V International Scientific and Technical Conference Actual Issues of Power Supply Systems

Development of a Package of Energy-Saving Measures and a Technical and Economic Assessment of Their Effectiveness

AIPCP25-CF-ICAIPSS2025-00398 | Article

Development of a Package of Energy-Saving Measures and a Technical and Economic Assessment of Their Effectiveness

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Abstract. This article presents the results of an energy audit of heating systems in Uzbekistan. A list of measures was developed to reduce fuel and energy consumption and improve the overall efficiency of equipment operation. The article examines actual measurement data, the results of energy balance analysis, and identified technical and organizational shortcomings in equipment operation.

INTRODUCTION

In the context of implementing state policy on energy conservation and improving energy efficiency in the Republic of Uzbekistan, particular attention is paid to heating systems as major consumers of fuel and energy resources. An energy audit is our primary tool for comprehensively assessing the current state of energy consumption, identifying losses, and determining ways to improve resource efficiency [1-4]. Given rising energy tariffs, the need to reduce the carbon footprint, and the importance of enhancing the competitiveness of utility infrastructure, the rational use of energy is becoming particularly significant. Central heating plants within heating systems are among the largest consumers in urban areas, and their efficiency directly impacts the overall energy expenditure at the scale of a metropolis [5-9]. Over the last decade, electricity generation from wind farms has gained enormous importance worldwide and has reached a point where it has a significant impact on the energy supply in many countries, both in terms of installed capacity and in terms of the annual share of energy produced. Thus, installed capacity (Fig.1) has increased by approximately 100-200% since 2010. According to statistics, 20-30% of consumed energy can be lost due to equipment wear and tear, lack of automation, insufficient thermal insulation, suboptimal boiler operating modes, and improper operation of water treatment and circulation systems. The following methods are employed [10-14]:

- Direct measurement (where metering devices are installed);
- Calculated equivalents (where data is unavailable - standards and specifications are used);
- Energy coefficients (efficiency, loss coefficients, specific consumption rates);
- Comparative analysis with data from previous years and industry standards.

1. Calculation of Input Energy. The energy input from fuel is calculated using the following formula:

$$Q_{in} = VU_{lh} \quad (1)$$

Where, Q_{in} - Thermal energy supplied with the fuel, kWh; V - Volume of fuel consumed, m^3 (for natural gas); U_{lh} - Lower heating value of the fuel, kWh/m^3.

2. Calculation of Useful Energy. The heat produced (hot water) is determined by the following formula:

$$Q_{useful} = Gc(T_{out} - T_{in}) \quad (2)$$

Where, Q_{useful} - Useful heat, kWh; G - Flow rate of the heat transfer medium, t/h; c - Specific heat capacity; T_{out}, T_{in} - Outlet and inlet temperatures.

3. Loss Calculation. Heat losses through flue gases are calculated using the following formula:

$$Q_{loss} = Q_{in} - Q_{useful} \quad (3)$$

The following are also considered:
- Radiation and convection losses (thermographic measurements);
- Heat transfer fluid leaks;
- Idle operation;
- Underloading of equipment.

4. Calculation of Boiler and Unit Efficiency. Actual efficiency (η) is calculated using the following formula:

$$\eta = \frac{Q_{useful}}{Q_{in}} \cdot 100\% \quad (4)$$

Balancing Data by Facility. All data for each boiler and boiler house is summarized in tables. The following graphs are also created:
- Sankey diagrams;
- Pie charts of proportions;
- Bar charts of specific consumption.

Units of Measurement and Conversion to Fuel Equivalent. For ease of analysis and comparison, all energy parameters are converted to consistent units:
- Thermal energy - in Gcal or kWh;
- Gas - in m^3, then in kWh or in tonnes of conventional fuel (tce) (Table 1);
- Electricity - in kWh.

Everything is converted to tce using the following coefficients:

TABLE 1. Conversion of Units of Measurement to tce

Energy Resource	tce Coefficient
1000 m^3 Natural Gas	1.16 tce
1000 kWh Electricity	0.123 tce
Gcal Heat	0.143 tce

EXPERIMENTAL RESEARCH

Measurement Methods and Equipment Used. To ensure objective and reliable energy audits, measurements were taken in accordance with ISO 50002:2014, GOST 32144-2013, and other Uzbek standards [15-19].

