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Economic Evaluation of the Influence of Water/Steam Injection on the Performance of a Microturbine in Combined Heat and Power Cycle

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ABSTRACT

This thesis studies the economic evaluation of the influence of water and steam injection into the microturbine (MT) cycle under combined heat and power (CHP) operation for enhance in system performance. Heat and electricity cogeneration is a way for optimizing energy consumption. Cogeneration power plants produce both electric and thermal from one energy source. One of the most important prime Movers in these systems is Microturbines. Microturbines are small electricity generators which their power is below 500 kW and by use of recuperator in their cycle their efficiency can reach to 30% approximately. By water/steam injection into the MT cycle, the power will be enhanced and its efficiency will be changed too.

The main goal of this study is economic evaluation of adding water/steam injection system to this cycle. Here after the presentation of cogeneration systems, there are explanations of Microturbines. Then the experimental and simulation results of water and steam injection to the different points in the cycle were compared. At last the economic evaluation of these cases was evaluated. Despite the increase of produced power, but according to the energy and set prices, the injection to the system is not economical. But between the injection cases, water injection into the combustor with 7.1 year as capital payback period and the least disadvantage (-89.8 $) in compare to other case of injection is preferable choice.

KEY WORDS: Cogeneration, Microturbine, Water and steam injection, Economic evaluation.

1. INTRODUCTION

Electricity and heat cogeneration systems are those which generate both electricity (axial power) and thermal power by using energy from one prime source. Thermal power is obtained through regenerating the thermal losses existing in the exhaust hot gasses and it is used as hot water or steam in different sections of the industrial, commercial and residential buildings. Figure (1) shows block diagram of the cogeneration system.

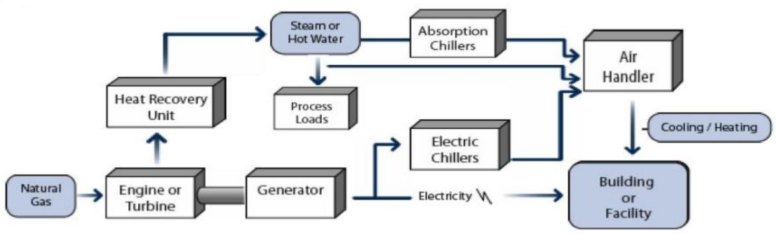

Figure (1): block diagram view of the cogeneration system

Cogeneration was presented in Europe and America in the last 1880s so that about 58 percent of the total generated power was produced as cogeneration in America at the first decade of 1900s. With the notable increase in the fuel costs in the year 1974, following that the emergence of a crisis to the energy, this systems which have higher energy efficiency, were taken into consideration more. The efficiency of the current conventional systems in localized way is about 27 to 55 percent that the most efficiency of it is belong to the combined cycle power plants while the energy efficiency of cogeneration systems even reaches to 80 percent. The most important component of the cogeneration power plants are their prime movers from which the most useable ones are reciprocating engines, gas turbines, steam turbines and fuel cells. Microturbines are also placed at the gas turbines class. The main difference between movers involves their type of used fuel, combustion process, total efficiency, the amount and temperature Degree of exhaust energy. On the table (1) the most important operational characters and costs related to the all kinds of CHP systems have been compared.

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Table (1): Comparison of installation cost and operational characters of different CHP systems

	microturbine	Gas turbine	Reciprocating engine	Steam turbine	Fuel cell
Mechanical efficiency base on HHV(%)	18-27	22-36	22-40	15-38	30-63
Total efficiency base on HHV(%)	65-75	70-75	70-80	80	55-80
Fashion capacities (MW)	0.4-0.7	0.5-2	0.1-5	0.5-250	1-2
Power to heat ratio	0.5-0.7	0.5-2	0.5-1	0.1-0.3	1-3
Conformity with low loads	Normal	low	Normal	Normal	Good
CHP installation cost($/KW)	2400-3000	970-1300	1100-2200	430-1100	5000-6500
o &m cost	0.012-0.025	0.004-0.011	0.009-0.022	Less than0.005	0.032-0.038
Operation time for periodic maintenance (1000 hour)	20-40	25-50	25-50	More than 50	32-64
Set out time	60 sec	10 min-1hour	10 sec	1 hour-1day	3 hour-2day
Kind of used fuel	Natural gas- oil propane-bio gas-	Natural gas-propane-bio gas-oil	Natural gas propane-bio gas-landfil	All kinds	Natural gas-propane-hydrogen-methanol
Recovered heat usage	Heat, Hot water & high pressure steam	Heat, Hot water & low pressure steam	Hot water & low pressure steam	High & low pressure steam	Hot water & low pressure steam

2. Microturbines

Microturbines are small electricity generators which burn gaseous or liquid fuel and rotate an electric generator. Microturbines examination was started from 1997 and it was applied in the commercial use in 2000. The power generation range of developing Microturbines is usually below 500 kW. Low Manufacturing costs, higher efficiency, lower noise, quick operation and low emission have made this technology successful to the extent it has become one of the most popular choice for using in heat and power cogeneration on the scale of commercial uses. In figure (2) you can see different parts of MT. In the more advanced cycles, Microturbines transmit some of the exhaust gases heat into the air by using of recuperator and thus MT electric efficiency is increased by 25 to 33 percent.

