



ARTICLE

Temporal Simulation of Boiler Efficiency Projects for Environmental Performance in Industrial Facilities

Rumana Subnom^{1,*}, Bibek Prajapati², Zhichao Liu², Hailin Li¹ and Bhaskaran Gopalakrishnan²

¹Mechanical, Material and Aerospace Engineering, West Virginia University, Morgantown, WV, USA

²Industrial and Management Systems Engineering, West Virginia University, Morgantown, WV, USA

*Corresponding Author: Rumana Subnom. Email: rs00081@mix.wvu.edu

Received: 04 June 2026; Accepted: 06 July 2026; Published: 18 October 2026

ABSTRACT: Industrial facilities are under increasing pressure to reduce energy consumption, lower greenhouse gas emissions, and demonstrate measurable progress toward sustainability and environmental-performance goals. Boiler and steam systems are major fuel consuming assets in many facilities, yet facility managers often lack accessible tools for comparing the energy, cost, and emissions impacts of alternative boiler-efficiency measures before implementation. This study develops an Excel Visual Basic for Applications (VBA) based temporal simulation tool for evaluating boiler energy efficiency projects under facility specific operating conditions. The model estimates baseline boiler energy use and CO₂ emissions from user defined operating parameters, applies selected efficiency measures from specified implementation dates, and calculates daily and annual changes in fuel consumption, energy cost, and carbon emissions. Nine scenarios were evaluated, including eight individual boiler-efficiency measures and one combined scenario. Under the selected baseline operating conditions, condensate recovery produced the largest energy reduction among the individual measures, followed by burner replacement, air-fuel ratio optimization, steam pressure reduction, blowdown heat recovery, blowdown rate reduction, flue gas heat recovery, and insulation of exposed hot surfaces. The combined scenario, which incorporated condensate recovery, air-fuel ratio optimization, and steam pressure reduction at different implementation dates, produced the highest overall savings. The model was verified using 12 months of natural gas utility bill data from a manufacturing facility. The simulated annual energy consumption differed from the utility bill total by 1.48%, while monthly absolute percentage errors ranged from 1.48% to 12.09%. These differences were attributed to production variation, weather effects, simplified load factor assumptions, and real world operating variability. The proposed tool provides a transparent and low cost decision support framework for preliminary boiler project evaluation, energy savings estimation, emissions accounting, and ESG oriented environmental performance tracking.

KEYWORDS: Boiler efficiency; excel VBA simulation; industrial energy management; carbon emissions reduction; utility bill validation

1 Introduction

Industrial facilities are under increasing pressure to reduce energy consumption, lower greenhouse gas emissions, and demonstrate measurable progress toward sustainability and environmental performance goals. Industrial sector emissions include both direct emissions from on site fuel combustion and indirect emissions associated with purchased electricity, making energy use a central target for emissions reduction [1]. Sustainability disclosure standards also require companies to report climate related risks, opportunities, performance, and progress toward climate related targets, increasing the need for measurable energy and emissions indicators [2].

Boiler and steam systems are important targets for industrial energy efficiency improvement because they are widely used for process heating, space heating, hot water generation, and in some cases, power generation. Boiler performance depends on several operational and design parameters, including steam pressure, stack temperature, O₂ concentration in flue gas, feedwater temperature, blowdown rate, condensate return, burner performance, insulation condition, operating schedule, and load variation. Because boilers often consume substantial amounts of fuel, even moderate efficiency improvements can produce meaningful reductions in energy use, operating cost and carbon emissions [3].

Several boiler efficiency measures are commonly used in industrial practice, including air-fuel ratio optimization, burner replacement, steam pressure reduction, blowdown rate reduction, blowdown heat recovery, condensate recovery, flue gas heat recovery, and insulation of exposed hot surfaces. These measures affect different components of boiler energy loss and may vary substantially in their savings potential depending on baseline operating conditions. Therefore, facility managers need practical tools that can compare multiple efficiency options under site specific conditions before implementation.

Although boiler-efficiency calculation methods and individual energy saving measures are well established, many facilities still lack simple and transparent tools for evaluating the combined effect of different measures over time. Existing energy management and sustainability reporting tools often focus on historical energy tracking, aggregate emissions reporting, or annual performance indicators. However, facility managers frequently need forward looking decision support that can estimate how much fuel, cost and CO₂ emissions can be reduced if specific boiler projects are implemented on different dates during the year. Static annual calculators are limited for this purpose because they do not represent daily load variation, project timing or the cumulative effect of multiple operational changes.

Utility bills provide an important independent basis for checking whether simulated energy use is realistic, because they reflect actual facility consumption under site specific weather, production, and operating conditions. However, monthly utility bills are too aggregated to directly represent the effects of boiler level parameters such as stack oxygen, steam pressure, feedwater conductivity, blowdown rate and condensate recovery. Therefore, a practical simulation framework should estimate energy consumption from operational and design parameters, while using utility bill data for verification rather than direct model fitting [4].

This study develops an Excel VBA-based temporal simulation tool for evaluating the energy, cost, CO₂-emission and environmental performance impacts of boiler-efficiency projects. The tool estimates baseline boiler energy consumption using user defined operating parameters and daily load factor adjustment, applies selected efficiency measures from specified implementation dates and calculates daily and annual changes in fuel consumption, energy cost and CO₂ emissions. The model is verified using 12 months of natural gas utility bill data from a manufacturing facility. The contribution of this work is engineering oriented and application driven. It integrates boiler loss modeling, date specific implementation of efficiency measures, daily load-factor adjustment, cost and emissions accounting, ESG (Environmental, social, & Governance) oriented environmental performance estimation, and utility bill verification into a transparent decision support framework. The proposed model is intended for preliminary boiler project evaluation, scenario comparison and environmental performance tracking in industrial facilities.

2 Background and Related Work

2.1 Boiler Efficiency, Industrial Energy Performance, and Emissions Reduction

Manufacturing facilities are major energy consumers and therefore play an important role in reducing greenhouse gas (GHG) emissions and improving sustainability performance. Energy-efficiency improvement is one of the most practical strategies for industrial facilities because it can reduce fuel consumption,

operating cost and environmental impact without necessarily reducing production output. From an ESG-oriented environmental-performance perspective, energy consumption and carbon emissions are among the most measurable and actionable indicators for industrial facilities. Prior studies have also shown that environmental improvement can support economic performance through cost reduction, risk reduction, innovation, and market advantage [5]. Ref. [6] further showed that corporate sustainability practices can influence organizational processes and long-term performance. More recent ESG research has emphasized materiality, where the relevance of each ESG factor depends on the industry and operating context [7]. For industrial facilities, this makes energy and emissions reduction a practical engineering pathway for improving environmental performance.

Recent ESG literature further supports the need to connect broad sustainability objectives with measurable, sector-specific performance indicators. Ref. [8] developed a sector-specific ESG-SDG indicator system and showed that ESG indicators should be connected to practical sustainability objectives, implementation challenges, and sector-level operating conditions. Similarly, Ref. [9] reviewed ESG disclosure research and identified environmental performance, sustainability reporting frameworks, regulatory requirements, corporate governance standards, firm performance, and market outcomes as major themes in ESG reporting. From a risk and sustainable-finance perspective, Ref. [10] showed that ESG research is increasingly linked with resilience, risk management, performance evaluation, and value creation. In addition, Ref. [11] also highlighted the growing role of digitalization in ESG research, suggesting that digital and data-driven tools can support ESG-related measurement, reporting and decision making. These studies indicate that ESG-oriented assessment is moving beyond general corporate reporting toward measurable indicators that can support operational decision making. In industrial facilities, boiler energy use and CO₂ emissions serve as practical environmental performance indicators because they are directly connected to fuel consumption, operating cost and emissions reduction actions. Therefore, a boiler level simulation tool that quantifies energy savings, cost savings, and CO₂ reductions can support ESG-oriented environmental performance tracking by linking engineering interventions with measurable sustainability outcomes.

Boiler and steam systems are important targets for industrial energy efficiency improvement because they are widely used for process heating, space heating, hot water generation and power related applications. Boiler performance depends on several operational parameters, including steam pressure, stack temperature, O₂ concentration in flue gas, feedwater temperature, blowdown rate, condensate return, burner condition, insulation quality, operating schedule and load variation. Since boilers often consume substantial amounts of fuel, even moderate improvements in boiler efficiency can produce meaningful reductions in energy use, operating cost and CO₂ emissions.

Boiler efficiency is commonly evaluated using direct and indirect methods. The direct method estimates efficiency by comparing the useful heat absorbed by the working fluid with the heat supplied by the fuel. This approach is simple and useful for quick performance evaluation, but it does not identify individual sources of energy loss. Ref. [12] applied the direct method for boiler-efficiency analysis in a thermal power station, while ref. [13] used direct efficiency calculations for a 220 MW steam power plant. In contrast, the indirect method estimates boiler efficiency by quantifying individual heat losses and subtracting them from the total fuel input. These losses may include stack loss, blowdown loss, shell loss, radiation and convection loss, moisture-related loss, and other miscellaneous losses. ASME PTC 4 provides a standardized basis for evaluating fired steam generators using loss-based performance principles [14]. Ref. [15] developed a mathematical model of a steam boiler room that considered multiple thermal losses, including flue-gas enthalpy, surface losses, blowdown losses and deaeration related losses. Ref. [16] modeled time-varying boiler efficiency using indirect-method principles and experimental data, showing that boiler performance can be represented

through measurable operating variables. Ref. [17] also emphasized that the indirect method provides higher diagnostic value, although it requires more detailed measurements.

For scenario-based boiler simulation, the indirect method is especially useful because it links changes in operating parameters to specific loss components. For example, stack oxygen affects excess air loss, feedwater conductivity affects blowdown loss, steam pressure affects enthalpy requirements, and exposed surface insulation affects radiation and convection losses. This makes loss based modeling suitable for evaluating how different boiler-efficiency measures influence fuel consumption, cost and carbon emissions.

Several boiler-efficiency measures have been studied and implemented in industrial energy management practice. Combustion related measures, including air-fuel ratio optimization, burner replacement, and improved burner control, can reduce stack losses and improve fuel utilization. Ref. [3] identified high air-fuel ratios and high flue-gas temperatures as major contributors to boiler energy losses. Ref. [18] discussed low NOx burner applications for boilers, furnaces, and gas turbines, while ref. [19] examined energy-efficient burner systems for heat treatment furnaces. These studies show that combustion system improvements can support both energy savings and emissions reduction.

