Advanced Exergy Analysis of Gas Turbines

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Introductory Concepts

- **1st** Thermodynamic Law – **energy** analysis

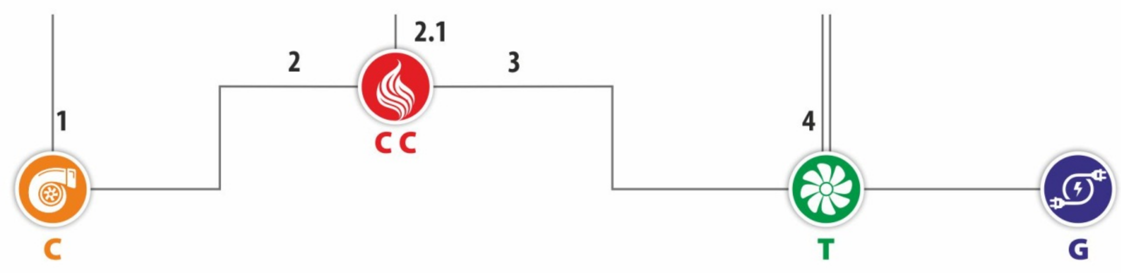
- **2nd** Thermodynamic Law – **exergy** analysis

based on

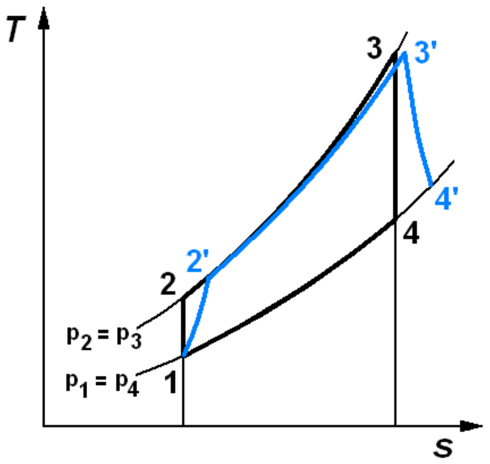
Entropy Generation → Exergy Destruction

$I = T_0 S_{gen} \geq 0$

Single-shaft Power Gas Turbine (GT)



- 1: Compressor
- 2-3: Combustion Chamber
- 4: Turbine



Performance of GT- Energy Analysis

p0 (bar)
T0 (oC)
Kin (%)
πc
ηis,c (%)
ηb (%)
qf (kJ/kg)
Kb
Tt4 (oC)
ηis,t (%)
Kex (%)
γa
cpa (J/kg/K)
γg
cpg (J/kg/K)
ηm
ea
eg
ma (kg/s)

