DESIGN AND TECHNICAL , ECONOMICAL AND ENVIRONMENTAL ANALYSES OF A HYDROGEN FIRED MULTI-PURPOSE CO-GENERATION SYSTEM

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1.INTRODUCTION

- In the long run, it will be expected that the use of hydrogen will be inevitable in all fields of life.
- As early as possible, new researches on the most economical integration alternatives of the system using H_2 as the source of energy in national economical sectors should be started
- The high production cost is the main handicap of the use of hydrogen in economical sector.

The main objective of this research is to determine the most economical application of the H_2 fired energy conversion system in national economy.

Table 1. Hydrogen Production Cost Depending On Hydrogen Row Material

Raw Material Cost	Natural Gas	Hydro-carbons	Pyrolysis **of Biomass**	Coal	Biomass **Gasification**	Water
C_f $[\$/kgH_2]$	3.01	3.97	4.39	5.36	5.8	7.85

System Structure Determination Criteria:

H_2 fired ECS to be used in econ. sectors should have;

- High fuel exergy potential,

- High exergy utilization efficiency,

- Feature of heat and electricity co-generation and the simultaneous demand of these energies by the related sectors,

- High operational load factor and high load change flexibility in operation,

- Low investment cost and high reliability.

Fuel Heat Exergy Potentials of Different Combustion and ECS

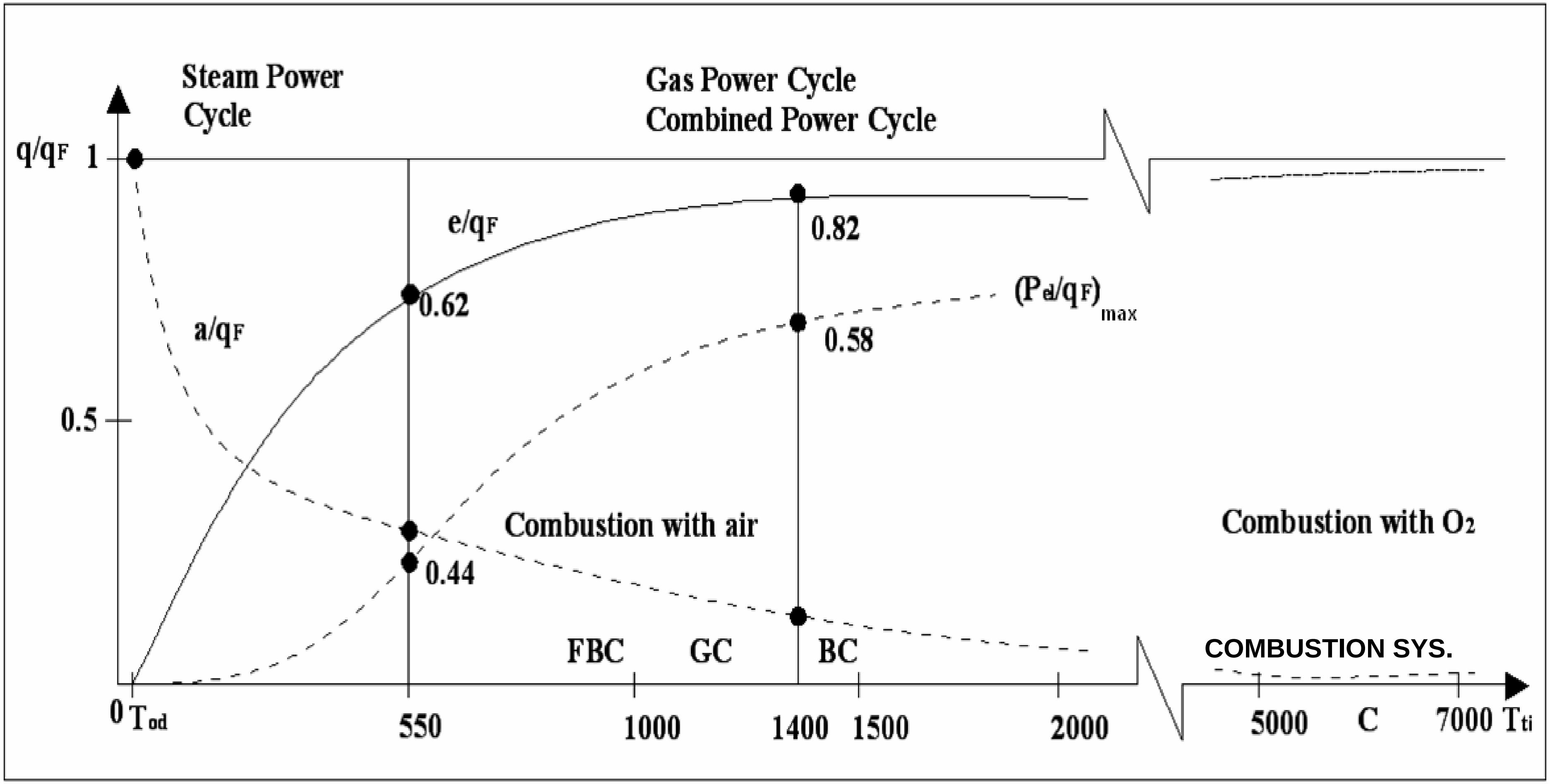

Fig.1: Fuel Exergy Ratio e/q_f Anergy Ratio a/q_f And Maximum Electricity Ratio $(p_{el}/q_f)_{max}$. Versus Turbine Inlet Temperature

Multi-purpose hydrogen fired gas turbine co-generation system (CGS)

