Comparison of repowering by STIG combined cycle and full repowering based on exergy and exergoeconomic analysis

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Abstract: Nowadays, repowering is considered as the most common methods for improving status of current power plants. Repowering is the transformation of an existing steam power plant into a combined cycle system by adding one or more gas turbines and heat recovery capacity. It is a cost-effective way to improve performance and extended unit lifetime while adding capacity, reducing emissions and lowering heat rejection and water usage per kW generated. Each methods of repowering from “para repowering” to “full repowering” shall probably be the best choice for special national and economical power plant. In this paper different repowering methods have been introduced. The design concept consists in adding a gas turbine to the combined cycle, integrated by steam injection into the existing gas turbine. The steam is produced in a simplified heat recovery steam generator fed by the additional turbine’s exhaust gas.
A 156MW steam cycle power plant has been chosen as a case study. Two repowering scenarios have been utilized for this case. Thermodynamics code has been supplied for combined cycle and STIG combined cycle and compare with each others. The exergy and exergoeconomic analysis method was applied in order to evaluate the proposed repowered plant. Also, computer code has been developed for exergy and exergoeconomic analysis. It is anticipated that the results provide insights useful to designers into the relations between the thermodynamic losses and capital costs, it also helps to demonstrate the merits of second law analysis over the more conventional first law analysis techniques.The efficiency of the STIG repowered plant compares favourably with repowered combined cycle.

***Keywords**: Repowering, Gas turbines, Steam injection, exergy, Exergoeconomic*

Nomenclature (Optional)

c cost per unit exergy ($/MW).....($/MW)
C cost flow rate ....($/hr)
e exergy rate per mass ....(MW/kg)
E specific exergy..............................(MW)
Z capital cost rate of unit ....($/hr)
St ....steam
f .... fuel
a ....air
GT .... gas turbine
CRF .... capital recovery factor
PWF .... Present worth factor
PW ....Present worth

1. Introduction

The country of Iran is experiencing in all fronts and areas and thus, consumption of electrical power is on the increase on a daily basis. Based on the ever increasing electrical energy consumption, changes in generating system load requirements, lower allowable plant emissions and changes in fuel availability, steam power plants repowering has been investigated much more as a method for energy conservation. Considering the increased electrical energy consumption and annual growth rate of 4.5 percent and according to the end of existing steam power plants life in Iran(like Montazer Ghaem power plant), repowering could be used as an economical method for increasing the output power with less investment than building a new power plant. Repowering of steam power plant can be achieved in several ways. In a full repowering, several gas turbines (GT) and heat recovery steam generators (HRSG) are installed in a parallel arrangement dispensing with the conventional boiler. Live steam from HRSG is used in the original steam turbine [1]. Industrial gas turbines are one of the well established technologies for power generation. Various additional cycle configurations such as reheating, regeneration, intercooling and steam injection have been suggested [2, 3]. All of them offer increased performance and increased output compared to a dry gas turbine cycle. Several types of water or steam injection gas turbine cycle (STIG) have been proposed in previous studies and the performance characteristics of them investigated [4]. The exhaust gas from the turbine is used as an energy source in a heat recovery steam generator (HRSG) where energy is transferred from the exhaust gases to the boiler feed water. The high pressure steam is generated from HRSG. The steam is then injected into the combustor. Injection of steam increases the mass flow rate through the expander and so the power output and the efficiency of the turbine increase. Steam injection also helps in reducing the NOx emissions from the gas turbine [5]. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components [6]. Furthermore, exergoeconomic analysis estimates the unit cost of products such as electricity, steam and quantifies monetary loss due to irreversibility. Also, this analysis provides a tool for the optimum design and operation of complex thermal systems [7]. Combined and steam injected gas turbine cycle power plants are being installed all over the world as compared to other plants. The current emphasis is on increasing the plant efficiency and specific work while minimizing the cost of power production per kW and emission. In this paper, simple repowered combined cycle and combined cycle with added steam injected gas turbine have been modeled as a repowering design for 156MW steam power plant. For each cases exergy and exergoeconomic analysis has been studied and compared as a economical analysis for product cost estimation.

