# Energy Efficiency Improvement in Thermal Power Plants

**Genesis Murehwa, Davison Zimwara, Wellington Tumbudzuku, Samson Mhlanga**

***Abstract - The purpose of the study outlined in this is to identify major energy loss areas in Zimbabwe's thermal power stations and develop a plan to reduce them using energy and exergy analysis as the tools. The energy supply to demand is narrowing down day by day around the world due to the growing demand and sometimes due to ageing of machinery. Most of the power plants are designed by the energetic performance criteria based not only on the first law of thermodynamics , but the real useful energy loss cannot be justified by the fist law of thermodynamics, because it does not differentiate between the quality and quantity of energy. The present study deals with the comparison of energy and exergy analysis of thermal power plants stimulated by coal. Our national electricity requirement is about 2100MW against 1615MW supply; this is evident of about 21% deficit in terms of power requirements. In view of this situation, the project seeks to increase output from the Power Stations (PS) in the process closing down on the power shortages now and in the future through effective and efficiency improvement.***

***Keywords- Energy, Exergy, Effective, Efficiency, Improvement, Thermal Power Station***

## I. INTRODUCTION

The SADC region including Zimbabwe they are suffering from critical shortage of power and this has negative impact on industrial development. The expansion on the demand side resulted in over stretching of the current electricity generation capacity coupled with aging thermal plants which are still utilising old technology. The paper will focus on the energy efficiency improvement in thermal stations.

Thermal Power Stations generate electricity through a thermal power plant; its installed capacity is designed with a common range of boilers feeding into common steam receivers from where any of the turbines tape the steam. Currently only few boilers are in operation with an output of approximately 1615MW. The power plants use coal as the primary input for generating electricity. The plant use 20-30% of energy value of primary fuels and the remaining 70-80% is lost during generation, transmission and distribution of which major loss is in the form of heat. The heat rate of a plant is the amount of fuel energy input needed (Btu, higher heating value basis) to produce 1 kWh of net electrical energy output. This study was done to identify various methods to reduce the heat rate of existing coal-fired power plant in Bulawayo by identifying areas that cause the most heat losses and introducing the new technologies that cater for the losses. Energy and exergy analysis is used for the identification of these loses. Energy analysis evaluates the energy generally on its quantity only, whereas exergy analysis assesses the energy on quantity as well as the quality. The aim of the exergy analysis is to identify the magnitudes and the locations of real energy losses, in order to improve the existing systems, processes or components, (Tekin and Beyramogle: 1998). This study identifies specific plant systems and equipment where efficiency improvements can be realized either through new installations or modifications, and provides estimates of the resulting net plant heat rate reductions and the order-of-magnitude costs for implementation.

**Manuscript published on 30 December 2012.**
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### 1.1 Aim

The main aim of the study is to identify areas where energy losses are occurring and develop them for efficient and effective improvement in a thermal power station.

### 1.2 Objectives

The object to satisfy this are

- To conduct energy analysis of the overall plant and determine the efficiencies and energy losses of all the major components on the power plant.
- Select and develop the areas where energy losses are being experienced.
- Determine the costs and payback periods for the new technologies suggested for efficiency improvement.

### 1.3 Scope

The study scope encompasses three major tasks, energy and exergy analysis and the identification of methods to reduce the energy losses of power plant and the determination of their associated costs involved with the installation of the possible measure to cater for the problem. Energy analysis is to be done on components from the combustor to the electrical generator.

### 1.4 Need Justification

Electricity supply in Zimbabwe is becoming a shortage due to increase in demand made up of import displacement, urban expansion, expanded rural electrification program, new investments and the need of spinning reserves. The current electricity supply situation in the country is as shown in Table 1 below.

