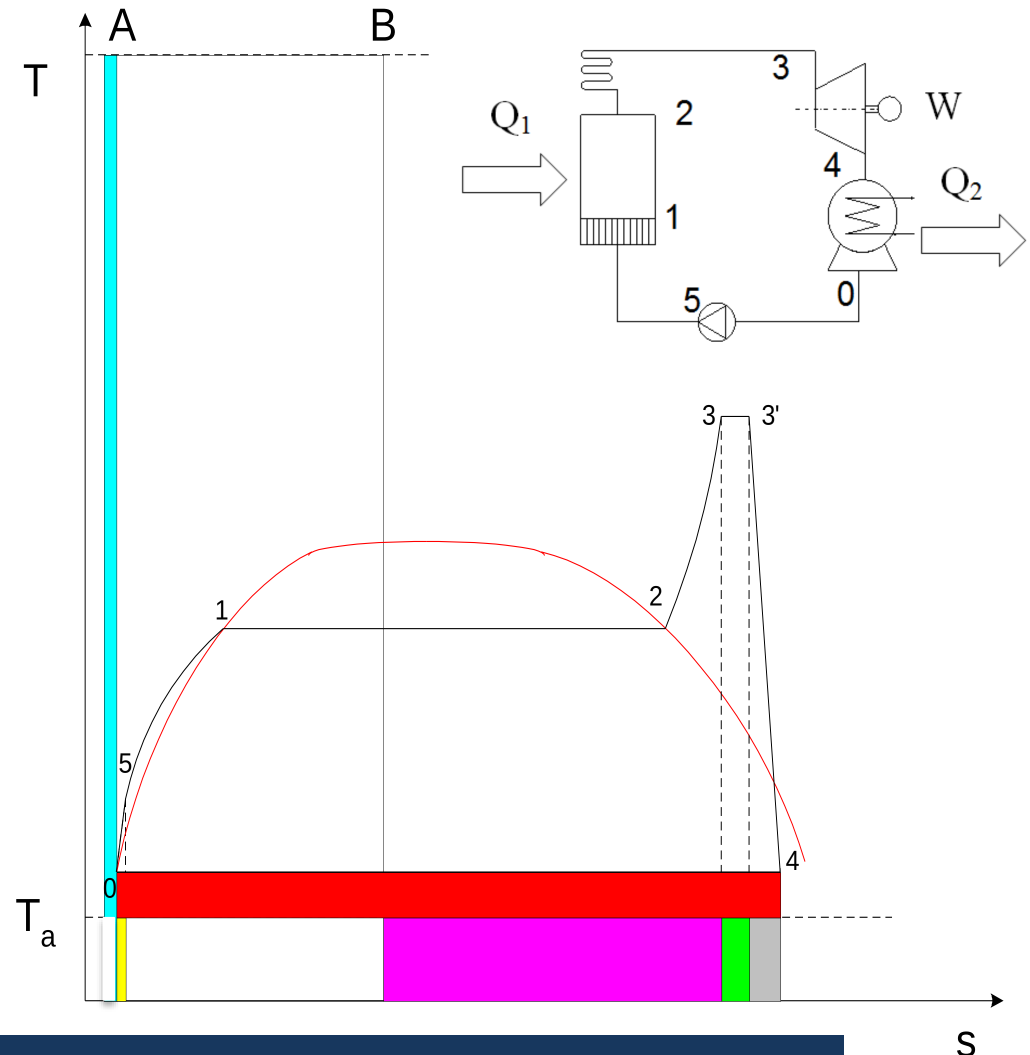
Elementary – Steam cycle (Graphics)

Exergy Destructions D are represented by rectangles $T_a \Delta S_{irr}$

Exergy Losses L are represented by rectangles over T_a

6 EXDLs:

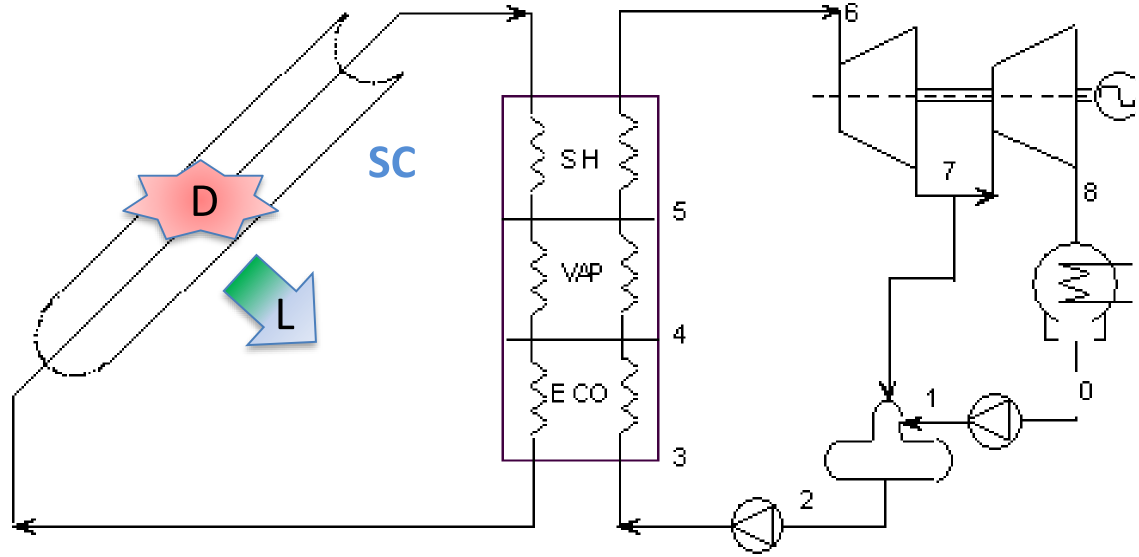
L = **Condenser**, **Boiler insulation**

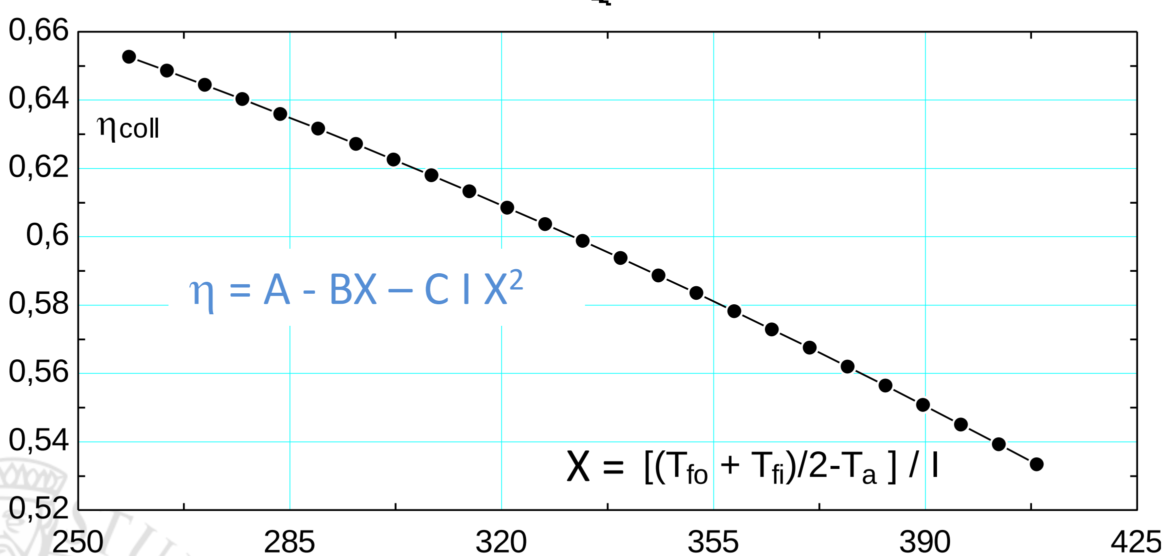


D= **Boiler HT**, **Boiler Friction**, **Turbine**, **Pump**

Solar Thermal Energy Conversion Flowrate Optimization

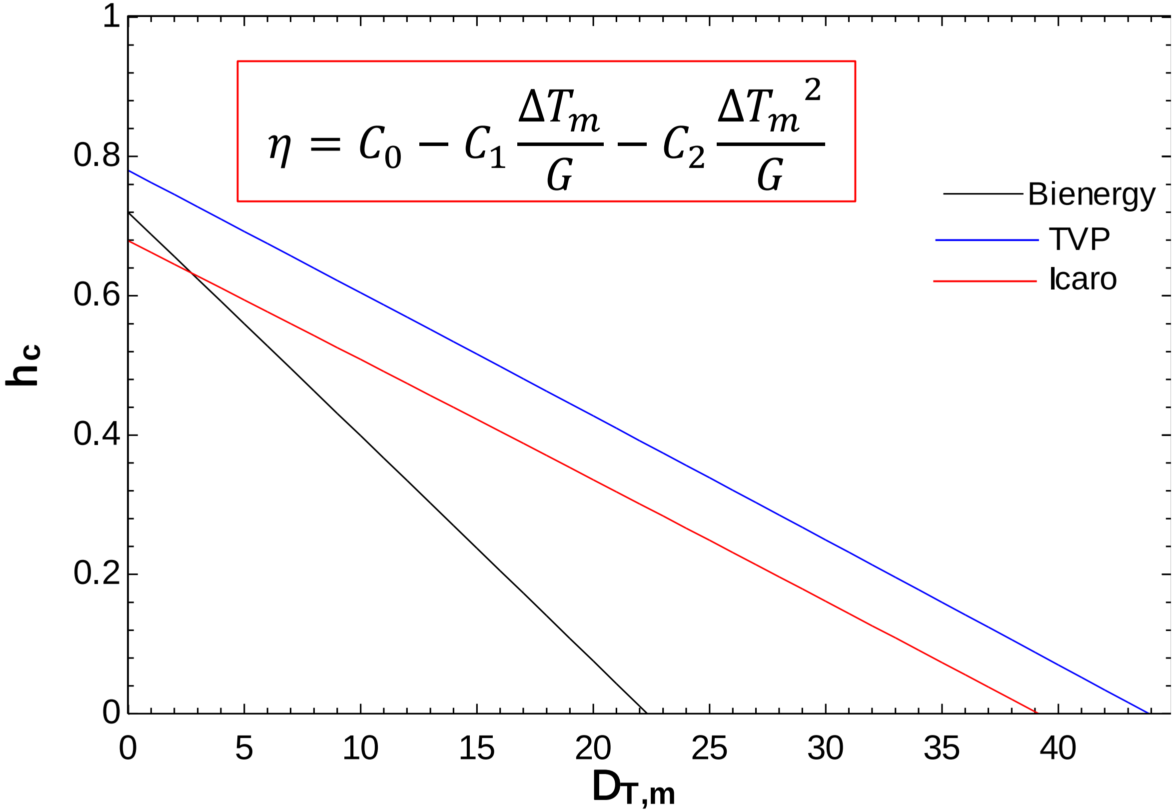
A **Solar Collector SC** is responsible of both an Exergy Loss (thermal efficiency = waste of heat) and an Exergy Destruction (degradation of the solar resource from very high radiation exergy to that of the heat transfer fluid circuit).

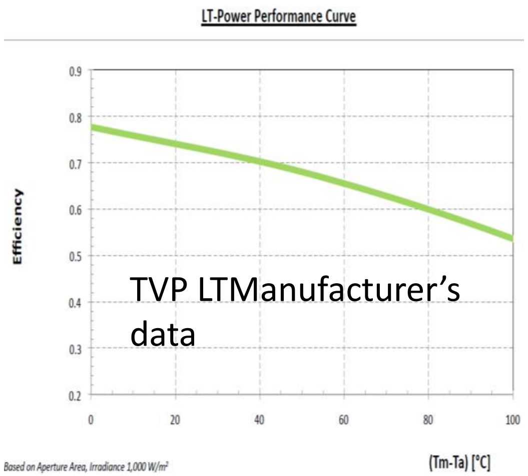




D and L have opposite trends with increasing X: this determines an optimization condition for the outlet exergy, which can be implemented with MEO (Maximum Exergy Optimum Control)

Solar Collectors – Thermal efficiency (test data)



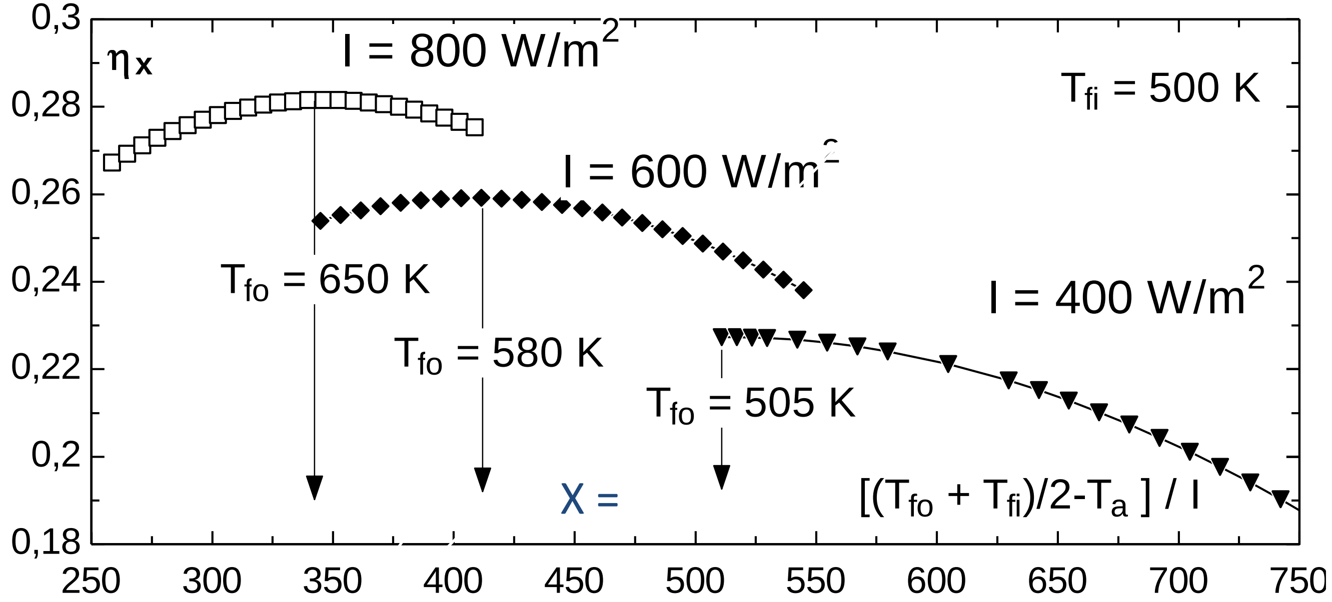


G=1000 W/m²

	C_0 [-]	C_1 [W/m² K]	C_2 [W/m² K]	S [m²]	$\dot{V}_{test}$ [l/h]	V [l]
TVP	0.78	1.75	0.00625	1.95	100	1.2
ICARO	0.679	1.696	0.0099	1.939	135	1.2
Bienergy	0.72	3.2	0.011	1.95	100	4

