VOL. 11, NO. 22, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

THE INDICATORS AND CRITERIA OF EFFICIENCY, WATER CONSUMPTION AND EMISSION OF THERMAL POWER PLANTS

S. Reza Shamshirgaran[1], Mohammad Mahdi Nouzari[2], M. Khalaji Assadi[1], Kian Najafzadeh[3] and G. Reza Bayati[3]
[1]Department of Mechanical Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, Perak, Malaysia
[2]NOANDISH Energy Engineering Consultants, Ltd., Tehran, Iran
[3]Iran Energy Efficiency Organization, Tehran, Iran
E-Mail: shamshirgaran@hotmail.com

ABSTRACT

Having the current constraints of serious water shortage which might cause more concern rather the depleting fuel resources and also the worrying global warming phenomenon, the power plants performance has to be evaluated based on not only energy efficiency but also water efficiency and environmental emission point of view. Therefore, power plants water consumption and emission production should be optimized simultaneous with the optimization of energetic performance. In other words, a high performance power plant would be considered as a high efficient, low water consumer and low emitting plant. In this paper the main indicators for the evaluation of energetic performance, water consumption and emission level of different pollutants are studied and then the global trend of these indicators for IRAN power plants investigated over a ten-year period, ending to 2012. The results show that the energetic performance of gas power plants seems to be higher than that of for steam and combined cycle power plants. Obtaining a 28 percent growth in overall energy efficiency of gas plants compared to the first year and achieving an average 85 percent peak load provision during ten years proved this fact. The water consumption criterion for wet-cooling steam plants decreased significantly to 0.6 m^3/MWh at the end of tenth year. Finally, using the low quality fuel, whether oil or gas, has led to an 8.5 g/kWh SO_x emission level from steam power plants. The most increase in CO_2 emission is related to the steam power plants which has been equal to overall CO_2 emission from the gas power plants, 850 g/kWh, at the end of ten-year period.

Keywords: indicator, efficiency, water, emission and power plant.

INTRODUCTION

In the last decades the water consumption and emission level have been given less attention by power plants owners. In other words, the energy conservation problem has been solely in the center of attention. However, the global water crisis especially in arid regions and also global warming phenomenon persuade the power plants, through the new restrict laws legislated in the recent decades, to control their water consumption and emission production in addition to fuel saving.

The depletion of energy resources necessitates exploiting the available energy based on optimum manner which includes a chain, from its extraction to operation and conversion. In other words, the energy productivity should be as high as possible especially in the case of heavy industries with enormous amount of energy consumption. Therefore, the energy consumption should be evaluated via the certain indicators which could be measured or calculated [1]. In the past it was common to evaluate the performance of power plants in terms of energy consumption and therefore, the energy efficiency was evaluated as main indicator. However, nowadays the energy management has focused not only on the energy efficiency, but also on the concepts of water and emission efficiency as other important indicators. Ironically, the major concerns about the limitation of water resources and also about damaging the natural environment have been more and more rather the depletion of energy resources in the last decades. It brings it to mind that the energy, water and emission performance evaluation of power plants, as enormous energy and water consumers and major sources of pollutants as well, should be carried out simultaneously. To do this, it is necessary to have an appropriate tool for performing the evaluation. Different indicators are defined for using in measurement or calculation process and then for comparison with the standard allowable values which called performance criteria. The final performance evaluation will show the current status of whole plant and its components. The existing standard criteria would be upgraded periodically to improve as much as possible the operating conditions of the plants to a better situation compared with the past.

The present study deals with the main indictors for the performance evaluation of different thermal power plants and then investigates the global status of these indicators for IRAN power plants. Using the trends, it's possible to plan new standard criteria for enhancing the plants performance.

KEY PERFORMANCE INDICATORS

The key performance indicators which are known as KPIs, play a significant role in all evaluation processes [2]. All industries, including engineering and even non-engineering ones, use the certain KPIs to evaluate and then to improve the performance of systems which they are working on. The main global KPIs for evaluating annual performance of different types of thermal power plants have been listed in Table-1 [1].

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Table-1. Power plants performance main global KPIs [1].

