Importance and Value of Predictive Approach for Boiler Operating Performance Improvement

M. Kljajić[*], D. Gvozdenac[*], S. Vukmirović[*]
[*] University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia
kljajicm@uns.ac.rs; gvozden@uns.ac.rs; srdjanvu@uns.ac.rs

***Abstract*—Energy waste detection as a reactive approach is not proper for high demanded, complex and intensive energy systems. Efficiency forecasting by analytic modeling is essentially preventive or proactive approach which leads to avoiding inefficiency.**

A comprehensive insight and added awareness, which presented approach enables, in combination with expert and soft computing assistance can locate, recommend and specify opportunities for increasing energy efficiency of boiler houses and reduce irrational energy use and related costs.

Presented analysis is led by finding possibilities how energy resources can be used wisely to secure more efficient final energy supply, to save money and limit environmental impacts. But the biggest problem and challenge are related to the stochastic nature and variety of influencing factors in energy transformation process. In that context, reliable prediction of energy output variation for expected influencing factors is very valuable.

The paper presents one method for modeling, assessing and predicting efficiency of boilers based on measured operating performance. The method implies the use of neural network approach to analyze and predict boiler efficiency. Neural network calculation reveals opportunities for efficiency enhancement and makes good insight into influencing factors onto boiler operating performance.

The analysis is based on energy surveys for randomly selected 65 boilers in the Province of Vojvodina carried out at over 50 sites covering the representative range of industrial, public and commercial users of steam and hot water. The sample formed in such a manner covers approximately 25% of all boilers in the Province of Vojvodina and provides reliability and relevance of obtained results.

Keywords: boiler efficiency; operating performance; neural nets; modeling; predicting.

I. INTRODUCTION

The consumers' area of Vojvodina can be considered as a rounded entirety. It covers the area of 21,506 km^2 on which 2,031,992 (2003) inhabitants live satisfying their energy needs for life and work by using the following primary energies: natural gas, liquid oil derivatives, coals, heating wood, and agricultural wastes, primarily from farming production.

Industrial, commercial and public companies and institutions are mostly run by old-fashioned energy technologies and energy intensive production technologies. Measuring and automation equipments are also old-fashioned and often inoperative. In the last ten years it is notable that there is a low level of investments in the energy sector. Inadequate maintenance additionally aggravates existing low energy efficiency which is expectable.

Above facts indicate that energy supplying processes are accompanied by high specific energy consumption per production/service unit and low energy efficiency. Not only is that it necessary to start again production capacities in some cases but also to reconstruct plants and installations. In order to improve energy efficiency, it is necessary to make investments which will produce benefits and energy savings on the long run. After resuming production/service capacities and essential rebuilding of plants and installations, investments in energy efficiency improvement are essential.

With right selection of plant, equipment and fuel, innovation of technology, better organization we can reduce costs and use resource and achieve higher quality in the supplying process. The next topics provide insight in such assessment.

A. Importance of energy efficiency

There are numerous reasons for the desire to improve energy efficiency in boiler operation but perhaps the most compelling one is wasted money for energy costs reflected in the balance sheet bottom line. In many cases, improvements can be made for low or no cost involving slight changes to the way a process or equipment is operated to optimize their performance rather than to purchase expensive equipment.

Saving energy has many benefits including:

- Reduced energy costs (increasing profits or releasing resources for other activities)
- Improved environmental performance due to reduced carbon dioxide emissions
- Improved competitiveness of products or services
- Enhanced public image with customers and other stakeholders
- Reduced exposure to Government drivers such as the Climate Change Levy.

II. OBJECTIVE OF ANALYSIS

Because of increasing fuel prices, industries, district heating companies and public institutions that use steam or hot water boilers for heating, process or power generation are hard-pressed to operate at peak efficiencies. While insufficient efficiency of heat energy production and distribution contributes to overall energy costs, efficiency analysis gains significance and puts into focus the heart of energy generator - a boiler.

The creation of relevant and comprehensive performance evidence for regional boiler plants population in the region of the Province of Vojvodina provides numerous possibilities for implementing energy management approach and for critical evaluation of accepted practices in the field of energy efficiency. A comprehensive insight and added awareness, which presented approach enables, in combination with expert and soft computing assistance can locate, recommend and specify opportunities for increasing energy efficiency of boiler houses and reduce irrational energy use and related costs.