**Table 1 Power Station in Zimbabwe**

| Power Station | Type Of Station | Year Commissioned | Installed Capacity | Dependable Capacity |
|---|---|---|---|---|
| Hwange | Thermal | 1987 | 920MW | 780MW |
| Kariba | Hydro | 1970 | 750MW | 750MW |
| Bulawayo | Thermal | 1950 | 120MW | 25MW |
| Harare | Thermal | 1960 | 120MW | 30MW |
| Munyati | Thermal | 1938 | 120MW | 30MW |
| TOTALS | | | 2 030 MW | 1 615MW |

Table 1 shows the installed capacity against the dependable capacity, so our goal is to work towards increasing the dependable supply to as close as possible to the installed capacity. Our power plants in the country currently provide about 87.6% of the installed capacity, a situation we intend to increase through efficiency improvement of the entire power plants.

### 1.5 Current Supply-Demand Situation

Table 2 shows the current demand supply in Zimbabwe.

**Table 2 Current demand**

| | |
|---|---|
| Dependable Capacity | 1615MW |
| Available Maximum Capacity | 1615MW |
| Maximum Demand | 2100MW |

Our national electricity requirements are about 2100MW against 1615MW supply; this is evident of about 21% deficit in terms of power requirements as shown in table 2, the future supply- demand forecast in Zimbabwe will require an additional of 1750MW by 2015 to further increase the power shortage.

### 1.6 Future Supply-Demand Situation

Zimbabwe will require an additional 1750MW by 2015. In view of this situation, the project seeks to increase output from Thermal Power Station (TPS) in the process closing down on the power shortages now and in the future. Energy efficiency improvement measures provide a win-win situation by promoting cost-savings, lowering environmental impacts while at the same time promoting economic growth and social development. In addition to generating very large annual energy savings, present outlays on energy efficiency would avoid investment in energy infrastructure that would otherwise be needed to keep pace with accelerating demand. Efficiency improvement in all power plants can result in a sustainable gain in terms of electricity supply but this will need to be aided by other supply options such as imports and commissioning of new plants around the country.

### 1.7 Methodology

The project is going to cover the following areas:

- A description of the facilities and their principal operation on the plant.
- A discussion of all major energy consuming systems.
- A description of all recommended Energy Conservation Measures (ECMs) with their specific energy impact.
- Energy and exergy analysis of the whole plant.
- A review on the implementation costs, benefits and payback period.
- Specific conclusions and recommendations.

### 1.8 Inputs and Outputs

The inputs to the thermal power plant processes at Power Stations are coal and water. The source of these is Hwange Colliery Company about 480 kilometres away from Bulawayo. The coal chemistry is as given in Table 3.

**Table 3 Coal chemistry**

| | |
|---|---|
| Total Moisture | 3.6 – 6.4% |
| Ash | 1.5 -12.4% |
| Volatile Matter | 19.3 - 42% |
| Fixed Carbon | 23.8-66.7% |
| Gross Calorific Valve (Specific Energy) | 13.87-32.08MJ/kg |
| Sulphur | 0.15- 4.67% |
| Crucible Swelling Number | 0-9+. |
| | |
| Ash Fusion Temperature | 1550-1080ºC |

Outputs to the process are combustion products and the power generated. Power generated for the year 2011 is as shown in Figure 1 below.