Heat recovery measures also represent important opportunities for boiler energy savings. Feedwater preheating and flue gas heat recovery use economizers or related heat-recovery devices to transfer heat from exhaust gases to incoming feedwater or combustion air. Ref. [20] reported that feedwater economizers can reduce fuel use in many industrial boiler applications. Ref. [21] also discussed the integration of transient waste heat into the water-steam cycle to improve steam production and system performance. Similarly, condensate recovery reduces the need for cold makeup water by returning thermal energy already supplied to the steam system. Ref. [22] identified condensate return and steam system improvements as important energy saving opportunities in industrial steam systems, and Ref. [3] noted that steam trap monitoring and condensate recovery can reduce steam losses and improve system efficiency.

Blowdown control, blowdown heat recovery, and insulation address additional loss mechanisms. Boiler blowdown is required to control dissolved solids and prevent scaling, foaming, and corrosion; however, excessive blowdown removes hot water from the boiler system and increases both water and heat losses. Ref. [23] discussed boiler blowdown energy recovery, while ref. [24] analyzed energy losses caused by boiler blowdown. Insulation of exposed hot surfaces can reduce radiation and convection losses from boiler shells, steam pipes, valves, and fittings. Ref. [25] quantified heat losses from steam-boiler surfaces and evaluated the energy-saving and payback potential of insulation, while ref. [26] examined the effect of boiler-part insulation on energy savings. Although the relative impact of each measure depends on site-specific operating conditions, these studies provide the technical basis for evaluating boiler-efficiency scenarios using a parameter-driven simulation model.

2.2 Environmental and Social Governance in Organizations

ESG has become an important framework for evaluating how organizations manage their environmental responsibilities, social relationships, and governance practices. In organizational settings, ESG is not limited to corporate reputation or investment screening; it increasingly represents a structured way to measure operational performance, disclose sustainability progress, manage risk, and communicate accountability to stakeholders. The environmental dimension generally includes energy use, greenhouse gas emissions, pollution, waste management, water stewardship, biodiversity impact, and resource conservation. The social dimension includes employee health and safety, labor practices, human rights, diversity, community relationships, customer responsibility, and supply chain impacts. The governance dimension includes board oversight, internal controls, transparency, audit practices, executive compensation, shareholder rights, ethics, and regulatory compliance [27–30].

For industrial organizations, ESG is especially relevant because environmental performance is closely connected to measurable engineering variables such as fuel consumption, electricity use, thermal losses, carbon emissions, waste generation, and water use. Unlike some qualitative ESG indicators, energy and emissions can be quantified directly and linked to specific operational decisions. This makes energy-efficiency projects a practical pathway for improving the environmental component of ESG performance. Boiler and steam system improvements are particularly relevant in this context because boilers are fuel intensive assets, and changes in combustion efficiency, condensate recovery, blowdown control, insulation, heat recovery, and steam pressure can directly affect natural gas consumption, operating cost, and CO₂ emissions.

Recent ESG studies also show that ESG has moved from a voluntary or ethical concern toward a broader business and policy issue. Ref. [31] argued that ESG considerations increasingly influence global business practices, policy formulation, consumer expectations, market behavior, and investment decisions. Ref. [32] further examined ESG factors in relation to investment returns of American companies and showed the growing importance of ESG indicators in evaluating financial performance and long-term value. Similarly, Ref. [33] reviewed the relationship between ESG performance and firm risk, highlighting that ESG is increasingly viewed as a risk management and strategic performance issue rather than only a sustainability reporting activity. The Nature Portfolio collection on ESG impacts and risks also reflects the growing research attention to ESG practices in relation to sustainable development, industry, innovation, infrastructure and climate action [34].

At the organizational level, ESG implementation requires more than setting broad sustainability goals. Companies must identify material ESG topics, collect reliable data, validate performance indicators, monitor progress and prepare transparent reports for internal and external stakeholders. Professional ESG guidance and consulting organizations emphasize that many companies struggle with ESG data quality, authenticity, materiality assessment, operational integration, leadership accountability and stakeholder trust [29]. These challenges are particularly important for industrial facilities because facility level energy data may be distributed across utility bills, equipment logs, production schedules, maintenance records, and engineering calculations. Without a transparent calculation framework, it can be difficult to connect reported environmental improvements with specific operational actions.

The increasing availability of ESG and sustainability software also shows the growing demand for data-driven ESG management. Current ESG software platforms commonly support data collection, metric tracking, reporting, compliance management, audit trails, carbon accounting, data validation, dashboard visualization, and risk management [35–37]. These tools help organizations organize sustainability information and prepare reports, but many are broad corporate level platforms rather than engineering specific calculation tools. For industrial energy applications, there remains a need for transparent facility level tools that connect equipment-level changes with measurable environmental outcomes.

This study is positioned within that practical need. The proposed boiler efficiency simulation tool does not attempt to calculate a complete ESG score because social and governance factors are outside the scope of the model. Instead, it provides an ESG oriented environmental performance indicator based on quantifiable reductions in boiler energy use and CO₂ emissions. By linking boiler-efficiency measures to annual fuel savings, cost savings, and emissions reductions, the tool supports the environmental component of ESG reporting and helps facility managers evaluate how specific engineering actions contribute to organizational sustainability goals. Therefore, the model serves as a bridge between facility-level energy assessment and ESG oriented environmental performance tracking.

2.3 Load Variation, Utility Bill Verification, and Accessible Simulation Tools

Boiler fuel consumption varies with production demand, weather related heating demand, operating schedule, and load factor. Industrial boilers may operate below their rated capacity or experience frequent load changes due to process variability. Partial-load operation can reduce efficiency, increase cycling losses, and affect emissions. Ref. [38] showed that flexible boiler operation under varying loads must consider thermal stress and environmental constraints. Because real facilities experience both weather and production variation, simulation models require a practical method for load adjustment. Heating degree days can represent weather-driven heating demand, while production schedules or production proxies can represent process-driven boiler demand. A combined load-factor approach can therefore provide a practical representation of daily boiler demand when detailed sub-metered data is unavailable.

Utility bills are widely used in energy management because they provide measured facility-level consumption data. Monthly natural-gas and electricity bills can support benchmarking, energy audits, and performance tracking. Ref. [4] proposed baseline modeling using both weather and non-weather variables, showing that utility data can be used more effectively when combined with operational information. Ref. [39] used monthly utility bills and change point regression to estimate thermal performance and energy saving potential in residential buildings. However, monthly utility bills are usually too aggregated to explain the effects of specific boiler parameters such as stack oxygen, steam pressure, feedwater conductivity, blowdown rate, or condensate recovery. Therefore, for boiler scenario analysis, utility bills are better used as an independent verification source rather than as direct inputs to parameter level simulation. Combining operational parameter based modeling with utility bill verification can provide both engineering transparency and practical credibility.

Accessible simulation tools are important for small and medium-sized industrial facilities, where advanced simulation software may be costly, difficult to customize, or unnecessary for preliminary project evaluation. An Excel VBA tool is useful in this context because it can combine spreadsheet calculations, user-input forms, automation, and visualization in a familiar environment. Ref. [40] developed an Excel VBA based educational module for simulation and energy optimization of a spray drying process. Ref. [41] used Excel VBA to simulate electric power plant performance and reliability using probabilistic methods. Ref. [42] used simulation to evaluate boiler electrification as a decarbonization strategy. These studies show that spreadsheet based and simulation based tools can support practical modeling, scenario testing, and energy system decision making when the calculation structure and assumptions are clearly defined.

Several existing tools support industrial steam system and insulation analysis. MEASUR provides assessment tools for systems such as steam, pumps, fans, process heating, and compressed air, while 3E Plus focuses on insulation calculations such as heat loss and surface temperature. These tools are valuable for energy-audit and thermal performance applications; however, the proposed Excel VBA tool is positioned as a complementary facility level decision support framework. It integrates boiler loss calculations, load factor adjustment, date specific implementation of efficiency measures, and annual energy, cost, and CO₂ estimation within a single spreadsheet environment. This structure allows users to evaluate how different boiler efficiency projects affect annual performance when implemented at different times during the year.

Scenario analysis is widely used in energy planning and environmental assessment because it allows decision makers to evaluate alternative technologies, operating strategies, or policy conditions before implementation. Ref. [43] discussed scenario analysis as a strategic management tool, while ref. [44] argued that scenario analysis can improve environmental impact assessment by considering alternative future conditions. Ref. [45] showed that combining scenario planning, energy system analysis, and multi-criteria evaluation can improve transparency in energy decision making. For boiler energy-efficiency assessment, scenario analysis is useful because facility managers often need to compare multiple possible projects before

implementation. However, scenario tools must capture not only the type of measure but also the timing of implementation and the cumulative effect of multiple measures. A date specific simulation structure can provide more realistic annual estimates than a static before and after calculator, especially when projects are implemented at different times during the year. Although time dependent scenario analysis is common in energy modeling, this study applies it specifically to track boiler-efficiency projects within an ESG-oriented framework. The model assigns implementation dates to individual measures and evaluates their impact on energy use, cost, CO₂ emissions, and environmental performance over time. This approach reflects the gradual implementation of efficiency actions in industrial facilities and supports continuous ESG monitoring. The contribution lies in integrating date specific project tracking with facility level energy and environmental performance reporting for steam systems.

2.4 Research Gap and Contribution of This Study

The literature shows that boiler-efficiency methods, energy saving measures, utility bill analysis, Excel based simulation, and scenario analysis have each been studied separately. Boiler-efficiency studies provide methods for estimating losses and identifying improvement opportunities [14–16]. Energy management studies emphasize utility bill analysis, baseline modeling, and performance verification [4,39]. Scenario-analysis studies show how alternative actions can be evaluated before implementation [43–45]. Excel VBA and spreadsheet based studies demonstrate the practicality of accessible simulation tools for engineering and energy applications [40,41].

In this context, the novelty of this study lies in linking facility level boiler-efficiency analysis with ESG-oriented environmental-performance assessment in a practical and measurable way. Unlike many ESG studies that focus on broad indicators or disclosure practices, this study demonstrates how specific engineering interventions can produce quantifiable improvements in energy use, operating cost, and CO₂ emissions. By translating boiler-efficiency measures into measurable environmental performance indicators, it provides a practical framework for supporting project level decision making and sustainable operational improvements in industrial facilities.

However, fewer studies integrate these elements into a single facility level decision support framework for boiler-efficiency projects. Existing approaches often focus on technical efficiency calculation, historical energy tracking, broad ESG reporting, or isolated scenario analysis. They typically do not provide an accessible parameter driven tool that can simulate multiple boiler efficiency measures, assign different implementation dates, adjust daily load factors, estimate annual fuel use and CO₂ emissions, and verify modeled consumption against real utility bills. In addition, ESG-oriented tools often report environmental indicators without directly linking them to specific engineering actions.