2. Process description

In this paper, 156MW steam cycle power plant has been selected as a case study for exploring two repowering methods and comparing with each other. The steam cycle power plant encompasses three turbines, that work with three different pressures and 6 feed water heaters. The Steam cycle has been modeled by MATLAB code and STEAM PRO (THERMOFLOW). Results of modeling steam cycle have been introduced and compared with real data in table.1.

Table1. Compare result of modeling steam cycle

	THERMOFLOW	Simulation code	Real
Plant Gross power(kW)	156300	156305	156294
Plant Gross Heat Rate(kJ/kWh)	9010	9120	8976
Plant Gross Efficiency (LHV)	39.9%	39.4%	40.1%
Superheater Capacity(kg/s)	133	130	136
Reheater Capacity(kg/s)	115	114	117

3. Repowering

There are several alternatives to combine and integrate a gas turbine into an existing steam power plant. As a result of ending boiler life time and exploring another aspect for this case, the best alternative is full repowering. Full repowering is defined as complete replacement of the original boiler with a combination of one or more gas turbines (GT) and heat-recovery steam generators (HRSG), and is widely used with very old plants with boilers at the end of their lifetime. It is considered as one of the simplest ways of repowering for existing plant.

For this power plant, Full Repowering with SGT5-4000F (formerly known as CC 2.V94.3A) with triple pressure reheat cycle has been considered as a first method for repowering old steam cycle power plant. Schematic flow diagram of combined cycle with the components is shown in Fig. 1. The gas cycle is selected as a topping cycle.

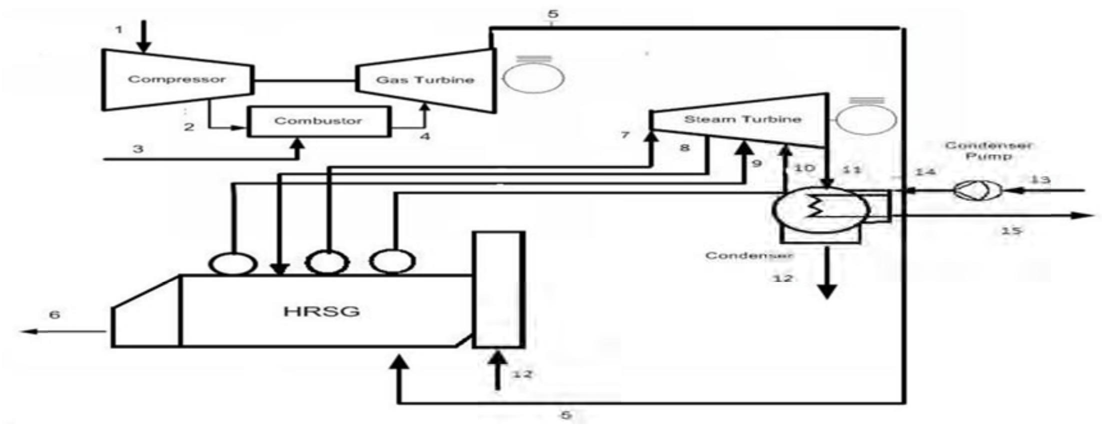

Fig 1. Combined cycle power plant (Repowering 1)

Second repowering scheme is based on the addition of a gas turbine and of a HRSG to a baseline of combined cycle. This method includes two main parts, the first part is combined cycle and the second part is a small gas turbine with a single pressure HRSG. These new components are integrated within the existing plant by injecting the steam produced by the additional HRSG into the existing gas turbine. The second part generates needed steam for injecting into main gas turbine of combined cycle in addition of producing extra power. In this way, the original turbine is transformed into a STIG (steam injected gas turbine), thereby increasing power. CC power augmentation is, thus, the sum of the power generated by the new gas turbine and the additional power of the original plant, comprising both the gas turbine and steam cycle. This scheme figure is shown in Fig.2.