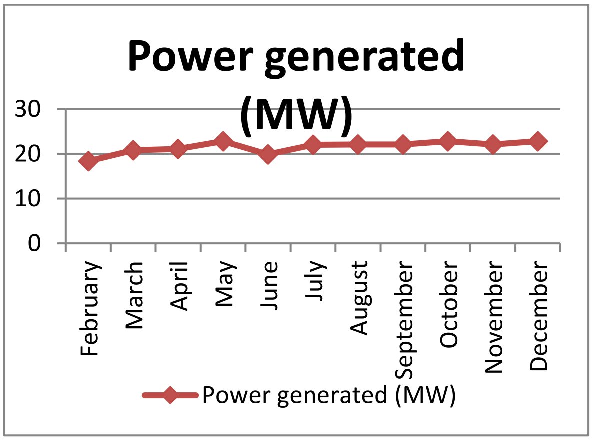


Figure 1.Power generated for the year 2011

## II. DESCRIPTION OF THE PLANT

A schematic diagram of a plant with its various significant components is shown in Figure 2. The continuous supply of de-mineralized water is ensured to the condenser hot well for the normal running of the plant at a constant load. The condensate extraction pump (EXP) feeds the feed water to the ejector from the hot well. After the ejector exit, the feed water passes through the gland steam cooler, and the low pressure heater (LP). From the outlet of the low pressure heater (LP) the condensate enters into the boiler feed pump (BFP) where the condensate is pumped from the high pressure heater one (HP1) to high pressure heater three (HP3). Then the condensate passes through the economizer, and then enters into the boiler drum. There is a continuous circulation of water between the drum and the water walls and a part of the feed water is converted into steam. The steam is separated in the boiler drum and supplied to the super heater section and the boiler condenser section. The super heated steam produced in the super heater then enters into the turbine through the turbine stop valve and then rotates the electrical generator. After expansion in the turbine the exhaust steam is condensed in the condenser and is used for the closed cycle as shown in Figure 2.


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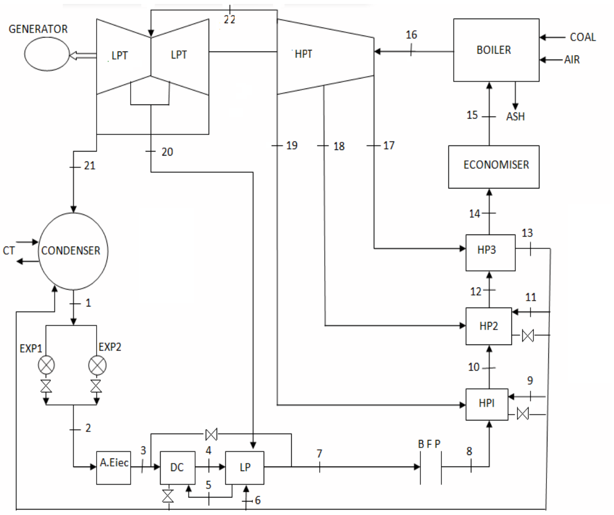


Figure 2 Schematic diagram of thermal plant

## III. RELATED LITERATURE

The related literature is Rankine cycle, energy and exergy analysis.

### 3.1 Rankine cycle

Rankine cycle is the idealized cycle for steam power plants; it is a heat engine with a vapour power cycle (Wiser, 2000). The common working fluid is water, and the cycle consists of four processes as shown in Figure 3.