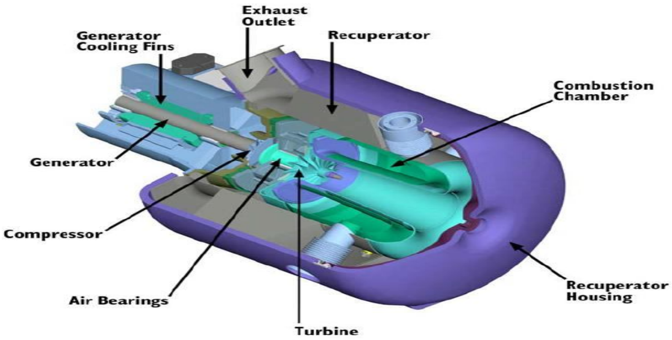

Figure (2): components of MT

Figure (3) also shows the effect of the recuperator on MT efficiency. Microturbines have simple structures because of having one rotator axis which turbine and compressor are installed on it.

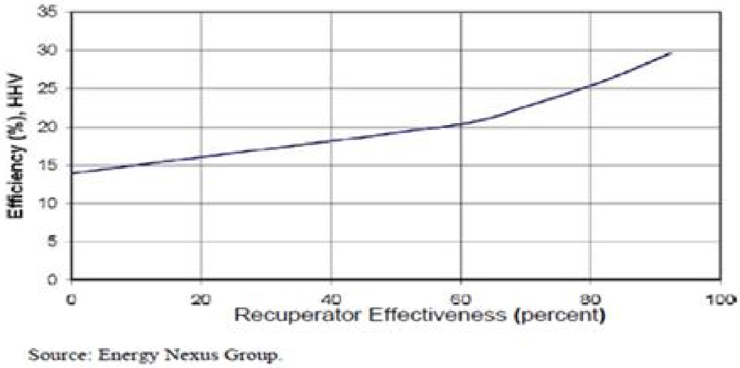

Figure (3): The effect of recuperator on Microturbines efficiency.

Microturbines in CHP mode transmit the heat of the exhaust gas (which has been passed from recuperator before) into the water by a heat exchanger.

3. The injection of water and steam to the cycle:

Ambient conditions have a big effect on the MT operation in a way that we face intense power and efficiency drop in the high temperature. The elevation from the sea level also decrease its exhaust power [3]. Figure (3) shows the effect of the ambient conditions on the MT operation.

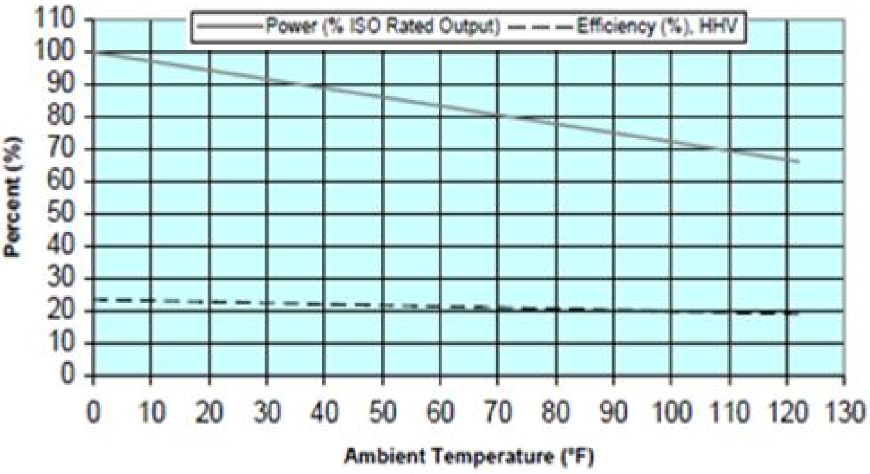

Figure (3): changes of MT power and efficiency with ambient temperature

One propounded method for optimizing energy consumption and decreasing undesirable effects of ambient conditions is to inject water or steam into the cycle. Water and steam injection can be done to the different points in the cycle. In this study, four case of water and steam injection to the combustor and recuperator inlet have been examined. In figure (4) the cycle with injection system has been shown.