Physics equations →

pt1
Tt1
pt2
Tt2
pt3
Tt3
pt4
Tt4
pt5
Tt5
pt6
Tt6

1st Thermodynamic Law →

wc
wt
wκ
ηθ
sfc

Exergy Analysis-Kinds of Exergy

- Thermal Exergy

$$E^{T} = C_p{}^{h}\left(T - T_0 - T_0 \ln\frac{T}{T0}\right)\ (J/kg)$$

- Mechanical Exergy

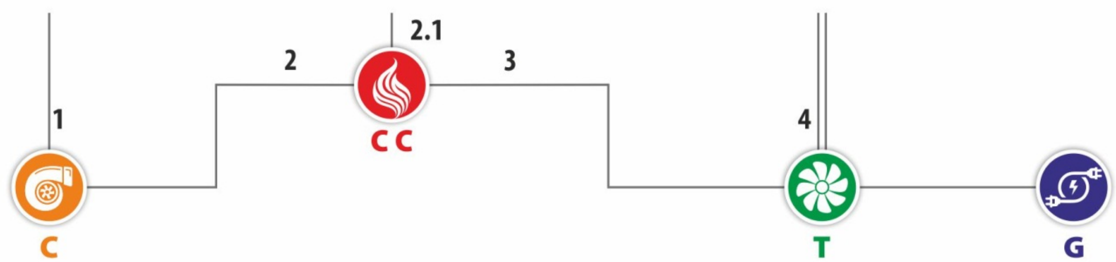
$$E^{M} = RT0 \ln\frac{p}{p0}\ (J/kg)$$

- Chemical Exergy

$$E^{CHE} = \frac{\varepsilon^{\sim 0,M}}{MBfuel}(J/kg)$$

CEA Results 1/3

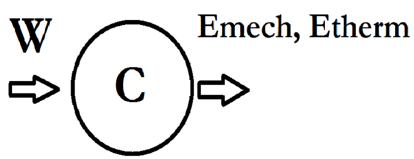
	State	Mass flow (kg/sec)	Pressure (bar)	Temperature (K)	E^T (kW)	E^M (kW)	E^{CHE} (kW)
Air in C	1	1,00	0,995	273	0,000	-1,172	0,000
Air in CC	2	1,00	13,057	643,8	137,272	200,530	0,000
Fuel in CC	2.1	0,023	2	298	0,042	0,,613	1115,54
Gas in T	3	1,023	12,405	1373	690,366	198,934	0,000
Exhaust Gases	4	1,023	1,031	822,8	260,437	1,632	0,000



CEA Results 2/3

Exergy Balance: $E_{F,k} = E_{P,k} + I_k$

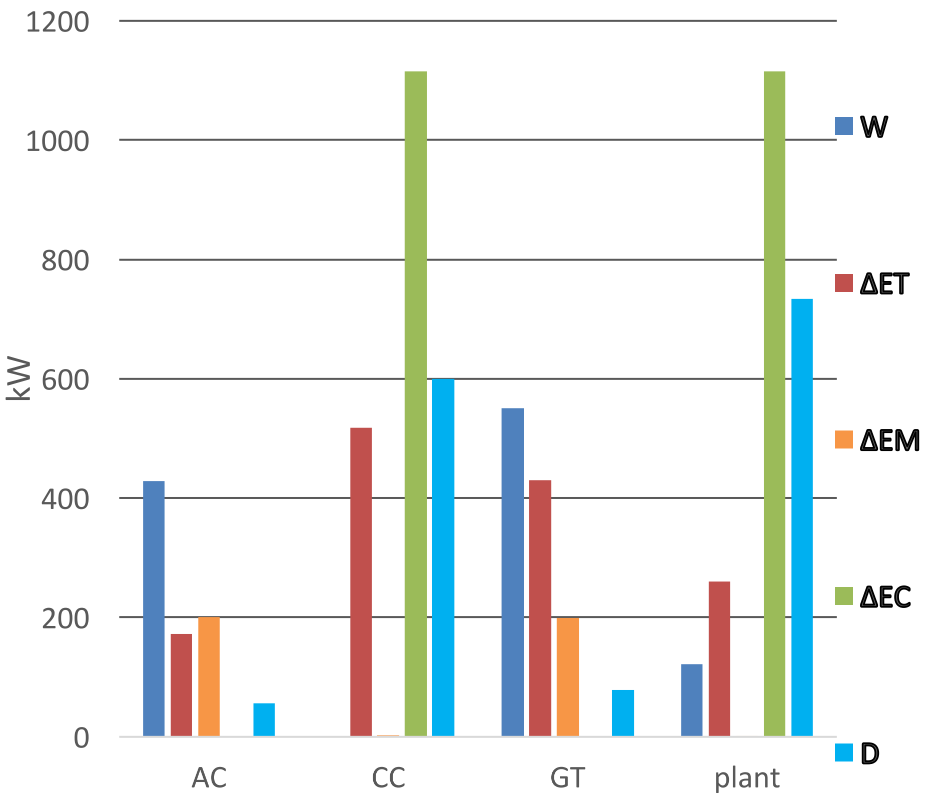
For example:

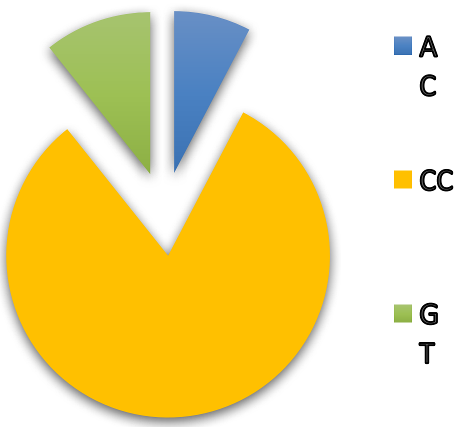


Also, we define **ε** as: $\frac{EP,k}{EF,k}$

	EF,k (kW)	EP,k (kW)	ED,k = Ik (kW)	ε (-)	ε %
C	372,654	336,629	36,025	0,9033	90,33
CC	1115,54	550,844	564,696	0,4938	49,38
T	627,231	576,363	50,868	0,9189	91,89
Plant	1115,54	463,951	651,589	0,4159	41,59