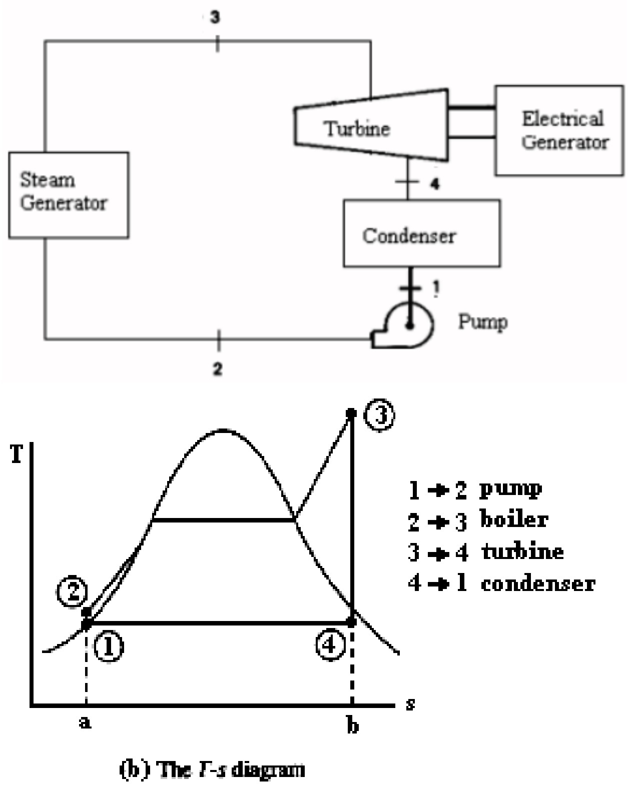


Figure 3. Rankine cycle representation of power plant

**(a) Power plant circuit**

- **Process 1-2**: *Isentropic compression (Pump;* during the isentropic compression process, external work is done on the working fluid by the pumping. Pumping takes place from low to high pressure.
- **Process 2-3**: *Isobaric heat supply (Steam Generator or Boiler;* heat from the high temperature source is added to the working fluid to convert it into superheated steam. Pressurised liquid enters a boiler where it is heated at constant pressure to dry saturated vapour.
- **Process 3-4**: *Isentropic expansion (Steam turbine);* an isentropic process, the entropy of working fluid remains constant. The dry saturated vapour expands through a turbine, generating power. The temperature decreases and pressure drops, and condensation can take place may occur.
- **Process 4-1**: *Isobaric heat rejection (Condenser;* An isobaric process, in which the pressure of working fluid remains constant. The wet vapour then enters a condenser where it is condensed at a constant temperature to become a saturated liquid, (Kapooria, et al, 2008)

### 3.2 Energy analysis

In an open flow system there are three types of energy transfer across the control surface namely working transfer, heat transfer ($Q_k$), and energy associated with mass transfer and/or flow. The temperature ($T_k$) from the heat source and the network (W) developed by the system are used for the analysis of open flow systems and to analyze plant performance whilst kinetic and potential energy changes are ignored. The energy or first law efficiency of a system is defined as the ratio of energy output to the energy input to system (Jin et al, 1997).

### 3.3 Exergy analysis

Exergy is a generic term for a group of concepts that define the maximum possible work potential of a system, a stream of matter or heat interaction; the state of the environment being used as the datum state. In an open flow system there are three types of energy transfer across the control surface namely working transfer, heat transfer, and energy associated with mass transfer or flow. The work transfer is equivalent to the maximum work, which can be obtained from that form of energy (Naterer et al, 2010).

Energy analysis is based on the first law of thermodynamics, which is related to the conservation of energy. Second law analysis is a method that uses the conservation of mass and degradation of the quality of energy along with the entropy generation in the analysis, design and improvement of energy systems. Exergy analysis is a useful method; to complement but not to replace energy analysis, (Bajan, 2002).

The irreversibility maybe due to heat transfer, through finite temperature difference, mixing of fluids at different temperature and mechanical friction. Exergy analysis is an effective means, to pinpoint losses due to irreversibility in a real situation (Dincer and Rosen, 2003).

## IV. THERMAL POWER PLANT PERFORMANCE MEASURES

The thermal performance indicator is used to monitor thermal power station units' efficiency. It is an indication of the thermal units' success in meeting thermal design capabilities and enables comparison among similar units.

Thermal performance indicator =


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$$\frac{\text{gross design heat rate}}{\text{adusted actual gross heat rate}} \times 100 \text{ ..................Eqn 1}$$

This indicator is used to evaluate operating parameter deviation from the design values and take appropriate corrective action where necessary.

The following indicators are used to evaluate station performance on daily, monthly, quarterly and annually basis. These indicators can be calculated for the unit or Station basis.

- **Plant Availability**

$$\text{Availability} = \frac{\text{operating hours}}{\text{total hours for period under riview}} \times 100$$

............Eqn 2

- **Plant load factor**

$$\text{Plant load factor} = \frac{\text{energy generated}}{\text{MCR X hours in period}} \times 100$$

............Eqn 3

- **Planned outage rate**

$$\%\text{planned outage rate} = \frac{\text{outage hours}}{\text{hours in period under riviev}} \times 100$$

............Eqn 4

- **Forced outage rate**

$$\%\text{forced outage rate} = \frac{\text{forced outage hours}}{\text{hours in period under riview}} \times 100$$

.............Eqn 5

- **Reliability**

It is an indication of how well maintenance management programmes are being executed %reliability = 100% - forced outage rate .................. Eqn 6

- **Thermal efficiency**

It is an indication of how well the plant is being operated as compared to the design characteristics.

$$\text{Thermal efficiency } ή = \frac{\text{energy generated x time}}{\text{MC x CV}} \times 100$$