A. Analysis approach

Steam and hot water are used throughout industry, commerce and the public sector for a wide range of processes and space heating requirements, and can represent significant proportion of the organization's energy costs. It is, therefore, important for owners and operators of boilers to ensure that the plant operates as efficient as possible and consequently reduce avoidable energy costs.

All sectors, industrial, commercial and public use efficiency as the basic performance indicator. However, defining, assessing and predicting energy efficiency is not easy, primarily because it is affected by more factors than anticipated. Therefore, the basic intention of the analysis is to apply neural network approach which can create necessary preconditions and guidelines for assessing and anticipating boiler operating performance.

The approach is designed with a capability for identifying, investigating and predicting possible influence factors which should be taken into account for a reliable energy efficiency analysis. The approach uses neural network computation which reveals opportunities for efficiency enhancement and makes good insight into influence factors for efficiency.

Also, the analysis alerts to the possibility of efficiency drop in heat energy production, and timely preconditions for suggesting effective measures to ensure efficiency of power plants.

B. Model formulation

Operating performance analysis is based on computational model which uses data from energy surveys and measurements in the group of randomly selected 65 boilers. The audit has been carried out at over 50 sites covering the representative range of industrial, public and commercial users of steam and hot water. The sample covers approximately 25% of all boilers in the Province of Vojvodina which provides reliability and relevance of obtained results.

For this purpose, 65 × 5 experimental measurements are collected (input parameters). About 300 of those are used as training data for neural network model and the rest (25) is used for testing.

Presented approach develops a model for assessing and predicting efficiency based on real (measured) operating performance. The approach understands the use of neural network model for analyzing and identifying operational scenarios which lead to peak efficiencies.

The significance of applied method is in providing extensive possibilities for identification of inefficiencies. Proposed approach can be effectively used to assess operating performance and find optimum operational regime. The significance is more noticeable in predicting the response of a complex energy system that cannot be easily modeled mathematically.

C. Auditing methodology

The first step is selecting necessary parameters for each site and particular boiler plant. Chosen relevant information and parameters are grouped into boiler nameplate information, boiler operational performance, occupation dynamic, capacity engagement, flue gas composition and state or conditions of the plant and its subsystems.

Techniques used to carry out each audit are: metering, internal monitoring records analysis, engineering calculations and specifics based on opinions of operational staffs in energy department of each company [3]. Through measurements, direct communications and interviews with a responsible person in the energy department of each company or institution and physical audit of the plant, necessary information is collected and organized in several categories in the following way:

- Common information about the company: Activity; Sector.
- Common information for selected boiler: Basic / Optional fuel; Boiler type (steam or hot-water boiler); Exploitation time (years); Boiler purpose (technology or heating); Capacity [t/h] and [MW]; Operational parameters [oC/bar]; Plant engagement (permanent, seasonal, etc).
- Boiler operational performance: The most usual load range regarding to nominal load capacity [%]; Annual working hours [h/a]; Specific fuel consumption [m3/h, kg/h].
- Measurement parameters: Flue gas temperature [oC]; Flue gas velocity [m/s]; Load range during the measuring of flue gas composition [%].
- Calculated performances: Flue gas flow rate [m^3/h]; Boiler efficiency according to GCV [%]; Boiler efficiency according to NCV [%]; Flue gas losses [%]; Annual fuel consumption [GWh/a]
- Combustion quality (flue gas composition): O2 [%] / λ [%]; CO2 [%]; SO2 [ppm]; CO [ppm]; NO [ppm]; NOX [ppm] and H2 [ppm]; MCO [kg/h] and MNOX [kg/h].
- Monitoring and control existence: Stationary and continuity oxygen control; Measurement of heat energy delivery rate; Flow rate measurement of boiler feed water and condensate return; Combustion quality control, etc.
- Control type: Manual; Semiautomatic; Automatic.
- Reconstruction and/or revitalization record: Burners and associated equipment; Heat recovery systems (economizer); Pipes; Automatic control equipment etc.

D. Overview of existing boiler operating performance

Overview of existing boiler operating performance in the Province of Vojvodina is carried out for selected sectors: industry, district heating systems and healthcare facilities. The main reason for adopting mentioned sectors arrangement is dominant contribution rate of large and middle scale boiler plants of these three sectors in the overall energy activities in the Province of Vojvodina. Similar, selected type of input fuel is only natural gas and heavy fuel oil, because of dominant sharing rate in fuel structure. The Fig.1 presents percentage distribution according to the sector structure and activity structure for industrial sector, where companies are structured according to their activities.