As can be seen, the steam line feeding the original gas turbine connects the plant to the added section that comprises a gas turbine and a heat recovery steam generator. However, many other subsystems may be shared to reduce the repowering cost such as, for examples, flue gas treatment, electric power conditioning etc. One major addition to the plant is the water flow entering the new HRSG, which is inevitably lost at the stack. This can be a major drawback in certain situations and limits the applicability of the present scheme to sites with large fresh water availability, though the specific water requirements are fairly low, as will be shown later. If a low temperature thermal load is available nearby the power plant, the steam in the exhaust could eventually be condensed and the water could be recovered. Obviously, the very large size and the very low temperature level of such a heat sink restrict this option to quite uncommon cases, and its feasibility has to be carefully evaluated. Another significant feature of the proposed repowering scheme is its operational flexibility. Because of the inherent flexibility of the gas turbine, the entire additional section can be switched off in a short time, yielding part load efficiency equal to that of the original plant. At full load, the efficiency does not differ substantially, as will be demonstrated by the thermodynamic simulation. Fitting both the new and original gas turbines with variable intake guide vanes (IGVs) should provide a fairly wide operating range with efficiency close to rated.

4. Exergoeconomics analyses

All costs due to owning and operating a plant depend on the type of financing, the required capital, the expected life of a component, and so on. The annualized (levelized) cost method of Moran [9] was used to estimate the capital cost of system components in this study. The amortization cost for a particular plant component may be written as:

$$PW = C_i - S_n PWF(i,n) \quad (1)$$

$$\dot{C}(\$ / year) = PW \times CRF(i,n) \quad (2)$$

The present worth of the component is converted to annualized cost by using the capital recovery factor CRF (*i*,*n*), i.e [7]. Dividing the levelized cost by 8000 annual operating hours, We obtain the following capital cost for the *k*th component of the plant.

$$Z_k = \Phi_k \dot{C}_k / (3600 \times 8000) \quad (3)$$

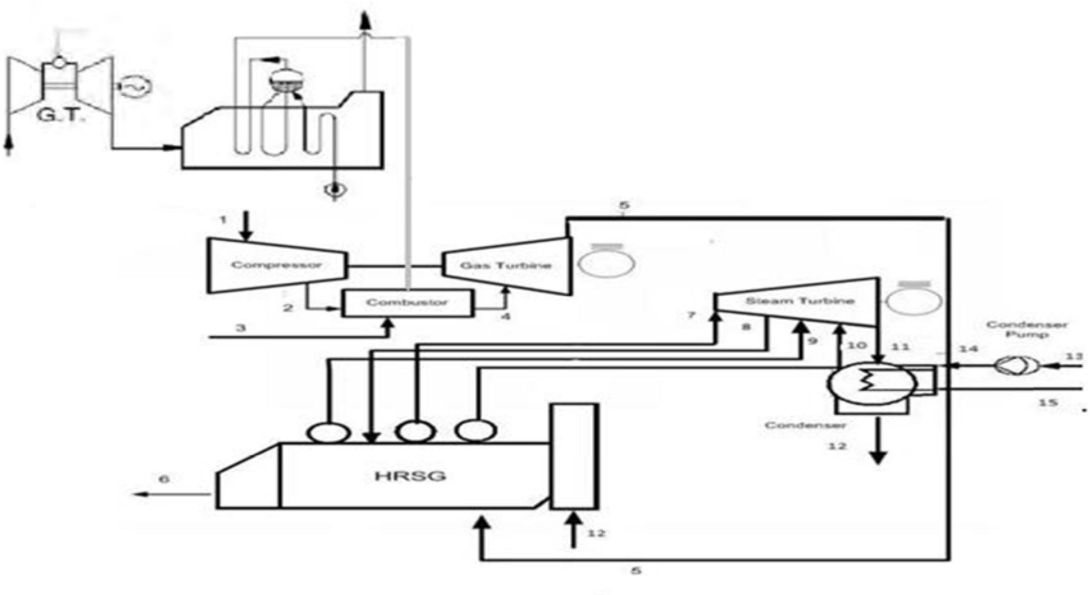

Fig 2. Combined cycle with STIG power plant (repowering2)

The maintenance cost is taken into consideration through the factor $\Phi_k = 1.06$ for each plant component whose expected life is assumed to be 15 years [9].