#	KPI	Concept
1	P (MW)	Average practical generated power
2	E_{GG} (MWh)	Gross generated energy
3	E_{in} (MWh)	Internal consumption of energy
4	P_{nel} (MW)	Net generated power
5	E_{NG} (MWh)	Net generated energy
6	E_{in} (%)	Internal consumption percent
7	PLF	Plant load factor
8	PCF	Plant capacity factor
9	POF	Plant operation factor
10	FGC (m^3)	Fuel gas consumption
11	FOC (lit)	Fuel oil consumption

Table-2. Power plants performance main global KPIs (cont'd).

#	KPI	Concept
12	HR (kcal/kWh)	Heat rate
13	η (%)	Average efficiency
14	WC (m^3)	Water consumption
15	SWC (m^3/kWh)	Specific water consumption
16	CO_2 (Ton)	Carbon dioxide emission
17	SCO_2 (g/kWh)	Specific carbon dioxide emission
18	NOx (Ton)	Nitrogen oxides emission
19	SNOx (g/kWh)	Specific nitrogen oxides emission
20	SOx (Ton)	Sulfur oxides emission
21	SSOx (g/kWh)	Specific sulfur oxides emission
22	PM (Ton)	Particulate matter emission
23	SPM (g/kWh)	Specific particulate matter emission
24	CH_4 (Ton)	Methane emission
25	SCH_4 (g/kWh)	Specific methane emission
26	N_2O(Ton)	Nitrous oxide emission
27	SN_2O (g/kWh)	Specific nitrous oxide emission

Most of KPIs listed above are clear in concept. However, some of them are very significant although might seem to be simple, apparently.

Energetic performance indicators

The first 13 items in the Table-1, represent the main relevant indicators for energetic performance of thermal power plants. For instance, PLF shows the average generated load of each plant rather the peak load and PCF indicates the ratio of generated load to the rated load of plant. Both of these indicators would be assessed over a specific time period (T), e.g. annually. POF indicator reveals the fraction of gross practical generated energy rather its practical 100% capacity [3].

$$\mathrm{PCF} = \frac{P_{\mathrm{avg}}}{P_{\mathrm{rated}}} = \frac{E_{\mathrm{avg}}}{P_{\mathrm{rated}} T} \quad (1)$$

$$\mathrm{PLF} = \frac{P_{\mathrm{avg}}}{P_{\mathrm{max}}} = \frac{E_{\mathrm{avg}}}{P_{\mathrm{max}} T} \quad (2)$$

$$\mathrm{POF} = \frac{P_{\mathrm{avg}}}{P_{100\%}} = \frac{E_{\mathrm{avg}}}{P_{100\%} \mathrm{T}} \quad (3)$$

There are different definitions for efficiency concept, i.e. energetic, thermal, economic and operational. However, among them the energetic and thermal efficiency are most applicable. The energy efficiency stands for the amount of energy consumption (H) for production one unit of electrical energy (E). It is also known as plant heat rate (HR) [4].

$$\mathrm{HR} = \frac{H}{E} \quad [\mathrm{kcal/kWh}] \quad (4)$$

The plant thermal efficiency is defined as the inverse of its heat rate. In other words, it describes the ratio of useful electrical output to the thermal input of the plant.

$$\eta = \frac{3412}{\mathrm{HR}} \quad [\%] \quad (5)$$

Since one kilo-Watt-hour electrical energy corresponds with 3412 kcal thermal energy, the figure 3412 applied in the numerator. The efficiency and heat rate would be stated as either gross or net if the energy considered as gross or net basis. The efficiency of power plant major components is considered as an efficiency chain [5]:

$$\begin{aligned}\eta_{\mathrm{gen,net}} &= (\eta_{\mathrm{b}} \times \eta_{\mathrm{tg}}) \times \eta_{\mathrm{aux}} = (\eta_{\mathrm{b}} \times \eta_{\mathrm{th}} \times \eta_{\mathrm{it}} \times \eta_{\mathrm{m}} \times \eta_{\mathrm{g}}) \times \eta_{\mathrm{aux}} \\ &= (\eta_{\mathrm{gen,gross}}) \times (1 - \frac{P_{\mathrm{SS}}}{P_{\mathrm{G}}})\end{aligned} \quad (6)$$

where η_b, η_{tg}, η_{aux} and η_g are the efficiency of boiler, turbine-generator set, auxiliary devices such as different pumps, fans and compressors and electrical generator, respectively and η_{th}, η_{it} and η_m stand for the thermal efficiency of reversible cycle, isentropic efficiency of steam turbine and mechanical efficiency of turbine-generator set, respectively. Meanwhile, the term of P_{ss} to P_G represents the ratio of internal consumption of energy (P_{ss}) to generated power (P_G) and equals to E_{in} in the Table-1.