Measurements included [20-24]:
- Fuel consumption;
- Temperatures of heat transfer fluid, air, and structures;
- Flue gas composition;
- Electrical parameters (voltage, current, power factor);
- Power quality (THD, harmonics);
- Ventilation and water supply parameters;
- Building and pipeline heat losses.

Main Types of Measurements [25-29].

1. Temperature Measurements – of water, steam, gas, air, return flow, and equipment;
2. Flue Gas Analysis – measuring O_2, CO, CO_2, calculating efficiency, and determining excess air;
3. Vacuum and Pressure Measurements – in the furnace, stack, and under burners;
4. Water and Gas Flow Measurements – using meters and an ultrasonic flowmeter;
5. Thermographic Inspection – to identify heat loss;
6. Electrical Measurements – current, voltage, active/reactive power, power factor;
7. Power Quality Analysis:
- Phase voltages and currents;
- THD (Total Harmonic Distortion);
- Harmonics up to the 50th order;
- Power factor and phase unbalance;

- Voltage dips and surges;
- Total, active, and reactive power.

Applied Formulas:

1. Boiler Efficiency (from Flue Gas Analysis):

$$\eta = 100 - q_2 - q_4 - q_5 - q_6 \quad (5)$$

where: q_2 - losses with exhaust gases, q_4 - losses from incomplete combustion, q_5 - mechanical incomplete combustion, q_6 - losses from radiation and convection.

2. Heat Losses from Thermography:

$$Q = \lambda \cdot \frac{T_{surf} - T_{air}}{\delta} \cdot A \cdot t \quad (6)$$

where: λ - thermal conductivity (W/m·^{0}C); T_{surf} - surface temperature; T_{air} - ambient temperature; δ - wall thickness; A - area; t - time.

3. Water Mass Flow Rate:

$$G = \rho \cdot A \cdot v \quad (7)$$

where: G - mass flow rate (kg/s); ρ - density (kg/m^3); A - pipe cross-sectional area (m^2); v - flow velocity (m/s).

A list of buildings and premises was compiled to conduct the instrumental survey, and Table 2 provides information on the purpose of the buildings, their total area, and their letter designations according to the enterprise's technical passport. This data is used for further calculations of thermal energy consumption and for the assessment of energy efficiency [30-36].

TABLE 2. List of Buildings and Premises

№	Building name	Area (m^2)	Code
1	Production Workshop №1	7316	0001 A
2	Gatehouse	49	0005 B
3	Boiler House	701	0021 C
4	Warehouse	74	0006 D
5	Fuel Oil Preparation Building	480	0008 E

The total area of buildings and structures is 8,620 m^2, and the composition and distribution of building areas are considered when analyzing thermal loads, calculating the heat energy requirement for heating, and developing recommendations for energy efficiency [37-41].

As part of the energy audit conducted at the combined heat and power plant in July 2025, instrumental measurements were taken of boiler unit №1, a PTVM-50 type (manufactured in 1979). The boiler operates on natural gas and is equipped with 12 gas burners, each with a nominal capacity of 600 m^3/h. Air is supplied by V-Ts14-46 №4 fans, with a total of 12 units per boiler, each with a nominal capacity of approximately 7000 m^3/h.

During the instrumental survey of boiler unit №1, electrical parameters of the feed motors for the forced draft fans were measured. Phase currents, supply voltage, and power factor (*cosφ*) were measured, and used to calculate the actual power consumption of each fan. The obtained values were compared with the rated power of the electric motors, allowing for an assessment of the equipment load and identification of potential deviations from normal operating conditions [42-45].

The measurements revealed that the forced draft fans of boiler unit №1 are operating within normal parameters, with motor loading ranging from 59% to 91% of their rated power. This indicates that some motors are operating with a power reserve, which positively impacts equipment lifespan by reducing the risk of overheating and premature wear. The total electrical power consumption of the fans was 15.9 kW, which aligns with calculated values for this type of equipment. No overloads or abnormal deviations were detected in the operation of the electric motors, and the system is functioning stably [46-49].

To improve energy efficiency, it is recommended to consider implementing variable frequency drives (VFDs). This would allow for flexible adjustment of fan performance based on current demand and reduce excessive energy consumption [50-51].

Parameters recorded during measurements:

Boiler №1:

- Water flow through the boiler: 850 t/h;
- Water temperature before the boiler: 38.2^{0}C;
- Water temperature after the boiler: 61.9^{0}C;
- Gas flow: 2780 m^3/h at a pressure of 0.22 kgf/cm^2;

- Water pressure: inlet: 14.2 kgf/cm^2, outlet: 10.8 kgf/cm^2.