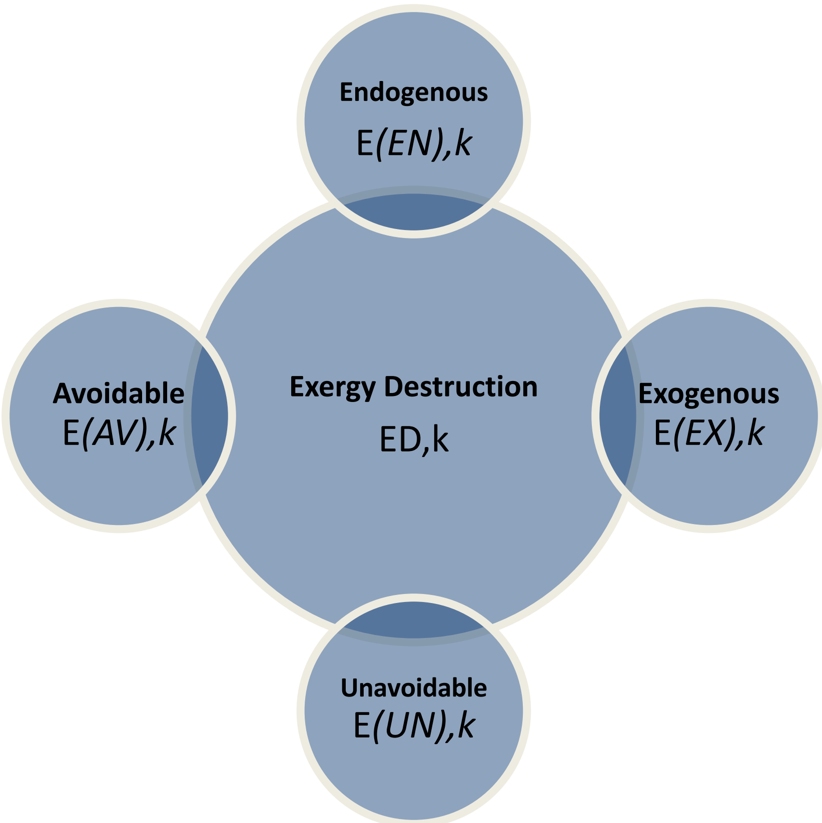
CEA Results 3/3





Advanced Exergy Analysis (AEA)

Introductory Concepts



Endogenous: irreversibilities occurring within the component operating with its ***real*** efficiency

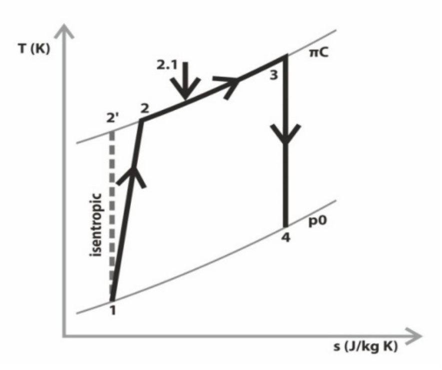
Exogenous: irreversibilities occurring within the other components operating with their ***ideal*** efficiency

Unavoidable: the part within the component, which cannot be reduced due to **thermodynamic limitations**

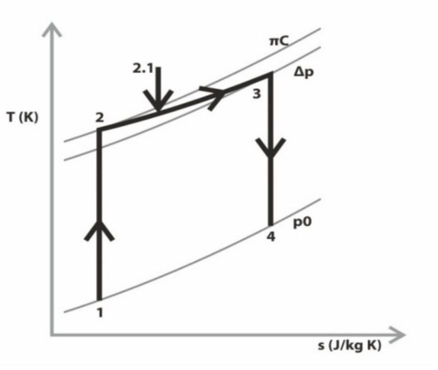
Avoidable: the part within the component, which **can be reduced** if the best available technology is applied.