Another key indicator which affects the economic and environmental aspects is specific fuel consumption:

$$\mathrm{SFC} = \frac{\mathrm{HR}}{\mathrm{GHV}} = \frac{3600\,\dot{m}_{\mathrm{f}}}{P_{\mathrm{nel}}} \quad [\mathrm{kg/kWh}] \quad (7)$$

It is the ratio of heat rate to the gross heating value (GHV) of fuel and represents the fuel flow ($\dot{m}_f$) which is consumed for generation of one kWh net electrical energy. Some believe that this indicator is the same with the concept of heat rate and it is not necessary to be evaluated [1].

The net electrical power (P_{nel}) shows that which fraction of total generated electrical power (P_{gel}) by a power plant has been consumed for driving pumps, fans, compressors and lighting etc (P_{aux}) and how much (P_{loss}) has been lost.

$$P_{\mathrm{nel}} = P_{\mathrm{gel}} - P_{\mathrm{loss}} - P_{\mathrm{aux}} \quad [\mathrm{kW}] \quad (8)$$

VOL. 11, NO. 22, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

Therefore, the net thermal or generation efficiency of the plant can be calculated as follows [5]:

$$\eta_{N,Gen} = \frac{P_{nel}}{\dot{m}_f GHV} \tag{9}$$

Since the fuel heating value can be stated as lower or higher basis, the generation efficiency would be evaluated on lower or higher basis, accordingly. The efficiency on the LHV basis is approximately two percent higher than that on HHV basis.

It should be noted that although the energetic performance indicators of different power plants are somehow different, the common ones have been presented here.

Water consumption indicators

For evaluation the amount of water, the key indicator is the water *usage* which is divided in two other indicators, viz. water *withdrawal* and water *consumption*. It is more common in water studies to use specific water consumption as the indicator in terms of m^3/kWh or lit/kWh. It is obvious that the value of this indicator is highly dependent on the type and size of the plant. The large plants with wet cooling towers use the most amount of water for production of one kWh electrical energy. The following equation relates the plant water usage (*I*) to its efficiency [6, 7]:

$$I = A\,(HR - B) + C \text{ [lit/kWh]} \tag{10}$$

where parameter *B* [kJ/kWh] is the total heat exiting the plant except for the heat rejection in cooling system. In other words, the total heat rejection of cooling system is equivalent with HR-*B*. Parameter *A* [lit/kWh] which is dependent on the type of cooling system, determines the water quantity required for one unit of heat rejected in plant cooling system and can be calculated as follows:

$$A_{OT\_W} = \frac{1}{\rho_W C_P \Delta T} \text{, water } \textit{withdrawal} \text{ of once-through system} \tag{11}$$

$$A_{OT\_C} = \frac{\alpha}{\rho_W C_P \Delta T} \text{, water } \textit{consumption} \text{ of once-through system} \tag{12}$$

$$A_{CT\_W} = \frac{(1-k_{sens})}{\rho_W h_{fg}}\left(1+\frac{1}{n_{cc}-1}\right) \text{, water } \textit{withdrawal}\text{, circulating system} \tag{13}$$

$$A_{CT\_C} = \frac{(1-k_{sens})}{\rho_W h_{fg}}\left(1+\frac{1-k_{bd}}{n_{cc}-1}\right) \text{, water } \textit{consumption}\text{, circulating system} \tag{14}$$

where ΔT represents water heating degree which is 10 K approximately, α is the fraction of cooling water which is evaporated or lost and considered as almost one percent [6]; it depends on environment conditions such as water bed temperature and wind velocity; k_{sens} stands for the percent of thermal load wasted by sensible heat transfer and is related to the cooling tower design, temperature and humidity; n_{cc} is the number of concentration cycle (COC) and is relevant to the amount of blowdown; k_{bd} corresponds with the difference of cooling system's water withdrawal and consumption and in fact is the cooling blowdown. Parameter *C* in Equation. (10) is related to total water usage irrelevant to the cooling process.