Optimal T_{fo} and flowrate with variable radiation

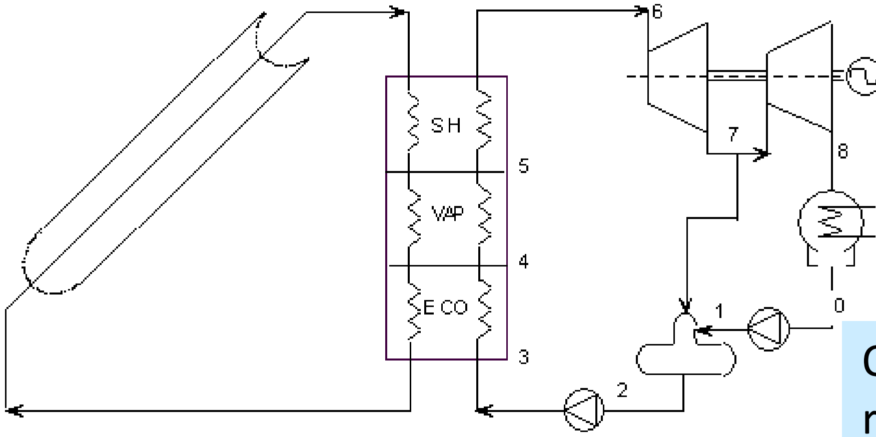
The effect of reducing radiation (Winter/Summer, Daily: Sunrise, Sunset)

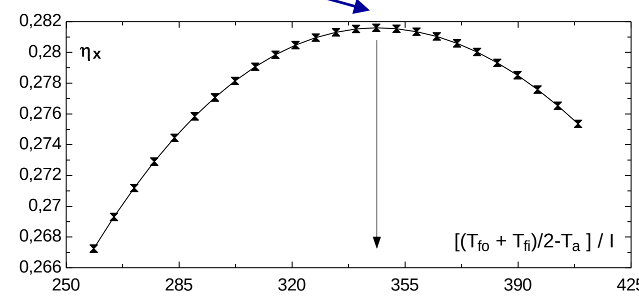


- When radiation is low (winter months; early morning and sunset) the collector outlet temperature T_{fo} should be reduced, so that it is allowed to collect the maximum exergy from the sun.
- The picture shows, for a fixed value of T_{fi} = 500 K, what should be the correct value of T_{fo} for three different conditions of beam radiation (800, 600 and 400 W/m^2.

Variable - DT MEO control – Variable collector heat loss factor

In the general case of variable heat loss factor $F'U_l$, the value of T_{fo} maximizing the collector exergy efficiency is determined by a direct search algorithm determining the optimum conditions for collector exergy efficiency.





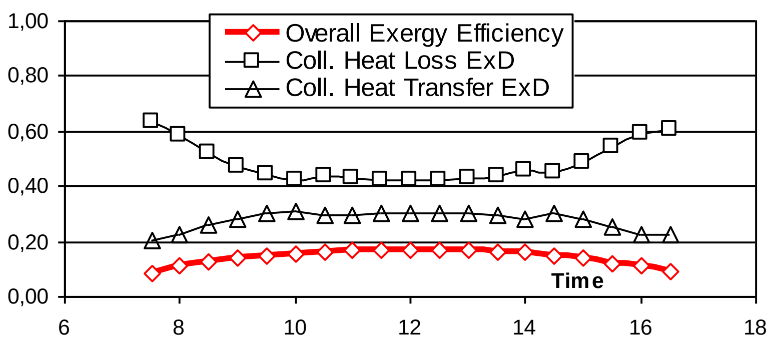
On the whole, the system exergy balance results from the combination of 7 exergy destructions/losses:

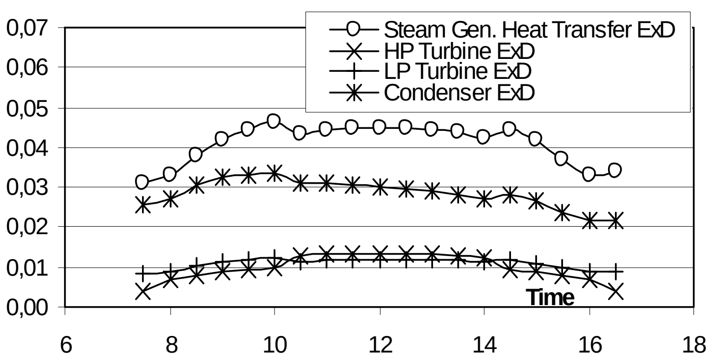
ED_{Coll_L}	collector heat-exergy loss	Collector
ED_{Coll_HT}	collector heat transfer exergy destruction	Collector
ED_{SG}	Steam Generator heat transfer exergy destruction	
ED_{ST}_HP	High-Pressure Steam Turbine irreversibility exergy destruction	Conversion system
ED_{ST}_LP	Low-Pressure Steam Turbine irreversibility exergy destruction	Conversion system
ED_{MFH}	Mixing Feedwater Heater exergy destruction	Conversion system
ED_{COND}	Condenser Exergy loss	Conversion system

Comparison of daily exergy balance (Fixed DT / Single Phase MEO)

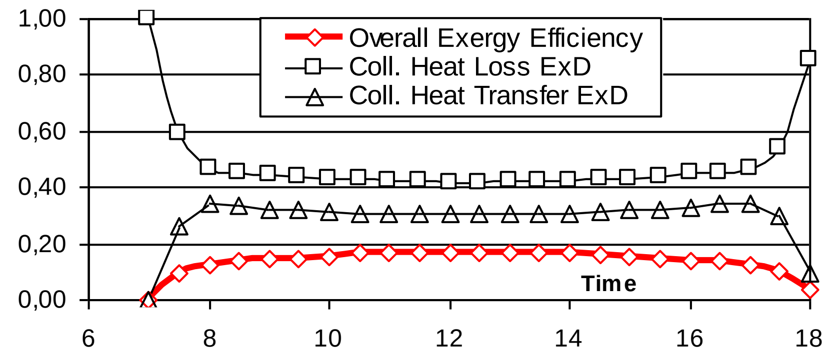
Reference day of June

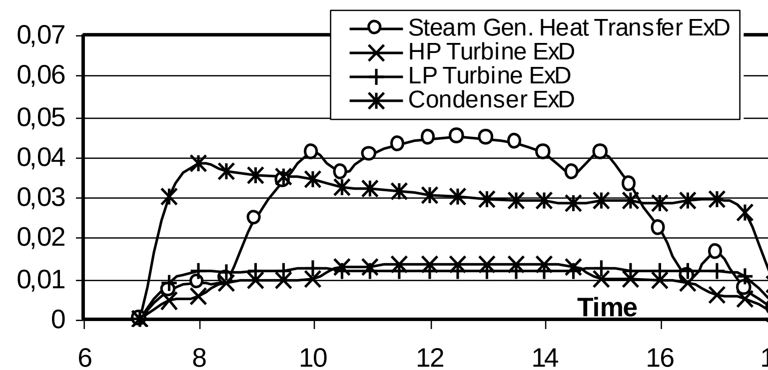
Fixed-DT (155 °C)





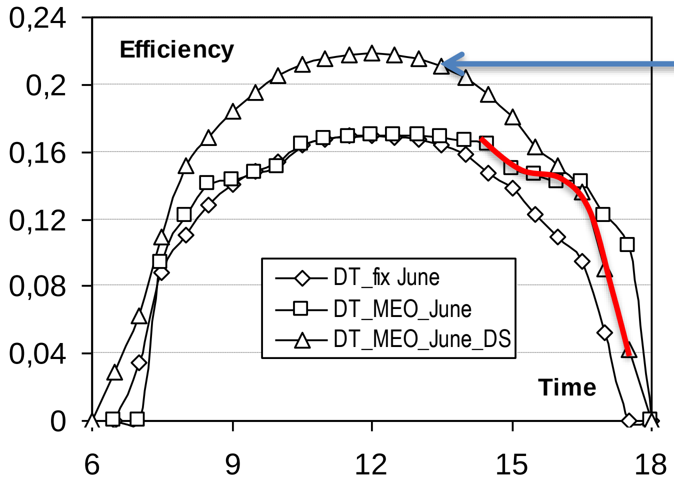
MEO - Single Phase Collector



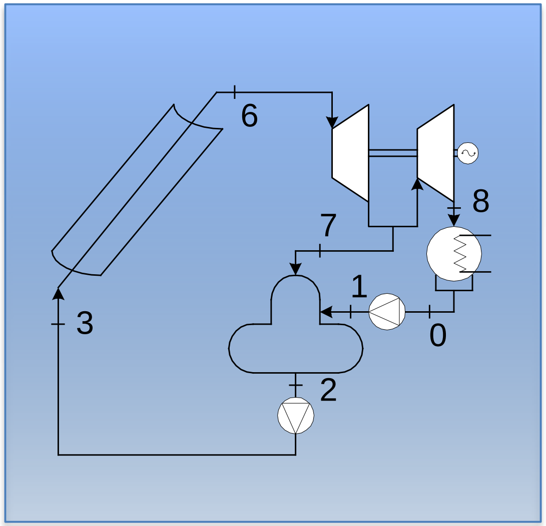


Maximum Exergy Control of a Solar Thermal Plant Equipped with Direct Steam Collectors; IJOT, 2008, 11 , 3, Pages 143 - 149; Giampaolo Manfrida, Vincent Gerard

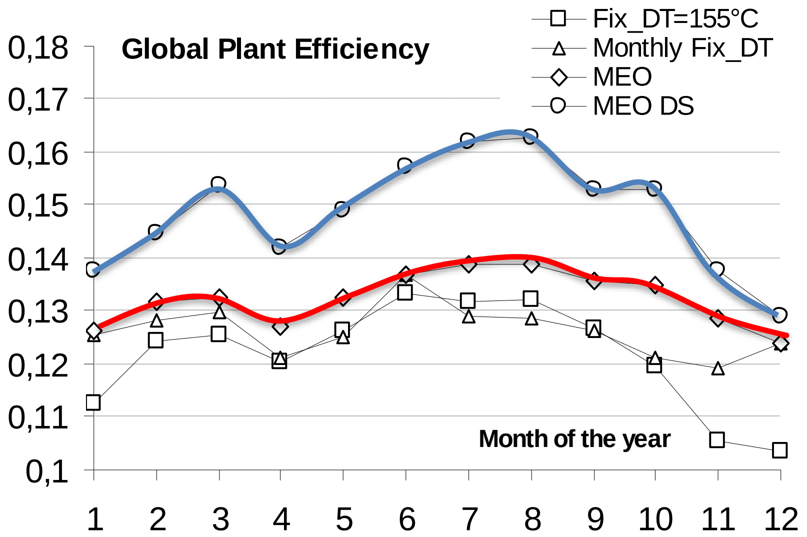
Fixed DT / Single Phase/Direct steam MEO



The Exergy-Optimized control methodology can be extended to collectors with **Direct Steam Generation**, with significant advantages.



Comparison of daily-averaged plant efficiency over the year with different control modes



Yearly-Average global efficiency of the solar thermal plant:

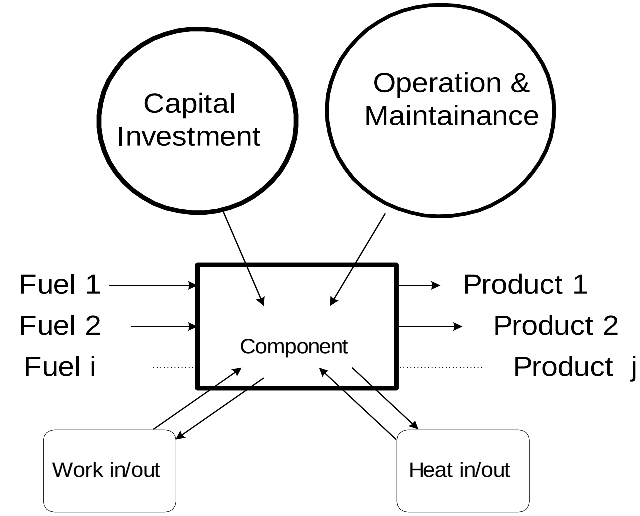
0,122 (Fixed-DT)
0,126 (Monthly-adj. Fixed-DT)
0,132 (MEO Single Phase Collector)
0,148 (MEO – Direct Steam Collector)

Exergo-Economics

Exergo-Economic Analysis (ExEcA) is a combination of exergy and economic analysis.

The goal is not only to determine the cost of one or more products (this could be done by a traditional input/output cost analysis) but rather to understand the **process of cost build-up** along the **transformation of energy** and its depreciation, described by the progressive decrease of exergy.

This type of information is very valuable, as it allows to identify the most relevant stages within the process, paving the way to system **improvement and optimization**.