2. DESIGN AND TECHNICAL ANALYSIS OF A CO-GENERATION SYSYTEM

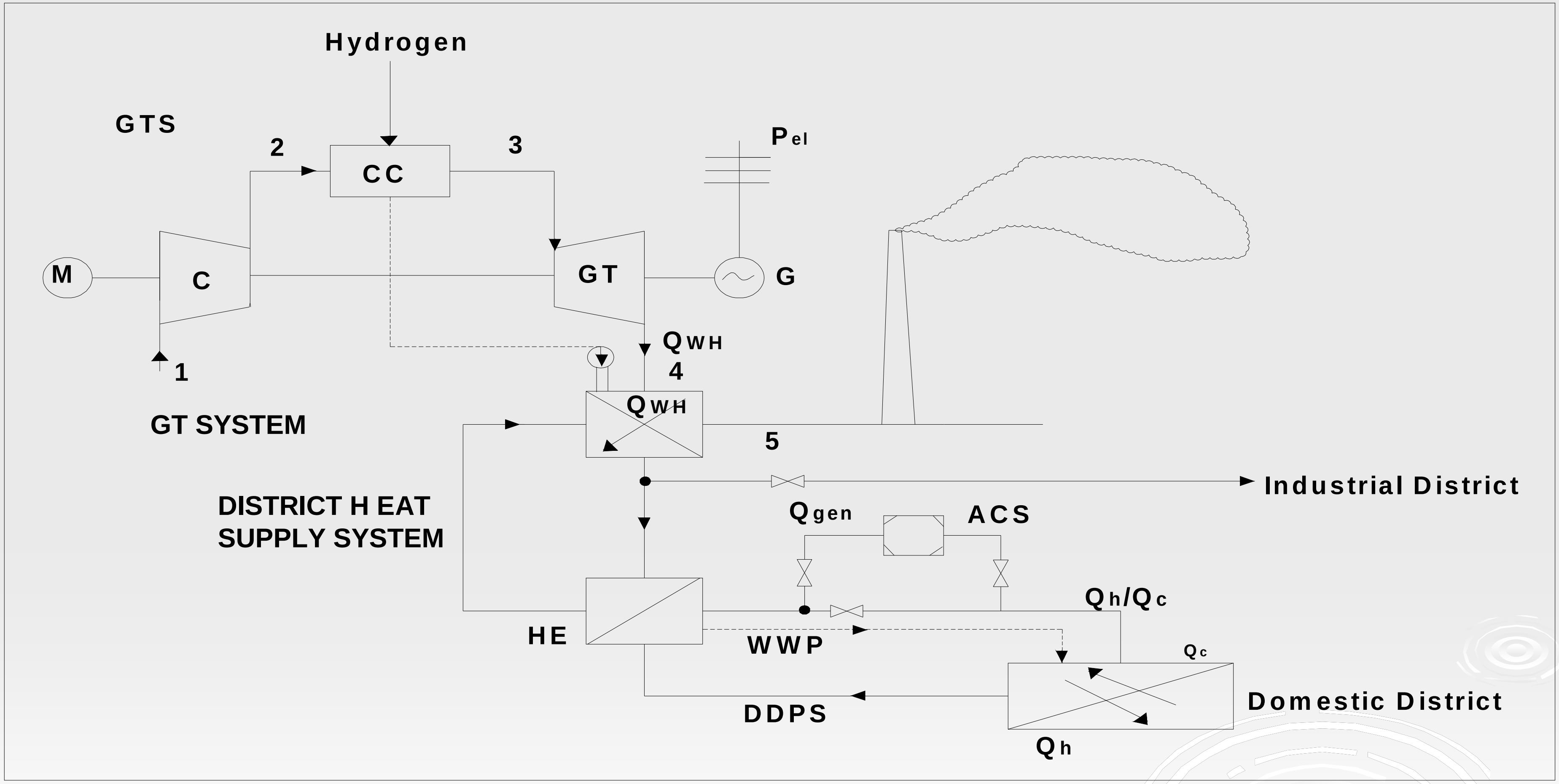

Fig. 2: System Structure and flow diagram of a hydrogen fired multi-purpose gas turbine co-generation system for district heating/cooling, warm water supply and steam supply for industry

2.1. Heat Load of a Gas Turbine Co-generation System

- Main heat load of a co-generation system consist of district heating/cooling

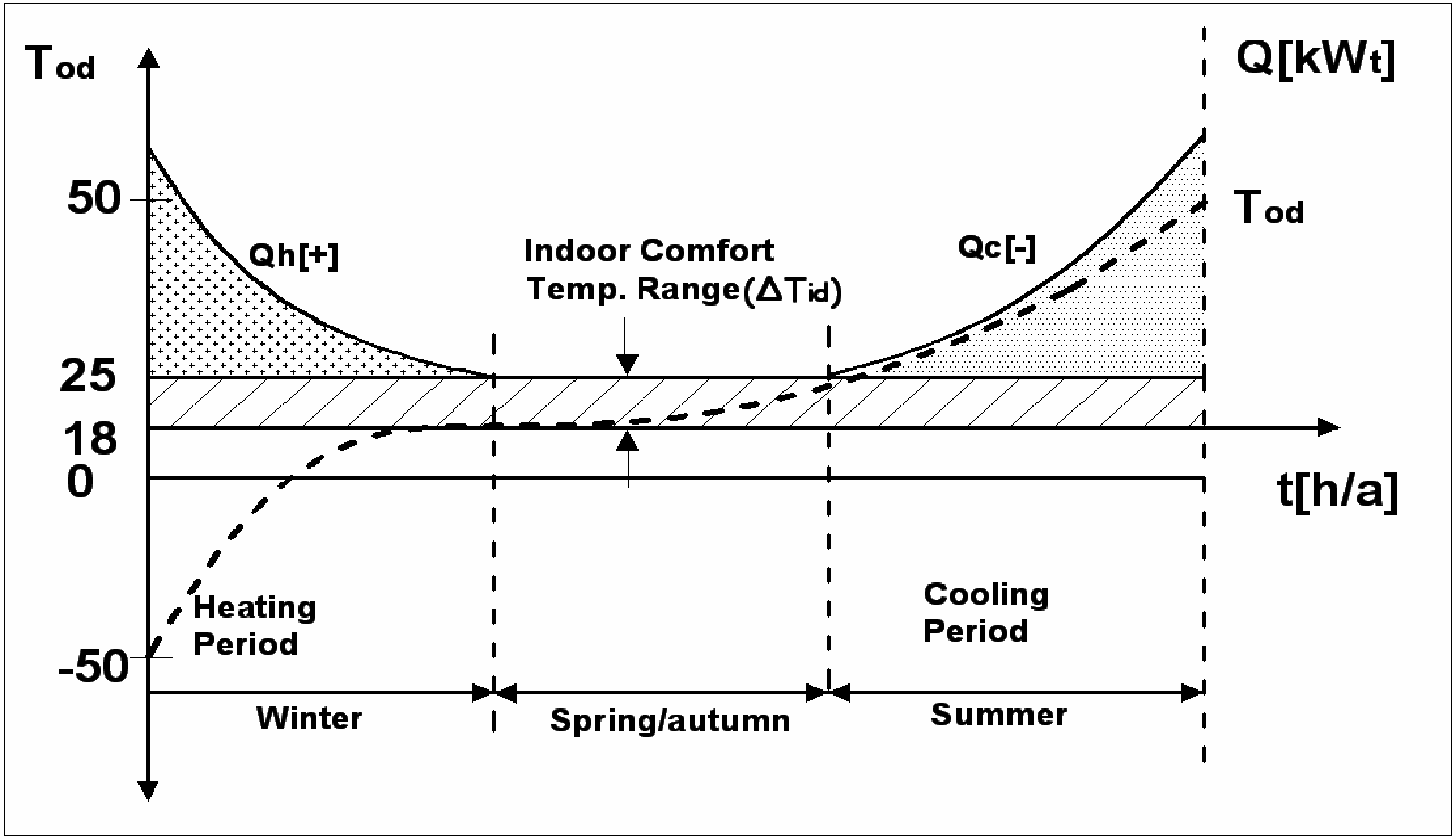

Fig. 3: Change of Outdoor Temperature (T_{od}), District Heating Load (Q_h), Cooling Load (Q_c), Indoor Comfort Temperature (ΔT_{id}) in a year