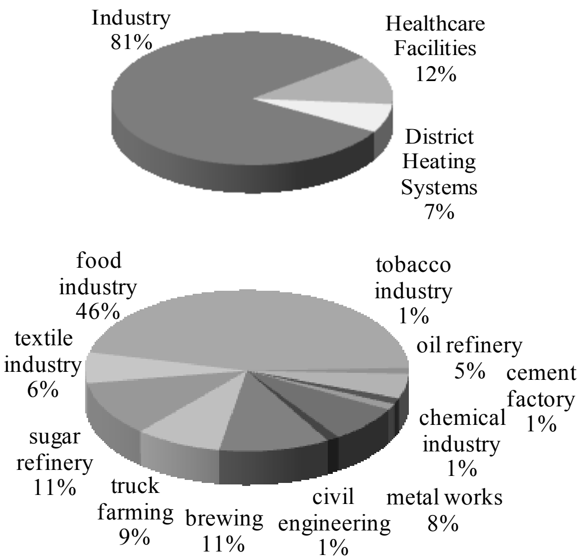

Figure 1. Distribution according to the Sector Structure and Activity Structure for Industrial Sector

Generally, in the Republic of Serbia, occupation dynamics and capacity engagement in energy departments are critical obstacles for reaching satisfactory energy efficiency [3]. By establishing reliable patterns for assessing rational use of energy, the energy audit includes information about operational character of the plant. For this purpose, for all sectors, the following categories are adopted and itemized by occupational intensity: permanent or seasonal operation, operation according to need, conserved, out of order, cut-off.

Similarly, fuel is structured for every sector and it is indicative that the dominant fuel types are natural gas and heavy fuel oil, and then sunflower shell, coal, combined sunflower shell and coal, light oil in much lower contribution rate.

Key results of measurements and calculations for the boiler population of the sample in the industrial sector, district heating systems and healthcare facilities are presented in the Table 1, structured by minimum, maximum and average values.

For configuration of input values, necessary for neural network model training, data from dominant categories in occupational intensity have been used such as: permanent or seasonal operation and operation according to need and fuel types: natural gas and heavy fuel oil.

TABLE I.
OVERVIEW OF EXISTING BOILER OPERATING PERFORMANCE

Value	Industrial Sector			District Heating Systems			Healthcare Facilities		
	Min	Av.	Max	Min	Av.	Max	Min	Av.	Max
Exploitation [years]	3	29	46	20	26	34	2	24	40
Capacity [MW]	0.4	10.5	81.6	6.8	14.0	23.0	0.5	2.6	6.7
Load range [%]	15	72	100	50	64	75	40	69	95
Oxygen content [%]	0.61	7.09	18.00	1.70	4.69	9.36	2.21	8.31	18.51
Efficiency [%]	60.1	87.8	94.0	85.5	91.3	97.6	61.1	86.0	93.4
Flue gas temp. [^{o}C]	115.3	203.3	330.8	49.3	135.1	203.5	136.3	199.1	284.8
Operating hours [h/a]	480	4,462	8,664	1,650	3,300	4,500	1,200	4,387	8,650
Fuel energy [GWh/a]	0.57	34.02	376.2	7.51	27.43	51.59	0.44	8.45	30.40

III. NEURAL NETWORK METHODOLOGY

The biggest problem in energy efficiency analysis is related to the stochastic nature of influencing factors. In such circumstances, adequate approach understands more accurately the prediction of energy output by variation of selected inputs. Neural network methodology enables reliable prediction which consequently allows planning and carrying out the necessary measures to reach mentioned goals.

Classic methods for forecasting include regression and state space methods. The more modern methods include expert systems, fuzzy systems, evolutionary programming, artificial neural networks and various combinations of these tools. Among many existing tools, neural networks have received much attention because of their clear model, easy implementation and good performance. Neural networks have become popular in various real world applications including prediction and forecasting, function approximation, clustering, speech recognition and synthesis, pattern recognition and classification, and many others [8].