Separating inputs (i) and outputs (e) one can write the cost balance as:

$$\sum_e \left(c_e \dot{E}_e + c_{Qe}\theta_e \dot{Q}_e + c_{We}\dot{W}_e\right) = \sum_i \left(c_i \dot{E}_i + c_{Qi}\theta_i \dot{Q}_i + c_{Wi}\dot{W}_i\right) + \dot{Z}_{CI,k} + \dot{Z}_{OM,k}$$

Costs are referred to unit exergy c [€/kJ]

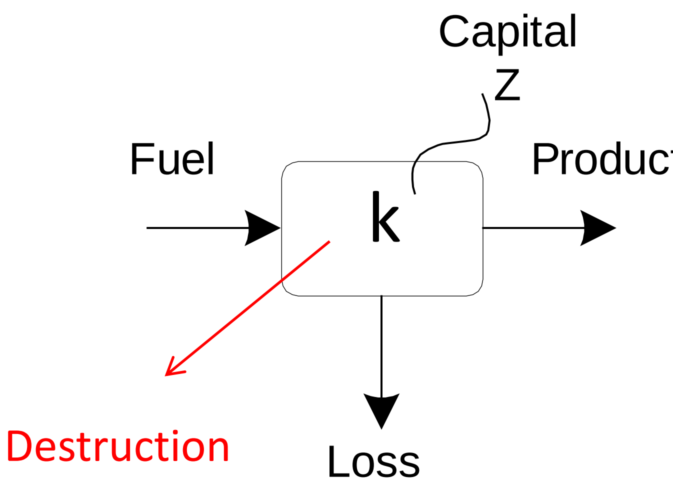
Fuels and Products (Component)

The application of Exergo-Economic Analysis (ExEcA) at component level requires a definition of the **Function of the component**. Auxiliary equations can be necessary when a component has multiple exit streams.

Guidelines are provided by the application of the "SPECO" approach.

This implies the definition of Fuels and Products for each productive component.

Moreover, a component can present an Exergy Destruction and an Exergy Loss.



An important performance indicator is the relative cost increase across the component, r_k:

$$r_k = \frac{c_{p_k} - c_{f_k}}{c_{f_k}}$$

SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems, Energy, Volume 31, Issues 8–9, July 2006, Pages 1257-1289; Andrea Lazzaretto, George Tsatsaronis

ExEcA- KPI

Another important performance indicator is the component exergy efficiency, ε_k:

$$\varepsilon_k = \frac{\dot{E}_{Pk}}{\dot{E}_{Fk}} = 1 - \frac{\dot{E}_{Dk} + \dot{E}_{Lk}}{\dot{E}_{Fk}}$$

ε_k and r_k are linked by the component Exergy Balance:

$$r_k = \frac{1-\varepsilon_k}{\varepsilon_k} + \frac{Z_k}{c_{fk}\dot{E}_{p_k}}$$

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{Fk}\left(\dot{E}_{Dk} + \dot{E}_{Lk}\right)}$$

The Exergo-Economic Factor f_k is useful as a non-dimensional indicator, stating how much the capital cost is relevant with respect to the costs of exergy destructions and losses.

From a system point of view, one should also keep an eye at the component relative exergy destruction y_k :

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$

It is not important to increase the performance of components with small exergy destructions; one should focus on components responsible of large irreversibilities.

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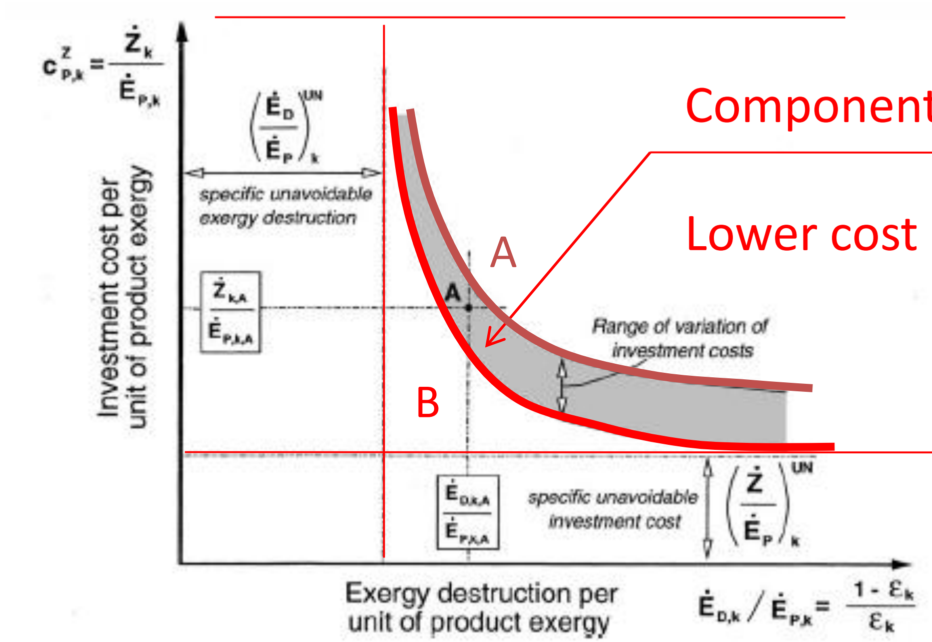
ExEcA – Capital cost vs. Exergy Destruction

UnavoidableExergy Destruction

Component B better than A:

Lower cost + Less irreversibilities



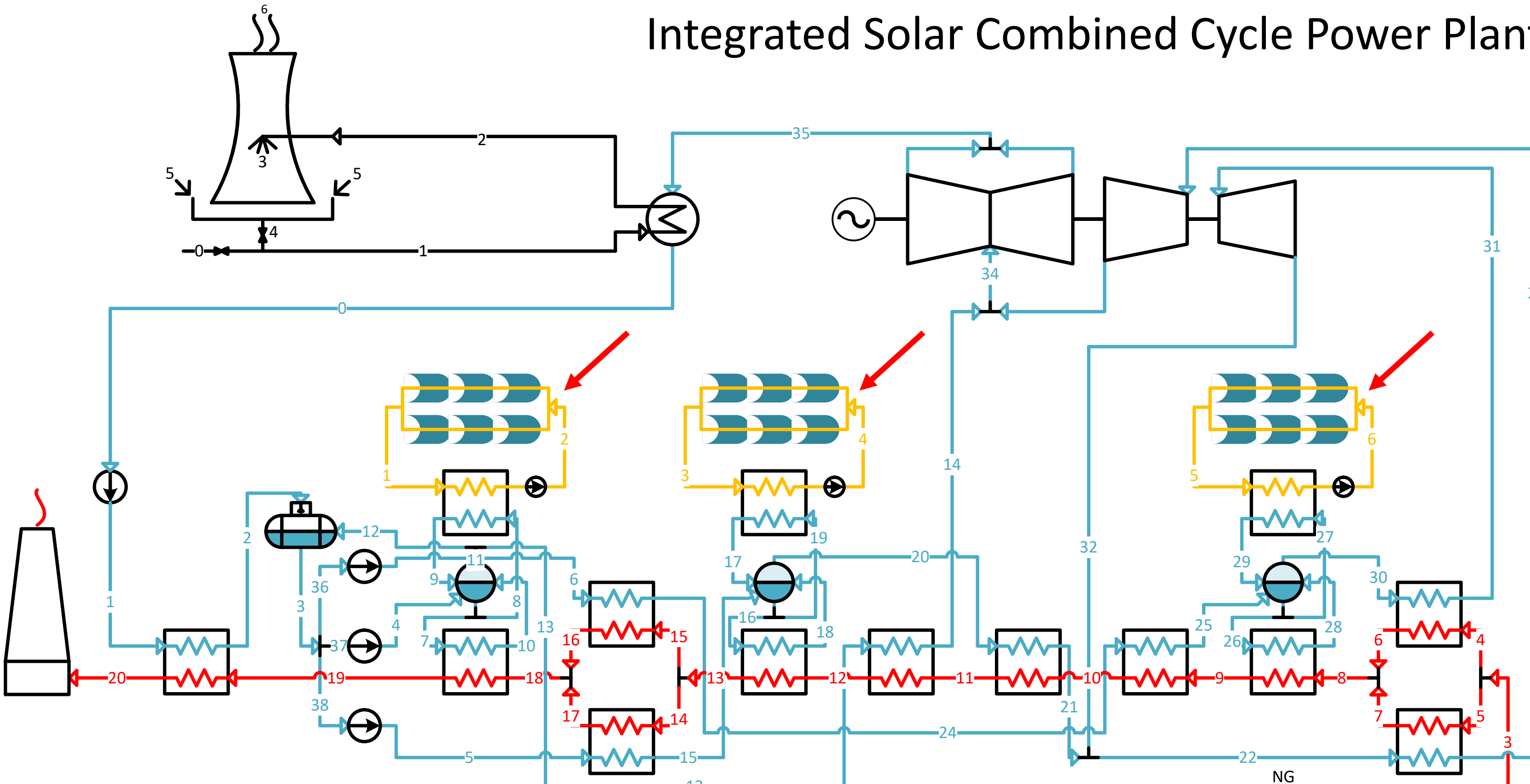
Lower limit to component cost

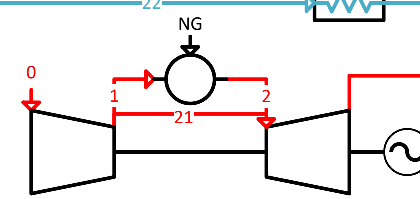
TUB Berlin

A breaktrough in technology is represented by a shift to a curve (B) with lower cost and better exergy performance than the base case (A).

ISCCGT system

Integrated Solar Combined Cycle Power Plant





Three solar fields assist the Heat Recovery steam generator. The solution includes MEO and smart flexible configuration of the HP and MP solar loops.

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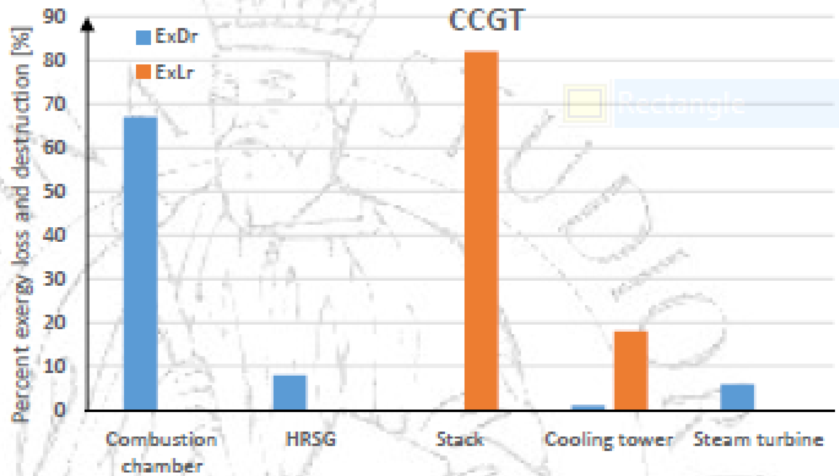
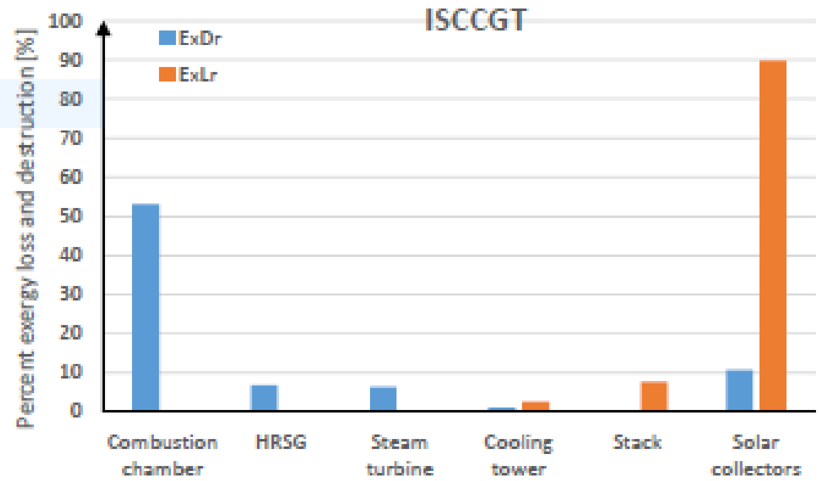
Exergy Analysis (Design)





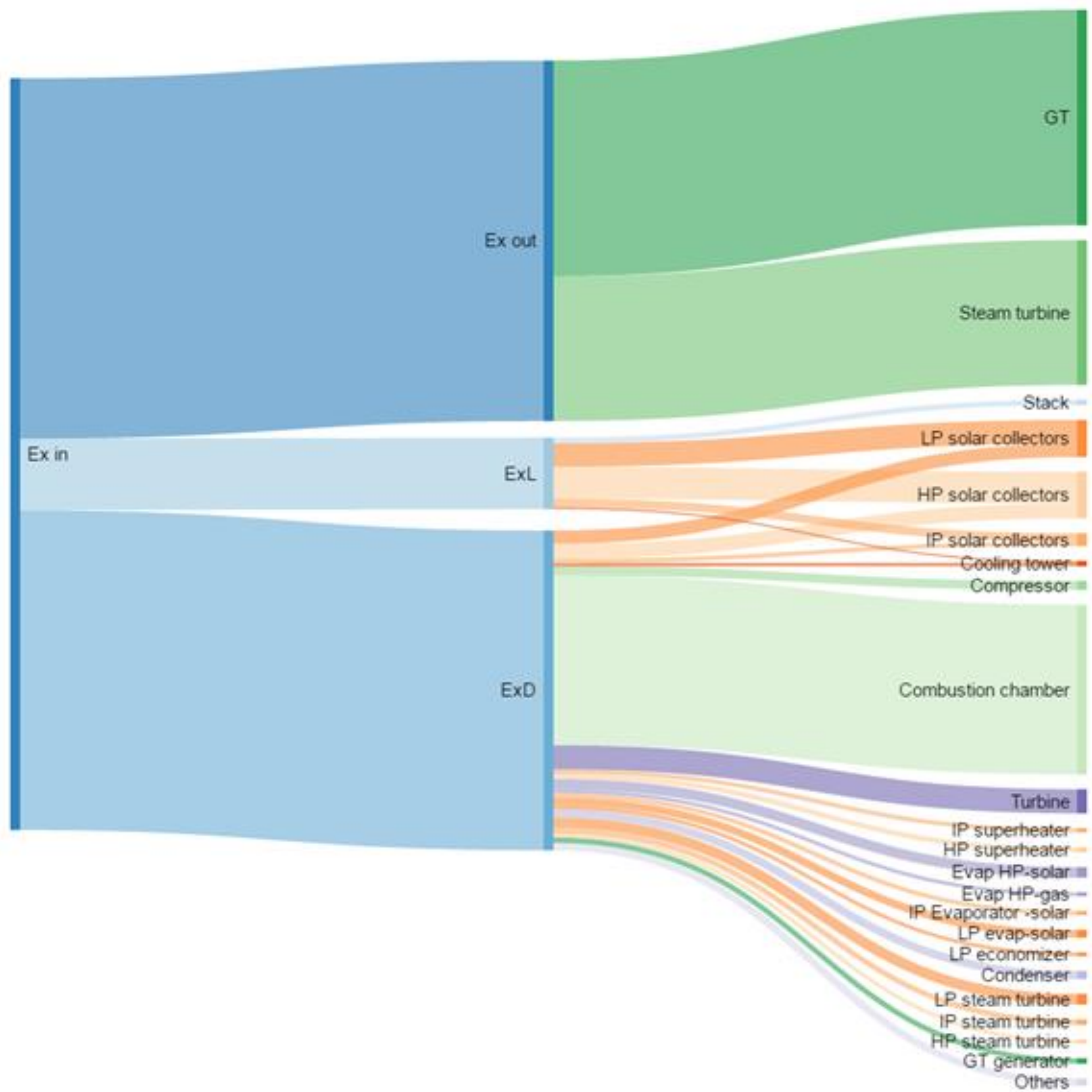
Main parameters at design conditions					
Configuration	Air/Steam mass flow	W_{GT}	W_{ST}	Electrical efficiency	Exergetic efficiency
CCGT	639/110 kg/s	288,81 MWe	153,97 MWe	57,91 %	**55,70 %**
ISCCGT	639/153 kg/s	288,81 MWe	194,01 MWe	63,45 %	**47,85 %**

Natural Gas only (marginal efficiency) ↗

The exhaust gas temperature at the stack is reduced from 367.7 K to 360.5 K (solar integration assists heat recovery).