This study provides an engineering oriented, application driven contribution by integrating established principles of thermodynamics, fluid flow, heat transfer, and mass transfer into a transparent simulation framework for boiler efficiency evaluation. The model does not introduce new theory but applies energy balance methods, combustion and stack loss analysis, blowdown and heat recovery calculations, and surface heat-transfer concepts. Its novelty lies in organizing these relationships within a temporal Excel VBA model that simulates project implementation, load variation, fuel use, cost, CO₂ emissions, and environmental performance. Thus, it serves as a practical decision support tool for industrial energy assessment and sustainability planning.

This study addresses this gap by developing an Excel VBA based boiler simulation tool that integrates indirect method boiler loss modeling, time-dependent scenario analysis, daily load-factor adjustment, energy cost and emissions estimation, utility bill verification, and ESG-oriented environmental performance

tracking. By connecting operational boiler parameters with measurable environmental performance indicators, the proposed tool supports practical decision making for industrial boiler efficiency projects and provides a transparent basis for evaluating energy and emissions reductions before implementation.

3 Methodology

3.1 Simulation Framework and Model Inputs

This study developed a parameter driven boiler energy efficiency simulation tool using Microsoft Excel and VBA. The objective of the model is to provide a transparent screening level decision support framework for estimating the effects of boiler-efficiency measures on annual fuel consumption, energy cost, CO₂ emissions, and ESG-oriented environmental-performance indicators.

The model operates on a daily time step over a 365 day simulation period. First, baseline boiler energy consumption is calculated from user defined operating parameters and predefined engineering assumptions. Second, selected efficiency measures are applied from user specified implementation dates. From each implementation date onward, the relevant boiler parameters are updated and modified daily energy consumption is recalculated. Annual baseline and modified energy consumption are then obtained by summing the daily values. The same structure is used to estimate annual cost savings and CO₂ emission reductions.

The simulation workflow consists of five main stages: baseline parameter definition, daily load factor calculation, baseline energy use estimation, scenario based modification, and output reporting. Fig. 1 represents the algorithmic workflow of the proposed Excel VBA-based temporal boiler-efficiency simulation tool, including baseline setup, load-factor adjustment, scenario selection, date specific parameter modification, and energy, cost, and CO₂ emission output calculation.

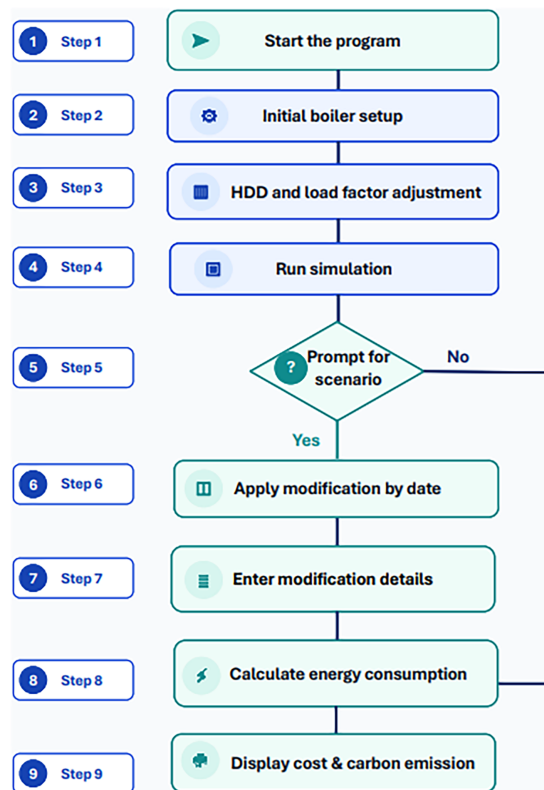


Figure 1: Algorithmic workflow of the Excel VBA-based boiler-efficiency simulation tool.

The Excel workbook contains separate worksheets for initial boiler setup, load factor calculation, boiler performance calculation, and simulation results. VBA is used to automate scenario selection, collect user defined implementation dates and modified parameter values, update model parameters, and generate results. A representative interface of the Excel VBA application is shown in Fig. 2, including the initial setup worksheet, scenario selection dialog, scenario parameter input, and simulation results worksheet. The methodological contribution is the temporal simulation structure and parameter driven scenario framework rather than the software platform itself.

Representative Excel VBA application interface

(a) Initial Setup Worksheet

Parameter	Value	Unit
Stack temperature	325	°F
Oxygen in stack gas	7	%
Steam pressure	60	psig
Steam production	10,350	lb/h

Only selected fields are shown; complete baseline inputs are reported in Table 1.

SIMULATION

(b) Scenario Selection Dialog

Modify Parameters

Do you want to modify Oxygen in stack gases? Yes No

Example scenario options

- Burner replacement
- Air-fuel ratio optimization
- Steam pressure reduction
- Condensate recovery
- Heat-recovery scenarios

(c) Scenario Parameter Input

Modification date

Enter implementation day (1–365): OK

Scenario parameter

Enter modified parameter value: % OK

The dialogs collect only the values required for the selected scenario.

(d) Simulation Results Worksheet

Output summary	Reported value
Baseline energy use	45,875.75 MMBtu/year
Modified energy use	41,589.72 MMBtu/year
Net energy savings	4,286.04 MMBtu/year
Net CO ₂ reduction	228.44 tons/year
Net Energy savings (%)	9.34%

Complete numerical inputs and scenario results are provided in Table 1 and the Results section; this figure illustrates the application layout and user interaction.

Figure 2: Representative Excel VBA application interface showing (a) initial setup worksheet, (b) scenario selection dialog, (c) scenario parameter input, and (d) simulation results worksheet. Complete numerical inputs and scenario results are provided in Table 1 and the results section.

Table 1: Baseline boiler operating parameters used in the simulation model.

Baseline Operating Parameters		
Feedwater temperature	21.1	°C
Specific enthalpy of steam	2752	kJ/kg
Specific enthalpy of feed water	88.4	kJ/kg
Ambient air temperature	21.1	°C
Stack gas temperature	162.8	°C
Natural gas cost	2.85	\$/GJ
Oxygen in stack gases	7	%
Boiler operates	24	h/day
Steam production	4695	kg/h
Saturated steam pressure	414	kPa(g)
Blowdown Parameters		
Feedwater conductivity	0.02	S/m
Blowdown conductivity	0.5	S/m

The model uses a combination of user-defined inputs and predefined engineering parameters. User defined inputs are entered in the InitialSetup worksheet and represent the baseline operating condition of the boiler. These inputs include feedwater temperature, ambient air temperature, stack gas temperature, natural gas cost, O₂ concentration in stack gases, boiler operating hours, steam production rate, saturated steam pressure, and feedwater conductivity. The baseline operating parameters used in the simulation are summarized in [Table 1](#).

Blowdown conductivity is set to 0.5 S/m. The flash-tank pressure is assumed to be 103 kPa(g). The specific heat of flue gas is assumed to be 1.10 kJ/kg·K. Heat-recovery effectiveness is assumed to be 85% for blowdown and flue-gas heat recovery scenarios. For insulation scenarios, the model first estimates exposed surface heat loss and then assumes that insulation reduces this heat loss by 90%. These default values can be modified when site specific data are available.

3.2 Daily Load Factor Adjustment

Boiler demand varies with weather conditions, production activity, operating schedule, and facility use. To represent this variation, the model applies to daily load factor adjustment. The load factor represents the ratio of actual boiler demand to the theoretical maximum boiler output for a given day.

The model assumes that boiler demand may be driven by both weather related space-heating demand and production related steam demand. Heating Degree Days (HDD) are used to represent weather driven heating demand, while production demand is represented by a normalized production factor. When measured production data is unavailable, production demand can be approximated using a bounded user-defined range.

The daily load factor is calculated as:

$$L_{F,t} = \alpha \left(\frac{HDD_t}{HDD_{\max}} \right) + (1 - \alpha) \left(\frac{P_t}{P_{\max}} \right) \quad (1)$$

where $L_{F,t}$ is the load factor on day t , α is the weighting factor for weather-related demand, HDD_t is the heating degree day value on day t , $HDD_{\max}$ is the maximum HDD value during the year, P_t is the production demand on day t , and $P_{\max}$ is the maximum or baseline production demand. The coefficient α allows the user to represent facilities in which boiler demand is dominated by space heating, production activity, or a combination of both.

3.3 Boiler Loss and Energy Consumption Model

The model estimates boiler energy consumption using an indirect boiler-efficiency framework. The indirect method was selected because it links changes in operating parameters to specific loss mechanisms, including stack loss, blowdown loss, shell loss, and miscellaneous losses. This structure is suitable for scenario analysis because each efficiency measure modifies one or more loss terms.

3.3.1 Blowdown Loss

Boiler blowdown is required to control dissolved solids and reduce the risk of scaling, corrosion, and foaming. However, blowdown removes hot water from the system and therefore produces thermal energy loss. The blowdown rate is estimated from feedwater and blowdown conductivities:

$$R_{bd} = \frac{\sigma_{fw}}{\sigma_{bd} - \sigma_{fw}} \quad (2)$$

where R_{bd} is the blowdown rate, σ_{fw} is feedwater conductivity, and σ_{bd} is blowdown conductivity.

The blowdown mass flow rate is calculated as:

$$\dot{m}_{bd} = R_{bd} S_p \quad (3)$$

where $\dot{m}_{bd}$ is the blowdown mass flow rate and S_p is the steam production rate.

The blowdown heat loss is calculated as:

$$\dot{Q}_{bd} = \dot{m}_{bd} c_{p,w} (T_{bd} - T_{mp}) \quad (4)$$

where $c_{p,w}$ is the specific heat of water, T_{bd} is the blowdown temperature, and T_{mp} is the makeup water temperature. In the daily fuel use calculation, this heat loss is converted into an equivalent loss fraction and included in the total boiler loss term.

3.3.2 Stack Loss and Excess Air

The O_2 concentration in stack gas is used as an indicator of excess combustion air. Although some excess air is required to support complete combustion, excessive air increases stack loss because additional air is heated and exhausted through the stack. The model assumes complete combustion and calculates stack loss from two terms: sensible heat loss in dry flue gases and enthalpy loss associated with water vapor in flue gases.