............ Eqn 7

Where: MC – quantity of coal consumed
CV- calorific value of coal

Overall unit efficiency, $ή = ή_{Boiler} \times ή_{Turb} \times ή_{Gen} \times ή_{wrks}$

Where: $ή_{Boiler}$ – boiler efficiency
$ή_{Turb}$ - turbine efficiency
$ή_{Gen}$ – generator efficiency
$ή_{wrks}$ – works efficiency

- **Operational Efficiency**

Operational efficiency is the ratio of the total electricity produced by the plant during a period of time compared to the total potential electricity that could have been produced if the plant operated at 100 percent in the period.

$$\text{Operational efficiency} = \frac{E}{E_{100\%}} \times 100 \text{ ..........Eqn 8}$$

where:
E = energy output from the power plant in the period (kWh)
$E_{100\%}$ = potential energy output from the power plant operated at 100% in the period (kWh)

- **Economic Efficiency**

Economic efficiency is the ratio between productions costs, including fuel, labour, materials and services, and energy output from the power plant for a period of time.

Economic efficiency=

$$\frac{\text{production costs for a period}}{\text{energy output from the power plant in the period (kWh)}} \text{........Eqn 9}$$

## V. DISCUSSION OF RESULTS

From the energy analysis, the overall plant energy loss is calculated as 81.72%. The comparison of energy losses between different components is given in Figure 4. It is observed that the maximum energy loss (47.79%) occurred in the condenser, this is due to the reason of heat energy expulsion from the condenser. Thus the energy analysis diverts our attention towards the condenser for the plant performance improvement. Approximately half of the total plant energy losses occur in the condenser only and these losses are practically useless for the generation of electric power. Thus the analysis of the plant based only on the First law principles may mislead to the point that the chances of improving the electric power output of the plant is greater in the condenser by means of reducing its huge energy losses, which is almost impracticable.

Hence the First law analysis (energy analysis) cannot be used to pinpoint prospective areas for improving the efficiency of the electric power generation. However, the Second law analysis serves to identify the true power generation inefficiencies occurring throughout the power station.

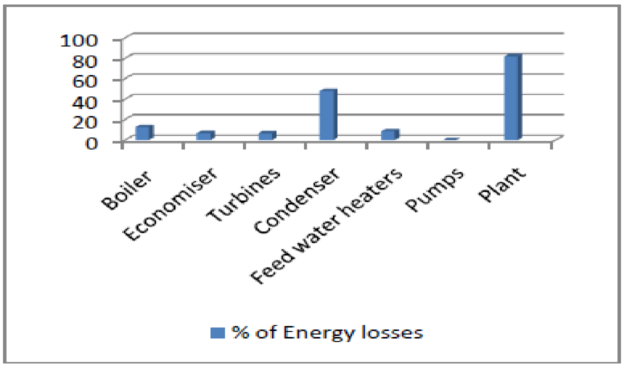


Figure 4.Comparison of energy losses in the plant and components

The first law efficiency (the energy efficiency) of different components is also calculated and their comparison is depicted in Figure 4. It is noted that the energy efficiency of the boiler is 70.27%, which upon replacement or retrofitting can yield 20% more on efficiency. So, replacing boilers or retrofitting makes good sense for reasons like, significant fuel cost savings and improved reliability and safety. The overall plant energy efficiency is 18.28%, which upon replacement or retrofitting of other plant components can result in an increase of about 20%.