ISCCGT- Exergy Grassmann Diagram

Exergoeconomic and exergoenvironmental analysis of an integrated solar gas turbine/combined cycle power plant
Energy, 156, 2018, 352-359
Giuseppe Bonforte, Jens Buchgeister, Giampaolo Manfrida, Karolina Petela



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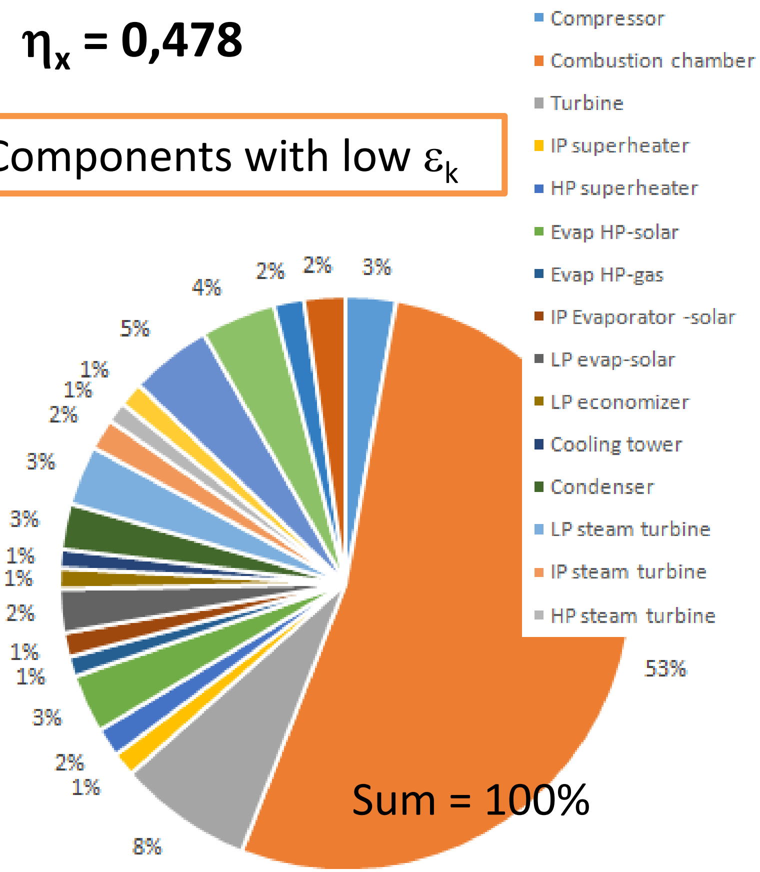
Component Exergy Analysis

Exergy efficiency:

$\eta_x = 0,478$

Components with low ε_k



Component name	$\dot{E}_F$ [kW]	$\dot{E}_P$ [kW]	y_D [%]	ε_k [%]
Compressor	265994,2	253872,2	4,557	95,44
Combustion chamber	788640,6	561295,2	28,83	71,17
Gas Turbine	594534,2	562149,6	5,447	94,55
IP superheater	41667,6	35901,85	13,84	86,16
HP superheater	51992,34	44976,22	13,49	86,51
Evap HP-solar	50140,62	36049,38	28,1	71,9
Evap HP-gas	50663,9	45777,32	9,645	90,35
HP economizer	29589,14	27108,18	8,385	91,62
IP1 superheater	188,643	179,026	5,098	94,9
LP superheater	1673,792	1367,374	18,31	81,69
IP Evaporator-gas	3137,687	3007,638	4,145	95,86
IP Evaporator -solar	14424,07	8591,062	40,44	59,56
IP economizer	1853,804	1546,838	16,56	83,44
HP1 economizer	17117,72	14539,18	15,06	84,94
LP evap-gas	4438,862	3945,844	11,11	88,89
LP evap-solar	22397,26	11889,45	46,92	53,08
HP pump	1842,051	1638,85	11,03	88,97
LP pump	4,095	3,642	11,06	88,94
IP pump	45,3	40,29	11,06	88,94
Deaerator	4019,027	3301,109	17,86	82,14
LP economizer	10998,27	6014,47	45,31	54,69
CEP	36,121	30,989	14,21	85,79
Cooling tower	14302,75	9695,137	32,21	67,79
Condenser	18135,53	7111,938	60,78	39,22
LP steam turbine	105373,9	90979,27	13,66	86,34

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IS CCGT Power Plant

ExEcA

Exergo-Economic Analysis

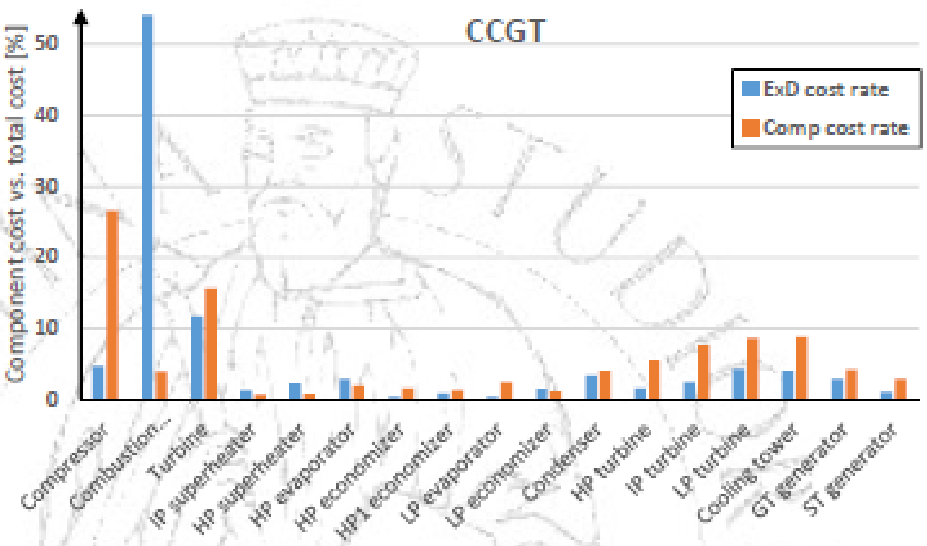
When analyizing the results of an ExEcA, it is recommended for system improvement to focus on components combining a low f_k and a low ε_k ; in these components, it is worth to apply a higher investment in order to reduce exergy destructions and losses at a low cost.

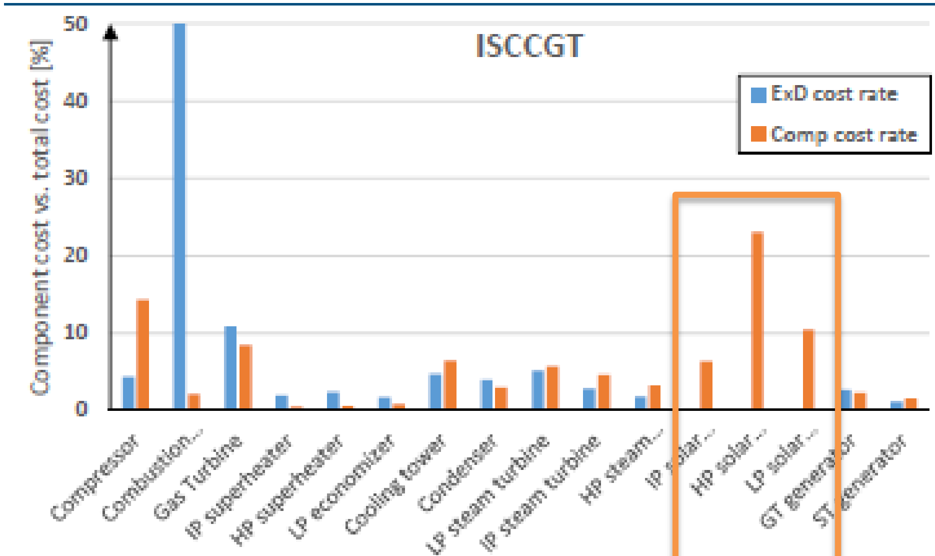
(solar collectors) Since the specific fuel cost is zero, the exergy destruction cost rate is also zero

Component name	$\dot{C}_D$ [$\$\cdot h^{-1}$]	$\dot{Z}_{TOT}$ [$\$\cdot h^{-1}$]	$\dot{C}_{TOT}$ [$\$\cdot h^{-1}$]	r_c [%]	f_c [%]
Compressor	732,6	1236,24	1968,84	12,83	62,79
Combustion chamber	8096,4	184,788	8280	41,43	2,232
Gas Turbine	1810,8	729	2539,44	8,08	28,7
IP superheater	322,38	64,836	387,36	19,29	16,74
HP superheater	392,4	95,652	487,8	50,52	19,6
Evap HP-solar	138,42	93,492	231,912	65,49	40,32
Evap HP-gas	273,24	118,728	392,04	15,31	30,29
HP economizer	138,708	80,388	219,096	14,46	36,69
IP1 superheater	0,53784	0,55836	1,0962	10,95	50,95
LP superheater	17,1324	26,1216	43,272	56,57	60,39
IP Evaporator-gas	7,272	9,5292	16,8012	9,991	56,72
IP Evaporator -solar	55,08	27,2232	82,296	101,4	33,07
IP economizer	17,1648	6,318	23,4828	130,4	26,91
HP1 economizer	144,18	61,992	206,172	25,36	30,07
LP evap-gas	27,5652	17,9568	45,54	20,63	39,45
LP evap-solar	91,62	54,108	145,728	110,5	37,13
HP pump	15,4764	14,3568	29,8296	23,9	48,12
LP pump	0,034477	0,187668	0,222156	80,09	84,48
IP pump	0,3816	1,03392	1,41552	46,13	73,05
MFH- Degasifier	24,6708	2,30436	26,9748	23,78	8,543
LP economizer	278,676	56,628	335,304	99,7	16,89
Stack	0	4,7448	4,7448	1,161	100
Feedwater pump	0,39096	0,8802	1,27116	53,86	69,26
Cooling tower	878,76	559,44	1438,56	77,79	38,9
Condenser	669,24	255,708	924,84	214,2	27,65
LP steam turbine	855	501,84	1356,84	25,11	36,98
IP steam turbine	461,52	413,64	875,16	21,48	47,26
HP steam turbine	298,152	282,24	580,32	24,84	48,63
IP solar collectors	0	136,224	136,224	Infinite	100
HP solar collectors	0	492,48	492,48	Infinite	100
LP solar collectors	0	223,524	223,524	infinite	100
GT generator	439,56	193,608	633,24	3,627	30,58
ST generator	204,768	150,66	355,464	2,465	42,39

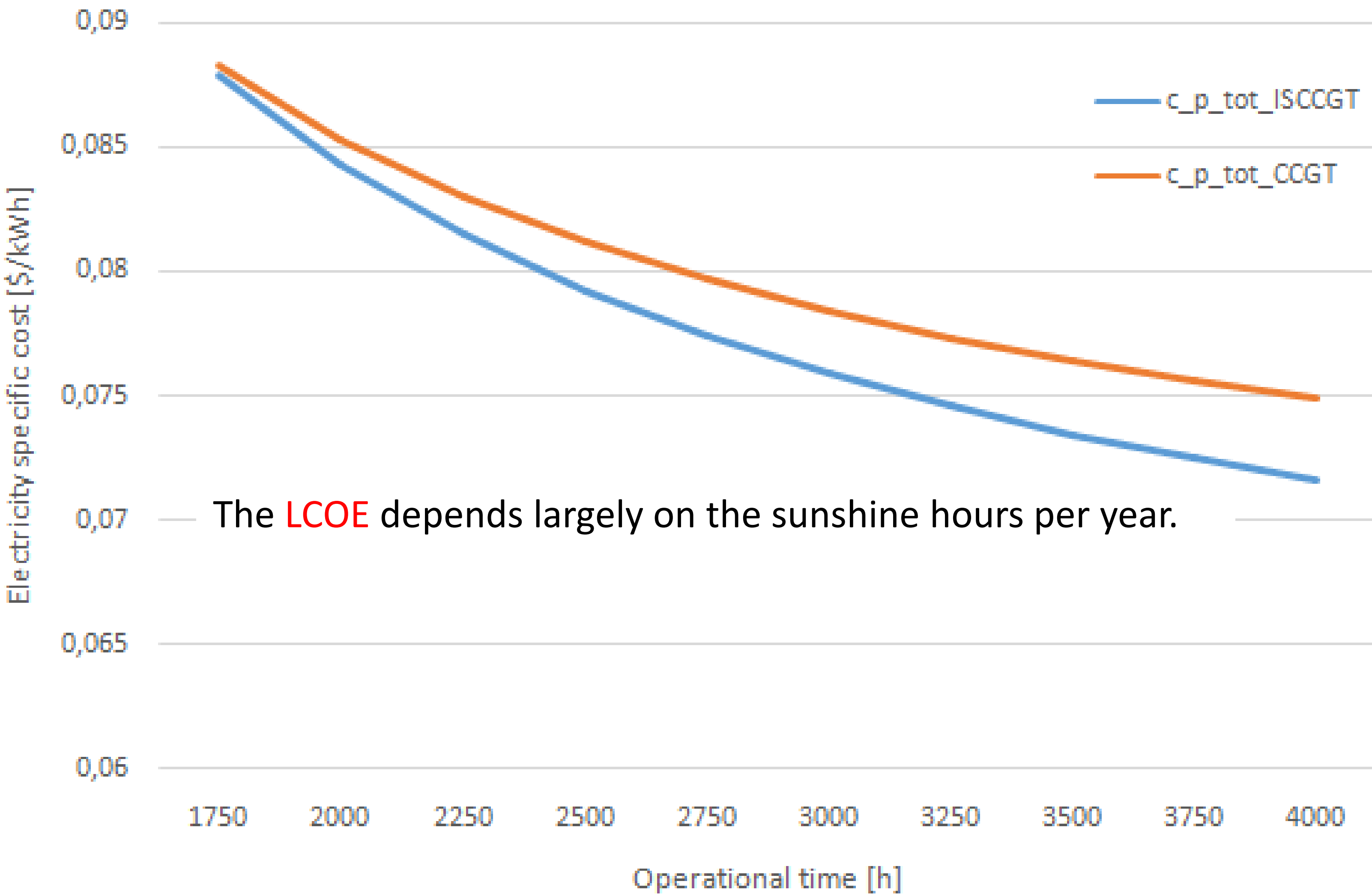
Results – Exergo-Economic Analysis

Component	($/kW)	ISCCGT	CCGT
HRSG		121	101
Gas turbine		400	400
Steam turbine		199	188
Condensing system		139	111
Solar collectors		395	0
Others		62	67
Total		**1282**	**867**
Fixed O&M ($/kW-y) or [$/kWh]		20.73 [0.0026]	13.80 [0.002]
Fuel-related running cost ($/kWh)		0.0628	0.0633





CCGT – ISCCGT Power Plant – Levelized Cost of Electricity



The LCOE depends largely on the sunshine hours per year.