MATLAB was chosen as the technical computing language for the ANN modeling and the Neural Networks Toolbox as predefined surroundings. A model of the boiler was developed, trained, tested and used in the MATLAB interactive environment, which is highly suitable for algorithm development, data visualization, data analysis, and simulative calculations.

A. Input and output parameters selection

To learn the network, a set of input-output data is needed. To learn the network based on known data, matched input and output parameters are used. These data include a series of input data that define operational conditions with the output data that define the efficiency of energy transformation.

Input and output parameters selection is carried out in accordance with specifics of boilers in a region and identified inefficiency thorough site surveys and measurements.

An output parameter is boiler's efficiency, defined as performance indicator. Selected input parameters are: type of fuel, type of boiler, exploitation period, nominal capacity, load range and oxygen content in flue gases.

B. *Learning network*

In multi-layer feed forward networks, input and output vectors are used for training the network. Network will learn to associate given output vectors with input vectors by adjusting its weights which are based on output error. The weight modification algorithm is the steepest descent algorithm (often called the delta rule) to minimize a nonlinear function. The algorithm is called back error propagation or back propagation because errors are propagated back through hidden layers [7].

The weights can be learned by training the network using a training set of target states for the output for a given set of inputs. The steepest descent algorithm essentially seeks to choose weights during training. The mean square error between the target output and the actual output of the network over all training data is minimized. Thus, the weights are chosen for output neurons so that the back propagation algorithm minimizes the mean square error for N training samples.

The neural network model used in this paper has one hidden layer with ten neurons. Activation function for all layers is Logarithmic a sigmoid transfer function.

C. *Neural Network architecture*

Several architectures of ANN were tested with different numbers of hidden layers and different numbers of neurons in layers. The first set of experiments showed that both one and two hidden layers produce similar results, so a network with one layer was adopted. After that, a new set of experiments were conducted to establish the correct number of neurons in layer. A range of layers with the number of neurons ranging from 5 to 30 were tested. Experiments showed that a network with ten neurons in hidden layers provided the best results. Final architecture or ANN is shown in Fig. 2.

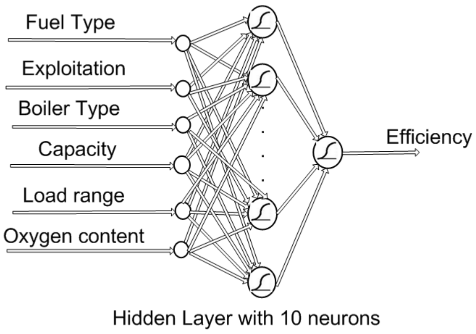

Figure 2 Architecture of proposed neural network

D. *Validation process*

The neural network model has been trained with 60 values in input and output values. As per recommended literature, ten percent of data have been used for validation purposes. We have limited the number of epochs to 100 but training was finished much earlier in all experiments. After few dozens of epoch errors on training, the set was less than 0.1%, which is acceptable taking into account precisions of input data. The error on verification set is less than 1 percents which suggests that trained neural network model can be used in exploration with data that are not used in training process.

The model was evaluated based on its prediction errors. The error measurement which is most commonly employed in ANN, and which was used in the evaluation of the results presented here, is the mean absolute percentage error (MAPE), which is defined as

$$\mathrm{MAPE} = \frac{\left| x_i - y_i \right|}{x_i} \times 100$$

Where xi is the actual values and yi is the predicted values at time instance i. MAPE calculated for test data is MAPE = 3.18%.

Accuracy of predictions can be enhanced by increasing the population of input parameters. In addition, as the input data can be attached to other boiler plant's data consequently increasing not only the network learning but also network accuracy. A greater number of samples have enabled better network training performance and more precise predictions of efficiency.

Larger deviations between the model results and the collected data are noticeable in ranges of operational characteristics with higher values of measured oxygen content in the flue gases or low plant load. During energy audits, data in these ranges appeared less frequently and consequently a smaller amount of data was collected and additionally these data were less useful for training the network.

IV. Value of the Approach

The value of the method can be assessed according to the potential for competent and reliable performance analysis and also according to the scope of method limitations. The analysis capability is described thorough following possibilities provided by the applied method:

1. Prediction of efficiency variation for different operating conditions and parameters.
2. Consideration of efficiency variation nature in accordance with any input changes.
3. Assessment of any particular previously defined input parameter onto influence potential.
4. Ranking of particular influence scaled input variable to efficiency.
5. Operating performance trend analysis.
6. Identification of reached amount of efficiency improvement for particular operate regime.