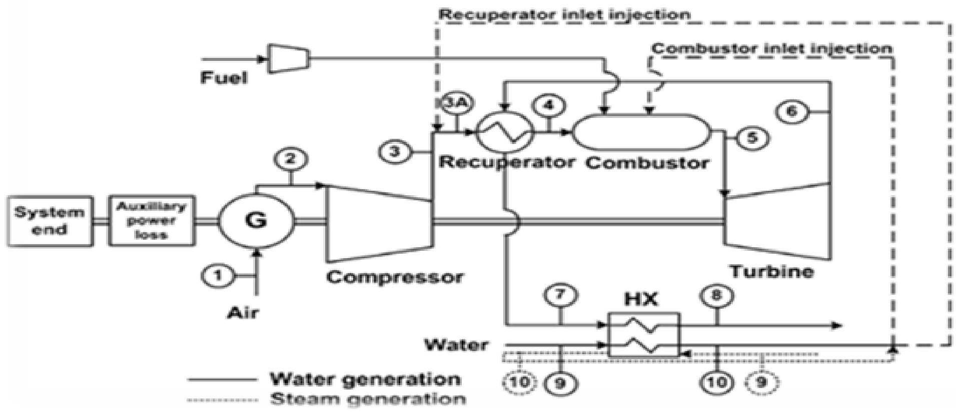

Figure (4): schematic of MT cycle with injection

In this part, the results of simulation have been compared with the results of the injection system examination for a 30 kW MT in CHP use. Computing the outgoing power and MT efficiency is one of the most important characteristics which has been considered in all modes of injection. According to relation (1), outgoing power of axis is computed as follows:

$$\dot{W}_{sh} = \left(\dot{m}_5 \cdot (i_5 - i_6) - \dot{m}_2 \cdot (i_3 - i_2)\right)/\eta_{mec} \quad (1)$$

Since generator is made cool with the compressor incoming air its outgoing power is also less than shaft power.

$$\dot{W}_{gen} = \dot{W}_{sh} - \dot{Q}_{gen} \quad (2)$$

$$\dot{Q}_{gen} = \dot{m}_1 \cdot (i_2 - i_1) \quad (3)$$

Some of powers are also used for auxiliary loss, therefore power and efficiency of MT are computed as follows:

$$\dot{W}_{MT} = \dot{W}_{gen} - \dot{W}_{aux} \quad (4)$$

$$\eta_{MT} = \frac{\dot{W}_{MT}}{(\dot{m} \cdot LHV)_{fuel}} \quad (5)$$

Figure (5) shows a good conformity between simulation results and experiment on operational characters of MT. The evaluation of the outgoing data shows that the amount of water injection to the cycle is limited to the such extent that saturate the gas mixture. System components will be damaged by more injection and water particle entry, this is while the total generated steam can be injected to the cycle.

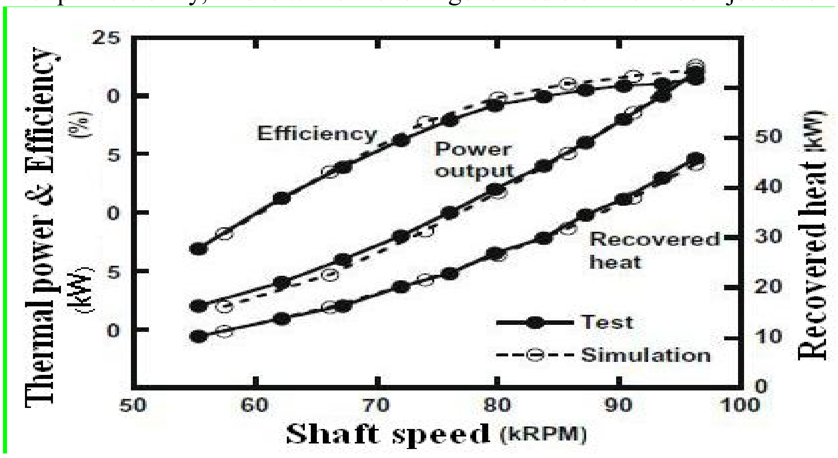

Figure (5): conformity between simulation and experimental result

Generation rate of hot water or steam depending on the injection place is also different.