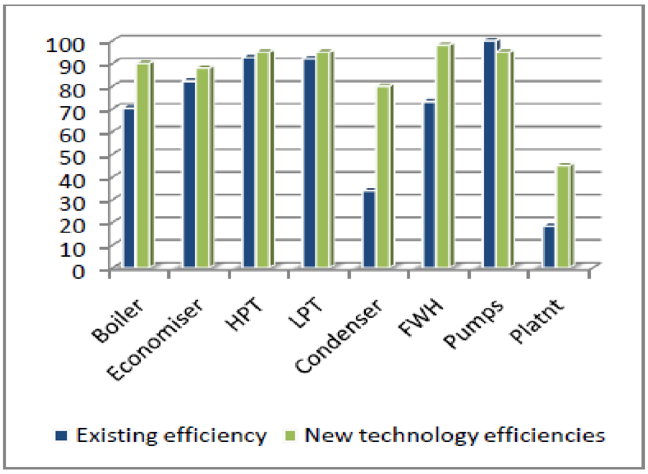


Figure 5. First law efficiencies of components and plants


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The comparison of exergy losses between the different components of the plant are shown in Figure 6. It is noted that the maximum exergy loss occurs in the Boiler (48.92%), which is approximately 60% of the total plant exergy losses occur in the boiler. This may be due to the irreversibility of the combustion process in the boiler/combustor. The percentage of exergy losses for the plant components are compared and shown in Figure 6. The total plant exergy destruction is calculated as 81.72%.

The exergy loss in the boiler is mainly due to the combustion reaction and to the large temperature difference during heat transfer between the combustion gas and steam. Factors that contribute to high amount of irreversibility's are tubes fouling, defective burners, fuel quality, inefficient soot blowers, valves steam traps and air heaters fouling.

The exergy loss in the turbines is due to the frictional effects and pressure drops across the turbine blades as well as the pressure and heat losses to the surroundings. The HPT and LPT contribute 6.36% of the total exergy destruction which indicates a need for reducing its irreversibility's. Other factors that may contribute to the irreversibility's are most likely due to the throttling, losses at the turbine governor valves, silica deposited at the nozzles. Overhauling the turbine maybe needed to check the real causes for improving plant performance.

The exergy losses in the FWH, from the thermodynamic point of view are due to the finite temperature difference between the streams, which interchange heat loss to the atmosphere and also due to the pressure drop. HP3 shows the highest exergy loss, so tubes inspection should be recommended during plant outage to determine the real cause. Other causes include wrong venting operation, high percentage of plugged tubes, poor maintenance and wrong operating water level.

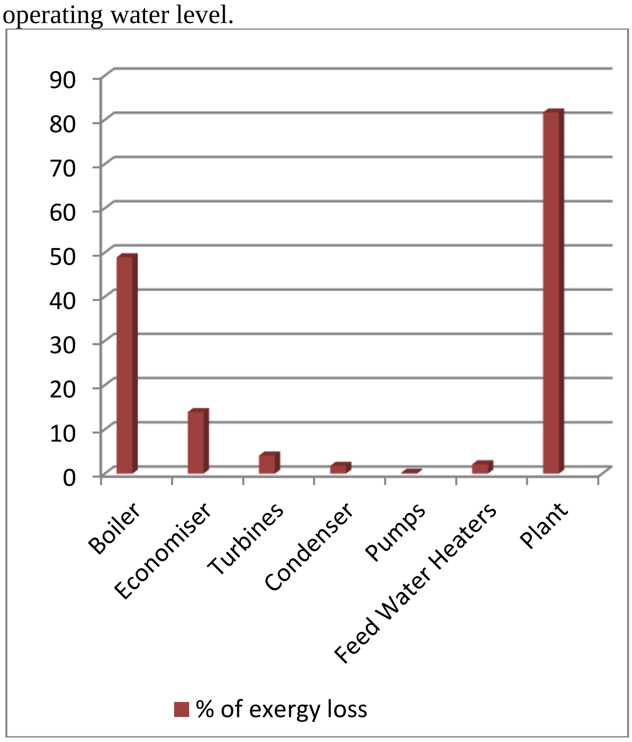


Figure 6 Comparison of exergy losses in the power plant and components

The Second law efficiency (the exergy efficiency) of different components is also calculated and their comparison is depicted in Figure 7. It is noted that the exergy efficiency of the turbine, the feed water heaters and the heat pumps are 90.07%, 77.23%, and 83.63% respectively. The exergy efficiency of the boiler and the condenser are calculated as 69.53% and 84.20% respectively. The overall plant exergy efficiency is 18.28%. Thus the exergy analysis of the plant pinpoints that the prospective improvement in the combustor can improve the overall plant efficiency.

