EXERGY ANALYSIS OF GAS-TURBINE COMBINED CYCLE WITH CO_2 CAPTURE USING AUTO-THERMAL REFORMING OF NATURAL GAS

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CO_2 capture

A concept for capturing and sequestering CO_2 from a natural-gas fired combined-cycle power plant is presented.

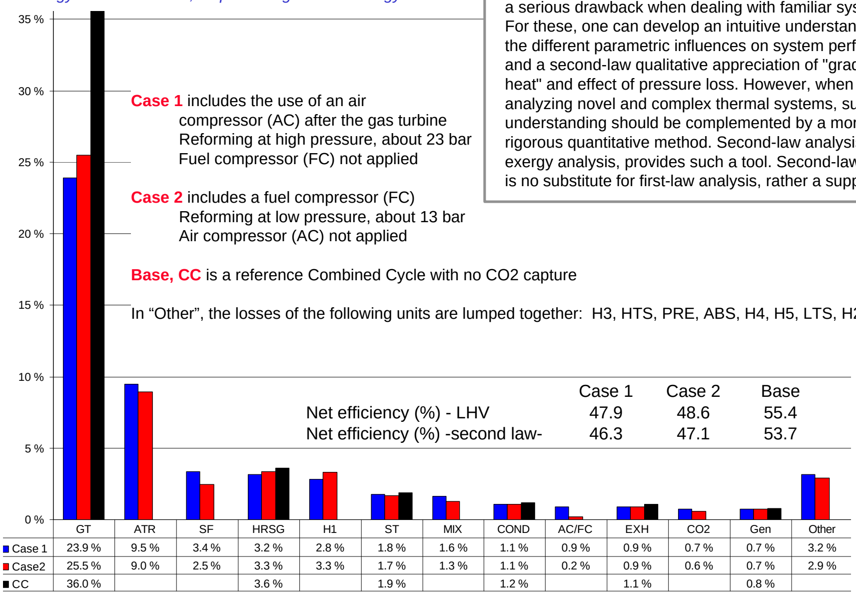
The present approach is to **de-carbonise the fuel prior to combustion** by **reforming natural gas**, producing a **hydrogen-rich fuel**. The reforming process consists of an air-blown pressurised auto-thermal reformer (ATR) that produces a gas containing H_2, CO and a small fraction of CH_4 as the combustible components. The gas is then led through a water-shift reactor (HTS, LTS), where the equilibrium of CO and H_2O is shifted towards CO_2 and H_2. The CO_2 is then captured from the resulting gas by chemical absorption (ABS). The gas turbine of this system is then fed with a fuel gas containing approximately 50% H_2. A very important aspect of this type of process is the **integration** between the combined cycle and the reforming process.

A model of the gas turbine GE9351FA from General Electric was used in the simulations.

Computational results. Cases explained in diagram below

	Case1	Case2	Base
Natural gas LHV (MW) (1)	879	864	683
Air extracted to ATR (kg/s) (8)	83.2	79.5	
ATR outlet pressure (bar) (11)	22.8	12.8	
ATR inlet (kg/s) (6+10)	141.3	117	
Fuel composition (%) (21c)			
H_2	55.6	56.3	
N_2+Ar	41.2	40.7	2.0
CO	0.3	0.4	
CO_2	2.0	2.0	1.0
CH_4	0.5	0.4	93.0
C_2H_6			4.0
H_2O	0.3	0.2	
Fuel flow to GT (kg/s) (21c)	67.9	67.4	14.6
Fuel flow to SF (kg/s) (21a)	7.8	5.6	
Power output GT (MW)	253.	256	243.
Power output ST (MW)	179	181	140
Auxiliary power (MW)	5.1	5.1	4.6
Air / fuel compression (MW)	5.5	10.8	
Net power output (MW)	422	421	378
Net efficiency (%) – LHV	47.9	48.6	55.4
Net efficiency (%) -second law-	46.3	47.1	53.7
CO_2 emissions (g_{CO2}/kWh_{el})	57	56	365
CO_2 reduc. vs. Base (%/kWh_{el})	84.4	84.7	

Exergy loss breakdown, as percentage of fuel exergy



Case 1 includes the use of an air
compressor (AC) after the gas turbine
Reforming at high pressure, about 23 bar
Fuel compressor (FC) not applied

Case 2 includes a fuel compressor (FC)
Reforming at low pressure, about 13 bar
Air compressor (AC) not applied