The sensible heat loss in dry flue gases is calculated as:

$$L_{dry,t} = k_1 \frac{T_{s,t} - T_a}{[CO_2]_t} \quad (5)$$

where $L_{dry,t}$ is the dry flue-gas sensible heat-loss fraction on day t , k_1 is the Siegert constant for natural gas, $T_{s,t}$ is stack temperature, T_a is ambient air temperature, and $[CO_2]_t$ is carbon dioxide concentration in the stack gas.

The CO_2 concentration is estimated as:

$$[CO_2]_t = CO_{2,max} \left(\frac{20.9 - O_{2,t}}{20.9} \right) \quad (6)$$

where $CO_{2,max}$ is the maximum carbon dioxide concentration under stoichiometric combustion and $O_{2,t}$ is the O_2 concentration in the stack gas. For natural gas, $CO_{2,max}$ is taken as 11.9%.

The water vapor related flue gas loss is calculated as:

$$L_{vap,t} = k_2 [1185 + T_{s,t} - 2T_a] \quad (7)$$

where $L_{vap,t}$ is the water-vapor-related stack-loss fraction and k_2 is a natural-gas-specific constant.

The total stack-loss fraction is:

$$L_{stack,t} = L_{dry,t} + L_{vap,t} \quad (8)$$

3.3.3 Steam Pressure and Enthalpy Requirement

Steam pressure affects the enthalpy of saturated steam and therefore the fuel energy required to generate steam. In the model, a change in steam pressure modifies the steam enthalpy used in the energy-consumption calculation. The direct boiler-efficiency relationship can be expressed as:

$$\eta = \frac{\dot{m}_{steam}(h_s - h_f)}{\dot{m}_{fuel}HHV_{fuel}} \quad (9)$$

where η is boiler efficiency, $\dot{m}_{steam}$ is the steam mass flow rate, h_s is the specific enthalpy of steam, h_f is the specific enthalpy of feedwater, $\dot{m}_{fuel}$ is the fuel mass flow rate, and HHV_{fuel} is the higher heating value of the fuel. This direct relationship is provided for reference; the simulation itself calculates daily fuel use using the indirect loss-based formulation.

3.3.4 Heat-Recovery and Insulation Measures

Condensate recovery reduces fuel consumption by returning hot condensate to the boiler system and reducing the amount of cold makeup water that must be heated. The heat recovered from returned condensate is calculated as:

$$\dot{Q}_{cond,t} = \dot{m}_{cond,t}c_{p,w}(T_{cond} - T_{mp}) \quad (10)$$

where $\dot{m}_{cond,t}$ is the mass flow rate of recovered condensate, T_{cond} is the condensate temperature, and T_{mp} is the makeup-water temperature.

Flue-gas heat recovery captures a portion of thermal energy leaving through the stack. Recoverable heat from flue gas is estimated as:

$$\dot{Q}_{fg,t} = \dot{m}_{fg,t}c_{p,fg}(T_{fg,in} - T_{fg,out}) \quad (11)$$

where $\dot{m}_{fg,t}$ is the flue-gas mass flow rate, $c_{p,fg}$ is the specific heat of flue gas, $T_{fg,in}$ is the inlet flue-gas temperature, and $T_{fg,out}$ is the outlet flue-gas temperature after heat recovery. In the simulation, $T_{fg,out}$ is limited to 137.8°C to reduce the risk of condensation and corrosion, and heat-recovery effectiveness is assumed to be 85%.

Surface heat loss from exposed boiler surfaces, steam pipes, valves, and fittings is estimated using a combined convection and radiation heat-transfer coefficient:

$$\dot{Q}_{surf,t} = hA(T_{surf} - T_a) \quad (12)$$

where $\dot{Q}_{surf,t}$ is the exposed-surface heat loss, h is the combined convective and radiative heat-transfer coefficient, A is the exposed surface area, T_{surf} is the surface temperature, and T_a is the ambient temperature. For insulation scenarios, the original exposed-surface heat loss is estimated first, and the model assumes that insulation reduces this loss by 90%.

3.3.5 Baseline and Modified Daily Energy Use

Daily boiler energy consumption is calculated from steam production rate, enthalpy difference between steam and feedwater, boiler operating hours, daily load factor, and estimated boiler loss fractions:

$$E_t = \frac{S_p(h_s - h_f)O_H k L_{F,t}}{1 - L_{stack,t} - L_{shell} - L_{bd,t} - L_{misc}} \quad (13)$$

where E_t is daily boiler energy consumption in GJ/day, S_p is steam production rate, h_s is steam enthalpy, h_f is feedwater enthalpy, O_H is daily operating hours, k is the kJ to GJ conversion factor, $L_{F,t}$ is the daily load factor, $L_{stack,t}$ is the stack loss fraction, L_{shell} is the shell loss fraction, $L_{bd,t}$ is the blowdown loss fraction, and L_{misc} is the miscellaneous loss fraction.

For the baseline case, all operating parameters remain fixed at their initial values. Annual baseline energy consumption is obtained by summing daily baseline energy consumption:

$$E_{annual,base} = \sum_{t=1}^{365} E_{base,t} \quad (14)$$

For the modified case, the model updates the relevant parameters from the implementation date of each selected scenario. Modified daily energy consumption is calculated as:

$$E_{mod,t} = E_{p,t} - \dot{Q}_{cond,t} - \dot{Q}_{bd,rec,t} - \dot{Q}_{fg,rec,t} - \dot{Q}_{ins,t} \quad (15)$$

where $E_{mod,t}$ is modified daily energy consumption, $E_{p,t}$ is daily energy consumption after parameter modifications, $\dot{Q}_{cond,t}$ is the energy reduction from condensate recovery, $\dot{Q}_{bd,rec,t}$ is the energy reduction from blowdown heat recovery, $\dot{Q}_{fg,rec,t}$ is the energy reduction from flue gas heat recovery, and $\dot{Q}_{ins,t}$ is the energy reduction from insulation. All recovered-energy terms are converted to GJ/day before subtraction.

Annual modified energy consumption is calculated as:

$$E_{annual,mod} = \sum_{t=1}^{365} E_{mod,t} \quad (16)$$

Net annual energy savings are calculated as:

$$E_{save} = E_{annual,base} - E_{annual,mod} \quad (17)$$

3.4 Scenario Implementation

The model supports eight individual boiler-efficiency scenarios and one combined scenario. Each scenario is selected through VBA input dialogs. The user provides the implementation day between day 1 and day 365, and the corresponding parameter change is applied from that day through the end of the simulation year. This structure allows the tool to represent realistic project timing rather than assuming that all measures are implemented at the beginning of the year. Table 2 summarizes the boiler-efficiency scenarios implemented in the simulation model. It identifies the required user input for each scenario and describes how the model updates the relevant boiler operating parameters after the selected implementation date.

Table 2: Boiler-efficiency scenarios implemented in the simulation model.

Scenario	Required User Input	Model Action
(1) Burner replacement	Implementation date	Reduces stack oxygen to 3% from the selected date
(2) Insulation of hot surfaces	Date, surface temperature (°C), surface area (m ²), geometry, diameter (m)	Calculates exposed-surface heat loss and applies 90% reduction
(3) Blowdown-rate reduction	Date, new feedwater conductivity (S/m)	Recalculates blowdown rate and blowdown heat loss
(4) Air-fuel ratio optimization	Date, new stack oxygen percentage	Recalculates excess air and stack loss

(Continued)

Table 2 (continued)

Scenario	Required User Input	Model Action
(5) Steam-pressure reduction	Date, new steam pressure kPa(g)	Updates steam enthalpy and energy requirement
(6) Condensate recovery	Date, condensate recovery percentage	Calculates recovered condensate heat and subtracts it from fuel demand
(7) Blowdown heat recovery	Date, activation input	Calculates recovered blowdown heat using 85% effectiveness
(8) Flue-gas heat recovery	Date, activation input	Calculates recovered flue-gas heat using 85% effectiveness and a 137.8°C outlet-temperature limit
(9) Multiple measures	Any combination of individual measures	Applies selected measures sequentially based on implementation dates

The combined scenario option allows users to evaluate multiple improvement measures implemented on different dates. When multiple scenarios are selected, the model applies parameter changes sequentially according to implementation date and recalculates daily energy consumption using the updated parameter set. Therefore, combined savings are not treated as a simple arithmetic sum of individual savings.

3.5 Cost, Emissions, and Environmental Performance Calculations

Carbon emissions are calculated from natural-gas consumption using an emission factor of 50.3 kg CO₂/GJ. Because 1 metric ton equals 1000 kg, daily CO₂ emissions are calculated as:

$$\text{CO}_{2,t} = \frac{E_t \times 117}{2204.62} \quad (18)$$

where CO_{2,t} is daily CO₂ emission in metric tons.

Annual CO₂ emissions are calculated by summing the daily values:

$$\text{CO}_{2,\text{annual}} = \sum_{t=1}^{365} \text{CO}_{2,t} \quad (19)$$

The same equation is applied to baseline and modified energy consumption. Net annual CO₂ emission reduction is calculated as:

$$\Delta\text{CO}_2 = \text{CO}_{2,\text{base}} - \text{CO}_{2,\text{mod}} \quad (20)$$

Annual energy cost is calculated as:

$$C_{\text{annual}} = E_{\text{annual}} C_{\text{gas}} \quad (21)$$

where C_{annual} is annual energy cost and C_{gas} is the natural-gas cost in \$/GJ. Net annual cost savings are calculated as:

$$C_{save} = C_{base} - C_{mod} \quad (22)$$

Because this study focuses only on boiler energy consumption and carbon emissions, the model estimates an ESG-oriented environmental performance indicator rather than a complete ESG score. The indicator reflects modeled changes in boiler energy use and CO₂ emissions. Social and governance factors are outside the scope of the model, and other environmental factors such as water, waste, biodiversity, and policy related indicators are held constant.

The change in environmental performance is calculated using a weighted linear expression:

$$\Delta I_{env} = \left[w_E \left(\frac{\Delta E}{E_{base}} \right) + w_C \left(\frac{\Delta CO_2}{CO_{2,base}} \right) + w_O \left(\frac{\Delta O}{O_{base}} \right) \right] \times 100 \quad (23)$$

where ΔI_{env} is the change in the ESG-oriented environmental-performance indicator, ΔE is annual energy-use reduction, E_{base} is baseline annual energy use, ΔCO_2 is annual CO₂ emission reduction, $CO_{2,base}$ is baseline annual CO₂ emission, ΔO is the change in other environmental factors, and O_{base} is the baseline value of other environmental factors.