Total Heat Load of the Co-generation System

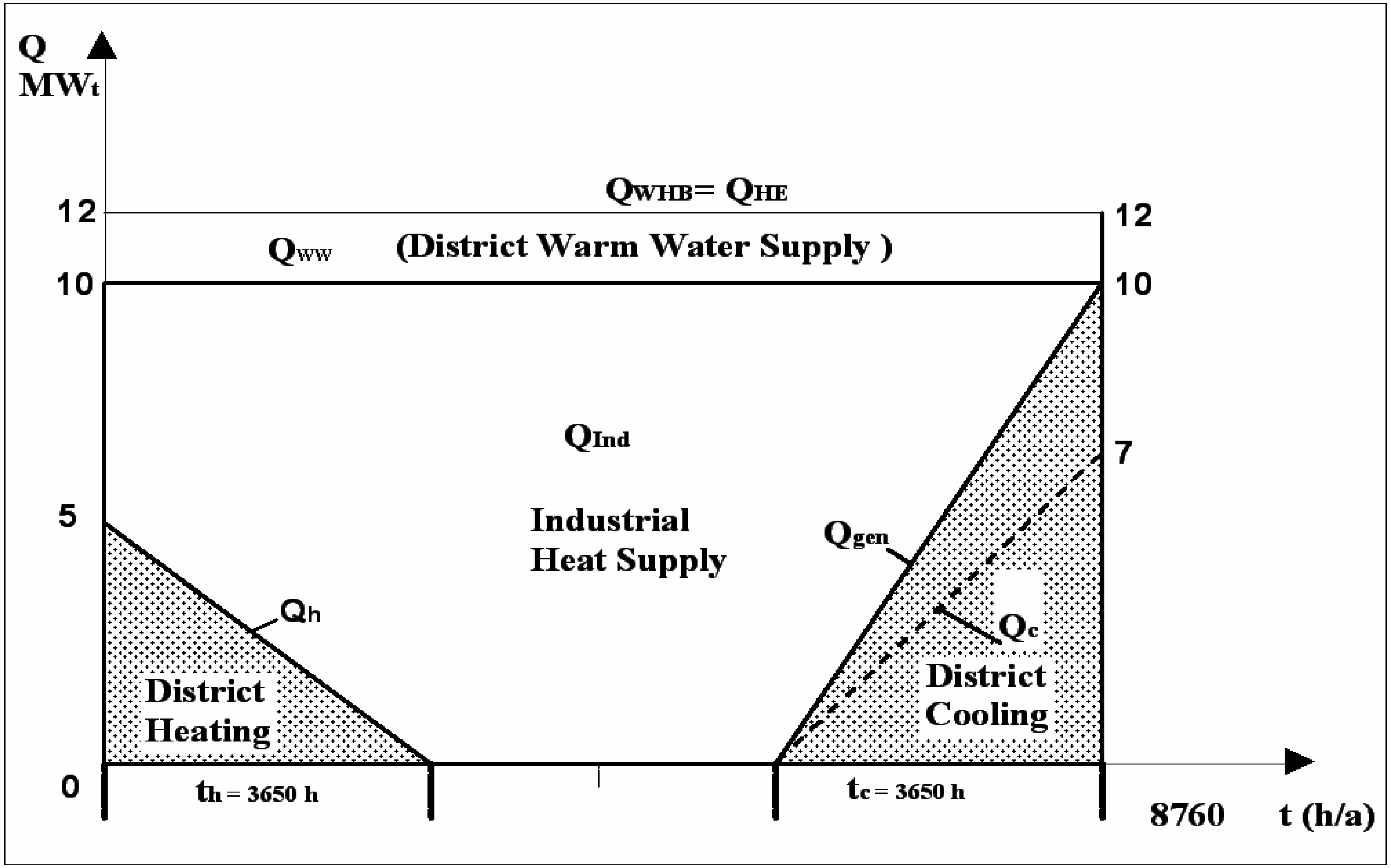

Fig. 4: Heat Load Diagram of the Gas Turbine Co-generation System Designed.

2.2 Design Data of the Co-generation System

Table 2: Design Data for the Gas Turbine CGS at Full Load Operation Conditions (F$_L$ = 1)

	Flat	Flat Spec. Load kWt	Qmax MWt	Qmin	Ann. Uti.	Ann. Load [kWh/a]
District Heating	500	10	5	0	3650	9.13E+06
District Warm Water	500	4	2	0	8760	1.75E+07
District Cooling	500	14	7	0	3650	2.56E+07
ACS Gen. Heat (COP=0.7	500	20	10	0	3650	3.65E+07
Industrial Steam	---	---	10	5	8760	1.54E+07
Waste Heat Boiler	1	---	12	---	8760	1.05E+08
Domestic Dist. Heat Exc.	1	---	12	2	8760	6.31E+07
Electric Load	---	---	7.15	---	8760	6.26E+07

2.3 Design and Optimization of the GT Power Cycle

- Gas turbine inlet temperature T_{ti} = 1200 C is selected
- Comb. with 96% of excess air to obtain T_{ti} = 1200 C
- Power cycle optimization gives opt. compression ratio, P_2/P_1 = 1 for T_{ti} = 1200 C
- Results of the power cycle analyses:

Compression ratio of compressor, p_2/p_1= 13
Compressor outlet temperature, T_2= 377 [˚C]
Specific compressor work, w_c = 368 [kJ/kg]
Specific turbine work, w_t = 700 [kJ/kg]
Turbine exhaust temperature, T_4= 590 [˚C]
Brayton power cycle efficiency, η_{BC} = 0.4
Overall gas turbine efficiency, η_{GT}= 0.36
Specific electricity generation, P_{sel}=29.8 [kWe/kg-pf]
Electricity generation capacity, P_{el} = 7.152 MW
For the calculation of over all gas turbine efficiency, the following efficiencies are assumed:
η_{comb}= 0.99, η_{mech}= 0.99, η_G=0.97, η_{transf}= 0.98, $\eta_{int-cons.}$= 0.96

2.4 Design Data of the Waste Heat Boiler (WHB)

- -Heat capacity : 12 MWt
- -WHB inlet temprature : 590 ^{o}C
- -Steam capacity : 86 t/h
- -Live steam temprature : 200 ^{o}C
- -Live steam pressure : 8 bar

2.5 Design Data of the Single Effect LiBr-H2O District Absorption Cooling System (ACS)

-District cooling load : 7 MWt
-ACS generator heat load : 10 MWt
-ACS evaporator temprature : 5 C
-ACS absorber temp. : 30 C
-ACS generator temp. : 120 C → **COP=0.7**
-ACS condenser temp. : 40 C
-Chilled water supply temp. : 6 C
-Chilled water return temp. : 12 C

2.6 Design Data of the District Piping System (DPS)

-Piping System is used for district heating in winter and for district cooling in summer

-The supply temperature of DPS in winter: 120 C

-The return temperature of DPS in winter: 50 C

-The supply temperature of DPS in summer: 6 C

-The return temperature of DPS in summer: 12 C

-Heat capacity of the district heat exchanger: 12 MWt

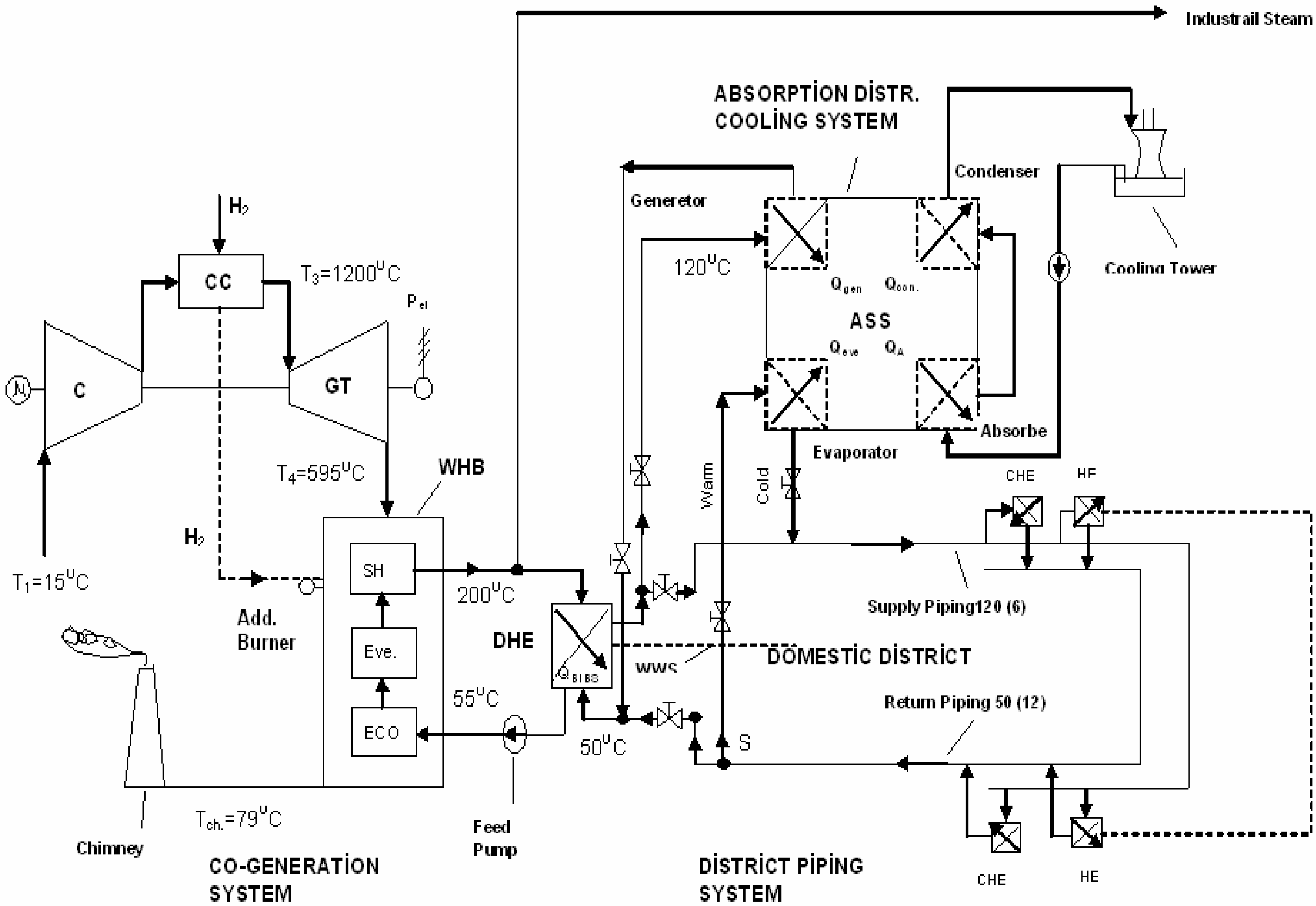

Fig. 5: System flow diagram and operational data of the hydrogen fired multi-purpose co-generation system designed.