Based on instrumental measurements, the boiler's useful thermal output was calculated. Gas consumption during the survey period was 2,780 m^3/h, taking into account the net heating value of natural gas, equal to 8,114 kcal/m^3.

Therefore, the fuel heat input to the boiler furnace was determined to be:

$$Q_{fuel} = V_{gas} \cdot q_{nr} = 2780 \cdot 8{,}114 = 22{,}55\ Gcal/h \quad (8)$$

The boiler's useful thermal output was calculated based on water flow rate and its inlet and outlet temperatures. With a feed rate of 840 t/h, heated from 61^{0}C to 74.4^{0}C, the heating output was:

$$Q_{floor} = G \cdot c \cdot \Delta T = 850 \cdot 1 \cdot (61.9 - 38.2) = 20{,}15\ Gcal/h \quad (9)$$

Where: G is the water flow rate, t/h; c is the specific heat capacity of water, assumed to be 1 kcal/kg·^{0}C; ΔT is the difference in water temperature at the boiler inlet and outlet.

The boiler efficiency (COP) is defined as the ratio of the useful thermal power to the fuel heat input:

$$Q = \frac{Q_{floor}}{Q_{fuel}} \cdot 100\% = \frac{20.15}{22.52} \cdot 100\% = 89\% \quad (10)$$

RESEARCH RESULTS

Thermal imaging surveys of the boiler surfaces revealed that the temperature of the outer walls in various areas ranged from 47^{0}C to 102^{0}C. The average values ranged from 65-75^{0}C; however, localized overheating points reaching 100-102^{0}C were observed, indicating significant heat loss through the insulation layer [52-55].

Particularly high temperatures were observed at joints and connections, where the thermal insulation had partially lost its properties. The temperature difference between the coldest and hottest spots reached 50^{0}C, indicating unevenness of the thermal insulation coating. Thermogram data confirm that the current thermal insulation thickness is insufficient. To reduce heat loss and bring boiler operation into compliance with energy efficiency requirements, it is recommended to increase the thermal insulation layer on the boiler surface by 5-10 cm and perform localized restoration of the insulation coating in areas with maximum losses [56-60].

Implementing these measures will reduce heat loss to the environment, decrease specific fuel consumption, and improve the overall efficiency of the boiler units.

As part of the energy audit, instrumental measurements of the pump operating parameters were taken, including power consumption, pressure, flow rate, and water temperature. Additionally, a thermal imaging inspection of the electric motors and pump housings was performed to identify localized overheating and assess the condition of the insulation [61-65].

Particular attention was paid to the electric motor load factor, the operating efficiency of the pump units in various modes, and the presence or absence of automatic control systems (frequency converters, pressure regulators). The results obtained allow us to assess the compliance of actual parameters with rated specifications and identify areas for improving energy efficiency.

As part of the energy audit at TC-3, instrumental measurements and an analysis of the network pumps were conducted. Pumping equipment is one of the main consumers of electrical energy and directly impacts the reliability and efficiency of heat supply. The survey assessed the actual electrical parameters of the operating pump, its compliance with rated specifications, and the level of electric motor load (Table 3) [66-69].

TABLE3. Specifications of the SN-1 network pump

Pump brand	Flow rate, m^3/h	Head, mwc	Motorpower, kW	Voltage, V	Speed, rpm
CT 1000-180x2	1000	180	630	6000	1500

TABLE 4. Calculated pump operating parameters during inspection

Flow rate, m^3/h	Head, m	Motor efficiency	cosφ	Load, %	Current, A
1090	180	0,90	0,85	94	67

Analysis revealed that during the inspection of the SN-1 network pump, the actual water flow rate was 1,090 m^3/h at a head of 180 m. The 630 kW electric motor operated at approximately 90% load, with a power factor ($cos\varphi$) of 0.85. The calculated current consumption was 64 A, which is below the nominal value (71.2 A), confirming the absence of overload. Overall, the pump's operation complies with technical requirements; however, the high load level requires systematic monitoring and regular control to prevent overloads [70-72].