AEA Methodology 1/4

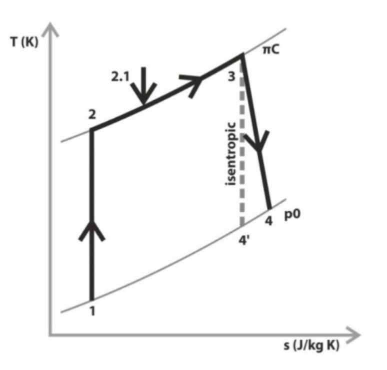
Endogenous Exergy Destruction → **Hybrid** Cycles



Hybrid Cycle C



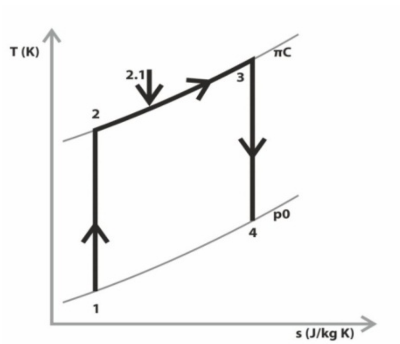
Hybrid Cycle CC



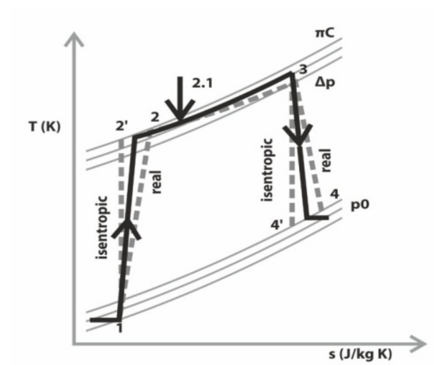
Hybrid Cycle T

AEA Methodology 2/4

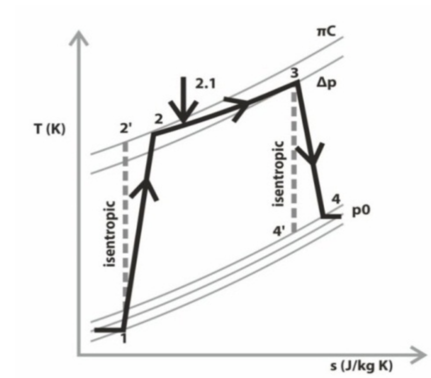
Unavoidable Exergy Destruction → **Unavoidable** Cycle



Ideal Cycle



Unavoidable Cycle

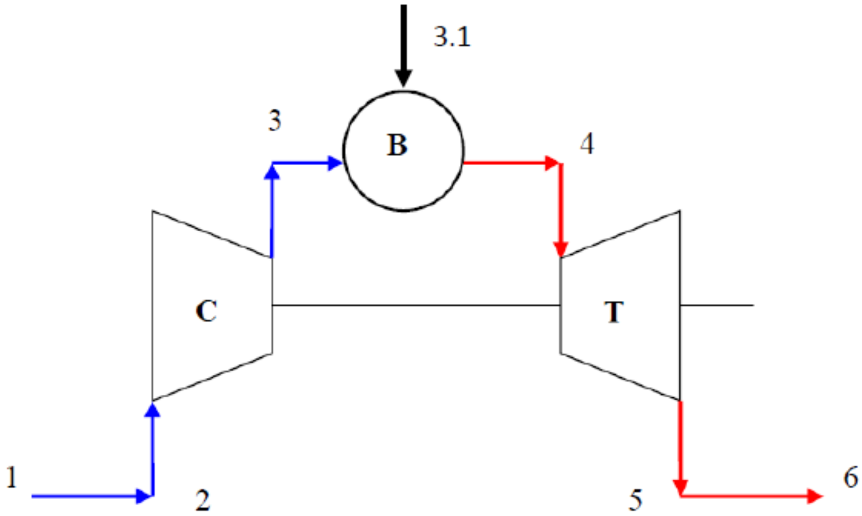


Real Cycle

a (IDEAL) > **a** (UNAVOIDABLE) > **a** (REAL)

a *could be replaced with:* $\eta_{is,T}$, $\eta_{is,C}$, η_{b}, Δp, K_{IN} , K_{OUT}

AEA Methodology 3/4



Constant in all cycles

- Gas Turbine Inlet Temperature **(T_{t4})**
- Engine Net power **(W)**
- Air-fuel ratio **(λ)**

Real cycle *(RE)*

$\mathbf{m_3+m_{3.1}=m_4}$

$E_3+\varepsilon_{CC,\ real}E_{3.1}=E_4$ με $\varepsilon_{CC,\ real}\neq 1$

Compressor's and Turbine's Hybrid Cycles *(H.C, H.T)* & Unavoidable cycle *(UN)*

$\mathbf{m_3+m_{3.1}\neq m_4}$**,**

$E_3+\varepsilon_{CC}E_{3.1}=E_4$, with $\varepsilon_{CC}=1$ *(hybrid C,T)*, $\varepsilon_{CC}>\varepsilon_{CC,\ real}$ *(Unavoidable)*