Emission indicators

The pollutants generated by the power plants are considerable in terms of quantity and variety. Some are emitted through the stack of the plants and are harmful for the air. One group is included in greenhouse gases (GHGs) such as Nitrous oxide, N_2O, and methane, CH_4, while another group comprised of emissions which can hurt the human body and whole environment [8]. Others can be hazardous for water resources and the remained pollutants may damage the soil structure. Here only the air relevant emissions are introduced. Nitrogen oxides, NOx, which are different from Nitrous oxide, present as NO and NO_2 in combustion products and can result in the formation of ozone (O_3) and smog event. Similarly, sulfur oxides, SOx, are divided in two categories, i.e. SO_2 and SO_3, and their presence in combustion products would lead to the formation of sulfuric acid and corrosion event or acid rain. Pollutant CO will form when the combustion process is incomplete and therefore, the boiler's burners need to be tuned up. Particulate matter (PM) pollution is known as ROx too and categorized as $PM_{2.5}$ and PM_{10} which stand for fine particles with diameter of 2.5 micrometers or less and for coarse dust particles with diameter of 2.5 to 10 micrometers, respectively. Fine particles ($PM_{2.5}$) can only be seen with an electron microscope. They are produced from all sorts of combustion processes, including motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, and some industrial processes.

The temporal quantity of all pollutants is expressed in terms of ppm (parts per million) while their quantity for a time period is considered on ton basis [9]. However, it is common to evaluate the emissions' level as a specific quantitative indicator which represents the amount of generated pollutant for one unit of electrical energy; in terms of g/kWh.

THE TREND OF PERFORMANCE CRITERIA

As mentioned before, the criteria are discussed as the quantitative value of performance indicators. Some indicators are measured directly and some of them should be calculated by using the other indicators or appropriate parameters. Here the main performance indicators have been evaluated globally for all three different sorts of (steam, gas and combined cycle) thermal power plants of IRAN over the last 10-year time period. The results of this evaluation depicted as appropriate graphs which can be seen in the following. It should be kept in mind that this paper deals only with the most important criteria achieved from the comprehensive evaluation.

ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

Energetic performance criteria

The changes of generated power from steam, gas and combined cycle power plants have been illustrated base on different points of view in Figure-1 to Figure-3.

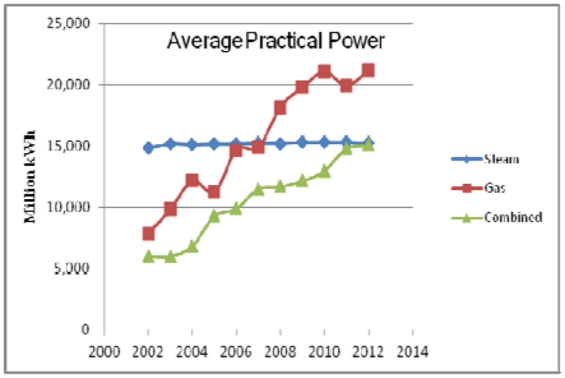

Figure-1. Ten-year trend of average practical power.

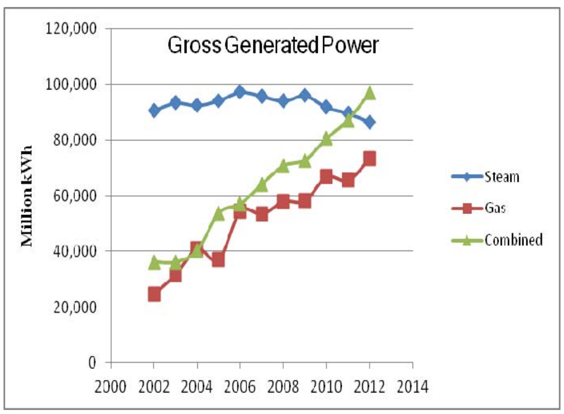

Figure-2. Ten-year trend of gross generated power.