As part of the instrumental inspection of the TC-3 pumping equipment, thermal imaging measurements of the electric motors of the network pumps were conducted. Thermal imaging was performed under normal operating conditions while the pumps were operating at full load. The purpose of the inspection was to assess the thermal state of the electric motors, identify localized overheating, and determine whether the actual temperature conditions comply with regulatory requirements [73-74].

CONCLUSION

With an annual operating time of 4,320 hours for boiler #4 and an actual hourly fuel consumption range of 3,400-5,000 m^3, the estimated savings at 0.5% range from 73,400 m^3/year to 108,000 m^3/year. The average fuel savings are estimated at approximately 90,700 m^3/year.

With each boiler operating for 4,320 hours annually and an hourly natural gas consumption range of 3,400-5,000 m^3, the estimated fuel savings from a 2% efficiency increase for one boiler range from 293,800 m^3/year to 432,000 m^3/year, and for two boilers combined, from 587,500 m^3/year to 864,000 m^3/year. The average expected savings are estimated at approximately 726,000 m^3 of natural gas per year.

Adjusting the burner units of PTVM-50 boilers №1 and №2 to achieve the excess air coefficient (λ=1.2-1.3) reduces heat loss with exhaust gases and lowers specific fuel consumption. With each boiler operating for 4,320 hours annually and an actual hourly natural gas consumption range of 1,500-3,000 m^3, the estimated savings from implementing this measure for one boiler range from 32,400 m^3/year to 64,800 m^3/year. When calculated for two boilers, the expected effect ranges from 64,800 m^3/year to 129,600 m^3/year, which equates to approximately 97,200 m^3 of natural gas per year.

Restoring and increasing the thermal insulation layer on TC-3 boilers with localized surface overheating of up to 100-102^{0}C will reduce heat loss and reduce excess fuel consumption. With actual annual natural gas consumption in 2024 at 94,168.9 thousand m^3, the estimated savings potential from implementing this measure is approximately 470.8 thousand m^3 of natural gas per year, confirming its technical feasibility and effectiveness.

Installing variable frequency drives (VFDs) on the blower fans of PTVM-100 boilers №4 and №5 will optimize the operation of the fan equipment and reduce excess energy consumption under variable loads. With each boiler operating for 4,320 hours per year, with four to eight blower fans per unit, and an installed fan capacity of 5.5-11 kW, the estimated annual energy savings for the two boilers total between 19,000 and 76,000 kWh, or approximately 47,500 kWh per year. Implementation of this measure is technically feasible and ensures a sustainable reduction in operating energy costs.

Scheduled maintenance of blower fans, including bearing inspection and replacement, lubricant renewal, and cooling system maintenance, reduces mechanical losses and increases equipment reliability. The estimated savings from implementing this measure are approximately 14,700 kWh per year, confirming the technical feasibility and effectiveness of this solution.

Restoring locally damaged sections of pipeline and heat exchanger insulation reduces surface heat loss and ensures a stable thermal regime. With an annual thermal energy production of 669,407 Gcal and an assumed savings potential of 2%, the estimated savings are approximately 13,388 Gcal per year, equivalent to approximately 1,650,000 m^3 of natural gas.

A major overhaul of Storage Tank №2, including restoration of the protective coating and thermal insulation, will reduce surface heat loss and improve thermal energy storage efficiency. With an annual heat output of 393,839 Gcal and a 0.5% loss reduction potential, the estimated savings are approximately 1,969 Gcal per year, equivalent to approximately 243,000 m^3 of natural gas per year.

Replacement and restoration of damaged thermal insulation on the pipelines will reduce surface heat loss and improve the energy efficiency of the equipment. With an annual heat output of 393,839 Gcal and a 1% loss reduction potential, the estimated savings are approximately 3,938 Gcal per year, equivalent to approximately 485,000 m^3 of natural gas per year. This project is technically and economically feasible and will significantly reduce fuel costs.

Carrying out a major overhaul of the KVGM-180 №1 boiler with the restoration of thermal characteristics and the elimination of operational defects will increase the unit's efficiency and reduce specific fuel consumption. With an hourly natural gas consumption of 5,000-8,000 m^3/h and an annual operating time of 4,320 hours, the actual annual consumption ranges from 21.6 million to 34.6 million m^3/year. With an increase in efficiency by 2%, the estimated fuel savings will range from 432.0 thousand m^3/year to 691.2 thousand m^3/year. The average expected effect is estimated at approximately 568.3 thousand m^3 of natural gas per year, which confirms the technical and economic efficiency of this implementation.

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