3. ECONOMICAL ANALYSES OF THE H_2- FIRED MULTI- PUROSE CO-GENERATİON SYSTEM

3.1. Annual Expenditures of the Co-generation System (CGS)

3.1.1. Annual Fuel Cost (AFC)

Table 3: Annual Fuel (H_2) Consumption and Fuel Cost of the CGS

Hydrogen Consumpt./ Cost	Load Factor F_L			
	1.0	0.8	0.6	0.4
Hourly H_2-Consump. [kg/h]	606	485	364	242
Annual H_2 Consumpt. [kg/a]	$5.3x10^6$	$4.24x10^6$	$3.18x10^6$	$2.12x10^6$
Annual H_2 Cost [$/a]	$15.95x10^6$	$12.76x10^6$	$9.57x10^6$	$6.38x10^6$

3.1.2. Annual Amortization Cost of the Co-generation Systems (AAC)

Table 4: Investment Cost of Co-generation and District Heating-Cooling System

System Investment Cost [$]		
Co-generation and District Heating-Cooling System	Gas Turbine System, (10 MWe)	$4x10^6$
	Waste Heat Boiler, (17 MWt)	$0.75x10^6$
	Absorption Cooling System	$0.300x10^6$
	Others	$1.500x10^6$
	Sub Total	$6.55x10^6$
Piping Network	Piping and DHE Systems	$1.45x10^6$
Total	Total Cost	$8x10^6$

Amortization Calculation of the Co-generation System **(Linear Amortization)**

Annual Amortization Cost, AAC = TIC. AAR [$/a] (1)

where, TIC [$] = total investment cost,
AAR [1/a] = Linear annual amortization ratio, which is calculated as follows:

$$\text{AAR} = \frac{F(1+F)^{n_A}}{(1+F)^{n_A}-1} \qquad (2)$$

where, F [-] = interest rate
n_A[year] = amortization period in year.

For the economical analysis taking F = 0.1 (10%), n_A = 30 years and TIC = 8 x 10^6[$] (Table 4), from the related Eqn.s (1) &(2) one obtains: AAR = 1.06[1/a], AAC = 0.864[$/a] and the present value of TIC after 30 years amortization time, PTIC= 25.92 x 10^6[$].

3.1.3. Total Annual Expenditures of the Co-generation System (TAC)

Summing the annual fuel cost, (AFC), the annual amortization cost, (AAC) and the annual other costs, (AOC) the total annual cost can be obtained (Table 5, Table 6).

$$TAC = AFC + AAC + AOC \text{ [\$/a]} \quad (3)$$

Where, AOC can be taken 5-10% of the AFC, depending on the cases

Table 5: Annual Expenditures of the Co-generation System(n_A = 30 years).

Load	Load			
	1.0	0.8	0.6	0.4
Annual Fuel Cost [$/a]	15.95×10^6	12.76×10^6	9.57×10^6	6.38×10^6
Annual Amortization Cost [$/a]	0.864×10^6	0.864×10^6	0.864×10^6	0.864×10^6
Annual Other Cost [$/a]	0.786×10^6	0.786×10^6	0.786×10^6	0.786×10^6
Total Annual Cost [$/a]	17.6×10^6	14.41×10^6	11.22×10^6	8.03×10^6

Table 6: Annual Expenditures (EA) of the Co-generation System Depending on Amortization time (nA) and Load Factor (FL)

Annual Expenditure	Load Factor (F_L)			
	1,0	0,8	0,6	0,4
AE[$/a]($n_A$ = 30 year)	$17.6x10^6$	$14.41x10^6$	$11.22x10^6$	$8.03x10^6$
AE[$/a]($n_A$ = 10 year)	$18.82x10^6$	$15.64x10^6$	$12.4x10^6$	$9.27x10^6$
AE[$/a]($n_A$ = 5 year)	1 $9.63x10^6$	$16.45x10^6$	$13.21x10^6$	$10.07x10^6$

3.2. Annual Revenues of the Co-generation System from Heat and Electricity Selling

3.2.1. Annual Heat and Electricity Production by Co-generation System to Meet Clients Energy Requirements

Table 7: Annual electricity and heat produced by co-generation system to be purchased by electric network, domestic and industrial districts (Fig. 4).

Load	Load Factor, F_L			
	1.0	0.8	0.6	0.4
Electricity Load P_{elmax} [kWe]	7.125	5.722	4.275	2.850
Annual El. Production [kWhe/a]	62.415x10^6	49.932x10^6	37.449x10^6	24.966x10^6
District Heating Load $Q_{max.}$ [kWt]	5.000	4.000	3.000	2.000
Annual District Heating Demand [kWht/ a]	9.126x10^6	7.3x10^6	5.475x10^6	3.65x10^6
Warm Water Heat Load. Q_{max}[kWt]	2.000	1.600	1.200	800
Annual WW Heat Demand [kWht/ a]	17.52x10^6	14.02x10^6	10.51x10^6	7.01x10^6
District Cooling Load Q_{max}[kWt]	7.000	5.600	4.200	2.800
Annual District Cooling Demand [kWht/ a]	12.775x10^6	10.22x10^6	7.665x10^6	5.11x10^6
Annual steam load of industrial District [kWht/ a]	42x 10^6	33.6x 10^6	25.2x 10^6	16.8x 10^6

3.2. 2 Revenues of CGS from Heat Sellings

The heat generated is sold for following purposes:

- Domestic district heating and warm water supply,
- Domestic district cooling,
- Industrial steam supply.

3.2.2.1 Revenue from Heat Selling for District Heating and Warm Water (WW) Supply

This revenue is determined by multiplying unit heat selling price and total heat demand for district heating and WW supply(Table 7).

Determination of Unit Selling Prices for District Heating and Warm Water (WW) Supply, c_{sdh} [$/ kWht]

The unit heat selling price is determined considering the total unit heat generation cost of individual flat heating and WW supply using a natural gas fired combi heat generator

a) Spec. fuel cost, C_f , of individual flat heating and WW supply using a natural gas fired combi heat generator

Specific fuel cost for a heat generator can be calculated using Eqn.4;

$$C_f = \frac{g_f}{H_u \eta_b} \quad \text{[\$/ kWht]} \qquad (4)$$

Where; g_f [$/kg$_f$] = 0.812 average nat. gas price, Hu [kWh$_f$/kg$_f$] =13.46 average LHV of natural gas
η_b [kWht/kWhf]; average efficiency of heat generator (Fig. 6)