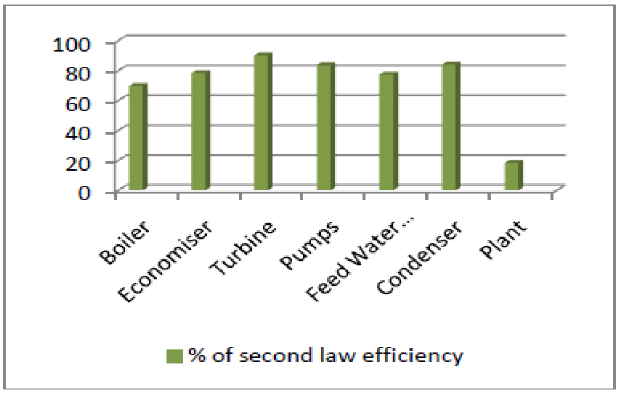


Figure 7. Second law efficiency of the plant and component

## VI. CHALLENGES

- Coal is very expensive as the mode of transport from Hwange Colliery which is about 480 kilometres away is by road instead of rail transport. Bulawayo is in region five geographically meaning water is very scarce and the city council resort to rationing. The industrial hub might be spared the rationing but at the end of the day the cost of the precious liquid has got an effect on the efficiency of the plant.
- Worker morale is very low due to the current economic situation of economic recovery in the country.
- The human resource base is another impending issue a situation which saw many qualified technical personnel including engineers and journey men left the country for greener pastures during the era 2007 and 2008 economic meltdown.
- Vandalism of machinery has proven a major challenge as the security is having a tough time as one can't tell whether it's an internal or external job which is in operation.

## VII. RECOMMENDATIONS

The research recommends that results from this study be used as a guide in determining future process improvement actions. Using exergy analysis, the boiler was found to have the highest percentage of exergy destruction (48.92%) of the overall plant (81.66%). To reduce this loss retrofitting and replacement of some boiler elements is necessary for the overall plant efficiency improvement.

The Power Station should also include the concepts of an intelligent power plant, the concepts include:

➢ Process Monitoring, Optimization and Management

-Real-time Process data collection

-Real-time process statistics

-Real-time process monitoring

-Schematics visualization and analysis

-Reports Generation

- ➢ Performance Calculation and Analysis, this should be done on the following areas: Plant Performance, Unit Performance, Mass and Energy Balance (Boiler, Turbine, Feedwater Heater, Condenser, Cooling Tower, Air Pre-heater, Feedwater Pump, Condensing Pump, Circulating Pump, Induced Draft Fans, Force Draft Fans, and Primary Air Fans).
- ➢ Economical analysis and optimal operation guidance
- Calculate and compare between the actually controllable parameters and expected parameters to obtaining the energy losses
- Analyze the reasons of deviation by expert system, and providing the operation direction
- Primary Controllable Losses
- • Main Steam Pressure
- • Main Steam Temperature
- • Reheat Steam Temperature
- • Carbon Content of Fly Ash
- Primary uncontrollable Losses
- • RH Pressure Loss
- • Fuel Thermal Value
- • HP Turbine Efficiency
- Advanced Control Technology, for example:
- • To optimize the excess air in the combustion process to decrease CO emission
- • Calculate the best relationship between oxygen, air flow, coal supply, main steam flow and so on
- ➢ Online Performance Test
- • Boiler Performance Test
- • Turbine Performance Test
- • Condenser Performance Test
- • Air Pre-heater Leakage Test
- • Vacuum Leakage Test

## VIII. CONCLUSION

The paper set to show the weakness of depending on energy analysis only power plants as a performance measure that will help improve efficiency. Exergy analysis was undertaken at the thermal power plant which highlighted the areas that could be addressed to improve the efficiency. A recommendation of retrofitting and replacement was done for the system. On going work in development of intelligent power plant is expected to improve stability of steam headers, responsiveness to steam demand, increase power generation flexibility, minimize operations cost, improve overall plant efficiency, increase fuel cost savings and reduce $CO_2$ Emission.

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