4.1. Thermoeconomic Modeling

The results from an exergy analysis constitute a unique base for exergoeconomics, an exergy-aided cost reduction method. A general exergy-balance equation, applicable to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics [10].

The cost balance expresses that the cost rate associated with the product of the system (C_P), the cost rates equals the total rate of expenditure made to generate the product, namely the fuel cost rate (C_F), the cost rates associated with capital investment (Z^{CI}), operating and maintenance (Z^{OM}) [12].

In a conventional economic analysis, a cost balance is usually formulated for the overall system (subscript tot) operating at steady state [12]:

$$C_{P,tot} = C_{F,tot} + Z_{tot} \quad (4)$$

Accordingly, for a component receiving a heat transfer and generating power, we would write [4]:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} - \sum_i \dot{C}_{i,k} + Z_k \quad (5)$$

To solve for the unknown variables, it is necessary to develop a system of equations applying Eq. (6) to each component, and it some cases we need to apply some additional equations, to fit the number of unknown variables with the number of equations [11].

A general exergy-balance equation, able to any component of a thermal system may be formulated by utilizing the first and second law of thermodynamics. In a conventional economic analysis a cost balance is usually formulated for the overall system operating at steady state. To derive the cost balance equation for each component, we assigned a unit cost to the principal product for each component. Depending on the type of fuel consumed in the production process different unit cost of product should be assigned [11].

5. Result and discussion

In this paper full repowering method for 156MW steam power plant has been applied. Table 1 indicates specification of repowered plant. It shows that, 68% of total power is produced by gas turbine cycle with 39% efficiency, in addition remained power are produced by steam cycle with 34% overall efficiency.

Repowered cycle produces 250MW more than old power plant. Heat rate in repowering power plant is 6500(KJ/KWh) and 1500(KJ/KWh) more than old power plant. Efficiency increases 15% for repowering model more than old power plant.

Table 2- combined cycle results

	Repowering
Gas Turbine(kW)	278041
Steam Turbine(kW)	125655
Plant Total (kW)	403695
Plant net LHV efficiency (%)	55.27
Plant net LHV heat rate(kJ/kWh)	6514
Gas turbine LHV efficiency (%)	39.05
Steam turbine efficiency (%)	34.59

Second proposed method uses STIG and adds a small gas turbine with single pressure HRSG. Result of this method with three model of gas turbine for producing steam injected, is shown in Table 2. For each three gas turbine model efficiency and exergy efficiency has been calculated. These results show that, increasing amount of injected steam mass flow can improve efficiency, but obviously only a limited amount of steam can be injected into the original gas turbine. This method can improve efficiency also increasing net power. In second stage, exergy and exergeoconimcs analyses are studied for both repowering method as an economical analyses. Table 3 and 4 show Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in both repowered power plants.

Table 3- combined STIG cycle results

	V64.3A	V84.2	V84.3
Injected steam mass flow (kg/s)	26.2	49.2	53.2
added gas turbine power (MW)	68.7	108.2	138.2
Gas turbine power (MW)	306.1	330	334.5
Steam turbine power (MW)	123.8	140.2	142.1
Added gas turbine efficiency (%)	37.2	33.7	35.9
Gas turbine efficiency (%)	48.8	52.6	53.3
Steam turbine efficiency (%)	32.8	36.6	36.5
Net power (MW)	498.7	578.8	615
Efficiency (%)	61.2	60.32	60.8
Exergy efficiency (%)	59.6	58.6	59.1

Table 4-Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in combined cycle

Component	Exergy Destruction(MW)	CF0 ($/MW)	CP0 ($/MW)	CD0 ($.s)	CF ($/MW)	CP ($/MW)	CD ($/s)
COMP	46.2489	0.0061	0.0073	0.2821	0.0064	0.0078	0.2959
COMB	152.5663	0.0049	0.0059	0.7475	0.0051	0.0061	0.7780
GT	17.0101	0.0059	0.0061	0.1003	0.0061	0.0064	0.1037
ST	36.2881	0.0083	0.0092	0.3011	0.0089	0.0101	0.3229
HRSG	38.6824	0.0063	0.0073	0.2436	0.0065	0.0078	0.2514
COND	4.8385	0.0083	0.2376	0.0401	0.0083	0.2603	0.0401
FWP	0.0236	0.0064	0.0113	0.0001	0.0064	0.0177	0.0001
CWP	0.6226	0.0064	0.0006	0.0039	0.0064	0.0007	0.0039