It is mentionable that the generation rate of hot water is much more than the generation rate of steam because of its low enthalpy. In all four modes of injection, system power will be enhanced because of the increase in working fluid mass flow rate while the fuel Consumption of the system will also be enhanced. Power enhancement is to the extent that thermal efficiency of the cycle will also be enhanced at all modes except the water injection to the combustor (WI-C). In table (2) the summary of operational data of injected and non-injected MT cycles have been compared.

Table (2): summary of operational data of MT in different mode

	Dry op	SI-R	SI-C	WI-C	WI-R
Air flow rate	0.2685	0.2657	0.2652	0.2642	0.2645
Rate of water/steam generation(kg/s)	0.1600	0.0128	0.0150	0.2069	0.0831
Rate of injection(kg/s)	-	0.0128	0.0150	0.0180	0.0180
Rate of fuel flow (kg/s)	0.00205	0.00228	0.00246	0.00353	0.00253
System power (kW)	22.62	27.15	28.04	29.67	29.17
change of the system power from dry operation mode(%)	-	20.0	24.0	31.2	29.0
System efficiency (%)	22.3	24.21	23.15	17.09	23.47
Change of the system efficiency from dry operation mode (%)	-	8.6	3.8	-23.4	5.3
Thermal power (kW)	44.66	0	0	52.75	18.17

As table (2) shows, in the steam injection mode, system from cogeneration mode changed into single generation mode of electric power, Because the total generated steam is injected into the cycle [4].

4. Economic evaluation of water / steam injection to the cycle:

Economic evaluation of industrial plans is a necessary and unavoidable affair before their implementation. In spite of high cost of plans and without considering its economic explanation, the implementation of a plan can severely damage the economics and the industry of the society. A lot of economic studies on operation of CHP systems especially electricity and heat cogeneration Microturbines have been carried out in recent years. In [5] energy consumption and pollutant propagationof chp systems was compared with conventional systems and 12.1% saving in prime energy was reported. In [6] 2.6% decrease in annual energy costs due to use of CHP system was reported. [7,8] was reported economic advantage of micro CHP in residential and commercial buildings. In [9,10] the results related to the evaluation of different kinds of movers have been reported. In [15] a MT was examined from different viewpoint domestic and industrial customer and the result was achieved that using the MT for exclusive use is superior to buying electricity from network. In [11] a CHP MT was evaluated under four different plans and it is also evaluated its using by heat pomp or using only for a residential building at Tehran and the use of this MT for electric load generation and a portion of thermal loud was known as the most optimum. Reference [12,16] also report an example of economic evaluation of CHP system. In one study recently an economic evaluation of a 500 kW MT which was used for a hospital of 250 bedsteads in order to provide thermal and electric load that as a result of it, the capital payback period was computed about 9.5 year. The economic evaluation has been also reported by Capston company related to the use of a 30 kW MT for 200 commercial consumers and recuperated and non-recuperated Microturbines have been compared from an economic viewpoint. In reference [17] it has been carried out a technical, economic and environmental evaluation of CHP MT for different industries and the capital payback years has been computed.

Prime Energy Saving (PES):

In comparison with the conventional separated heat and power generation systems "PES" is an important economic factors which is representative of saving rate in prime energy by CHP systems. PES was described as relation (6) by European energy parliament in 2004.

$$PES = 1 - \frac{1}{\frac{\eta_{el}}{\eta_{el,ref}} + \frac{\eta_{th}}{\eta_{th,ref}}} \qquad (6)$$

The positive amounts of this factor means that the prime energy consumption in CHP system is less than single generation systems [13].

The ref index in this relation is related to the conventional single heat and electricity generation systems that the amount of their thermal and electric efficiency is nearly 30 and 70 percent respectively. The saving rate is seen on table (3). The conclusion which is realized from these tables among injected systems, only the water injection to the combustor saves its consumption of prime energy too little in comparison with the conventional systems.

Table (3): the PES values

	DRY	WI-R	WI-C	SI-R	SI-C
PES %	27.30	-0.94	0.30	-23.91	-29.58

- **The Economic comparison of CHP MT equipped with injected system with dry operation system:**

In this part of study, we're going to compare a MT in dry operation mode with several types of injected ones. Here the investor is supposed to utilize cogeneration system as a small private power plant and sells its electric and thermal power. The important point here is that investor intends to select one choice among 5 packages of CHP MT (one dry case and four injection cases). It means the packages are equipped with injection system beforehand.

- **Capital payback period:**

For computing capital payback period, it is necessary to compute annual incomes and costs and also prime costs in nth year after installation. Then according to relation, we compute the capital payback period for each case by considering that incomes and costs to be equal.