Exergo-Environmental Analysis (ExEnvA)

Exergoenvironmental costing

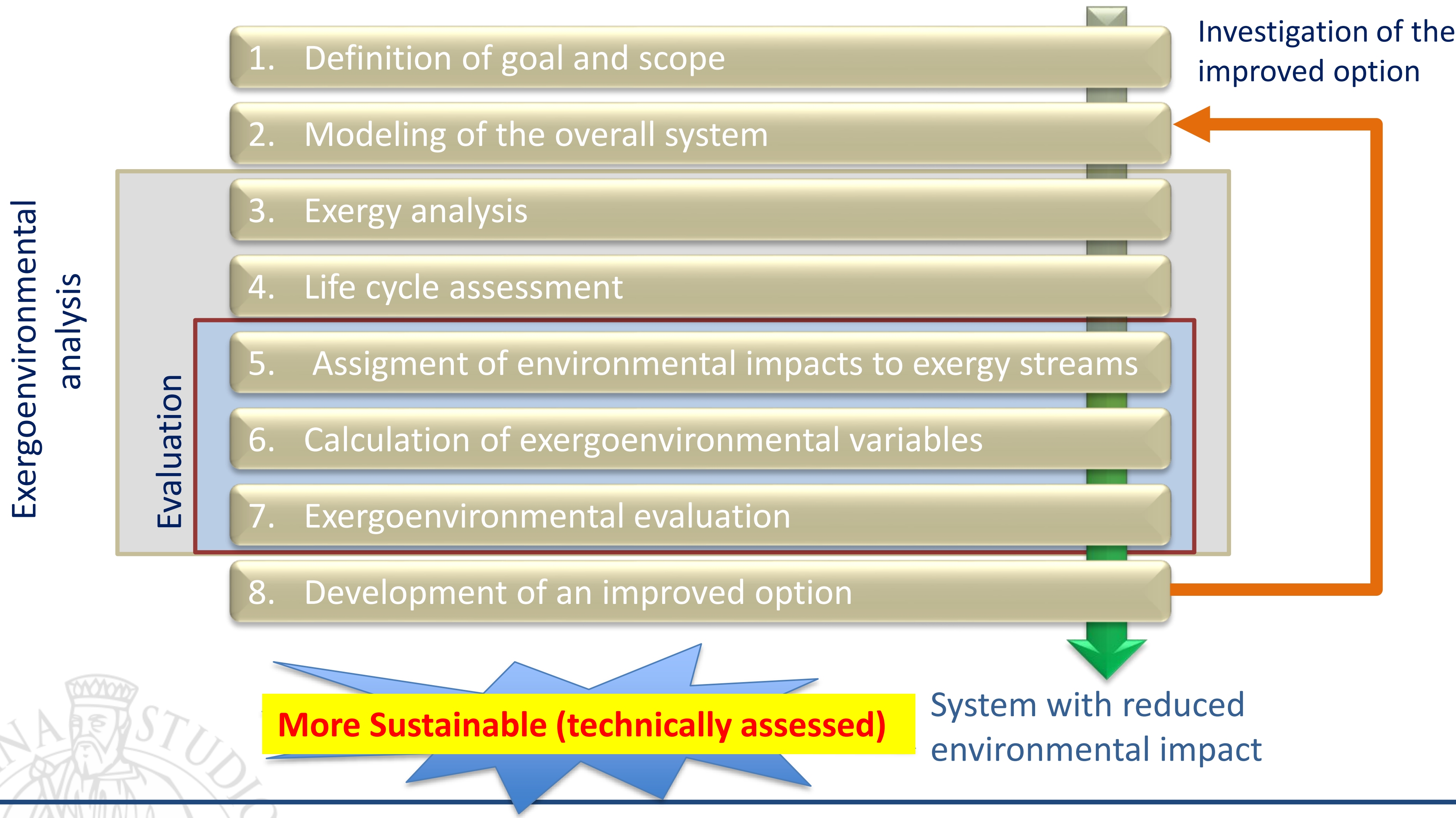
Steps:

1. Exergy analysis

2. LCA
   - Each relevant system component
   - All relevant input streams to the overall system

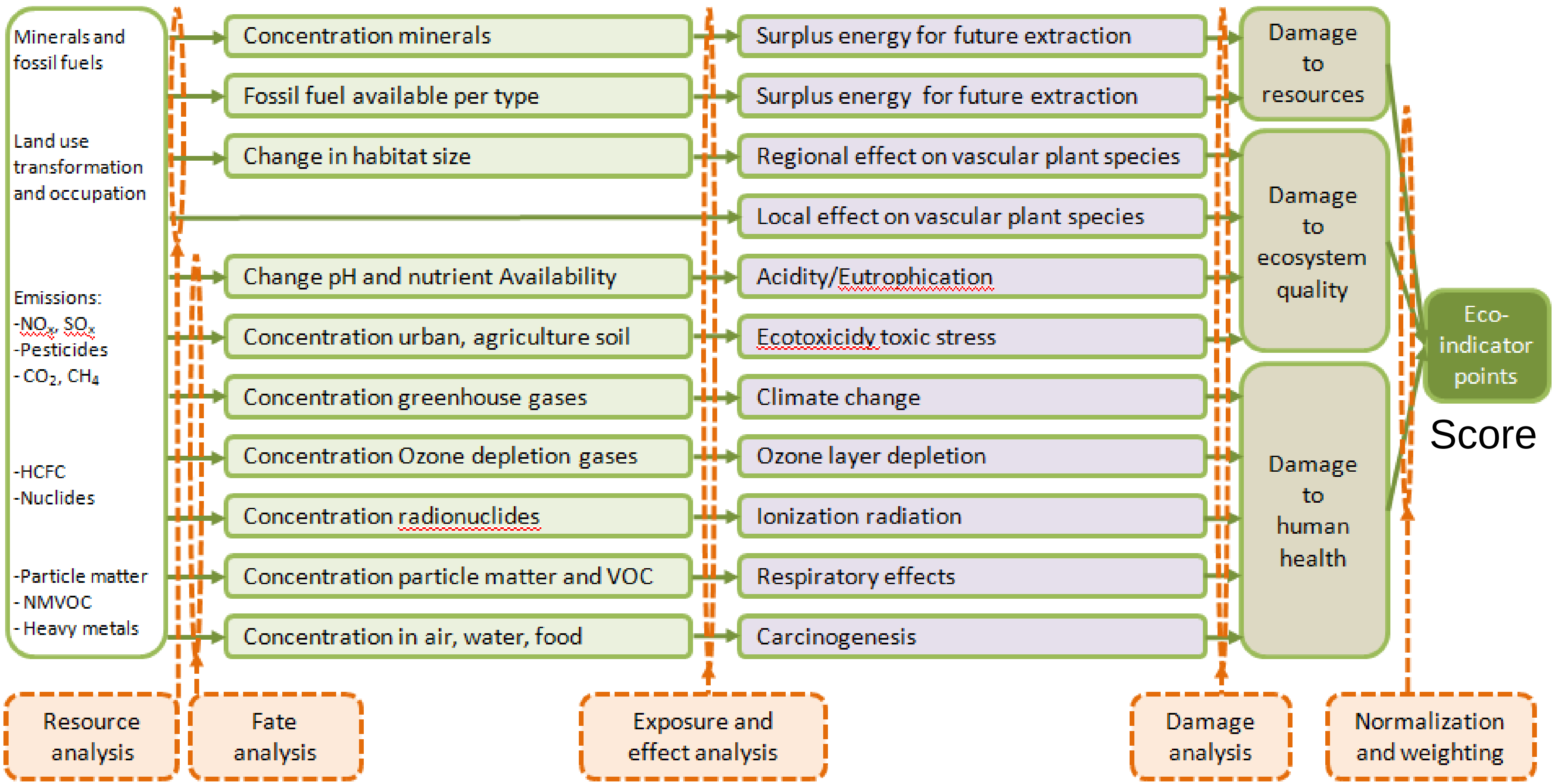
3. **ExEnvA**
   - Assign environmental impacts to exergy streams and components
   - Calculate exergo-environmental KPIs
   - Perform the Exergo-Environmental evaluation

Exergo-Environmental Analysis - ExEnvA



Life-Cycle Analysis

General structure and model of the Eco-Indicator 99 LCA method.



ReCiPe Mid-Point
(Eco-Indicator 95)

ReCiPe End-Point
(Eco-Indicator 99)

ExEnvA – Transformation of Fuel/Products across the component

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI}$$

Construction, Operation, Decommissioning

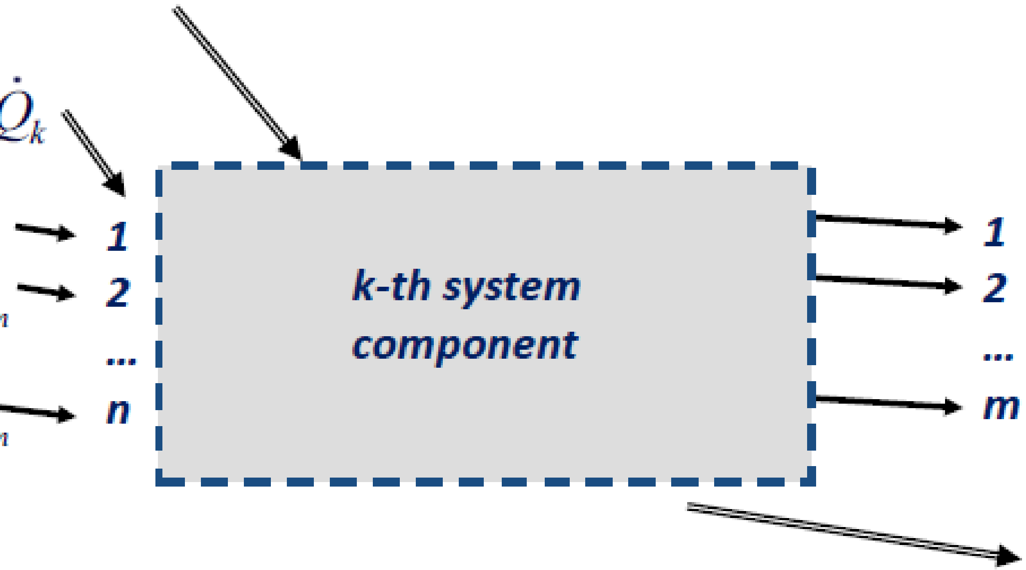
$$\dot{B}_{q,k} = b_{q,k} \; \dot{Q}_k$$

$$\dot{B}_{1,k,in} = b_{1,k,in} \dot{E}_{1,k,in}$$

$$\dot{B}_{2,k,in} = b_{2,k,in} \dot{E}_{2,k,in}$$

$$\dot{B}_{n,k,in} = b_{n,k,in} \dot{E}_{n,k,in}$$

Fuels



$$\dot{B}_{1,k,out} = b_{1,k,out} \dot{E}_{1,k,out}$$

$$\dot{B}_{2,k,out} = b_{2,k,out} \dot{E}_{2,k,out}$$

$$\dot{B}_{m,k,out} = b_{m,k,out} \dot{E}_{m,k,out}$$

$$\dot{B}_{w,k} = b_{w,k} \; \dot{W}_k$$

Products

Environmental Cost of the kth Component

$$\sum_{i=1}^{n} \dot{B}_{i,k,in} + \dot{B}_{q,k} + \dot{Y}_k = \sum_{i=1}^{m} \dot{B}_{i,k,out} + \dot{B}_{w,k}$$

ExEnvA – Env. Impact of Exergy Destruction; KPIs

Environmental impact of stream j

$$\dot{B}_j = b_j \dot{E}_j$$

$\dot{B}_j \left(Pts / s \right)$

$b_j \left(Pts / GJ\ exergy \right)$

Environmental Impact balances

$$\dot{B}_{P,k} = \dot{B}_{F,k} + \dot{Y}_k$$

$$b_{P,k} \dot{E}_{P,k} = b_{F,k} \dot{E}_{F,k} + \dot{Y}_k$$

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI}$$

Auxiliary environmental impact equations
(Meyer et al, 2008)