Base, CC is a reference Combined Cycle with no CO2 capture

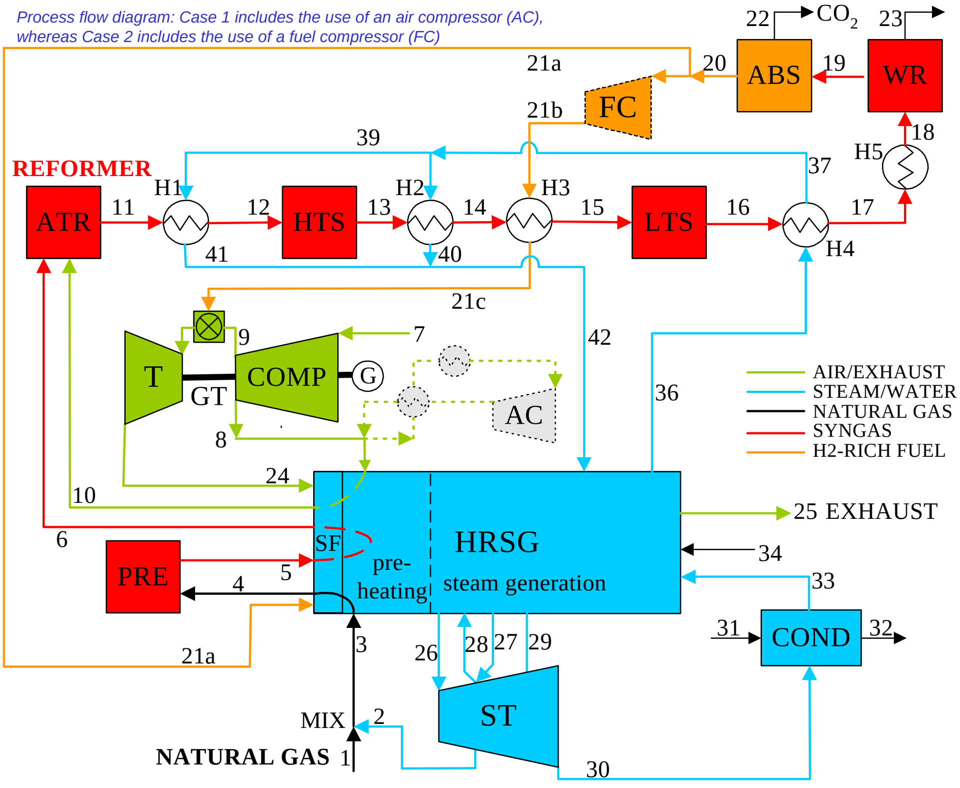
In “Other”, the losses of the following units are lumped together: H3, HTS, PRE, ABS, H4, H5, LTS, H2, WR

	Case 1	Case 2	Base
Net efficiency (%) - LHV	47.9	48.6	55.4
Net efficiency (%) -second law-	46.3	47.1	53.7

	GT	ATR	SF	HRSG	H1	ST	MIX	COND	AC/FC	EXH	CO2	Gen	Other
🟦 Case 1	23.9 %	9.5 %	3.4 %	3.2 %	2.8 %	1.8 %	1.6 %	1.1 %	0.9 %	0.9 %	0.7 %	0.7 %	3.2 %
🟥 Case2	25.5 %	9.0 %	2.5 %	3.3 %	3.3 %	1.7 %	1.3 %	1.1 %	0.2 %	0.9 %	0.6 %	0.7 %	2.9 %
■ CC	36.0 %			3.6 %		1.9 %		1.2 %		1.1 %		0.8 %	

Gas-turbine Combined Cycle with Auto-thermal reforming

Process flow diagram: Case 1 includes the use of an air compressor (AC), whereas Case 2 includes the use of a fuel compressor (FC)



T = TURBINE, COMP = COMPRESSOR, AC = AIR COMPRESSOR
SF = SUPPLEMENTARY FIRING, HRSG = HEAT RECOVERY STEAM GENERATOR
ST = STEAM TURBINE, COND = STEAM CONDENSER, PRE = PREREFORMER
ATR = AUTO-THERMAL REFORMER, HTS = HIGH TEMPERATURE SHIFT-REACTOR,
LTS = LOW TEMPERATURE SHIFT-REACTOR, WR = WATER REMOVAL,
ABS = CO2 ABSORBER, FC = FUEL COMPRESSOR

Exergy analysis

Traditional first-law analysis, based upon unit-performance characteristics coupled with energy balances, invariably leads to a correct final answer. However, such an analysis cannot locate and quantify the losses that lead to the obtained result. This is because the first law embodies no distinction between work and heat, no provision for quantifying the quality of energy. These limitations are not a serious drawback when dealing with familiar systems. For these, one can develop an intuitive understanding of the different parametric influences on system performance and a second-law qualitative appreciation of "grade-of-heat" and effect of pressure loss. However, when analyzing novel and complex thermal systems, such as understanding should be complemented by a more rigorous quantitative method. Second-law analysis, or exergy analysis, provides such a tool. Second-law analysis is no substitute for first-law analysis, rather a supplement.

Exergy analysis

Exergy balance, including the loss (Irreversibility)

$$\sum_{in} \dot{m}_j\, e_j + \sum_{l} \dot{Q}_l \left(1 - \frac{T_0}{T_l}\right) = \sum_{out} \dot{m}_k\, e_k + \dot{W} + \dot{I}$$

Flow exergy into system — Heat exchange — Flow exergy out of system — Work — Irreversibility

Computational tools: GTPRO 10.0 (Thermoflow, Inc.) and PRO/II 5.11 (Simsci, Inc.).

Conclusions

Two cases of a gas-turbine combined-cycle power plant with natural-gas reforming, CO_2 capture, and combustion of a hydrogen-rich fuel were simulated. The resulting **first-law (LHV) efficiencies** were 47.9 and 48.6, respectively. the **second-law (exergy) efficiencies** were 46.3 and 47.1. A comparable conventional natural-gas fired combined-cycle gave first- and second-law efficiencies of 55.4 and 53.7, respectively.

If was seen that a lower pressure (approx. 14 bar) in the reforming process and fuel compression was beneficial from a thermodynamic point of view compared to maintaining a high pressure (approx. 25 bar) throughout the process.

The irreversibility (exergy loss) was determined in each unit of the system, see diagram to the left. The greater loss in the new concepts resulted from **additional losses** in **supplementary firing** (SF) and **heat exchange** (H1-H3) between the reforming and power cycle process.

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