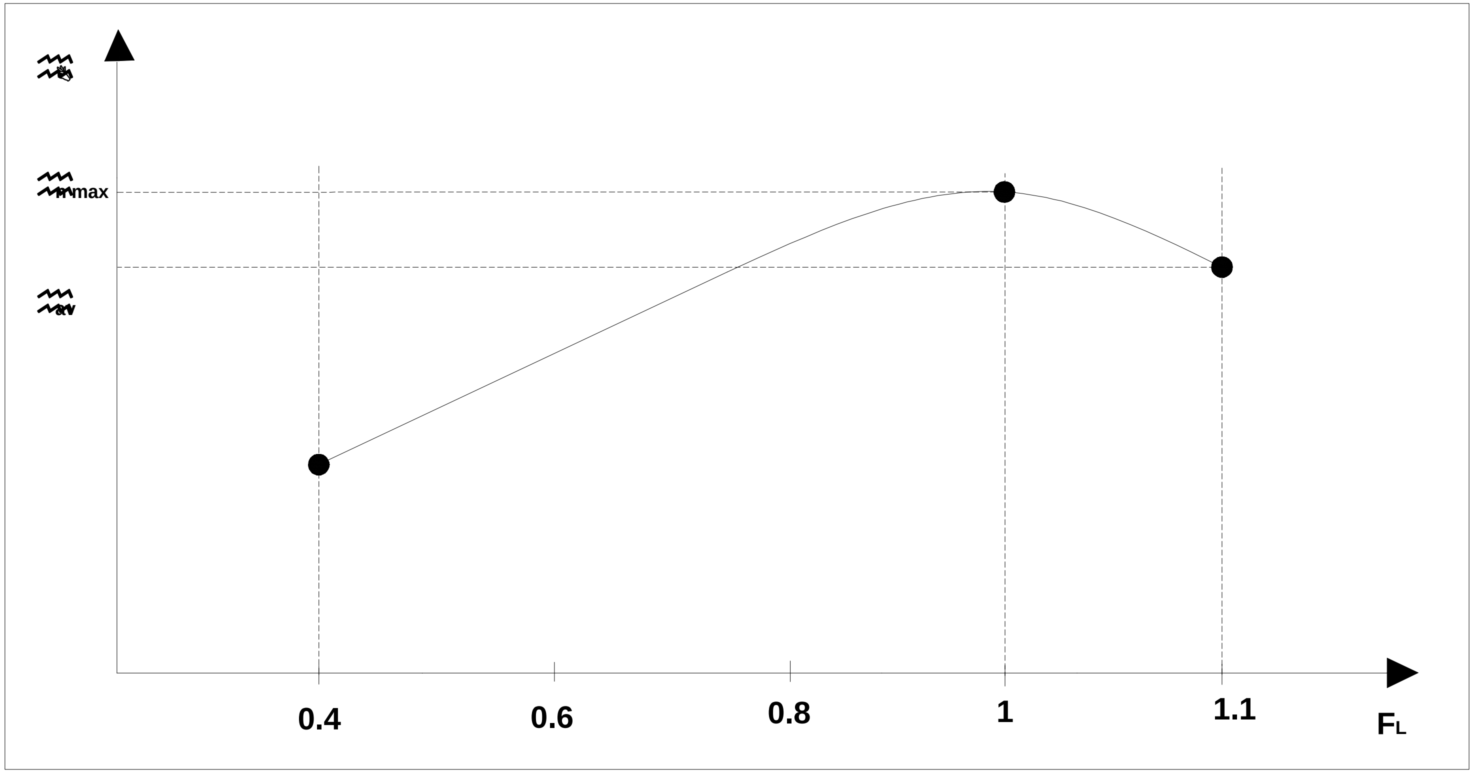

Fig. 6: Boiler (heat generator) efficiencies versus boiler operation load

Design and operational data of a combi heater used by client for individual flat heating

Installed capacity IC = 18 [kWt]

Total investment Cost TIC = 1900 [$]

Nominal thermal efficiency η_{nom} = 0.85 [kWht / kWhf]

Average thermal efficiency η_{avr} = 0.75 [kWht / kWhf] (Figure 6)

LHV of natural gas, Hu = 13.46 [kWhf /kgf]
Cost of natural gas g_f = 0.82 [$/kg]

,
Using above data one obtains C_f = 0.08 [$/kWht] (Eq. 4)

b) Specific amortization cost, c_{amr}, of individual flat heating and WW supply using natural gas fired combi heat generator

$C_{amr.}$ = Annual Amortization Cost / Annual Heat Generation = $\frac{TIC.AAR}{Q.F_L.8760} = \frac{\dot{Q}.SIC.AAR}{\dot{Q}.F_L.8760}$

$$= \frac{SIC.AAR}{F_L.8760} \quad [\$/kWh_t] \qquad (5)$$

Where;

SIC [$/kWt]; Specific investment cost of a individual heat generator,
AAR [1/a]; Ann. Amortiz. ratio, F = 0.25 , n_A = 10 years for combi, 15 years for ind.boiler (Eqn. 2)
F_L [-]; Load factor, 8760 [h/a]; number of hours in a year,
Q [kWt]; Nominal heat capacity of the heat generator.

Using the cost and operational data for the selected combi heat generator one obtains;

c_{amr}. =0.01 [$/kWht] (Eq. 5)

c) Specific total cost, ctotal, of individual flat heating and warm water supply using natural gas fired combi heat generator (IHPC)

IHPC = c_{total}= c_f + c_{amr} +c_{other} = 0. 0943 [$/kWht]

d). Annual Revenue from Heat Selling for District Heating and Warm Water (WW) Supply, ARDH [$/ a]

This annual revenue is calculated by multiplying unit heat selling price (HSP) and related annual heat load (Table 7) depending on the load factor (F_L).
Heat selling price (HSP) can be determined considering the individual heat production cost (IHPC) of the client.
In this work the following four (HSP) scenarios are investigated:

- HSP = IHPC
- HSP = 0,8 IHPC (20% less than clients production cost)
- HSP = 0,5 IHPC (50% less than clients production cost)
- HSP = 0 (No heat selling)

3.2.2.2 Revenue from Steam Supply to Industrial District

This revenue is determined by multiplying unit steam selling price and total steam demand for industrial district (Table 7).

Determination of Steam Unit Selling Price for Industrial District c_{sid} [$/ kWht]

This unit heat selling price is determined considering the total unit steam generation cost of individual natural gas- fired industrial boiler of the client.

Economical and operational data of a natural gas- fired industrial boiler used by the client for individual steam generation:

Investment cost= 80 000 [$], heat capacity= 500 [kWt], n_A=15 [y] , F=25%, F_L=0.7

a). Spec. fuel cost, Cf , of individual natural gas fired steam generator

Cf= 0.093 [$/ kWht] (Eqn. 4)

b). Spec. Amort. cost , Camr , of individual natural gas fired steam generator

Camr= 0.007 [$/ kWht] (Eqn. 5)

c) Specific total cost, c_{tsg}, of steam generation (IHPC)

IHPC = $c_{tsg} = c_f + c_{amr} + c_{other}$ = **0. 109 [$/kWht]**

d). Annual Revenue from Steam Selling to the Industrial District ARSS [$/ a]

This annual revenue is calculated by multiplaying unit heat selling price **(HSP ≤ IHPC)** and annual demand (Table 6).

3.2.2.2 Revenue from Absorption Type District Cooling

This revenue is determined by multiplying the unit heat pumping cost from indoor to outdoor temperature and total district cooling load of the domestic district (Table 7).

Determination of Unit Cooling Price for District Cooling c_{dc} [$/ kWht]

This unit price is determined considering the total unit cooling cost of individual split air conditioning system. This cost consist of unit electricity cost, amortization cost and the other unit costs of the individual split system.

Economical and operational data of the clients split cooling system:

Investment cost= 1500 [$], cooling capacity= 20 [kW], n_A=10 [y] , F=25%, F_L=0.6
Nominal cop=3, average cop= 1.5, η_{em}=0.95, η_c= 0.85, c_{el}= 0.08[$/kWhe]

a). Spec. electric cost of split cooler, C_{esp}

Using the economical and operational data one obtains,

C_{esp}=0.067[$/kWhc]

b). Spec. Amort. cost , C_{amr} , of individual split cooler

C_{amr}= 0.027 [$/ kWhc] (Eqn. 5)

c) Specific total cost, c_{tsc}, of cooling

ICPC= c_{tsc}= c_{ec}+ c_{am}r +c_{other} = 0. 097 [$/kWhc]

d). Annual District Cooling Revenue ADCR [$/ a]

This annual revenue is calculated by multiplaying unit coldness selling price **(CSP ≤ ICPC)** and the district cooling load (Table 7).

3.2.2.3. Annual Total Heat Selling Revenues (HSR)

It consist of:

- Revinues from district heating and warm water supply (DHR)
- Revinues from industrial steam supply (ISR)
- Revinues from district cooling (DCR)

HSR = DHR + ISR + DCR **(6)**

3.2.3. Unit Electricty Production cost of the Co-generation System

Difference between total annual expenditure **TAC** of the co-generation system (Eqn. 3) and total annual heat selling revinue **(HSR)**(Egn. 6) gives the annual electricty production cost (AEPC). Dividing this by annual electricty production (AEP) (Table 7) one optainds the unit electrcity production cost (UEPC).