In this study, the boiler efficiency measures affect energy use and CO₂ emissions but do not quantify changes in other environmental factors such as water use, waste generation, biodiversity, or policy-related indicators. Therefore, ΔO is set to zero. The weighting factor ($w_O = 0.5$) is retained to preserve the broader environmental-performance framework, but this term does not contribute to the calculated score because ($\Delta O = 0$). This ensures that the indicator reflects only the verified steam-system impacts without overstating broader environmental benefits. The weighting factors used for demonstration are $w_E = 0.2$, $w_C = 0.3$, and $w_O = 0.5$. These values are assumed and should be adjusted for industry-specific ESG frameworks, company specific sustainability priorities, or formal environmental-performance scoring systems.

The weighting factors in the ESG oriented environmental-performance indicator were based on observations and discussions with manufacturing personnel through West Virginia University Industrial Training and Assessment Center (WVU-ITAC) activities. These indicated that energy use and CO₂ emissions are the most measurable and actionable indicators for steam system improvements, while other factors vary by facility. As such, the weights provide a practical, not universal, representation of environmental performance and can be adjusted to fit specific sustainability goals, sector priorities, or reporting requirements.

3.6 Model Verification Using Utility Bills

The model is verified by comparing simulated monthly natural gas consumption with actual utility bill data from a manufacturing facility. Utility bills are not used as direct inputs to the simulation. Instead, the simulation is driven by boiler operating parameters, including steam production, stack temperature, O₂ concentration in stack gases, steam pressure, feedwater temperature, and daily load-factor adjustment. Monthly utility bill data are used only after simulation to evaluate whether the model produces realistic fuel consumption estimates.

The monthly percentage error between simulated and utility-bill energy consumption is calculated as:

$$Error_i(\%) = \frac{E_{utility,i} - E_{sim,i}}{E_{utility,i}} \times 100 \quad (24)$$

where $E_{utility,i}$ is utility-bill energy consumption for month i , and $E_{sim,i}$ is simulated energy consumption for the same month.

The absolute percentage error is calculated as:

$$APE_i(\%) = \left| \frac{E_{utility,i} - E_{sim,i}}{E_{utility,i}} \right| \times 100 \quad (25)$$

Annual percentage error is calculated using total annual simulated and billed energy consumption. This verification step provides a practical check on model reliability while preserving the model's ability to simulate future efficiency scenarios that are not present in historical utility data.

Monthly deviations between simulated energy use and utility bill data are partly due to operational factors not captured by the current load factor model. While HDD and daily load factors reflect general weather and production trends, they do not account for short term events such as shutdowns, start ups, maintenance, schedule changes, boiler cycling, or operator adjustments; start ups can increase fuel use, while shutdowns can reduce it, leading to monthly discrepancies despite accurate annual estimates. Additional differences arise from weather and production variability not fully represented by aggregated HDD adjustments or approximate load factors. These limitations suggest that incorporating more detailed data such as shutdown and start-up schedules, production records, steam flow measurements, or submetered fuel use could improve monthly accuracy; however, the low annual error indicates that the model remains suitable for annual screening and scenario analysis.

3.7 Model Outputs, Assumptions, and Limitations

The simulation outputs are reported in the SimulationResults worksheet. The outputs include annual baseline energy use, annual modified energy use, net annual energy savings, baseline and modified annual CO₂ emissions, annual CO₂ emission reduction, baseline and modified annual energy cost, annual cost savings, and daily baseline and modified energy use profiles. These outputs are intended to support project comparison, preliminary energy savings estimation, carbon emission accounting, and environmental performance documentation.

The simulation model is based on several assumptions that keep the tool transparent and suitable for screening level facility decision support. (1) First, the model assumes that natural gas is boiler fuel. Therefore, stack loss constants, emission factors, and selected default parameters are specific to natural gas fired boiler operation. (2) Second, combustion is assumed to be complete; therefore, incomplete combustion losses are not explicitly modeled. (3) Third, flue gas specific heat is assumed to be constant. (4) Fourth, heat recovery effectiveness is assumed to be 85% for blowdown and flue gas heat recovery scenarios. (5) Fifth, insulation is assumed to reduce exposed surface heat loss by 90%. (6) Sixth, when measured production data are unavailable, production-related load variation is approximated using a bounded random factor. (7) Seventh, utility bills are used only for verification and not for calibration or direct model fitting. (8) Finally, the environmental performance indicator is limited to energy use and CO₂ emissions, while other ESG factors are assumed unchanged.

Therefore, the model is intended as a transparent screening level decision support tool for comparing boiler-efficiency scenarios, estimating annual energy and emissions impacts, and supporting preliminary environmental performance assessment. Detailed site-specific calibration, higher resolution operational data, and investment grade measurement and verification would be required for final project validation or financial grade savings claims.

4 Results and Discussion

4.1 Baseline Boiler Energy Consumption

The baseline simulation was performed using the existing boiler operating parameters of the facility. These parameters served as the reference condition for all individual and combined efficiency scenarios. Under the baseline condition, the model estimated annual boiler energy consumption of 48,407 GJ/year. The corresponding annual CO₂ emission was 2434.64 metric tons/year, and the annual fuel cost was \$138,086.01/year.

Daily baseline energy consumption varied throughout the year because the model applied a load-factor adjustment based on weather related and production related demand. The monthly baseline profile showed higher consumption during colder months and lower consumption during warmer months, reflecting the contribution of heating degree days to boiler demand. This baseline case provides the reference against which all boiler-efficiency scenarios are evaluated. Fig. 3 shows the monthly baseline boiler energy consumption by the simulation model.

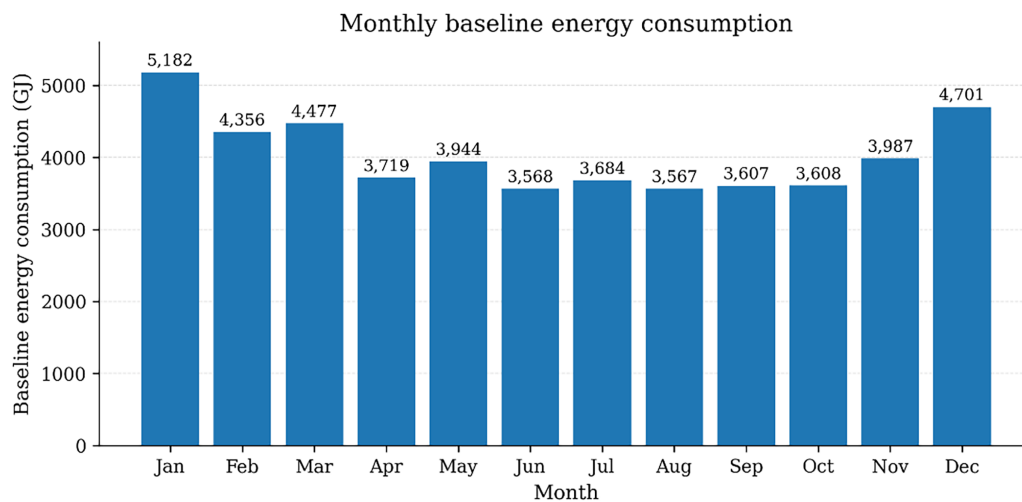


Figure 3: Monthly baseline boiler energy consumption estimated by the simulation model.

4.2 Energy, Emissions, and Cost Impacts of Individual Scenarios

Eight individual boiler-efficiency scenarios were simulated and compared with the baseline case. Each scenario was applied from its specified implementation date and remained active through the end of the simulation year. The annual energy, emissions, and cost impacts of the individual scenarios are summarized in Table 3.

Among the individual measures, condensate recovery produced the largest reduction in annual energy consumption. Recovering 50% of condensate reduced annual energy use by 4080 GJ/year, equivalent to an 8.43% reduction from the baseline. This also reduced CO₂ emissions by 205.21 metric tons/year and produced annual fuel-cost savings of \$11,639.16/year. The strong performance of condensate recovery is expected because returned condensate reduces the amount of cold makeup water that must be heated to generate steam.

The next most effective individual measure was burner replacement, which reduced the assumed stack oxygen concentration to 3%. This scenario saved 741 GJ/year, reduced CO₂ emissions by 37.29 metric tons/year and reduced annual fuel cost by \$2115.15/year. Air-fuel ratio optimization, which reduced stack

oxygen from 7% to 4%, saved 591 GJ/year, reduced CO₂ emissions by 29.73 metric tons/year, and saved \$1686.18/year. These results show that combustion related improvements can provide meaningful savings when the baseline oxygen concentration in the stack gas is relatively high.

Table 3: Annual impact of individual boiler-efficiency scenarios.

Scenario	Modified Energy Use (GJ/Year)	Energy Savings (GJ/Year)	CO ₂ Reduction (Metric Tons/Year)	Cost Savings (\$/Year)	Energy Reduction (%)
Burner replacement	47,666	741	37.29	2115.15	1.53
Insulation of hot surfaces	48,369	38	1.92	108.94	0.08
Blowdown-rate reduction	48,217	190	9.56	542.42	0.39
Air-fuel ratio optimization	47,811	591	29.73	1686.18	1.22
Steam-pressure reduction	48,112	295	14.82	840.72	0.61
Condensate recovery	44,322	4080	205.21	11,639.16	8.43
Blowdown heat recovery	48,153	254	12.78	724.85	0.52
Flue-gas heat recovery	48,349	52	2.63	148.93	0.11

Moderate savings were obtained from steam pressure reduction, blowdown heat recovery, and blowdown rate reduction. Reducing steam pressure from 414 to 276 kPa(g) saved 295 GJ/year, while blowdown heat recovery saved 254 GJ/year. Reducing feedwater conductivity from 0.02 to 0.01 S/m reduced the calculated blowdown rate and saved 190 GJ/year. These measures produced smaller savings than condensate recovery and combustion optimization but still provided measurable reductions in energy use, emissions, and cost.

The lowest savings were observed for flue gas heat recovery and insulation of hot surfaces under the assumptions used in this case. Flue gas heat recovery saved 52 GJ/year, while insulation of the selected exposed hot surface saved 38 GJ/year. These results are case specific and depend on stack temperature, recoverable temperature range, exposed surface area, insulation effectiveness, implementation date, and facility load profile.

Based on annual energy savings, the individual scenarios were ranked as follows: condensate recovery, burner replacement, air-fuel ratio optimization, steam pressure reduction, blowdown heat recovery, blowdown rate reduction, flue gas heat recovery, and insulation of hot surfaces. This ranking reflects the selected baseline operating conditions and scenario assumptions. The relative ranking may differ for facilities with different stack temperatures, condensate return potential, steam pressure requirements, blowdown rates,

exposed surface areas, implementation dates, or operating profiles. Fig. 4 indicates the annual energy savings from individual boiler efficiency scenarios.