- **Prime capital cost:**

Prime capital cost computed according to relation (7)

$$CC_{inv}\ [\$] = CC_{inv,u}\left[{\$}/{Kw}\right] \times E_{nom}\ [Kw] \quad (7)$$

that CCinv is amount of prime cost in exchange for per kW of generated electric power of MT and for the non-injected system is 1300 $/kW [11]. Furthermore about 150 $/kW is increased to the prime cost of dry system by adding injection system and this amount is equal to 1450 $/kW [1]. Enom is also nominal power of MT and is equal to 30 kW in this study. The prime investment cost in nth year after installation is computed according to relation(8) that n is the year that the engine operate and i is annual average interest rate and it is equal to 10%.

$$CC_{inv}^{n}\ [\$] = CC_{inv}\ [\$] \times (1+i)^{n} \quad (8)$$

- **Income of electric power selling:**

Annual income of selling the electric power to the network is computed according to relation (9) that in it Pel is electric power and Top is the time of annual operation of system which is supposed to 8640 hours in a year. Cel is the price of selling 1 kWh electricity to the network and according to the reliable contract of ministry of power is almost equal to 0.05 $. After installation, the annual income rate in nth year is computed by relation (10).

$$I_{el}\ [\$] = P_{el}[Kw] \times C_{el}\left[\frac{\$}{Kwh}\right] \times T_{op}\ [h] \quad (9)$$

$$I_{el}^{n}\ [\$] = I_{el}\ [\$] \times \left(\frac{(1+i)^{n}-1}{i}\right) \quad (10)$$

- **Income of thermal power selling:**

Investor earns income by selling generated Thermal of system to the network that its annual rate is computed as follows :

$$I_{th}[\$] = P_{th}\ [Kw] \times C_{th}\left[\frac{\$}{Kwh}\right] \times T_{op}[h] \quad (11)$$

In this relation Cth is the price of one kWh thermal power selling that its estimatal amount is 0.014 $. Thus, the income of heat power in the nth year is computed as follow relation

$$I_{th}^{n}[\$] = I_{th}\ [\$] \times \left(\frac{(1+i)^{n}-1}{i}\right) \quad (12)$$

- **Used fuel cost**

The cost of used fuel for each systems during annual operation and its equivalence in the nth year of installation are computed with relation (13) and (14) respectively.

$$CC_{f}\ [\$] = \dot{m}_{f}\left[\frac{kg}{s}\right] \times \frac{1}{\rho_{g}\left[\frac{kg}{m^{3}}\right]} \times 3600\left[\frac{S}{h}\right] \times T_{op}[h] \times C_{f}\left[\frac{\$}{m^{3}}\right] \quad (13)$$

$$CC_{f}^{n}[\$] = CC_{f}\ [\$] \times \left(\frac{(1+i)^{n}-1}{i}\right) \quad (14)$$

In this relation, $\dot{m}_f$ is the fuel rate and ρ_g=0.714 is the gas density. Cf is the price of one cube meter of natural gas. According to the gas company tariff the average price for per cube meter of gas delivered to the power plant is 0.076$ but by considering 20 percent reduction of fuel price to the small power plant, its price will be equal to Cf =0.06 $

- **Cost of annual used water**

The cost of annual used water through CHP system is computed as follows:

$$CC_w\,[\$] = \dot{m}_w \left[\frac{kg}{s}\right] \times \frac{1}{\rho_{w\left[\frac{kg}{m^3}\right]}} \times 3600 \left[\frac{s}{h}\right] \times T_{op}[h] \times C_w \left[\frac{\$}{m^3}\right] \qquad (15)$$

and ρ_w are the rate and density of water respectively , that the amount of density is ρ_w=1000 , C_w is the price of one cube meter of water that according to the tariff amount of it is equal to 0.047$ averagely. The annual cost of water in the nth year after installation is computed with the relation (16)

$$CC_w^n[\$] = CC_w[\$] \times \left(\frac{(1+i)^n - 1}{i}\right) \qquad (16)$$

- **Operation and maintenance costs:**

Almost 2 percent of the prime investment cost is averagely used for annual amount of this cost [11]. Thus annual amount and its equivalence in the nth year are computed according to the relation (17) and (18).

$$CC_{o\&m}[\$] = 0.02 \times CC_{inv} \qquad (17)$$

$$CC_{o\&m}^n\,[\$] = CC_{o\&m}\,[\$]\left(\frac{(1+i)^n - 1}{i}\right) \qquad (18)$$

After computing incomes rate and costs of each one of systems in nth year of installation, for computing capital payback period, we should consider costs and incomes to be equal.
It means the capital payback period is the time when incomes will be equal to the costs.