Environmental impact of exergy destruction

$$\dot{B}_{D,k} = b_{F,k} \dot{E}_{D,k}$$

$$\dot{B}_{TOT,k} = \dot{Y}_k + \dot{B}_{D,k}$$

Relative difference

$$r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}}$$

Exergoenvironmental factor

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}} = \frac{\dot{Y}_k}{\dot{B}_{TOT,k}}$$

EEA – Evaluation of Results

Steps:

1. Identify the environmentally relevant system components: $\uparrow \dot{B}_{TOT,k}$

2. Select the ones that have the highest improvement potential: $\uparrow r_{b,k}$

3. $f_{b,k}$

   - $\uparrow f_{b,k} \Rightarrow \uparrow \dot{Y}_k$ → The component related impact dominates the overall impact
   - $\downarrow f_{b,k} \Rightarrow \uparrow \dot{B}_{D,k}$ → The thermodynamic inefficiencies are the dominant source of environmental impact

IS/CCGT Power Plant – LCA Inventory Analysis

Steam turbine material inventory (larger for ISCCGT)

Material name	Reference plant [kg]	CCGT power plant [kg]	ISCCGT power plant [kg]
Ferroalloys	300904	343476	439033
Steel	214370	244699	312776
Unalloyed steel	122095	139369	178142
Low-alloyed steel	3467	3958	5059
High-alloyed steel	1571	1793	2292
Cr steel	29807	34024	43490
Cr-Ni steel	57429	65554	83792
Cast iron	86534	98777	126257

Condenser material inventory

Material name	Reference plant [kg]	CCGT power plant [kg]	ISCCGT power plant [kg]
Steel	261152	139603	178441
Unalloyed steel	212319	113498	145074
High-alloyed steel	48833	26104	33366

Cooling tower material inventory (larger for ISCCGT)

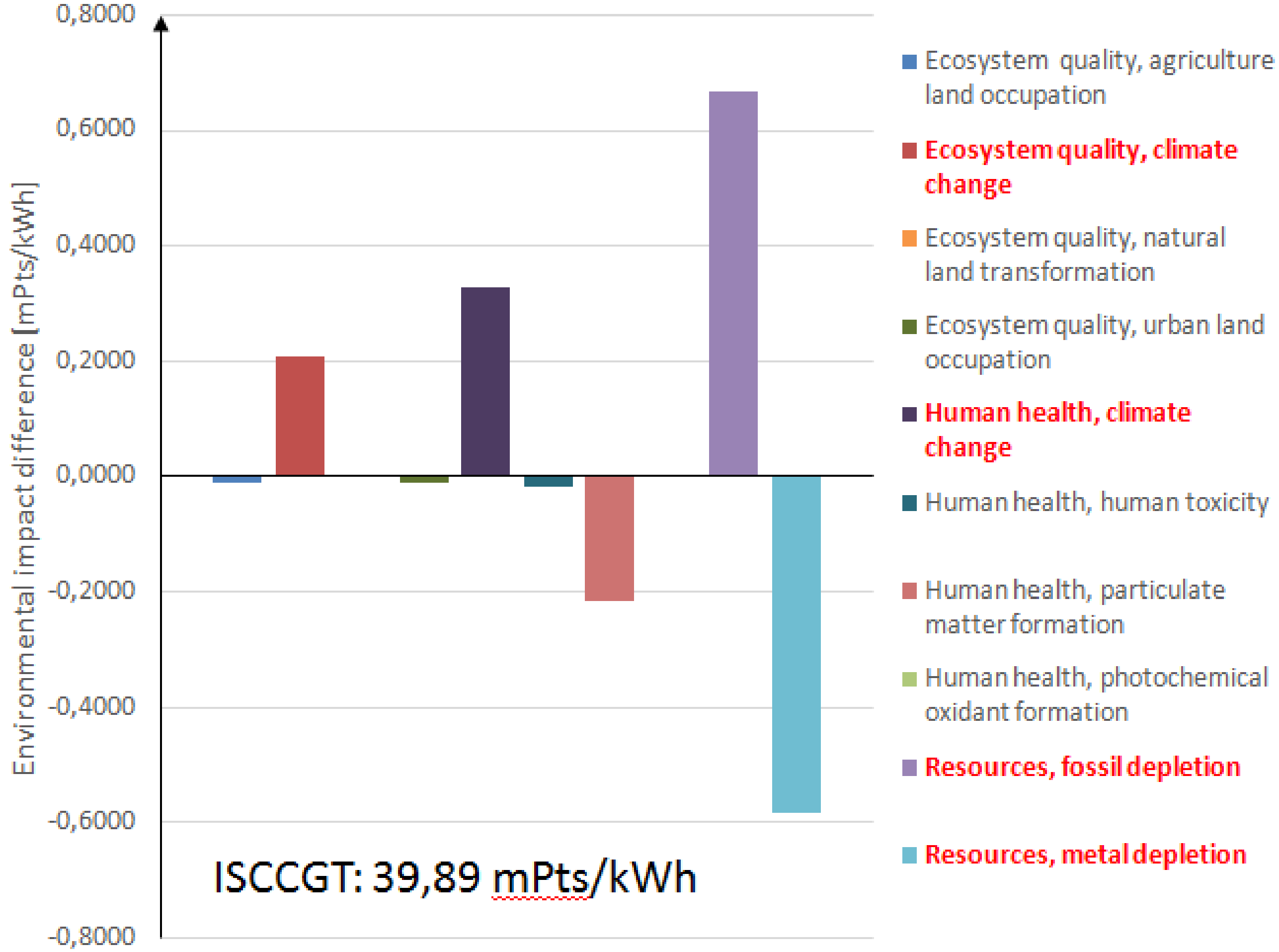
Material name	Reference plant [kg]	CCGT power plant [kg]	ISCCGT power plant [kg]
Concrete	16657182	8904378	11381606
Unalloyed steel	1850798	989375	1264622

IS/CCGT LCA Results (Recipe Mid-Point)

LCA

CCGT → ISCCGT

CCGT: 40,24 mPts/kWh

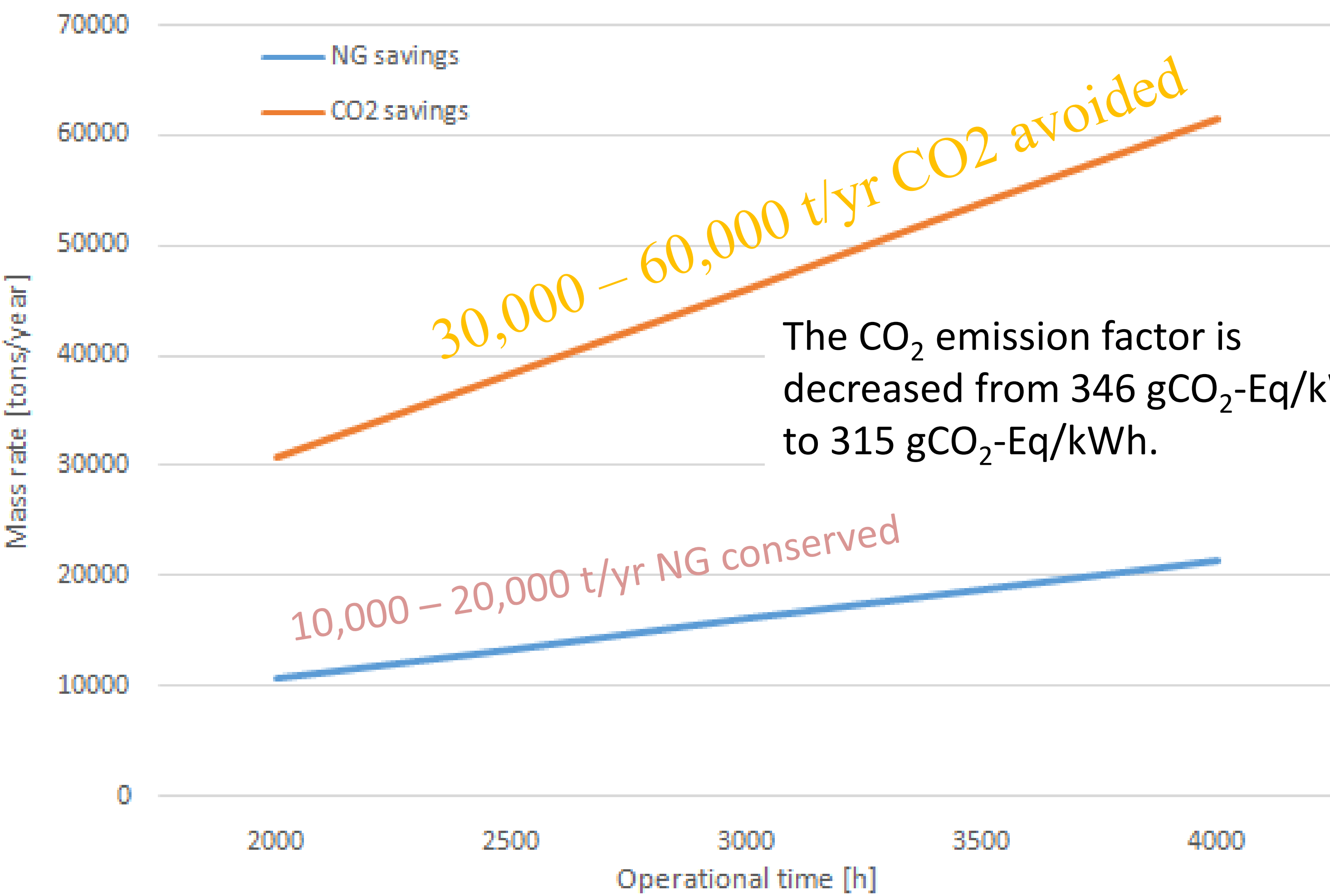


ISCCGT: 39,89 mPts/kWh

Environmental impact reduction by ReCiPe impact category

ISCCGT – GHG and Resource LCA Results

Resource (NG) savings and avoided CO2 Emissions



The CO_2 emission factor is decreased from 346 gCO_2-Eq/kWh to 315 gCO_2-Eq/kWh.