These results represented that combustion chamber and heat recovery steam generator in repowered combined cycle has most exergy and exergy cost destruction due to nature of combustion; however combustor in combined cycle plant shares about 51% TED, 44% TCD0 and 43% TCD. In next steps, compressor and steam generator have most exergy and exergy cost destruction.

Comparison of cost fuel and product of turbine for both schemes is shown in table 5. Gas turbine produce major of net power therefore cost product of gas turbine has important role in whole cost product. Gas turbine cost product for STIG combined cycle is less than ordinary combined cycle. However Cp of HPST in STIG cycle is more than ordinary combined cycle, HPST power is not as much important as other power product utility such as GT, LPST and IPST. Rate of total cost exergy destruction is specified in table 6.As shown, second repowering method can decrease TCD and TCD0 and therefore this scheme is more economical. Although exergy destruction increases in this method, ratio of exergy destruction to net power improves appreciably. Combined cycle with STIG can produce 498MW net power and has 356 MW exergy destruction but ordinary combined cycle produce 400MW net power with 346MW exergy destruction.

Table 4-Exergy destruction and cost fuel and product rates of exergy with and without considering capital investment for each component in STIG combined cycle

Component	Exergy destruction(MW)	Cf0 ($/MJ)	Cp0 ($/MJ)	CD0 ($/s)	Cf ($/MJ)	Cp ($/MJ)	CD ($/s)
Compressor	55.3869	0.0057	0.0073	0.3157	0.006	0.0079	0.3323
Combustion	120.8498	0.0049	0.0056	0.5921	0.0051	0.0058	0.6163
Gas Turbine	10.4329	0.0056	0.0057	0.0584	0.0058	0.006	0.0605
HPT	3.3937	0.0059	0.0078	0.0200	0.0074	0.0086	0.0251
IPT	21.4033	0.0069	0.0079	0.1476	0.0074	0.0087	0.1583
LPT	11.199	0.0069	0.0084	0.0772	0.0074	0.0093	0.0828
HRSG	38.2549	0.0056	0.0065	0.2142	0.0058	0.0069	0.2218
Condenser	9.6905	0.0069	0.202	0.0668	0.0074	0.2238	0.0717
CEP	0.0239	0.0069	0.0106	0.0001	0.0074	0.008	0.0001
deaerator	0.2376	0.0057	0.0074	0.0013	0.006	0.017	0.0014
LPFP	2.9043	0.0057	0.0067	0.0165	0.006	0.0151	0.0174
IPFP	0.4698	0.0057	0.0065	0.0026	0.006	0.0101	0.0028
HPFP	0.0878	0.0057	0.0063	0.0005	0.006	0.0075	0.0005
CWP	0.78	0.0057	0.0053	0.0044	0.006	0.0024	0.0046
added Comb	49.8	0.0051	0.0064	0.2539	0.0052	0.0066	0.2589
added Comp	15.8891	0.0064	0.0085	0.1016	0.0069	0.0091	0.1096
added GT	4	0.0064	0.0066	0.0256	0.0066	0.0069	0.0264
added HRSG	11.789	0.0066	0.0086	0.0778	0.0086	0.0089	0.1013

Table 5-comparsion of cost fuel and product with and without considering capital investment for both schemes

	combined cycle				STIG combined cycle				
	G.T.	HPST	IPST	LPST	G.T	HPST	IPST	LPST	added GT
Cf0 ($/MJ)	0.0064	0.0062	0.0074	0.0074	0.0056	0.0059	0.0069	0.0069	0.0064
Cf ($/MJ)	0.0065	0.0069	0.0083	0.0084	0.0057	0.0078	0.0079	0.0084	0.0066
Cp0 ($/MJ)	0.0065	0.0064	0.0078	0.0078	0.0058	0.0074	0.0074	0.0074	0.0066
Cp($/MJ)	0.0067	0.0073	0.0091	0.0092	0.0060	0.0086	0.0087	0.0093	0.0069