$$CC_{inv}^n + CC_f^n + CC_w^n + CC_{o\&m}^n = I_{th}^n + I_{el}^n \qquad (19)$$

Table (4): The summary of economic results of systems

SI-C	SI-R	WI-C	WI-R	DRY	Operation mode Cost or income
43500	43500	43500	43500	39000	Prime cost[$]
12413	12019.3	13134.9	12913.5	10013.9	Annual income of selling the electric power [$]
0	0	6337.4	2182.9	5365.4	Annual income of selling the thermal power [$]
6531.9	6054.0	9373.1	6717.8	5434.3	Annual cost of used fuel[$]
22.2	18.9	391.3	123.1	237	Annual cost of used water [$]
870	870	870	870	780	Annual cost of operation and maintenance [$]
4988.9	5076.4	8837.9	7385.5	8928	Net annual incomes[$]
21.3	20.4	7.1	9.3	6	Capital payback period [year]

- **Economic evaluation of outfit the CHP MT with injection system:**

As we understood from the previous part and from the economic viewpoint, MT in the dry mode has priority to the MT with injected system but in this part, we suppose that investor intends to add the injected system to his commercial MT. Yet we evaluate the changes which are made in costs and incomes of the power plant equipped with the injected system and among the injected system we select one plan. In fact, in the whole of all evaluations we consider dry mode MT as a base and evaluate the changes made toward it. Here we only mention the evaluations results because of similarity of relations with the previous viewpoint. Tease result have been shown in table (5). The minus amount in each row of table is representative of reduction in income rate or related costs. For example by adding water injection system to recuperator, the sum of 3182.5$ is decreased from income of thermal power selling annually, while it is saved the sum of 113.9$ in using water cost.

Table (5): the results of economic evaluation equipped with injected system

SI-C	SI-R	WI-C	WI-R	Operation mode
2399.1	2005.4	3121	2899.6	Income of the change in electric power [$]
-5365.4	-5365.4	972	-3182.5	Income of the change in thermal power [$]
1097.6	619.7	3938.5	1283.5	Added fuel cost [$]
-214.8	-218.1	154.3	-113.9	Added water cost [$]
90	90	90	90	Added maintenance cost [$]
-3939.1	-3851	-89.8	-1542.3	Change in annual income[$]

From the results related to the change of annual income, It is obvious that adding each one of these systems to prime system, cause to decrease from net income in any way. This net income reduction is actually endorsed on the results related to the capital payback period of previous part. These results showed that in the present condition, outfit a MT with injection system is not economical for the investor but WI-C has the least loss for him.

The economical evaluation of the use of steam injection system in the MT for electric power generation:

Although the use of MT in cogeneration has more economical profit in comparison to the state that electric power is only considered, but the evaluation to the use of steam injection system in this state is not ungraceful [4]. The capital payback period is evaluated through the division of prime cost on annual net benefit of system[9].

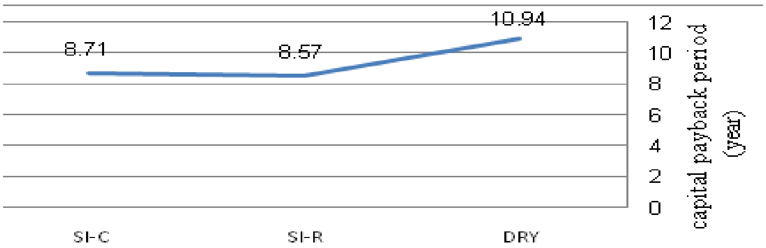

Figure (7): capital payback period

- **The sensibility evaluation of system:**

Among different parameters using in economic evaluation of energy projects, mostly the parameter related to the price are not announced exactly bye the producer or they can be different depending on the project condition. Also the experts have always squabble on the price of types of energy and fuel and their accuracy will have great influence on the result of the computations. Thus the parameter related to the price of projects in different strategies should be evaluated in term of the sensibility in order to generalize the obtained result and also to meet the expert opinion.

- **The sensibility of the system toward the price of electricity selling:**

Because of high generation of electric power, each one of these systems can show high sensibility toward the increase or decrease of electricity price.