Relevance of the method is proven and confirmed by multiplicity testing process where model provided data are well matched actual data measured at the plant.

The lack of the method is a need for long and complex time-matched measurements of parameters requiring certain period of time.

Also, the method treats and covers only the most usual operating regime which creates less reliable prediction in the range of extreme variations of particular input parameters and boundary regimes. This limitation can be effectively exceed by further development of auditing procedures and spread of measurement to additional different and predefined operating regimes.

The results obtained correspond well with collected and measured results and the computational effort of the neural network method and time required in the analysis is acceptable. This achievement indicates that the neural network method can be used efficiently for predictions.

V. PREDICTION OF BOILER OPERATING PERFORMANCE

The prediction of boiler operating performance is carried out by formed neural network model and findings are arranged and structured in a form of sensitivity analysis. Operational performance examination carried out for selected variable input parameters are: nominal capacity, average operational load range and oxygen content in flue gases. Variation rate is 10% from baseline boiler performance. The fixed input parameter is exploitation period because years of exploitation do not have significance and consistent influence onto efficiency. The output parameter is efficiency.

The analysis introduces typical boiler specifications from formed sample which is used as a baseline boiler performance and characteristics. Boiler specifications include the following issues: 25 years of exploitation, capacity of 10 MW, average operational load range 69% and oxygen content in flue gases of 6.33%. Efficiencies, calculated by neural network model, for different boiler fuel and types are: efficiency of fired natural gas, which for a steam boiler is 90.20%, for natural gas and hot water boiler is 89.54%, for heavy fuel oil and steam boiler is 88.83% and for heavy fuel oil and hot water boiler is 89.74%. Fig. 3 and 4 show predicted operational performance from all studied configurations.

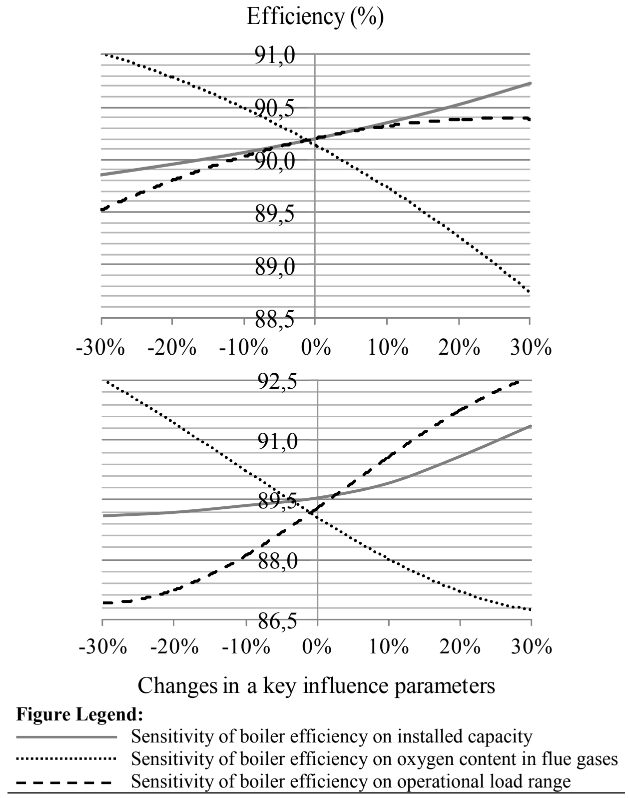

Figure 3 Natural gas fired, Steam (upper graph) and Hot water boiler (lower graph) - Sensitivity of Efficiency on Oxygen Content in Flue Gases, Installed Capacity and Operational Load Range for two Different Fuel and Types of Boilers