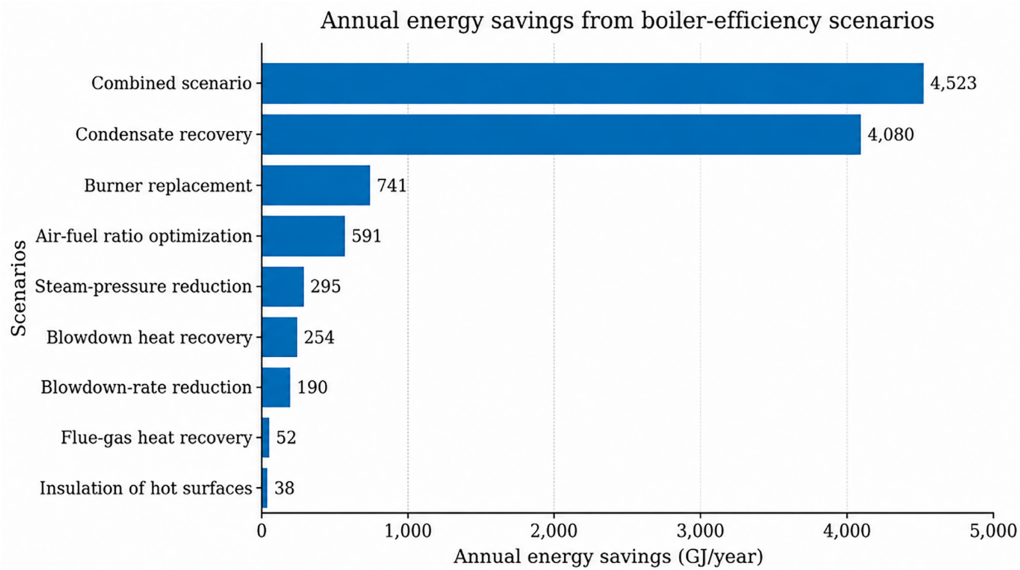


Figure 4: Annual energy savings from individual boiler-efficiency scenarios.

4.3 Combined Scenario and Effect of Implementation Timing

A combined scenario was simulated to evaluate the cumulative effect of implementing multiple measures at different times during the year. The combined case included 50% condensate recovery on day 32, air-fuel ratio optimization to reduce stack O₂ to 4% on day 60, and steam pressure reduction to 40 psig on day 91. Table 4 shows the annual impact of the combined scenario.

Table 4: Annual impact of the combined scenario.

Metric	Baseline	Combined Scenario	Reduction
Energy use (GJ/year)	48,407	43,881	4523
CO ₂ emissions (metric tons/year)	2434.64	2207.18	227.46
Energy cost (\$/year)	138,086.01	125,185.05	12,900.97
Energy reduction (%)	—	—	9.34

The combined scenario reduced annual energy consumption by 4523 GJ/year, corresponding to a 9.34% reduction from the baseline. This resulted in annual CO₂ reduction of 227.46 metric tons/year and fuel-cost savings of \$12,900.97/year.

The combined savings were larger than those from any individual scenario. However, they were not equal to the arithmetic sum of the individual savings because the measures were implemented on different days and affected overlapping portions of the energy consumption calculation. This demonstrates the value of the date specific simulation structure. In practical industrial settings, efficiency projects are often implemented at different points during the year rather than simultaneously. A temporal model therefore provides a more realistic annual estimate than a static before and after calculator. Fig. 5 shows the monthly baseline and modified energy consumption for the combined scenario.

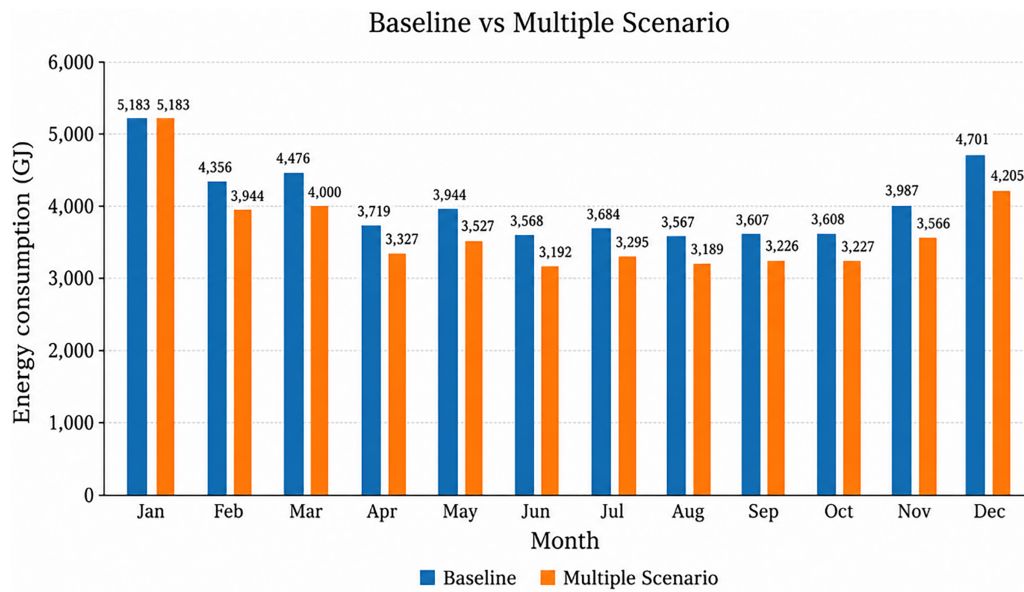


Figure 5: Monthly baseline and modified energy consumption for the combined scenario.

4.4 Comparative Environmental and Economic Impacts

Fig. 6 summarizes annual energy savings from the individual and combined scenarios. The comparison shows that condensate recovery dominated the individual measures, while the combined scenario produced the highest total savings. The large difference between condensate recovery and the remaining individual measures indicates that the baseline boiler system has substantial recoverable thermal energy in the condensate stream. Combustion related measures also provided meaningful savings because the baseline stack O_2 concentration was relatively high at 7%.

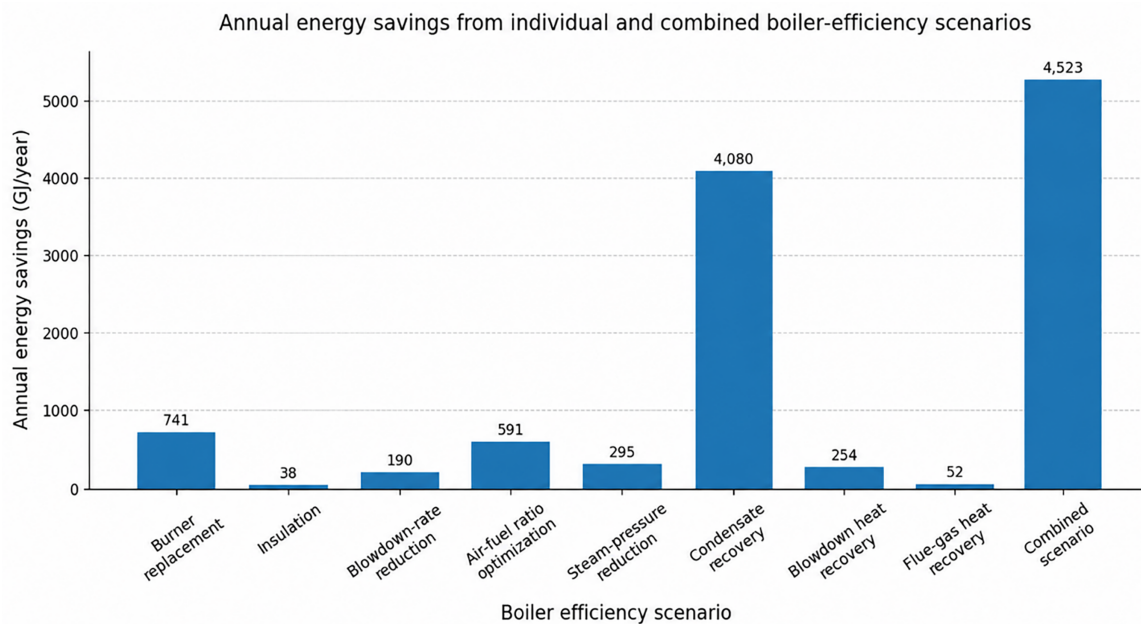


Figure 6: Annual CO_2 reduction and fuel-cost savings by scenario.

[Table 4](#) compares annual CO₂ reductions and fuel savings across scenarios. Because CO₂ emissions and fuel are both directly proportional to natural-gas consumption in the model, their trends follow the same order as energy savings. The combined scenario and condensate recovery case provided the largest environmental and economic benefits, while insulation and flue gas heat recovery produced smaller benefits under the selected assumptions.

4.5 ESG-Oriented Environmental Performance Indicator

The simulation results were converted into an ESG-oriented environmental performance indicator based on percentage reductions in energy use and CO₂ emissions. This indicator should not be interpreted as a complete ESG score because the model does not evaluate social, governance, water, waste, biodiversity, or policy related factors. Instead, it represents the environmental performance change associated with boiler energy and emissions reduction under the selected weighting assumptions. [Table 5](#) indicates the environmental performance change for each scenario.

Table 5: Environmental performance change for each scenario.

Case	Energy Use (GJ/Year)	CO ₂ (Metric Tons/Year)	Energy Reduction (%)	CO ₂ Reduction (%)	Environmental- Performance Change
Baseline	48,407	2434.64	0	0	0
Burner replacement	47,666	2397.35	1.53	1.53	0.77
Insulation of hot surfaces	48,369	2432.72	0.08	0.08	0.04
Blowdown-rate reduction	48,217	2425.08	0.39	0.39	0.20
Air-fuel ratio optimization	47,811	2404.91	1.22	1.22	0.61
Steam-pressure reduction	48,112	2419.82	0.61	0.61	0.31
Condensate recovery	44,322	2229.43	8.43	8.43	4.22
Blowdown heat recovery	48,153	2421.86	0.52	0.52	0.26
Flue-gas heat recovery	48,349	2432.02	0.11	0.11	0.06
Combined scenario	43,881	2207.18	9.34	9.34	4.67

The environmental performance indicator followed the same trend as energy and CO₂ reductions because it was calculated from those two modeled quantities. The combined scenario produced the largest improvement, 4.67 points, followed by condensate recovery with 4.22 points. Combustion related scenarios produced smaller but measurable improvements, while insulation and flue gas heat recovery produced the smallest changes under the selected case assumptions.