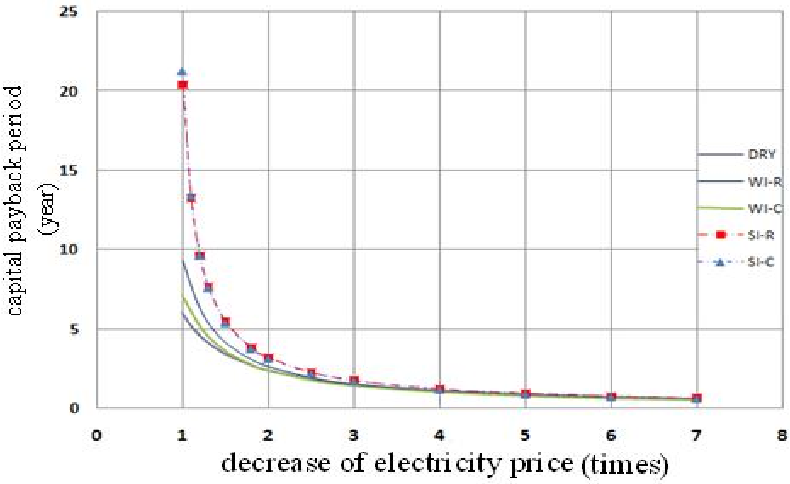

Figure (8): sensibility toward the increase in electricity price

This graph shows that two steam injection systems have high sensibility toward the increase of electricity price, because their outlet is only electric power in a way that for example if the price of electricity increases by 1.5 times, their capital payback period will be decreased to $\frac{1}{4}$ of previous amount.

- **Sensibility toward the MT set prices:**

Whit considering the decision of the companies producing MT on reduction in total price of the system, in this part the influence of increase or decrease of the price on the capital payback period has been evaluated. Both increase and decrease of prime price of the system have been spot in this evaluation. You can see the results of this evaluation in the following figures.

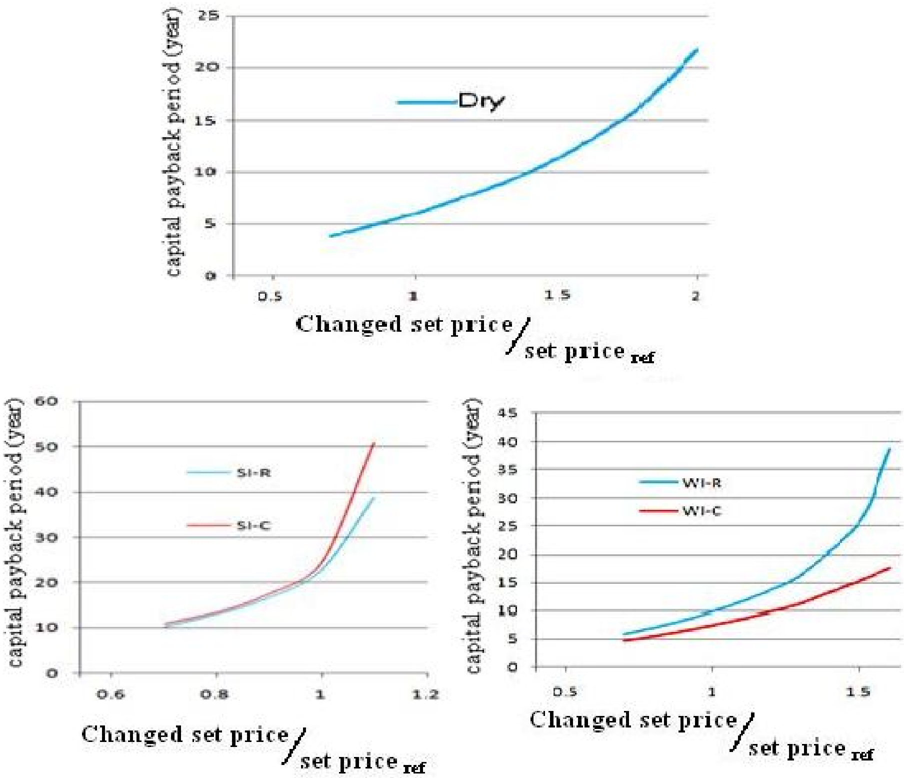

Figure (9): sensibility of the MT toward the fluctuation of prime price

The above graphs are representative of high sensibility of the system toward the fluctuation of prime price of the system.

•Sensibility toward the fluctuation of the fuel price:

The fuel price of each country can have high influence on the current costs of a power plant. As we saw on table (4), the fuel cost has the greatest proportion on the annual costs of the system. The sensibility toward the fluctuation of the fuel price is seen in the following graphs. These graphs are representative of high sensibility of the steam injection toward the fluctuation of the fuel price too.