UEPC = (TAC – HSR) / AEP **(7)**

4. RESULTS and DISCUSSIONS

In this study, a hydrogen fired multi-propose CGS was designed and the unit electricity production costs (UEPC) are calculated considering different amortization times (n_A), system load factors (FL) and heat selling price (HSP) scenarios.
For heat selling the following scenarios are considered:

Scenario 1: HSP = individual heat generation cost (IHGC) of client
Scenario 2: HSP = 0.8 IHGC (HSP is equal 80% of IHGC)
Scenario 3: HSP = 0.5 IHGC (HSP is equal 50% of IHGC)
Scenario 4: HSP = 0 (No heat selling)

The results are given below (See also Table 8 – 9, Fig. 7 – 11)

If n_A = 30 years and F_L= 1 (Table 9);
UEPC = 0.15 [$/kWh] for scenario 1,
UEPC = 0.17 [$/kWh] for scenario 2,
UEPC = 0.21 [$/kWh] for scenario 3,
UEPC = 0.28 [$/kWh] for scenario 4,

If n_A = 5 years and F_L= 1 (Table 9);
UEPC = 0.18 [$/kWh] for scenario 1,
UEPC = 0.21 [$/kWh] for scenario 2,
UEPC = 0.25 [$/kWh] for scenario 3,
UEPC = 0.31 [$/kWh] for scenario 4,

Table 8: Unit Electricity Production Cost (UEPC) of the CGS Depending on (n_A), (F_L) and Heat Selling Price (HSP) Which is Determined Considering of Clients Individual Heat Production Cost (IHPC)

UEPC [$/kWhe]		Load Factor (F_L)			
n_A [year]	Heat Selling Price (HSP)	1,0	0,8	0,6	0,4
n_A =30	HSP = IHPC	0,15	0,16	0,17	0,17
	HSP = 0,8IHPC	0,17	0,18	0,19	0,19
	HSP = 0,5 IHPC	0,21	0,22	0,23	0,23
	HSP = 0	0,28	0,29	0,30	0,29
n_A = 10	HSP = IHPC	0,17	0,18	0,20	0,21
	HSP = 0,8	0,19	0,21	0,22	0,24
	IHPCHSP = 0,5 IHPC	0,23	0,25	0,26	0,27
	HSP = 0	0,30	0,31	0,33	0,33
n_A = 5	HSP = IHPC	0,18	0,20	0,22	0,24
	HSP = 0,8	0,21	0,22	0,25	0,29
	IHPCHSP = 0,5 IHPC	0,25	0,26	0,29	0,30
	HSP = 0	0,31	0,33	0,35	0,36

Table 9. Unit electricity selling price (ESP) at full load operation condition of co-generation system depending on amortization time (n_A) and different heat selling prices (HSP)

Amortization Time(Years)	n_A = 30 years	n_A = 10 years	n_A = 5 years
ESP[$/kWhe] (HSP = IHPC)	0.15	0.17	0.18
ESP[$/kWhe] (HSP = 0.80 IHPC)	0.170	0.19	0.21
ESP[$/kWhe] (HSP = 0.50 IHPC)	0.21	0.23	0.25
ESP[$/kWhe] (HSP = 0, No heat selling)	0.28	0.30	0.31

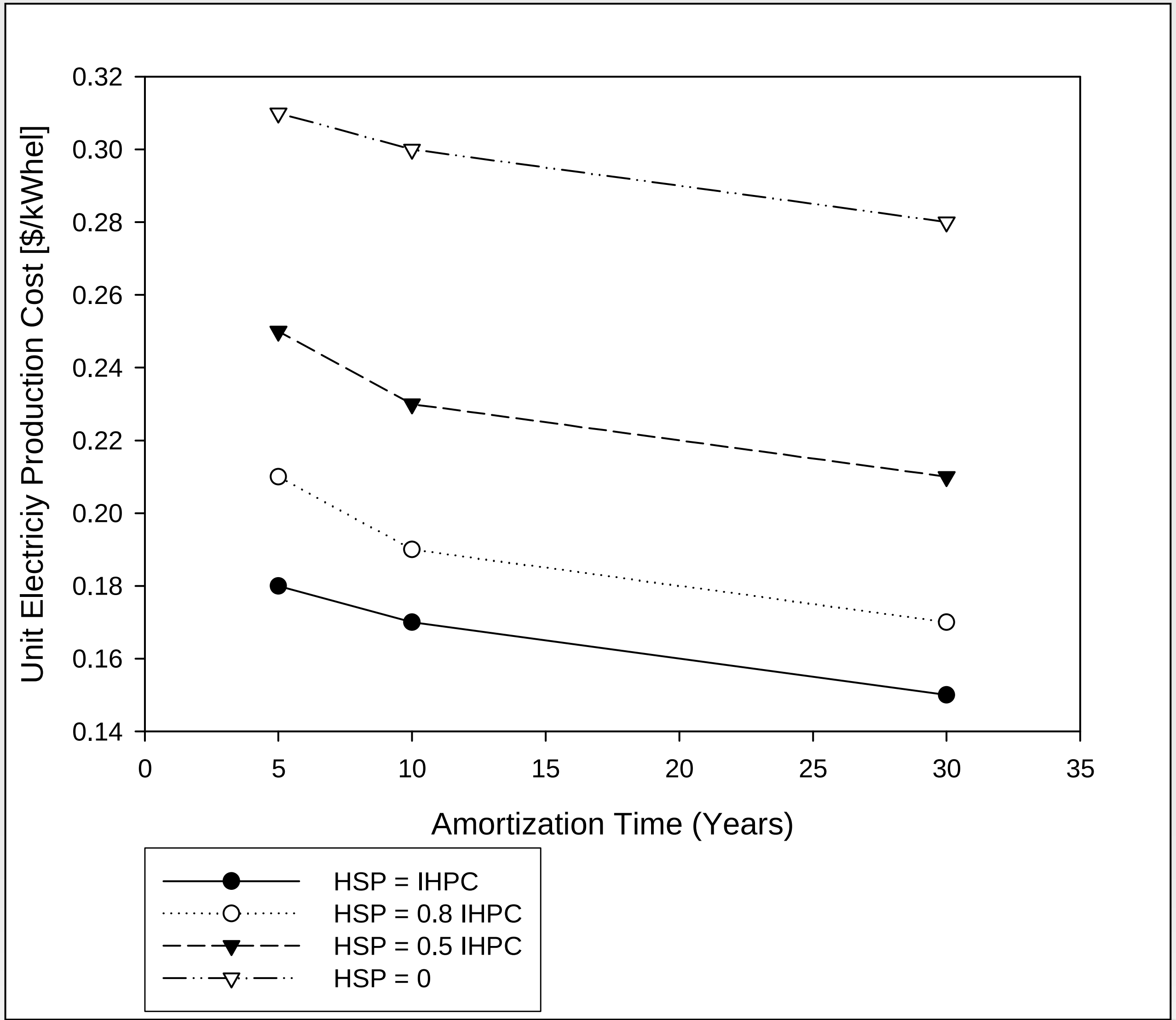

Fig. 7: Unit Electricity Production Cost of the Co-generation System versus Amortization time for different Heat Selling Price (HSP) Scenarios IHPC: Individual Heat Production Cost of the Client at full load conditions (F_L=1)