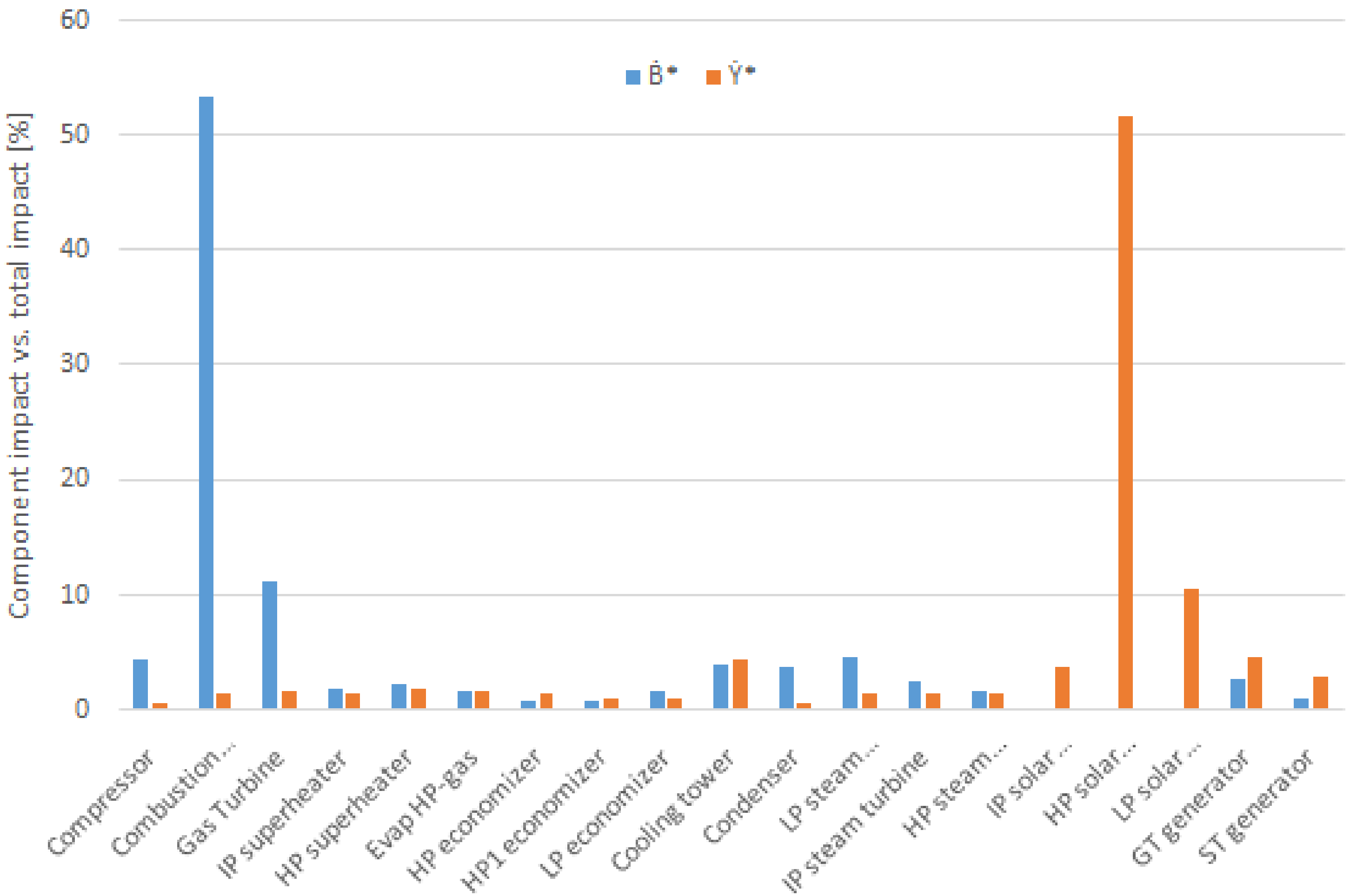
IS CCGT Power Plant

EEnvA

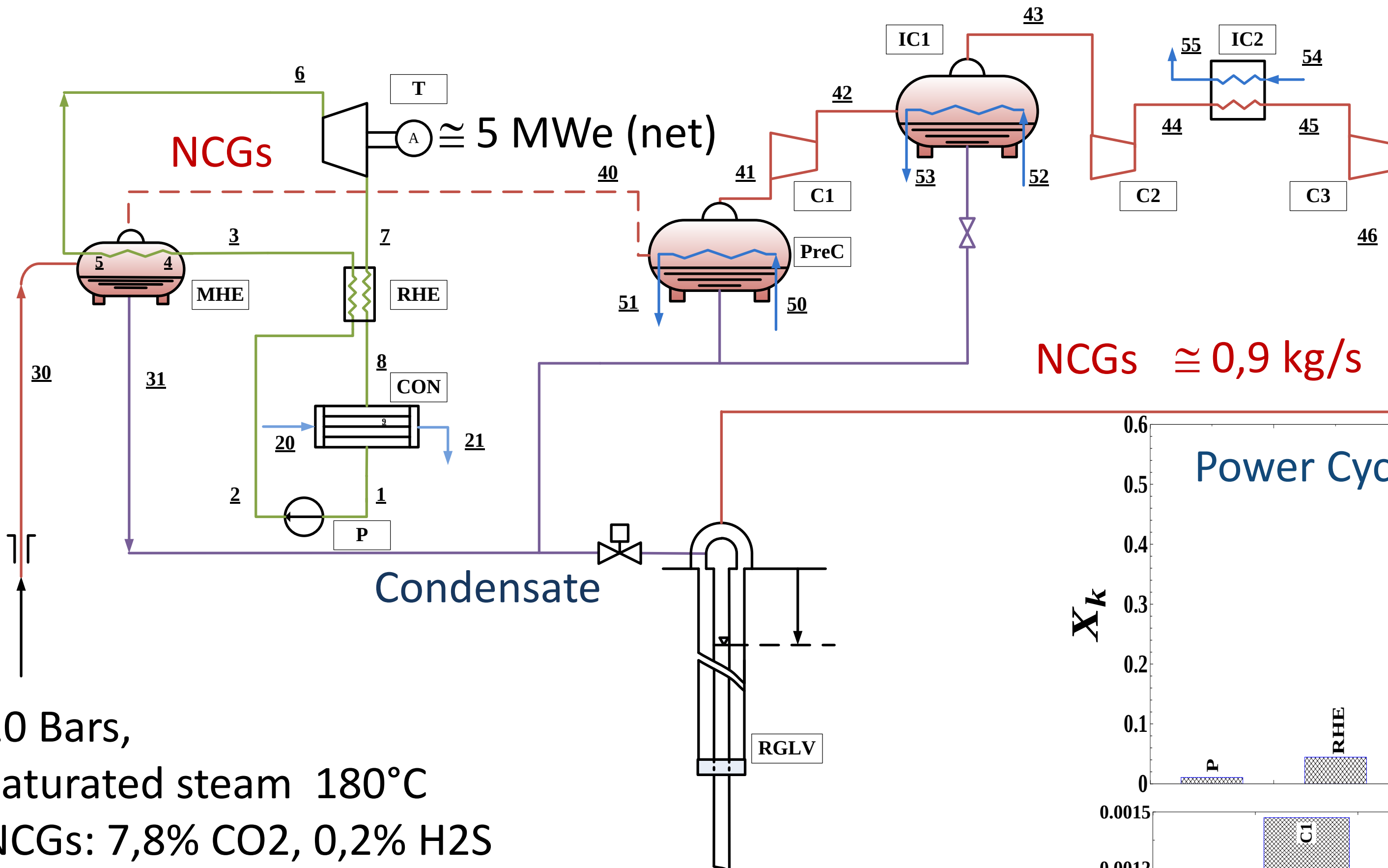
Exergo-Environmental Analysis

Component name	$\dot{B}_D$ [Pts·h^{-1}]	$\dot{Y}_{TOT}$ [Pts·h^{-1}]	$\dot{B}_{TOT}$ [Pts·h^{-1}]	f_b [%]	r_b [%]
Compressor	477,72	0,78696	478,44	0,1644	4,783
Combustion chamber	5734,8	1,66644	5734,8	0,02905	40,52
Gas Turbine	1206,72	1,77156	1208,52	0,1466	5,769
IP superheater	214,848	1,728	216,576	0,7979	16,19
HP superheater	261,432	2,1564	263,592	0,818	46,85
Evap HP-solar	16,146	1,8918	18,0396	10,49	43,67
Evap HP-gas	182,088	1,9044	183,996	1,035	10,79
HP economizer	92,448	1,64016	94,104	1,743	9,314
IP1 superheater	0,358344	0,0113	0,36972	3,057	5,541
LP superheater	11,4192	0,10476	11,5236	0,909	22,61
IP Evaporator-gas	4,8456	0,192816	5,04	3,827	4,496
IP Evaporator -solar	1,7622	0,5508	2,313	23,81	89,12
IP economizer	11,4372	0,127836	11,5668	1,105	23,59
HP1 economizer	96,084	1,18044	97,272	1,214	17,95
LP evap-gas	18,3708	0,36324	18,7344	1,939	12,74
LP evap-solar	4,8456	1,09476	5,94	18,43	85,17
HP pump	8,3664	0,28116	8,6472	3,252	12,82
LP pump	0,018637	0,000721	0,019357	3,726	12,91
IP pump	0,206244	0,007978	0,214236	3,725	12,92
Deaerator	8,1072	0,042048	8,1504	0,516	21,86
LP economizer	185,724	1,14588	186,876	0,6132	83,37
Stack	0	0,113256	0,113256	100	0,04157
CEP	0,211248	0,006361	0,21762	2,924	17,06
Cooling tower	427,68	4,9644	432,72	1,147	48,08
Condenser	401,04	0,75708	401,76	0,1885	155,3
LP steam turbine	504	1,59768	505,8	0,316	15,87
IP steam turbine	274,752	1,59768	276,372	0,5782	11,4
HP steam turbine	180,036	1,59768	181,62	0,8797	12,87
IP solar collectors	0	4,3596	4,3596	100	infinite
HP solar collectors	0	57,456	57,456	100	infinite
LP solar collectors	0	11,8188	11,8188	100	infinite
GT generator	286,704	5,112	291,816	1,752	2,563
ST generator	111,78	3,22092	115,02	2,801	1,461

Component assignment of Environmental impacts: Exergy Destruction and Construction/Materials

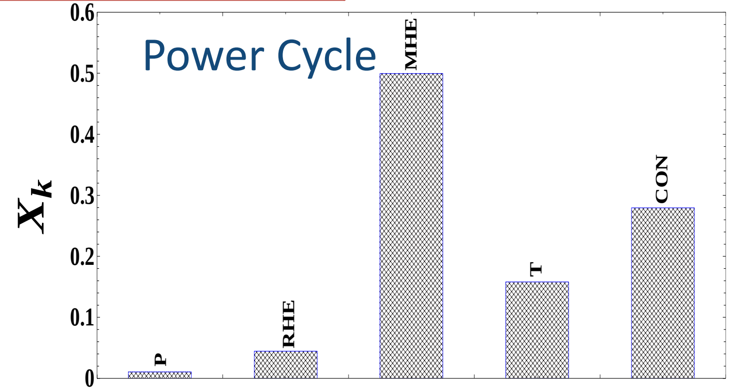


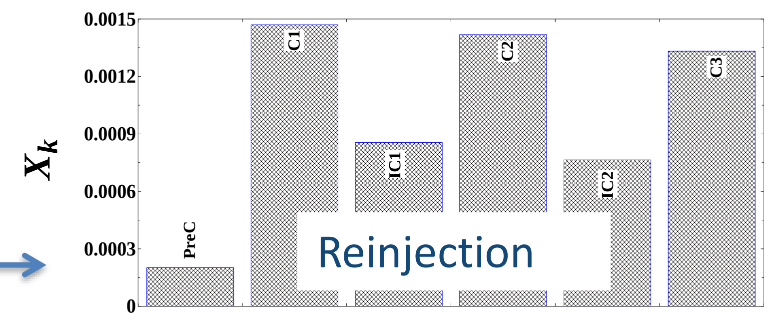
Geothermal Power Plant with CO2 reinjection – Castelnuovo - Exergy



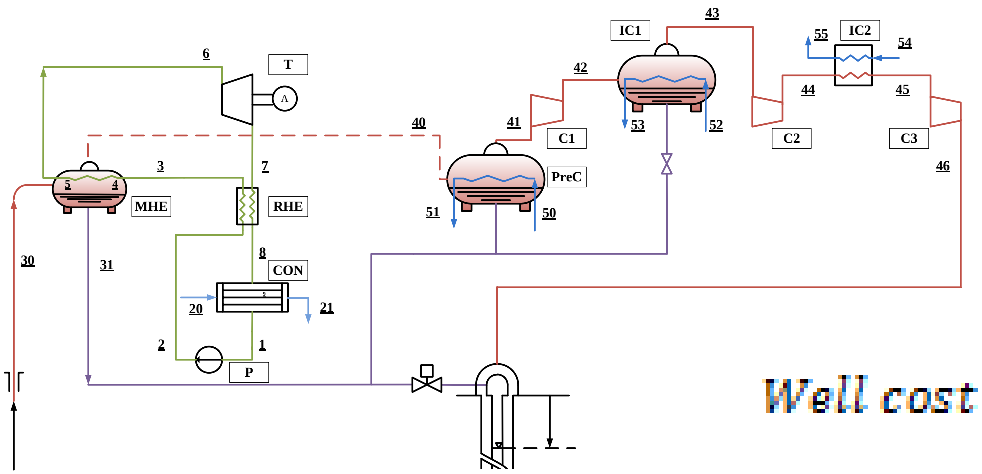
10 Bars,
Saturated steam 180°C
NCGs: 7,8% CO_2, 0,2% H_2S
≅ 12 kg/s

Exergy Balance
η_x= 0,185





Geothermal Power Plant with CO2 reinjection – Castelnuovo - ExergoEconomics



2 production wells,
1 Reinjection well

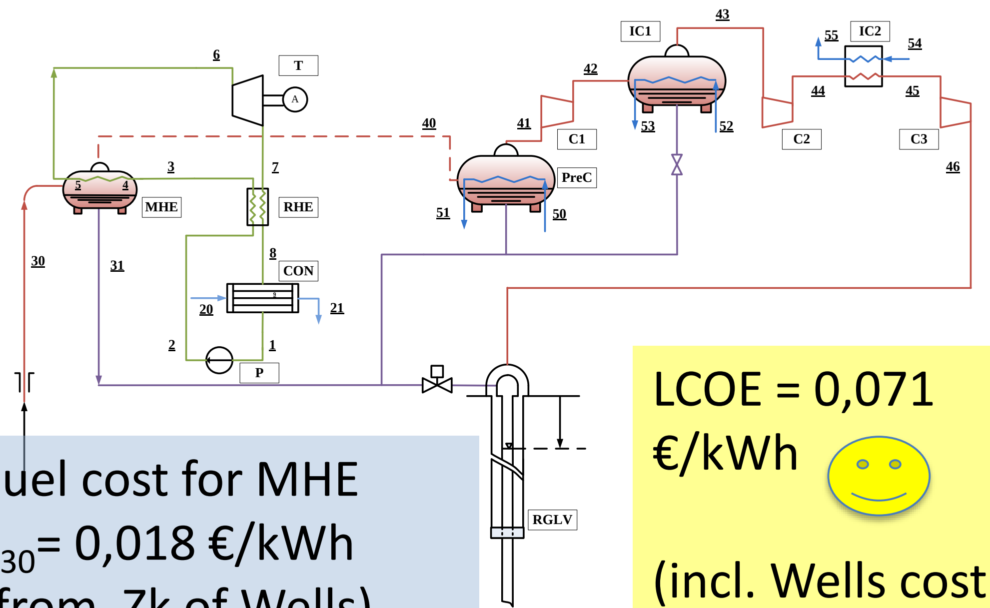
$$Well\ cost = n_{wells} * 2.5 * 1000 * D$$

k	Component	Cost balance equations	Auxiliary equations
1	P	$c_2\dot{E}x_2 = c_1\dot{E}x_1 + c_{W_p}\dot{W}_p + \dot{Z}_p$	$c_{W_p} = c_{W_t}$
2	RHE	$c_3\dot{E}x_3 + c_8\dot{E}x_8 = c_2\dot{E}x_2 + c_7\dot{E}x_7 + \dot{Z}_{HE}$	$c_7 = c_8$
3	MHE	$c_6\dot{E}x_6 + c_{31}\dot{E}x_{31} + c_{40}\dot{E}x_{40} = c_3\dot{E}x_3 + c_{30}\dot{E}x_{30} + \dot{Z}_{HEgeo}$	$c_{30} = c_{31}$ $c_{40} = c_{30}$
4	T	$c_7\dot{E}x_7 + c_{W_t}\dot{W}_t = c_6\dot{E}x_6 + \dot{Z}_t$	$c_6 = c_7$
5	CON	$c_1\dot{E}x_1 + c_{21}\dot{E}x_{21} = c_8\dot{E}x_8 + c_{20}\dot{E}x_{20} + \dot{Z}_{cond}$	$c_{20} = 0$ $c_{21} = c_{20}$
6	PreC	$c_{41}\dot{E}x_{41} + c_{51}\dot{E}x_{51} = c_{40}\dot{E}x_{40} + c_{50}\dot{E}x_{50} + \dot{Z}_{PC1}$	$c_{50} = 0$ $c_{40} = c_{41}$
7	C1	$c_{42}\dot{E}x_{42} = c_{41}\dot{E}x_{41} + c_{W_{c1}}\dot{W}_{c1} + \dot{Z}_{c1}$	$c_{W_{c1}} = c_{W_t}$
8	IC1	$c_{43}\dot{E}x_{43} + c_{53}\dot{E}x_{53} = c_{42}\dot{E}x_{42} + c_{52}\dot{E}x_{52} + \dot{Z}_{IC1}$	$c_{52} = c_{50}$ $c_{43} = c_{42}$
9	C2	$c_{44}\dot{E}x_{44} = c_{43}\dot{E}x_{43} + c_{W_{c2}}\dot{W}_{c2} + \dot{Z}_{c2}$	$c_{W_{c2}} = c_{W_t}$
10	IC2	$c_{45}\dot{E}x_{45} + c_{55}\dot{E}x_{55} = c_{44}\dot{E}x_{44} + c_{54}\dot{E}x_{54} + \dot{Z}_{IC2}$	$c_{54} = c_{50}$ $c_{45} = c_{44}$
11	C3	$c_{46}\dot{E}x_{46} = c_{45}\dot{E}x_{45} + c_{W_{c3}}\dot{W}_{c3} + \dot{Z}_{c3}$	$c_{W_{c3}} = c_{W_t}$