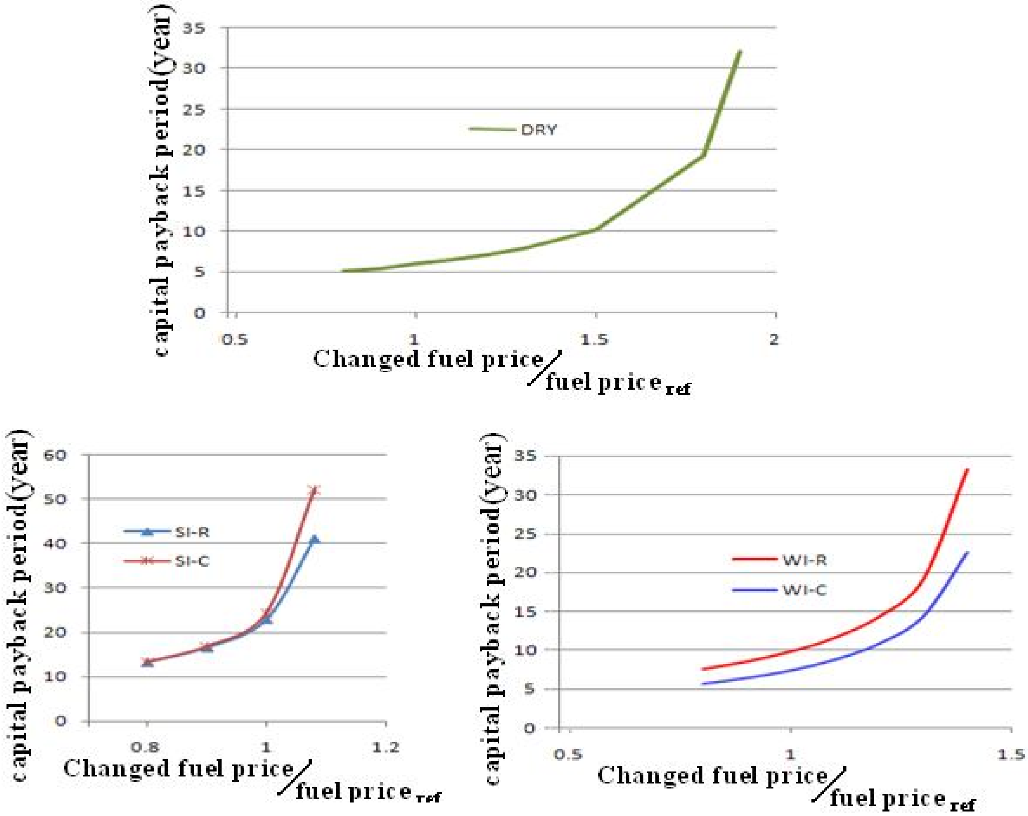

Figure (10): sensibility of MT system toward the fluctuation of the fuel price

Considering figures and results related to the sensibility of the systems toward each one of the effective factors and with the use of the superposition law , we can simply evaluate total influence of three factors on the MT for different operation mode of dry or injection mode and under several sets.

Table (6): list of used legend

Heat & power cogeneration	***CHP***	**price**	***C***
Mass flow rate	$\dot{m}$	Water injection in recuperator	*WI-R*
microturbine	*MT*	Water injection in combustor	*WI-C*
efficiency	η	Steam injection in recuperator	*SI-R*
Low heat value of fuel	*LHV*	Steam injection in combustor	*SI-C*
Thermal power	$\dot{Q}$	Dry operation	*DRY*
power	$P,E,\dot{W}$	income	*I*
Prime energy saving	*PES*	cost	*CC*

Table (6): list of used indices

Heat recovery unit	***HRU***	**simulation**	***sim***
Mechanical	*mec*	Examination	*test*
Recuperator	*rec*	loss	*aux*
Reference	*ref*	Operation	*op*
Fuel	*f , fuel*	Shaft	*sh*
Combuator	*cc*	Water	*w*
Compressor	*c*	electric	*el*
Turbine	*T*	thermal	*th*
Gas turbine	*GT*	operation and maintenance	*o&m*
Generator	*gen*	Investment	*inv*
microturbine	*MT*	Unit	*u*

5. Conclusion

As you see in this part of using injection system for MT was analysed be different viewpoints and approaches economically and the results were provided and reviewed. All injecting modes improve electric power and all of them are pernicious for investor. Systems which operate in dry mode due to costs and energy price strategies mentioned and their shorter capital payback period are economically better to be choosed. Also the most economic choice among the injection equipped systems is the WI-C that have 7.1 year as payback period and WI-R is the next proffer. By injecting the steam, system converts from cogeneration state to single production thus outfit the cogeneration MT to steam injection system is not commodious

But according to the second part of this analysis if we intend to add an injection system to a cogeneration microturbine, still the injecting water in combustor has the shortest capital payback and the least disadvantage. Though SI-R has shorter capital payback period in compare to SI-C but none of them is economic. But in case microturbine is just used for electric power production the one with steam injection in recuperator is superior and has the most advantage.

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