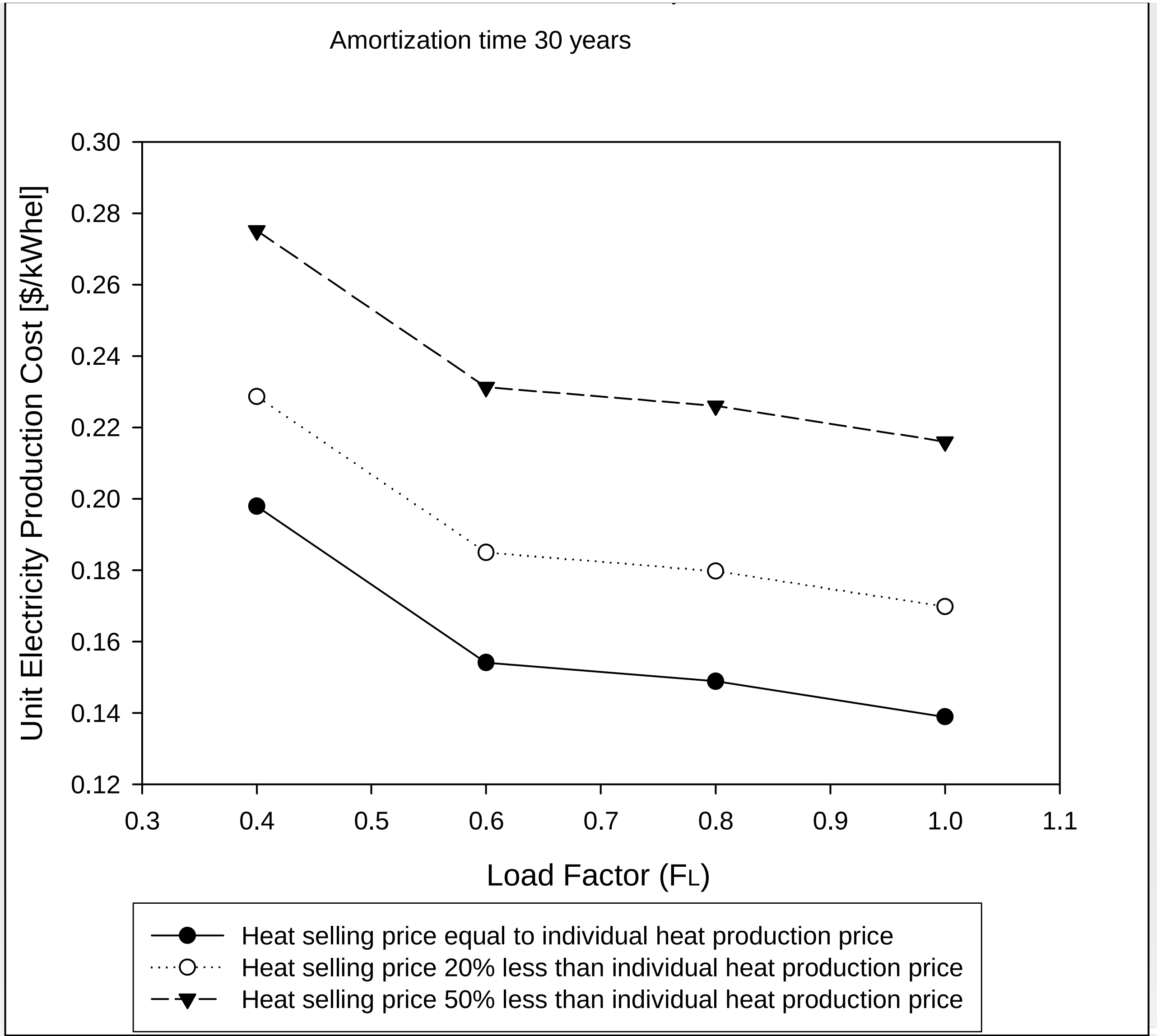

Fig. 8. Unit electricity production cost of the cogeneration system versus load factor (F_L) for different heat selling price (HSP) scenarios (n_A=30 years)

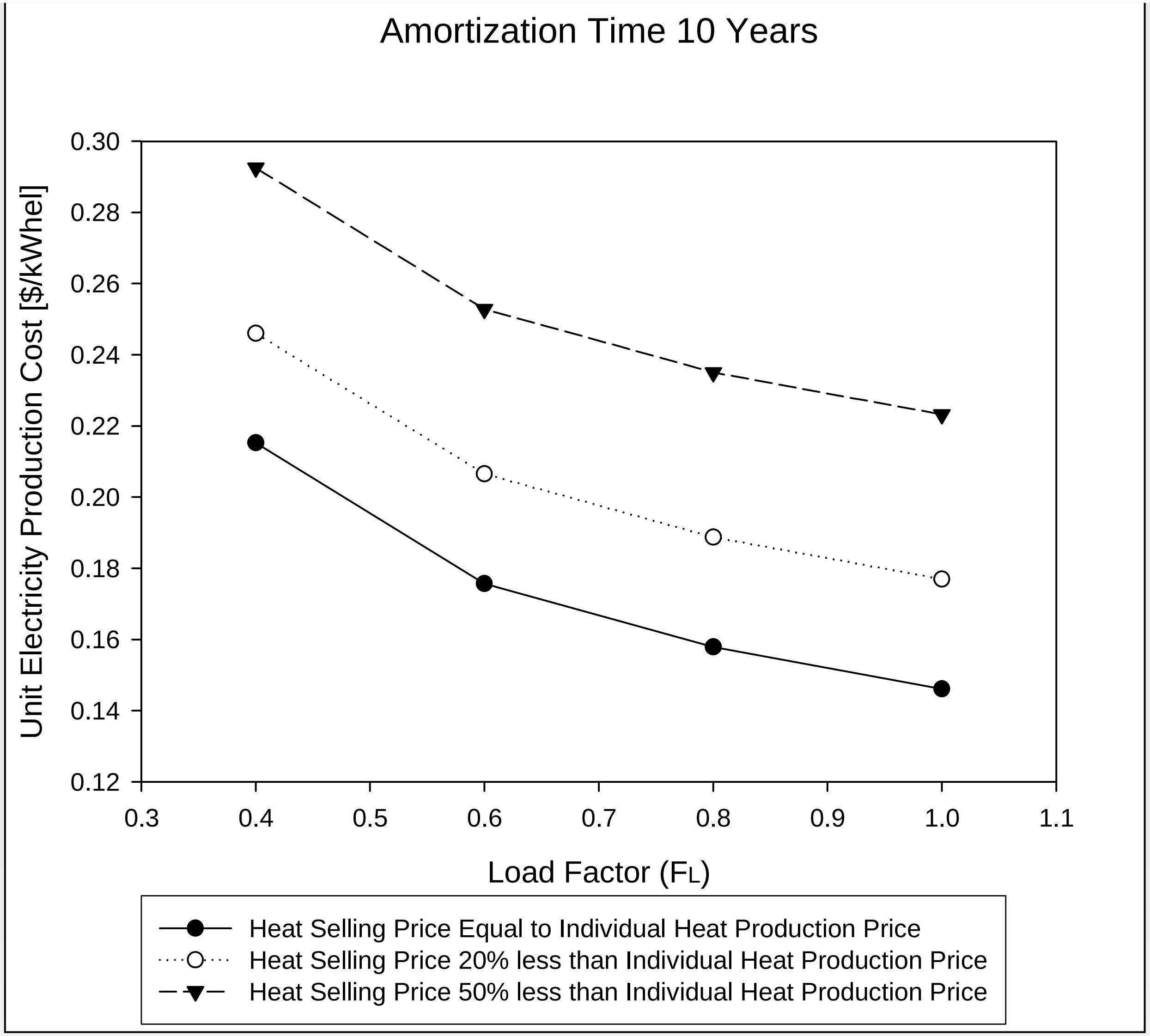

Fig. 9. Unit electricity production cost of the cogeneration system versus load factor (F_L) for different heat selling price (HSP) scenarios (n_A=10 years)