Table 6-comparsion of cost exergy destruction with and without considering capital investment for both schemes

	Exergy destruction(MW)	TCD0 ($/s)	TCD0 ($/h)	TCD ($/s)	TCD0 ($/h)
Simple C.C	346.2758	2.3209	8337.083	2.4188	8686.63
STIG C.C	356.5925	1.9771	7117.703	2.0925	7533.21

6. Conclusions

In this paper an old steam cycle has been chosen as a model for repowering. At first full repowering has been examined for this model and it changed into combined cycle that has 400MW net power. This repowering increases net power and improves efficiency. As a result of old boiler and power capacity for this model, full repowering is one of the useful an economical method. After that, a gas turbine and a single pressure HRSG added to combined cycle and it has been changed into STIG combined cycle. Net power increases with adding new gas turbine and using STIG in this method. However increasing amount of mass flow steam injected can heighten net power, there is limitation for mass flow. Exergy and exergoeconomic methods have been applied for analysis and comparison both repowering method. An exergy-costing method has been applied to both cases to estimate the unit costs of electricity produced from steam turbines. The computer program that was developed which shows that the exergy and the thermoeconomic analysis presented here can be applied to any energy system systematically and elegantly. If correct information on the initial investments, salvage values and maintenance costs for each component can be supplied, the unit cost of products can be evaluated. These analyses shows that cost product of combined cycle with STIG is less than ordinary combined cycle. Also net power and efficiency of combined cycle with STIG is more than ordinary combined cycle. Although using water for steam injection is the most problem of this new method, there are some suggestions to recycle water and reused in the cycle.

References

[1]. M.Frankle. The standardized repowering solution for 300 MW steam power plants in Russia. Siemens AG 2006.

[2]. A.bouam, S.aissani. Combustion chamber steam injected for gas turbine performance improvement during high ambient temperature operation. Journal of Engineering for Gas Turbines and Power JULY 2008, Vol. 130 / 041701-1

[3]. T Srinivas, AVSSK S Gupta. Parametric simulation of steam injected gas turbine combined cycle. J. Power and Energy Vol. 221 Part A

[4]. R.carapellucci, A.Milazzo. Repowering combined cycle power plant by a modified STIG configuration. Energy Conversion and Management 48 (2007) 1590–1600.

[5]. Haselbacher, H. Performance of water/steam injected gas turbine power plants consisting of standard gas turbines and turbo expanders. Int. J. Energy Technol. Policy, 2005, 3(1/2), 12–23.

[6]. Sanjay Y, Singh O, Prasad BN. Energy and exergy analysis of steam cooled reheat gas–steam combined cycle. *Applied Thermal Engineering* 2007; 27: 2779–2790.

[7]. Chao Z, Yan W. Exergy cost analysis of a coal fired power plant based on structural theory of thermoeconomics. *Energy Conversion and Management* 2006; 47:817–843.

[8]. Modesto M, Nebra SA. Analysis of a repowering proposal to the power generation system of a steel mill plant through the exergetic cost method, *Energy* 2006; 31: 3261–3277.

[9]. Feng X, Zhu XX. Combining pinch and exergy analysis for process modifications. *Applied Thermal Engineering* 1997*;* 17: 250-260.

[10]. Durmayaz A, Yavuz Y. Exergy analysis of a pressurized water reactor nuclear power plant. *Applied Energy 2001;* 69: 39-57.

[11]. Nafey AS, Fath HES, Mabrouk AA. Exergy and thermoeconomic evaluation of MSF process using a new visual package. *Desalination 2006;* 201: 224-240.

[12]. Dobrowolski R, Witkowski A, Leithner R. Simulation and optimization of power plant cycles. ECOS 2002, Proceedings of the 15th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, Berlin, Germany, 2002, pp. 766–772.

[13]. Joint Army-Navy–Air Force Thermochemical Tables. NSRDS-N3537, Washington, DC: National Bureau of Standard Publications; 1985.