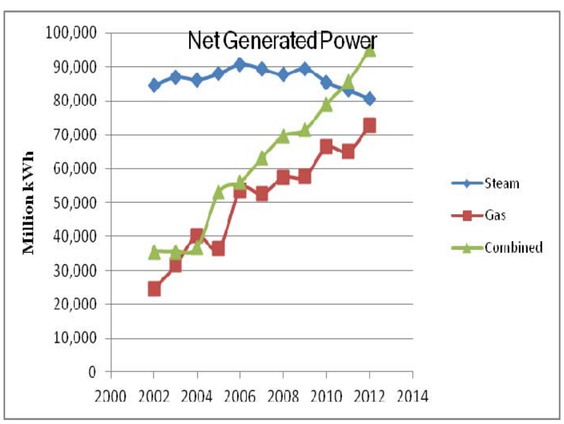

Figure-3. Ten-year trend of net generated power.

Figure-1 demonstrates that regarding the fact that no new steam power plant has been installed during the ten years, the average practical generated power remained nearly unchanged at a constant 15,000 million kWh. Instead, the new gas and combined cycle plants have been installed and operated successively so that the practical generated power by combined cycles increased to over 20,000 million kWh at the end of the period. Figure-2 and Figure-3 show that the contribution of steam plants to total generated power decreased steadily while the gas and specially combined plants contributed more than past. At the end of study period, combined plants power generation surpassed the power generated by steam plants so that the gross and net power generated by these plants increased to around 100,000 and 95,000 million kWh, respectively.

In accordance with Figure-4 the maximum available power from steam, gas and combined cycle plants increased up to around 90%, 85% and 82%, respectively. Therefore, the power sector performance for providing the peak loads improved.

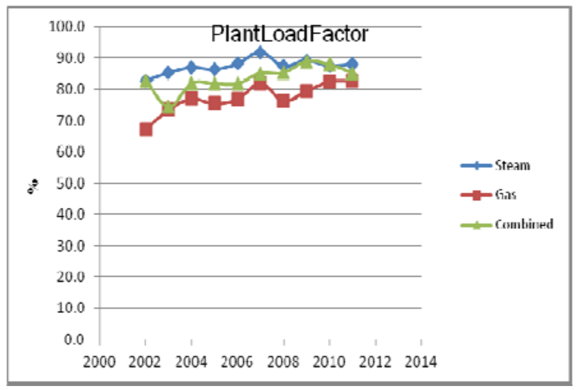

Figure-4. Ten-year trend of load factor indicator.

Figure-5 shows that the average efficiency of gas power plants rose to 36% in the ten years; however, no substantial changes can be seen for the efficiency of steam and combined plants over the period. The decreasing trend of gas power plants heat rate to 2,700 kcal/kWh in Figure-6, can also prove the increasing of these plants' average efficiency.

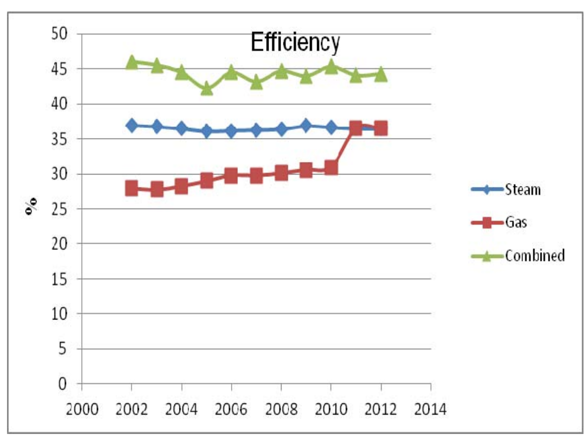

Figure-5. Ten-year trend of efficiency indicator.

The average heat rate of steam and combined cycle power plants, as can be seen from Figure-6,

VOL. 11, NO. 22, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

remained constant at around 2,400 and 1,850 kcal/kWh, respectively within the ten-year period.

Water consumption criteria

The global water performance of different power plants has been shown in Figure-7. It is obvious that the most water consumption is related to the plants with wet cooling towers; this demonstrated by the variation curve of Steam-Wet Cooling in the Figure. Although the quantity of water consumption in steam power plants with wet-cooling tower fluctuated during the first years, peaking at 0.8 m^3/MWh, the water performance improved remarkably after half of the study period, so that this criterion reached even below the initial value at the start of the period.