4.6 Model Verification Using Utility Bill Data

The model was verified using 12 months of natural gas utility bill data from a manufacturing facility. The facility operated two identical natural gas fired boilers, each with a steam production capacity of 2347 kg/h, giving a combined steam production capacity of 4695 kg/h. The boilers were equipped with Power Flame burners with low and high fire modulation rates of approximately 0.88 and 1.85 MW, respectively. The boilers operated at 414 kPa(g), with an average stack temperature of 162.8°C and a stack oxygen concentration of 7% based on combustion analysis. The facility used steam for both production and space heating loads and operated approximately 24 h/day, 6 days/week, and 50 weeks/year. HDD and operating information were used to construct the load factor adjustment for the simulation.

Table 6 compares the simulated monthly energy consumption with utility bill data.

Table 6: Comparison between simulated monthly consumption and utility-bill data.

Month	Simulated Data (GJ)	Utility Bills (GJ)	Error (%)	Absolute Error (%)
January	5182	5583	7.18%	7.18%
February	4356	4208	−3.52%	3.52%
March	4477	4313	−3.80%	3.80%
April	3722	4020	7.41%	7.41%
May	3946	4072	3.09%	3.09%
June	3568	3872	7.85%	7.85%
July	3684	3975	7.32%	7.32%
August	3567	3273	−8.98%	8.98%
September	3607	3218	−12.09%	12.09%
October	3609	3663	1.49%	1.49%
November	3987	4089	2.49%	2.49%
December	4702	4838	2.81%	2.81%
Total	48,407	49,125	1.48%	1.48%
Average	4034	4094	−	−

The simulated annual energy consumption was 48,407 GJ, while the utility-bill total was 49,125 GJ. The annual absolute percentage error was therefore 1.48%, indicating good agreement at the annual scale. Monthly absolute percentage errors ranged from 1.49% in October to 12.09% in September.

The monthly deviations are within the expected accuracy of a parameter driven model. While annual error is low, monthly energy use varies due to weather, demand, operations, and boiler conditions, which are hard to model without detailed data. Thus, the model is best used for reliable annual estimates and scenario comparisons, with greater uncertainty in monthly results.

A key feature of the verification approach is that utility bills were not used as direct simulation inputs. Instead, the simulation was driven by boiler operating parameters and load factor estimates, while the utility bills were used only to check the realism of simulated annual and monthly fuel consumption. This preserves the model's ability to evaluate future scenarios that are not present in historical utility data. Fig. 7 indicates the comparison of simulated monthly natural gas consumption with utility bill data used for model verification.

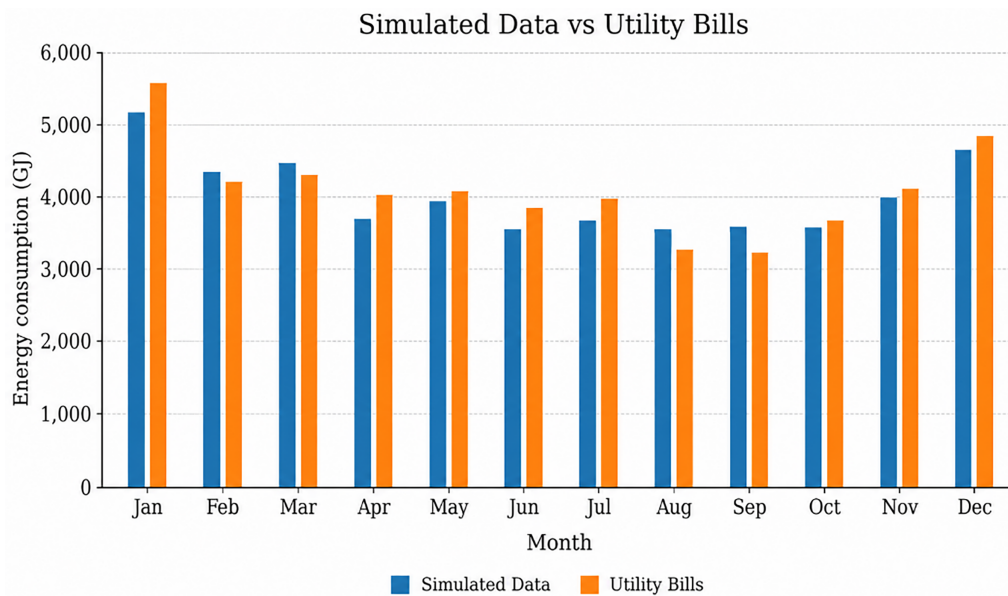


Figure 7: Comparison of simulated monthly natural gas consumption with utility bill data used for model verification.

The monthly differences can be attributed to factors not fully captured by the screening level model, including actual production variation, start up and shutdown events, maintenance periods, operator control changes, weather deviations, and differences between assumed and actual daily load factors. Despite these monthly deviations, the low annual error indicates that the model can provide useful facility level estimates of annual energy use and emissions when reasonable boiler operating parameters and load factor assumptions are available.

A key feature of the verification approach is that utility bills were not used as direct simulation inputs. Instead, the simulation was driven by boiler operating parameters and load factor estimates, while the utility bills were used only to check the realism of the simulated annual and monthly fuel consumption. This preserves the model's ability to evaluate future scenarios that are not present in historical utility data.

5 Discussion

5.1 Practical Implications and Limitations

The results demonstrate that the proposed simulation tool can distinguish between high-impact and low-impact boiler-efficiency measures under a given set of operating conditions. Condensate recovery produced the largest individual savings because it directly reduces the thermal energy required to heat makeup water. Combustion-related measures also produced meaningful savings because the baseline stack oxygen concentration was relatively high. In contrast, insulation and flue gas heat recovery produced smaller savings in this case because the assumed exposed surface area and recoverable flue gas heat were limited.

The combined scenario highlights the value of date specific implementation. In industrial facilities, efficiency projects are rarely implemented simultaneously at the beginning of the year. By allowing each measure to begin on a specified day, the model estimates annual impact more realistically and provides a practical basis for project scheduling, budgeting, and environmental performance tracking.

The utility bill verification results further support the usefulness of the tool for preliminary facility level analysis. The model is not intended to replace investment grade measurement and verification but

the low annual error relative to utility bill data suggests that it can provide credible annual estimates for screening level energy and emissions analysis. Therefore, the tool is most suitable for early stage project comparison, prioritization of boiler efficiency measures, and documentation of potential environmental performance improvements.

Several limitations should also be considered. The model relies on user defined operating parameters and default assumptions for heat recovery effectiveness, insulation performance, load variation, emission factors, and fuel cost. The production related load factor is simplified when measured production data are unavailable, which may increase monthly estimation errors. In addition, the model was verified using utility bill data from one manufacturing facility; therefore, additional validation across multiple facilities, boiler sizes, operating schedules, and industrial sectors is needed before generalizing the results. The ESG-oriented environmental performance indicator is also limited to energy use and CO₂ emissions and should not be interpreted as a complete ESG score. Although the model was validated using a natural gas fired boiler, its methodology can be applied to other fuels, boiler types, and industries. Adjustments to fuel properties, operating parameters, and site specific data are required. While broadly applicable, further validation across multiple facilities is needed for wider conclusions.

Also, the results depend on several assumed parameters, including heat recovery effectiveness, insulation performance, emission factors, fuel cost, and load factors. While suitable for screening level analysis, their impact on energy, cost, and CO₂ estimates requires further evaluation. A detailed sensitivity analysis is planned for future work to assess how variations in key parameters affect results and to improve the robustness of the framework.

5.2 Future Works

The proposed tool provides a practical screening level framework, but several extensions could improve its accuracy, scope, and applicability. First, the current production related load factor is approximated using a bounded random function when measured production data are unavailable. Future work should replace this approximation with actual production schedules, steam flow data, process operating records, or submetered fuel use data. Incorporating measured production information would improve the representation of daily boiler demand and reduce uncertainty in monthly energy consumption estimates.

Second, future work should include a detailed sensitivity analysis of key model inputs and assumptions. Parameters such as stack temperature, O₂ concentration in flue gas, feedwater temperature, steam pressure, condensate return fraction, blowdown rate, heat recovery effectiveness, insulation effectiveness, natural gas cost, and emission factor can influence the estimated energy, cost, and CO₂ savings. Sensitivity analysis would help identify which parameters most strongly affect the model outputs and would improve confidence in the tool's use for preliminary decision-making.

Third, the model should be further validated using data from additional boiler systems. The present study verifies the tool using utility bill data from one manufacturing facility. Future validation using multiple facilities, boiler capacities, operating schedules, and steam demand profiles would help evaluate the general reliability of the simulation framework. Higher resolution data, such as daily or hourly natural gas consumption, steam production, stack oxygen, stack temperature, feedwater temperature, and production output, would also support more rigorous comparison between simulated and measured performance.

Finally, future versions of the tool may include a limited number of additional steam system measures that are closely related to the current boiler efficiency framework. Examples include steam trap inspection and repair, steam leak reduction, oxygen trim control, boiler sequencing, deaerator optimization, and condensate return network improvements. These additions would remain within the scope of boiler and

steam system energy assessment while allowing the tool to represent a wider range of recommendations commonly identified during industrial energy audits.

6 Conclusion

This study developed a temporal, parameter-driven Excel VBA simulation tool for evaluating the energy, cost, carbon emission, and environmental performance impacts of boiler efficiency projects in industrial facilities. The tool was designed to support practical decision making by allowing users to define baseline boiler operating conditions, apply selected efficiency measures on specific implementation dates, and estimate the resulting daily and annual changes in fuel consumption, operating cost, and CO₂ emissions. By combining boiler-loss calculations, daily load factor adjustment, date-specific scenario implementation, cost and emissions accounting, ESG-oriented environmental performance estimation, and utility bill verification, the model provides a transparent and accessible framework for preliminary evaluation of boiler improvement projects.

The proposed tool differs from a static savings calculator because it accounts for when each efficiency measure is implemented during the year and how daily boiler demand changes with load variation. This temporal structure is important for industrial applications, where energy efficiency projects are often implemented at different times rather than simultaneously. The model therefore provides a more realistic estimate of annual savings and allows users to compare individual and combined project scenarios under facility-specific operating assumptions.