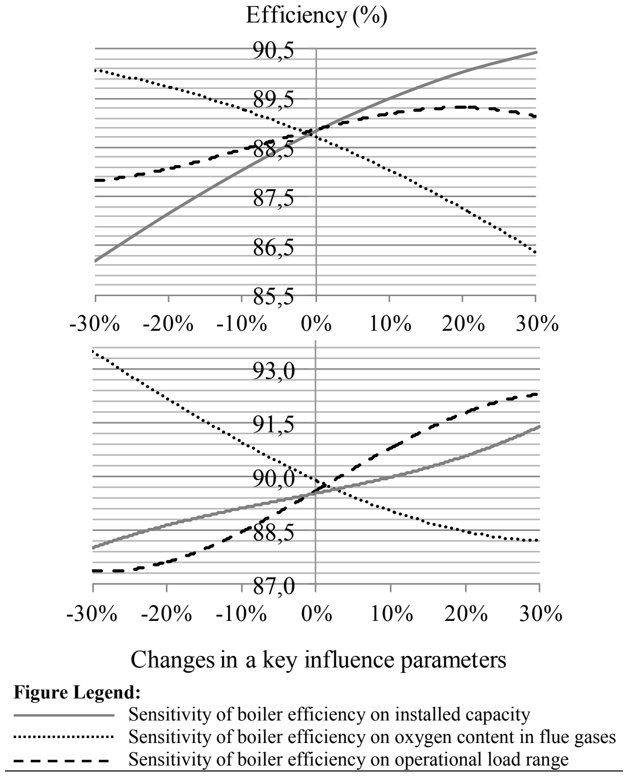

Figure 4 Heavy fuel oil fired, Steam (upper graph) and Hot water boiler (lower graph) - Sensitivity of Efficiency on Oxygen Content in Flue Gases, Installed Capacity and Operational Load Range for two Different Fuel and Types of Boilers

VI. PRACTICAL IMPLICATION

Currently, many opportunities for obtaining substantial energy efficiency improvements are not realized in the Province of Vojvodina in spite of availability of well known improvement methods and measures and necessary background data. Such a situation implicates the existence of space for implementation and valuable applications.

In terms of practicality, the ANN method can, in general, assist by indicating recommendations and guidelines for activities such as applying improved operational management and procedures, efficient use of a plant's equipment, improving maintenance of a plant's resources, establishing evidence and improved measurements, etc. Such activities can provide the preconditions for effective and systemic changes in all aspects of boiler house operations.

At the operational level, this approach raises the possibility of a more positive insight into the operational performance of a plant in circumstances where there multiple disturbances of input parameters occur simultaneously. Later on, it allows for a comprehensive analysis of resources the commitment of resources necessary for initiating and implementing systematic improvement measures and further development of operational procedures.

At a managerial level, forecasting operating performance is important for supporting the decision-making process in terms of frequent use of optional fuel as a result of fluctuations in energy prices or price parity on the open market or when certain types of fuels are periodically lacking.

At the sector level, this approach can contribute to the creation of new incentive programs at the state or provincial level, the promotion of new technological solutions, and to providing subsidies for the most urgent and effective investment, as well as many other possibilities.

Energy waste detection as a reactive approach is not proper for high demanded, complex and intensive energy systems. Efficiency forecasting by neural network method is essentially preventive or proactive approach which leads to avoiding inefficiency.

Predictive analysis with reliable and relevant obtained results can assist in recommending and specifying opportunities for reducing irrational energy use. For prediction, the neural network model can simulate wide scale of anticipated operational regimes and check efficiency for different favorable or undesirable values of input parameters.

VII. KEY CONSIDERATIONS

In all mentioned energy sectors, systemic solutions required for improving the current situation in the Republic of Serbia and also in the Province of Vojvodina do not exist. This particularly refers to the aspect of energy efficiency related to the introduction of energy management systems, modern energy and environmentally friendly technologies and regulatory activities aimed at improving the current situation.

General recommendations are the improvement of care (through better maintenance) for plant resources, existence and observing energy procedures, establishing evidence, measures and other activities which are aimed at systemic changes and continuous care for energy and energy plants and other aspects of boiler house operations. Such systematic approach in changing the situation and attitudes towards these issues is both important and necessary. The change is equally important and indispensable not only for the community itself but also for end users of final energy [4].

In the Republic of Serbia and also in the Province of Vojvodina, investments in energy efficiency are still a great challenge for local authorities, policy makers and business leaders. Very few public or commercial companies are aware of business benefits generated by efficient energy use and how it can help to cut costs and keep them ahead of their competitors.

The neural network method can assist in mentioned regional environment by recommendations and guidelines for activities such as applying improved operational management and procedures, efficient use of plant's equipment, improving of care for plant's resources, establishing evidence and improved measurements, etc.

Such activities open preconditions for effective and systemic changes and continuous care for energy and energy plants and other aspects of boiler house operations.

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