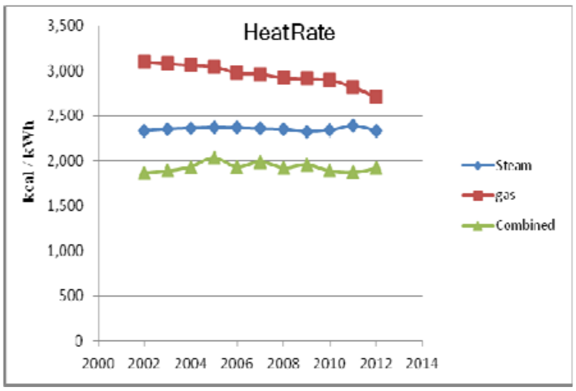

Figure-6. Ten-year trend of heat rate indicator.

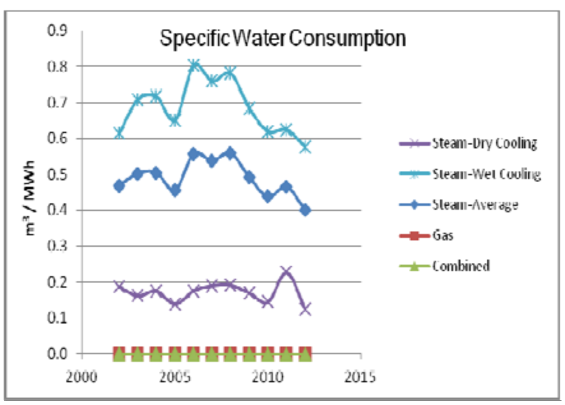

Figure-7. Ten-year trend of specific water consumption.

Meanwhile, the water consumed by gas and combined power plants are neglegible rather the steam plants specially because of Heller-type cooling towers application in the most of combined plants of IRAN. The average consumption of total steam power plants (dry-and wet-coolig systems) also shows a significant improvement at the end of last year.

Emission criteria

The variations of main emission criteria corresponding to the curves of Figure-8 to Figure-10, demonstrate that the amount of pollutants from all power plants rose gradually in last years.

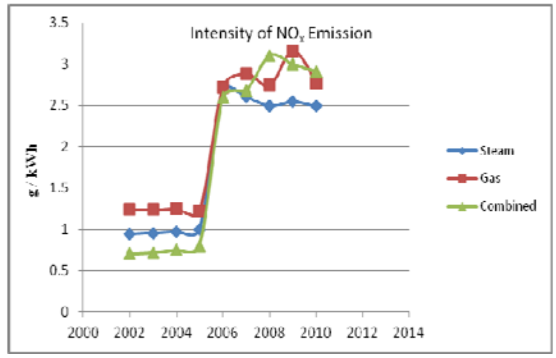

Figure-8. Ten-year trend of intensity of NO_x emission.

Firstly, it should be mentioned that the information of last two years of study period has not been available for the present evaluation. The comprehensive study has shown that not only all plants consumed low quality fuels, but also the quality of fuel whether gas or oil, decreased year by year [1]. Figure-8 shows that during year 2010, gas and combined cycle power plants have emitted more NO_x pollutant, i.e. approximately 2.8 g/kWh, rather the steam plants with 2.5 g/kWh.

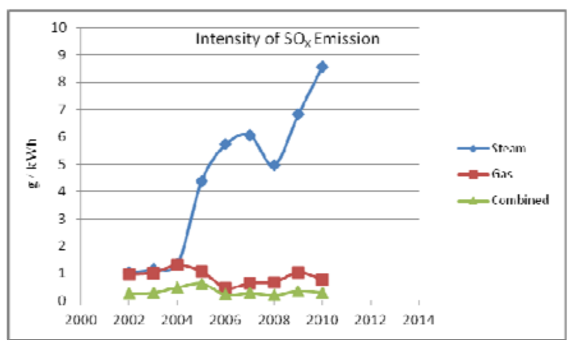

Figure-9. Ten-year trend of intensity of SO_x emission.

SO_x emission from steam power plants, going up to 8.5 g/kWh, resulted from low quality or high sulfure fuel oil consumption. It should be noted that sudden rise of SO_x and NO_x emission criteria is solely related to the change of standard evaluation rules at that year.