Geothermal Power Plant with CO2 reinjection – Castelnuovo – ExergoEconomics - Results

Component	PEC (€)	$\dot{Z}_k$ (€/s)	$\dot{C}_{D,k}$ (€/s)	$\dot{Z}_k + \dot{C}_{D,k}$ (€/s)	$c_{F,k}$ (€/kWh)	$c_{P,k}$ (€/kWh)	f_k (%)
P	193464	0.001558	0.0008032	0.002361	0.07148	0.1056	65.99
RHE	438204	0.00353	0.00242	0.00595	0.05154	0.1009	59.32
MHE	2.920E+06	0.02352	0.009514	0.03303	0.01804	0.03419	71.2
T	2.651E+06	0.02136	0.008596	0.02995	0.05154	0.07148	71.3
CON	656282	0.005286	0.01634	0.02162	0.05538	0.2662	19.36
PreC	181662	0.001463	0.000003835	0.001467	0.01804	1.819	99.74
C1	126231	0.001017	0.0001109	0.001128	0.07148	0.1835	90.16
IC1	185022	0.00149	0.000053	0.001543	0.05869	0.8226	96.57
C2	120236	0.0009685	0.0001071	0.001076	0.07148	0.1837	90.05
IC2	219831	0.001771	0.00006767	0.001838	0.08384	1.008	96.32
C3	113008	0.0009102	0.0001005	0.001011	0.07148	0.1834	90.06

- The largest environmental cost is connected with exergy destruction at MHE and T
- MHE and T also have high capital costs
- MHE, T, P, RHE have a low f_k and would benefit of larger capital investment



Fuel cost for MHE
c_{30}= 0,018 €/kWh
(from Zk of Wells)

LCOE = 0,071 €/kWh

(incl. Wells cost)

Geothermal Power Plant with CO2 reinjection – Castelnuovo – LCI (Inventory)

Wells

Equipment/material - geothermal wells	Quantity	Units	Ecoinvent record
Geothermal well - Material requirements for wellhead equipment	1	m	Total length: 3500 m (CAS_P1); 3615 m (CAS_P2); 3670 m (CAS_I)
Excavation	1,270	m^3	market for excavation, hydraulic digger, alloc. default, U - GLO
Fill	0,352	m^3	
Residue	0,918	m^3	market for drilling waste, alloc. default, U - GLO
Concrete	0,008	m^3	market for concrete, normal, alloc. default, U - GLO
Steel	6,625	kg	market for steel, low-alloyed, hot rolled, alloc. default, U - GLO
Stainless steel	0,007	kg	market for steel, chromium steel 18/8, hot rolled, alloc. default, U - GLO
Aluminum	0,554	kg	market for aluminium, cast alloy, alloc. default, U - GLO
Wells construction	1	m	Total length: 3500 m (CAS_P1); 3615 m (CAS_P2); 3670 m (CAS_I)
Steel	100,200	kg	market for steel, low-alloyed, hot rolled, alloc. default, U
Diesel	159,300	kg	market for diesel, burned in building machine, alloc. default, U - GLO
Portland cement	36,969	kg	market for cement, Portland, alloc. default, U - Europe without Switzerland
Drilling fluid	1	m	
Bentonite	7,449	kg	market for activated bentonite, alloc. default, U - GLO
Barite	39,722	kg	market for barite, alloc. default, U - GLO
Caustic Soda	0,248	kg	market for sodium hydroxide, without water, in 50% solution state, alloc. default, U - GLO
Poly_Plus RD	0,328	kg	chemical production, inorganic, alloc. default, U - GLO
Resinex e/o Rheomate	2,896	kg	market for chemical, organic, alloc. default, U - GLO
Spersene CF	0,414	kg	market for chemical, organic, alloc. default, U - GLO
Water (in cement)	17,803	kg	tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage, alloc. default, U - GLO
Water (in drilling well)	11219,286	kg	tap water production, seawater reverse osmosis, conventional pretreatment, baseline module, single stage, alloc. default, U - GLO

Geothermal Power Plant with CO2 reinjection – Castelnuovo – LCI (Inventory)

Power Plant 1

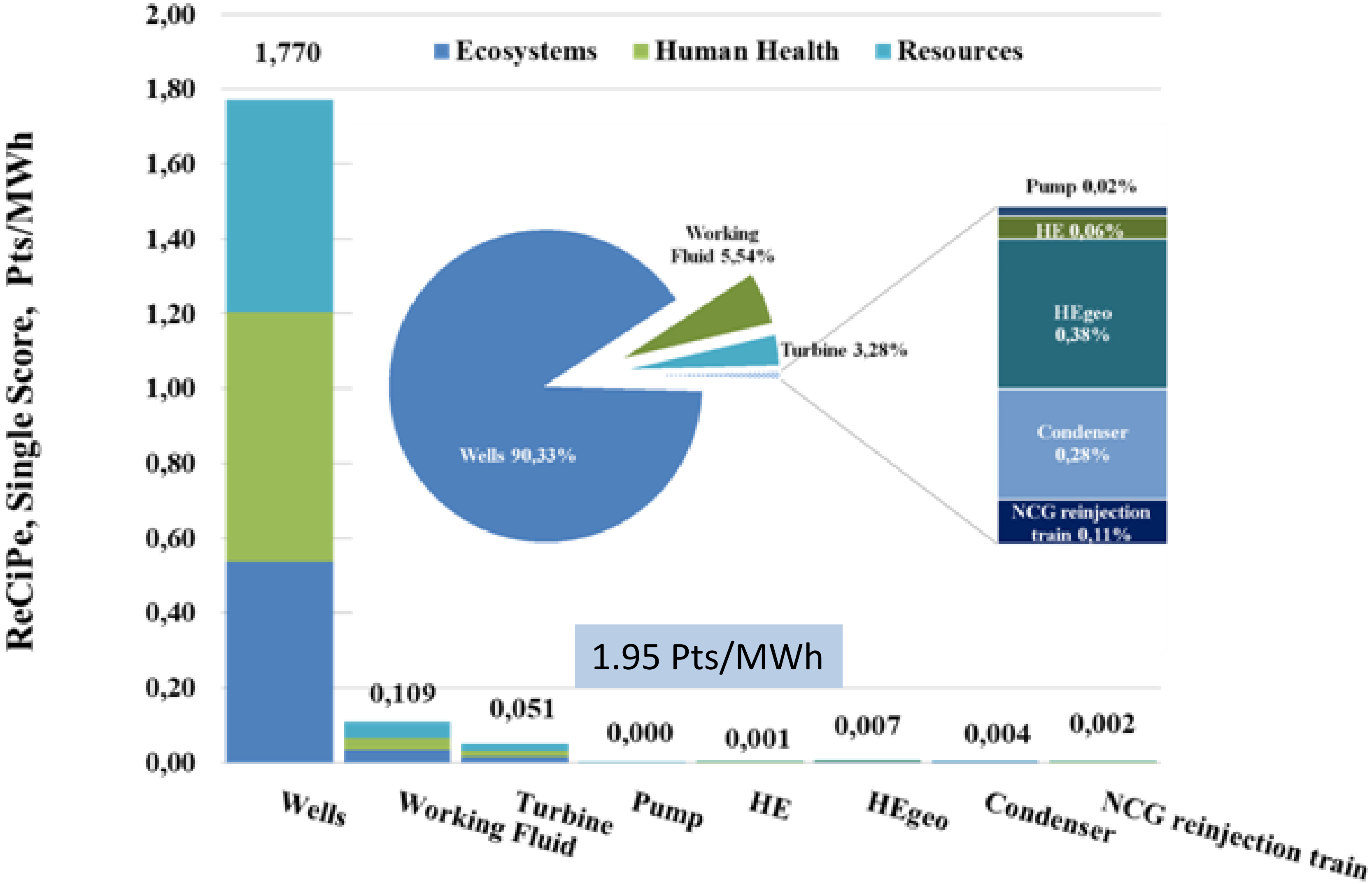
Piping ORC - wells	1	m	Total length: 390 m
Steel	6,767	kg	market for steel, low-alloyed, alloc. default, U - GLO
INOX 316 L	0,556	kg	market for steel, chromium steel 18/8, alloc. default, U - GLO
Mineral wool	2,577	kg	market for rock wool, alloc. default, U - GLO
Equipment/material machinery	**Quantity**	**Units**	**Ecoinvent record**
Turbine	5409	kW	
Reinforcing Steel	56176	kg	reinforcing steel production, alloc. default, U
Steel, low-alloyed	92530	kg	market for steel, low-alloyed, hot rolled, alloc. default, U
Chromium steel 18/8	2017	kg	market for steel, chromium steel 18/8, alloc. default, U
Copper	5452	kg	market for copper, primary production, alloc. default, U
Aluminum	3094	kg	market for aluminium, wrought alloy, alloc. default, U - GLO
Iron-nickel-chromium alloy	1644	kg	market for cast iron, alloc. default, U
Polyethylene, HDPE	1364	kg	polyethylene production, low density, granulate, alloc. default, U
Air cooled condenser	21775	kW	
Steel low-alloyed		kg	market for steel, low-alloyed, hot rolled, alloc. default, U
Chromium steel 18/8		kg	market for steel, chromium steel 18/8, alloc. default, U
Aluminum		kg	market for aluminium, wrought alloy, alloc. default, U - GLO
Polyethylene HDPE		kg	polyethylene production, low density, granulate, alloc. default, U
Economizer + Evaporator	26894	kW	
Copper tube	5353	kg	market for copper, primary production, alloc. default, U
Cast iron	611	kg	market for cast iron, alloc. default, U
Steel	86	kg	market for steel, low-alloyed, hot rolled, alloc. default, U

Geothermal Power Plant with CO2 reinjection – Castelnuovo – LCI (Inventory)

Power Plant 2

Pump	290	kW	
Stainless steel	319	kg	market for steel, chromium steel 18/8, alloc. default, U
Copper	106	kg	market for copper, primary production, alloc. default, U
Recuperator	4044	kW	
Copper tube	805	kg	market for copper, primary production, alloc. default, U
Cast iron	92	kg	market for cast iron, alloc. default, U
Steel	13	kg	market for steel, low-alloyed, hot rolled, alloc. default, U
Compressors	41.8/39.9/37.6	kW	
Steel	164/159/159	kg	market for steel, low-alloyed, hot rolled, alloc. default, U
Cast iron	123/119/119	kg	market for cast iron, alloc. default, U
Copper wire	82/79/79	kg	market for wire drawing, copper, alloc. default, U - GLO
Aluminum	57/56/56	kg	market for aluminium, wrought alloy, alloc. default, U - GLO
Precooler/Intercoolers	1.3/4.7/4.6	m^2	
Stainless steel	368.8/100.7/374.8	kg	market for steel, chromium steel 18/8, alloc. default, U
Working fluid R1233zd	30 831	kg	- (Ding *et al.*, 2018).

Geothermal Power Plant with CO2 reinjection – Castelnuovo – LCA - Results



1.95 Pts/MWh

Geothermal Power Plant with CO2 reinjection – Castelnuovo – ExEnvA - Results

- The largest environmental cost is connected with exergy destruction at MHE and T
- MHE, T, P, RHE have a low f_k and would benefit of larger investment in materials
- The PreC and Ics show high values of r_k (increase fuel-to-product), but they are interested by only minor environmental cost streams

Component	$\dot{Y}_k$ (Pts/h)	$\dot{B}_{D,k}$ (Pts/h)	$\dot{B}_{D,k} + \dot{Y}_k$ (Pts/h)	$f_{D,k}$ (%)	$r_{D,k}$ (%)
P	0.00313	0.02277	0.0259	12.09	18.46
RHE	0.004243	0.02158	0.02582	16.43	32.02
MHE	0.1143	0.4946	0.6089	18.77	33.19
T	0.135	0.2834	0.4183	32.26	17.47
CON	0.06413	0.4939	0.558	11.49	-
PreC	0.0002291	0.0001925	0.0004216	54.33	57.13
C1	0.0006466	0.002882	0.003529	18.32	18.88
IC1	0.000871	0.001107	0.001978	44.04	79.87
C2	0.0006277	0.002782	0.00341	18.41	19.16
IC2	0.0008416	0.00115	0.001991	42.27	70.31
C3	0.0006103	0.002611	0.003222	18.94	19.21

- On the whole, for the power plant equipment the environmental cost of exergy destruction is much larger than the environmental cost of materials/construction

Exergy, ExEcA, ExEnvA - Conclusions

- **Exergy analysis EA** is the starting point. The attractiveness is the possibiliy of **comparing irreversibilities of very different nature** (heat transfer, mixing, friction, chemical,…) and identify opportunities for system improvement (thermodynamic).
- It is recommended to use EA **separating Exergy Destruction and Exergy Loss.**
- EA has many applications (also in the RES field), from **design to off-design analysis and optimal control.**
- The **Exergo-Economic Analysis ExEcA** is a very powerful tool to evaluate the **progressive cost buildup** and the **components deserving more capital investment**.
- The **results of ExEcA** are largely dependent on the **accuracy of component cost evaluation** (internal data better than cost correlations), with special reference to RES (no fuel cost).

Exergy, ExEcA, ExEnvA - Conclusions

- The **Exergo-Environmental Analysis (ExEnvA)** is a very powerful tool to provide a quantitative evaluation of **Sustainability of a project in engineering terms**
- ExEnvA requires a **preliminary LCA**, which is already a valuable step for evaluating the overall sustainability of the project; when applying ExEnvA, **the LCI must be built keeping the Inventory separate for the components** (not common in LCA). Moreover, it is recommende to **split as far as possible the process in sub-processes** (many of them can be re-used: e.g. wells, Air-Cooled Condensers, Emissions treatmente equipment,…)
- Frequently **environmental costs are more certain** (= less market-dependent) than economic costs – uncertainty depends on the source of data but there are good LCA data bases and sub-processes can be built on purpose
- The **ExEnvA adds to LCA** the **evaluation of the progressive buildup of environmental costs**, identifying the **components deserving more investment on materials** in order to improve their performance (reduce the exergy destruction).

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From Exergy to Exergo-economic and Exergo-Environmental analysis of renewable energy systems: intro and selected case studies

Thanks for your Attention!

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