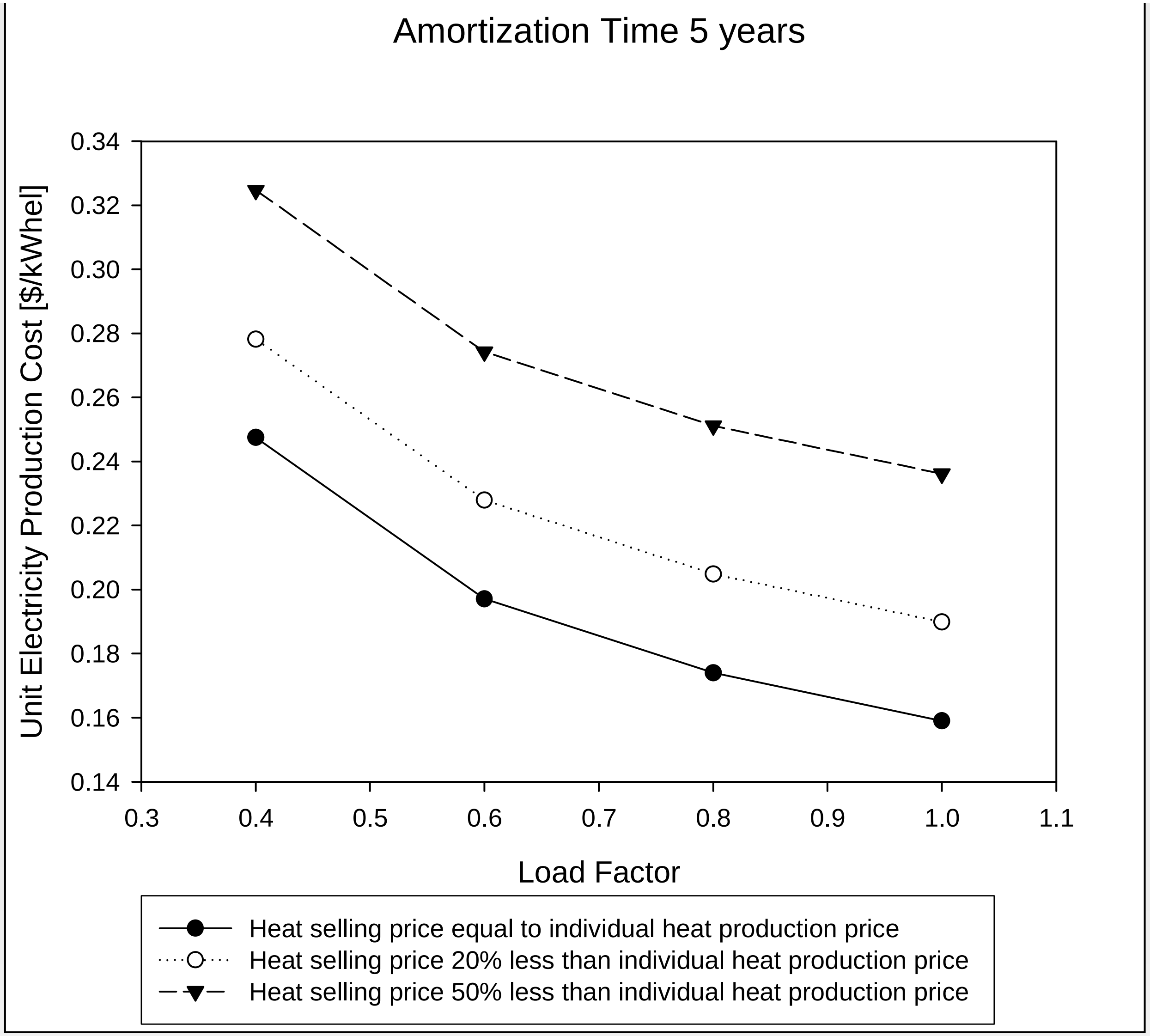

Fig. 10. Unit electricity production cost of the cogeneration system versus load factor (F_L) for different heat selling price (HSP) scenarios (n_A=5 years)

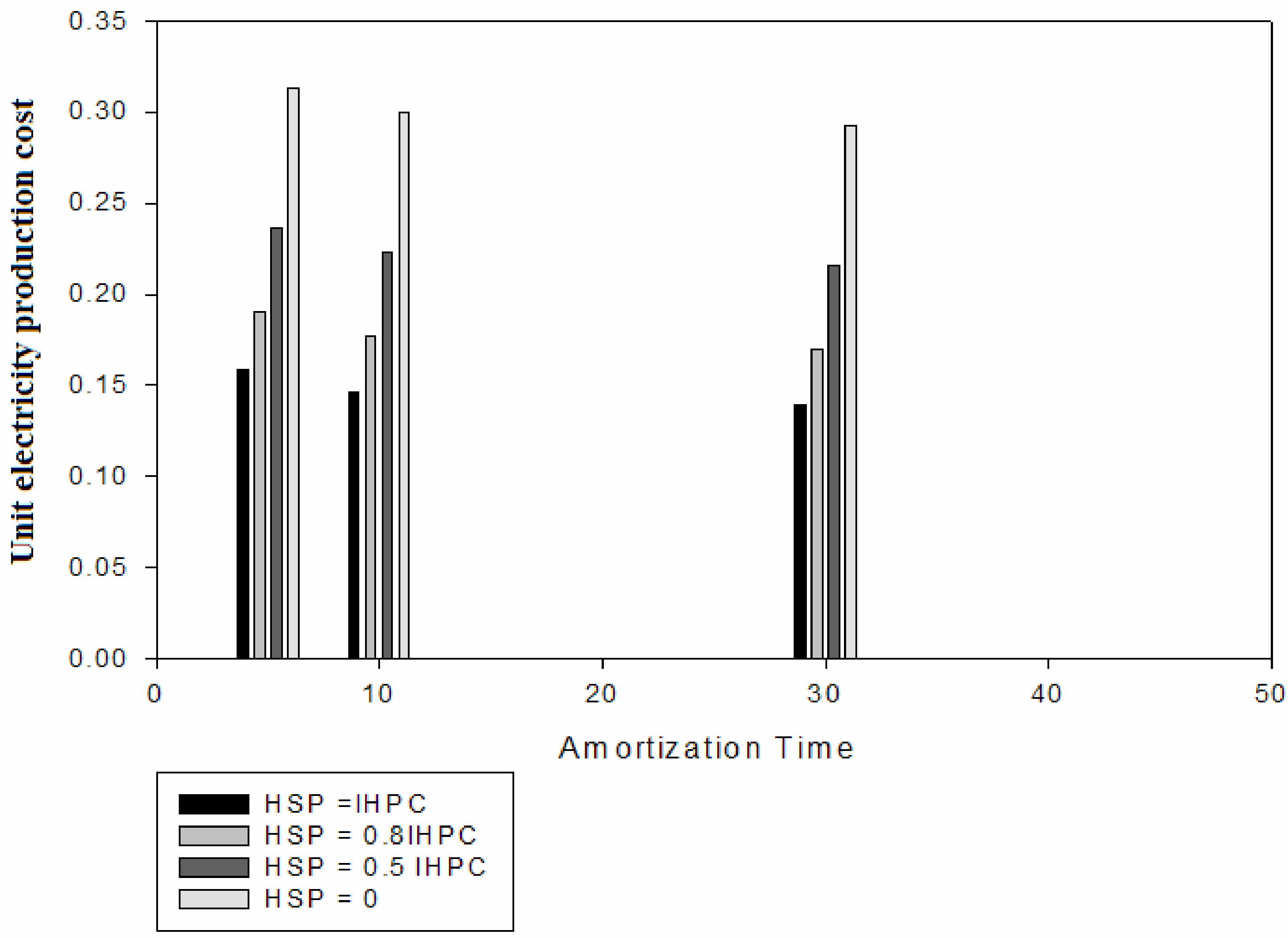

Fig. 11. Unit electricity production cost of the hydrogen fired co-generation system versus amortization time, n_A (years) for different heat selling price (HSP) scenarios. IHPC: Individual heat production cost of client

5. CONCLUSIONS

- In this paper the methodology and engineering approach for design, optimization and economical integration of a hydrogen fired multi-purpose co-generation system are given in detail.

-This methodology can also be applied to investigate the related problems of all new emerging technologies and to determine optimal application conditions of existing energy conversion systems in different sectors.

-Today, although the investigated CGS has high exergy potential, high exergy utilization property, and appropriate load and heat selling conditions, due to the high production cost of hydrogen, the electricity selling price of such a H_2 –Fired CGS becomes much grater than that of the conventional systems. (In order the designed and investigated CGS to be feasible for time being, the minimum electricity selling price of the system must be around 0.20 [$/kWh$_e$]).
Therefore, the electricity production costs of such systems should be subvented by the government.