VOL. 11, NO. 22, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

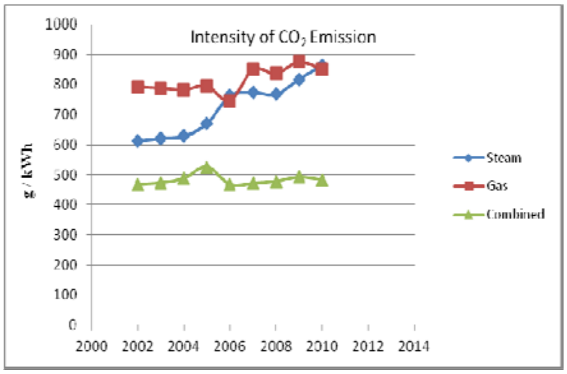

Figure-10. Ten-year trend of intensity of CO_2 emission.

As expected, Figure-10 confirms that the combined cycle power plants are produced the least, i.e. around 500 g/kWh, CO_2 emission. However, CO_2 emission from steam power plants increased by nearly 30% over the period and reached the gas plants CO_2 level at year 2010.

CONCLUSIONS

Regarding the necessity of simultaneous evaluation of energetic, water and emission performance of power plants, the global trend of quantitative values of key performance indicators (KPIs) for IRAN's steam, gas and combined cycle power plants demonstrated that the contribution of gas and combined plants to total power generation increased rather the steam power plants within the last decade because of the installation of new gas and combined plants. Having an average 85% PLF shows a good performance in providing the peak loads required.

On the other hand, the average energy efficiency of gas power plants improved by more than 28%, rather the other two plant types at the end of considered period. The specific water consumption of gas plants was insignificant and for combined plants their existed similar situation because most of the combined plants which have been installed in the last decade were of the Heller type. In the case of wet-cooling steam power plants, an efficient improvement is observed since the amount of water consumption decreased to just under 0.6 m^3/MWh at last year. However, using a low quality fuel over the study period has resulted to an increasing emission level from all thermal plants of the country. Due to this, SO_x level produced by total steam plants increased up to 8.5 g/kWh and NO_x emission by combined plants is higher than that for two other plant types. CO_2 emission level for both gas and steam plants is equal to 850 g/kWh while this value is remained approximately unchanged for the combined cycle power plants. Therefore, modifying actions should be taken on emission efficiency to further reduce the pollutants. Using the studied indicators and their criteria trend, the owners and managers of thermal power plants would be able to make the best decisions for improving the energetic efficiency, water consumption and emission performance and then to develop the new criteria for the key indicators in future periods.

REFERENCES

[1] Nouzari M. M. and Shamshirgaran S.R, 2015. Review and upgrading the current standard of thermal power plants performance evaluation, Technical Report, NOANDISH Energy Engineering Consultants Ltd., Tehran, Iran, Jul.

[2] De Souza G. F., 2012. Thermal power plant performance and analysis, Springer, Londen, UK.

[3] Tavanir Com. 2014, IRAN's Power Industry Detailed Statistics, Technical Report.

[4] Gugaliya J. K., Bhutani N. and Kumar M. S. 2013. Energy assessment for power plants, 6th Int. Con. Process Systems Engineering (PSE ASIA), 25-27 Jun., Kuala Lumpur.

[5] EPRI, 2001. Proceedings of EPRI's Twelfth Heat Rate Improvement Conference, Palo Alto, CA: Jan., 1001328.

[6] Delgado A. and Herzog J. H. A simple model to help understand water use at power plants, Working Paper, Massachusetts Institute of Technology, Energy Institute.

[7] Yang X. and Dziegielewski B. 2007. Water use by thermoelectric power plants in the United States, J. The American Water Resources Association, Vol. 43, No. 1, Feb.

[8] US. Environment Protection Agency (EPA), 2014. Regulatory impact analysis for the proposed carbon pollution guidelines for existing power plants and emission standards for modified and reconstructed power plants, EPA-452/R-14-002 Report, Jun.

[9] US. Environment Protection Agency (EPA), 2014. Standards of performance for greenhouse gas emissions for new stationary sources: electric utility generating units, EPA-HQ-OAR-2011-0660 Report.