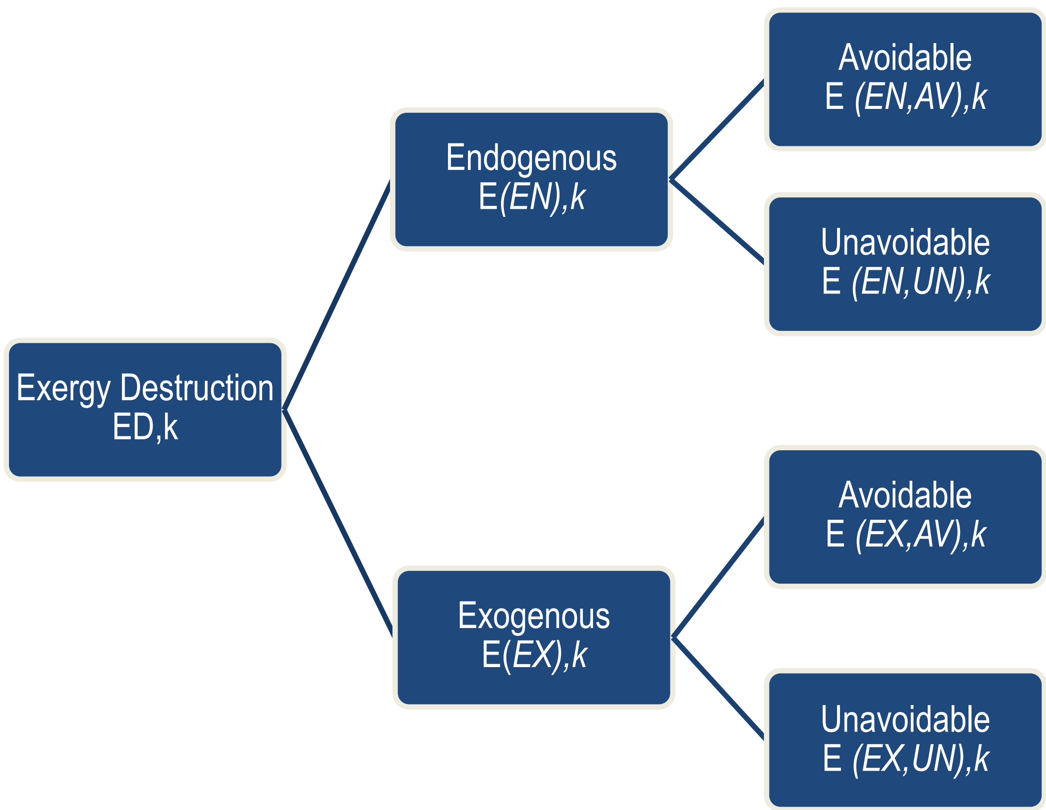
Combustion Chamber's Hybrid Cycle *(H.CC)*

$\mathbf{m_3+m_{3.1}\neq m_4}$

$E_3+\varepsilon_{CC}E_{3.1}=E_4$, με $\varepsilon_{CC}=\varepsilon_{CC,\ real}$

$m_3e_3+\varepsilon_{CC}m_{3.1}e_{3.1}=m_4e_4$
$W=\eta_{mm}w_T-m_3w_C$
$m_3=\lambda m_{3.1}$

AEA Methodology 4/4



Example:

EN,AV: part of the exergy destruction within the component **(EN)**, which can be reduced if the best available technology is applied **(AV)**

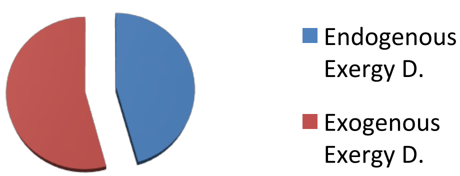
$$E(EN,AV),k + E(EX,AV),k + E(EX,UN),k + E(EN,UN),k = ED,k$$

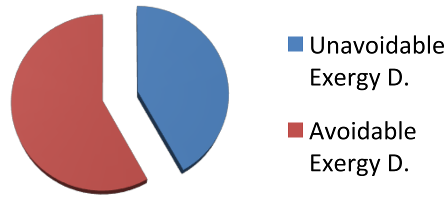
AEA Results 1/2

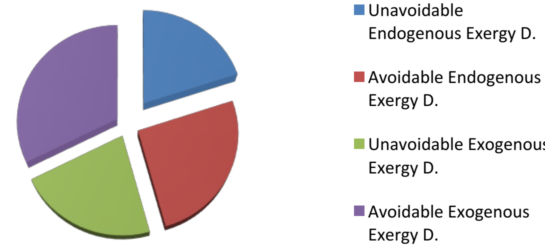
Exergy Destruction E D,k		C	CC	T
Endogenous	E D,k *(EN)*	482.4	14233.3	1091.1
Exogenous	E D,k *(EX)*	682.4	4650.8	533.8
Unavoidability Indicator	Λ,k	0.033	0.614	0.019
Unavoidable	E D,k *(UN)*	810.3	17971.8	798.6
Avoidable	E D,k *(AV)*	354.4	912.3	826.3
Unavoidable-Endogenous	E D,k *(UN,EN)*	360.6	13545.7	527.0
Avoidable-Endogenous	E D,k *(AV,EN)*	121.7	687.6	564.1
Unavoidable-Exogenous	E D,k *(UN,EX)*	449.7	4426.2	271.6
Avoidable-Exogenous	E D,k *(AV,EX)*	232.7	224.7	262.2

AEA Results 2/2

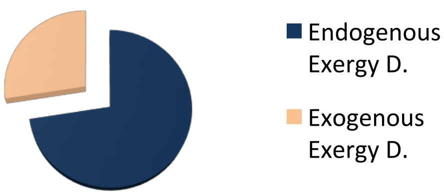
Compressor

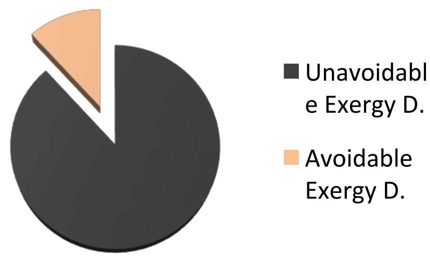


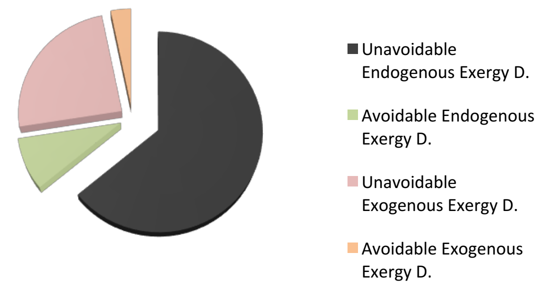




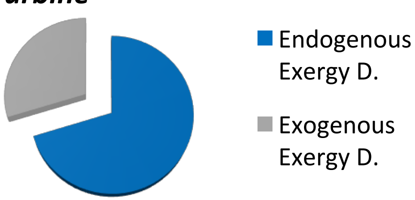
Combustion Chamber

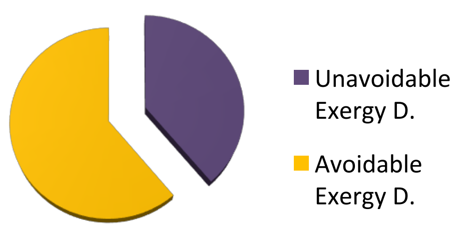


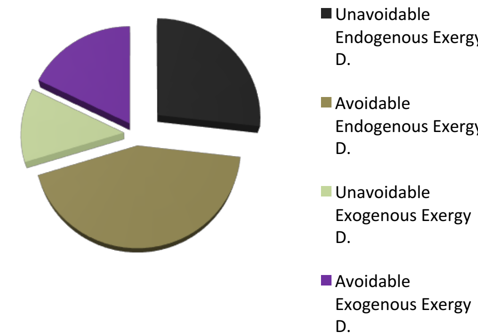




Turbine







CONCLUSIONS

- The main Exergy Destruction is caused by **CC** *(84,9%)*
- Exogenous Exergy Destruction is lower than Endogenous in **CC, T.**
- Avoidable Exergy Destruction is greater than the Unavoidable part in **C, T.**
- Unavoidable Exergy Destruction is much greater than Avoidable Exergy Destruction in the **CC**
- On the contrary, **C, T** have their greater contribution in the Avoidable part

Future Research

- *AEA methodology in a whole power range of gas turbines to examine how it scales with power*
- *AEA methodology in further applications of gas turbine technology (recuperator, water injection)*
- *Extension AEA methodology, which could also include environmental and/or economical issues.*

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Thank you for your attention!

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