Under the baseline operating conditions considered in this study, annual boiler energy consumption was estimated as 48,407 GJ/year, corresponding to 2434.64 metric tons of CO₂ emissions and an annual fuel cost of \$138,086.01. Among the individual measures, condensate recovery produced the largest reduction, saving 4080 GJ/year, reducing CO₂ emissions by 205.21 metric tons/year, and lowering fuel cost by \$11,639.16/year. This was followed by burner replacement, air-fuel ratio optimization, steam pressure reduction, blowdown heat recovery, blowdown rate reduction, flue gas heat recovery, and insulation of exposed hot surfaces. The combined scenario, which included condensate recovery, air-fuel ratio optimization, and steam-pressure reduction implemented on different days, produced the highest overall savings, reducing annual energy use by 4523 GJ/year, CO₂ emissions by 227.46 metric tons/year, and fuel cost by \$12,900.97/year.

The results show that the relative effectiveness of boiler-efficiency measures depends strongly on the baseline operating condition, available heat recovery potential, load profile, and timing of implementation. For the case studied, condensate recovery dominated the individual scenarios because returning hot condensate substantially reduced the energy required to heat makeup water. Combustion related measures also produced meaningful savings because the baseline stack O₂ concentration was relatively high. In contrast, insulation and flue-gas heat recovery produced smaller savings under the selected assumptions, although their impact may be larger in facilities with greater exposed surface area, higher stack temperature, or larger recoverable heat potential.

The model was verified using 12 months of natural-gas utility bill data from a manufacturing facility. The simulated annual energy consumption was 48,407 GJ compared with 49,125 GJ from utility bills, giving an annual absolute percentage error of 1.48%. Monthly absolute percentage errors ranged from 1.48% to 12.09%. These deviations reflect the screening-level nature of the model and may be attributed to actual production variation, weather effects, start-up and shutdown events, operating schedule changes, simplified load factor assumptions, and real world boiler control behavior. Nevertheless, the low annual error indicates that the tool can provide credible annual estimates for preliminary energy assessment and project comparison when reasonable boiler operating parameters are available.

Overall, the main contribution of this study is the integration of boiler loss based simulation, temporal project implementation, load-factor adjustment, cost and emissions accounting, ESG oriented environmental performance estimation, and utility bill verification into a low cost Excel VBA decision support tool. The framework provides industrial facilities, energy auditors, and plant personnel with an accessible method for comparing boiler efficiency projects before implementation and for linking engineering level improvements to measurable environmental performance outcomes.

Acknowledgement: Not applicable.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: The authors confirm contribution to the paper as follows: Conceptualization, Bhaskaran Gopalakrishnan and Bibek Prajapati; methodology, Bhaskaran Gopalakrishnan, Bibek Prajapati and Rumana Subnom; validation, Bibek Prajapati and Rumana Subnom; formal analysis, Rumana Subnom; investigation, Bibek Prajapati; resources, Bibek Prajapati; data curation, Bibek Prajapati; writing—original draft preparation, Rumana Subnom and Bibek Prajapati; writing—review and editing, Rumana Subnom, Hailin Li, Zhichao Liu and Bhaskaran Gopalakrishnan; visualization, Hailin Li; supervision, Hailin Li, Zhichao Liu and Bhaskaran Gopalakrishnan; project administration, Hailin Li and Bhaskaran Gopalakrishnan; funding acquisition, None. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: The data that support the findings of this study are available from the Corresponding Author, [Rumana Subnom], upon reasonable request.

Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. U.S. Environmental Protection Agency. Industry sector emissions [Internet]. [cited 2026 May 20]. Available from: <https://www.epa.gov/ghgemissions/industry-sector-emissions>.
2. Introduction to the ISSB and IFRS sustainability disclosure standards. London, UK: IFRS Foundation; 2023.
3. Barma MC, Saidur R, Rahman SMA, Allouhi A, Akash BA, Sait SM. A review on boilers energy use, energy savings, and emissions reductions. *Renew Sustain Energy Rev*. 2017;79:970–83. doi:10.1016/j.rser.2017.05.187.
4. Sonderegger RC. A baseline model for utility bill analysis using both weather and non-weather-related variables. *ASHRAE Trans*. 1998;104:859.
5. Stefan A, Paul L. Does it pay to be green? A systematic overview. *Acad Manage Perspect*. 2008;22(4):45–62. doi:10.5465/amp.2008.35590353.
6. Eccles RG, Ioannou I, Serafeim G. The impact of corporate sustainability on organizational processes and performance. *Manage Sci*. 2014;60(11):2835–57. doi:10.1287/mnsc.2014.1984.
7. Zatonatska T, Soboliev O, Zatonatskiy D, Dluhopolska T, Rutkowski M, Rak N. A comprehensive analysis of the best practices in applying environmental, social, and governance criteria within the energy sector. *Energies*. 2024;17(12):2950. doi:10.3390/en17122950.
8. Ma H, Lu S, Lee CKM, Moktadir MA, Ren J. A critical review of environmental, social, and governance (ESG) practices in the transportation sector: how does it contribute to SDGs? *Renew Sustain Energy Rev*. 2026;229:116654. doi:10.1016/j.rser.2025.116654.
9. Khamisu MS, Paluri RA. Emerging trends of environmental social and governance (ESG) disclosure research. *Clean Prod Lett*. 2024;7:100079. doi:10.1016/j.clpl.2024.100079.
10. Asmi F, Neher A, Wong A. The evolution of environmental, social, and governance (ESG) and risk and its implications for sustainable finance: a systematic literature review. *Corp Soc Responsib Environ Manag*. 2026;33:csr.70402. doi:10.1002/csr.70402.

11. Tan QL, Hashim S, Zheng Z. Environmental social governance (ESG) in digitalization research: a bibliometric analysis. *Sage Open*. 2025;15:21582440241310953. doi:10.1177/21582440241310953.
12. Shah S, Adhyaru DM. Boiler efficiency analysis using direct method. In: 2011 Nirma University International Conference on Engineering; 2011 Dec 8–10; Ahmedabad, India. p. 1–5. doi:10.1109/NUiConE.2011.6153313.
13. Ernest AO, David OA. Boiler efficiency analysis of A 220 MW steam power plant using direct method. *Int J Res Sci Innov*. 2022;9(8):111–6. doi:10.51244/IJRSI.2022.9802.
14. ASME. PTC 4-2013: fired steam generators. New York, NY, USA: American Society of Mechanical Engineers; 2013.
15. Bujak J. Mathematical modelling of a steam boiler room to research thermal efficiency. *Energy*. 2008;33(12):1779–87. doi:10.1016/j.energy.2008.08.004.
16. Rehan A, Habib MA, Elshafei M, Alzaharnah IT. Modeling time variations of boiler efficiency. *J Energy Resour Technol*. 2018;140(5):052001. doi:10.1115/1.4038236.
17. Mahmoudi Lahijani A, Supeni EE, Kalantari F. A review of indirect method for measuring thermal efficiency in fire tube steam boilers. *J Ind Pollut Control*. 2018;34(1):1825–32.
18. Beér JM. Low NO_x burners for boilers, furnaces and gas turbines; drive towards the lower bounds of NO_x emissions. *Combust Sci Technol*. 1996;121(1–6):169–91. doi:10.1080/00102209608935593.
19. Schmitz N, Schwotzer C, Pfeifer H, Schneider J, Cresci E, Wüning JG. Development of an energy-efficient burner for heat treatment furnaces with a reducing gas atmosphere. *HTM J Heat Treat Mater*. 2017;72(2):73–80. doi:10.3139/105.110314.
20. U.S. Department of Energy. Use feedwater economizers for waste heat recovery. Advanced Manufacturing Office [Internet]. 2012 [cited 2026 Jan 1]. Available from: <https://www.energy.gov/>.
21. Roth K, Scherer V, Behnke K. Enhancing the dynamic performance of electricity production in steam power plants by the integration of transient waste heat sources into the feed-water pre-heating system. *J Energy Technol Policy*. 2005;3(1/2):50. doi:10.1504/ijetp.2005.006739.
22. Einstein D, Worrell E, Khrushch M. Steam systems in industry: energy use and energy efficiency improvement potentials. Lawrence Berkeley National Laboratory [Internet]. 2001 [cited 2026 May 18]. Available from: <https://escholarship.org/uc/item/3ml781fl>.
23. Harrell G. Boiler blowdown energy recovery. *Energy Eng*. 2004;101(5):32–42. doi:10.1080/01998590409509277.
24. Kocabaş C, Savaş AF. Reducing energy losses of steam boilers caused by blowdown with using the FMEA method. *Smart Sci*. 2021;9(2):70–9. doi:10.1080/23080477.2021.1898794.
25. Savaş AF, Kocabaş C. Reducing surface heat loss in steam boilers. *Open Chem*. 2022;20(1):1458–66. doi:10.1515/chem-2022-0241.
26. Škrabul'áková EF. On the effect of insulation of boiler parts on savings. In: 2024 25th International Carpathian Control Conference (ICCC); 2024 May 22–24; Krynica Zdrój, Poland. p. 1–5. doi:10.1109/ICCC62069.2024.10569689.
27. Corporate Governance Institute. What is ESG and why is it important? Dublin, Ireland: Corporate Governance Institute; 2026.
28. IBM. What is environmental, social and governance (ESG)?. Armonk, NY, USA: IBM; 2026.
29. PwC. Environmental social governance (ESG): creating shared value [Internet]. [cited 2026 Jan 1]. Available from: <https://www.pwc.com/ng/en/services/environmental-social-governance.html>.
30. Diligent. What is ESG? an environmental, social and governance guide for 2025. New York, NY, USA: Diligent; 2025.
31. Warouw FF, Mashudi, Arafah M, Noviany H, Hendarto T. The rise of environmental, social, and governance (ESG): assessing the impact and implications for global business practices and policy formulation. *Int J Sci Soc*. 2024;6(1):810–21. doi:10.54783/ijssoc.v6i1.1066.
32. Lunawat RM, Elmarzouky M, Shohaieb D. Integrating environmental, social, and governance (ESG) factors into the investment returns of American companies. *Sustainability*. 2025;17(19):8522. doi:10.3390/su17198522.
33. Adardour Z, Ed-Dafali S, Derj A, Sbair H, Bami A. Environmental, social and governance (ESG) performance and firm risk: a systematic literature review, practical insights and future directions. *J Financ Rep Account*. 2026;31:1–27. doi:10.1108/jfra-05-2025-0343.

34. Addressing the impacts and risks of environmental, social and governance (ESG) practices towards sustainable development. London, UK: Nature Portfolio Collection; 2025.
35. AuditBoard/Optro. ESG & sustainability software [Internet]. [cited 2026 Jan 1]. Available from: <https://optro.ai/product/esg>.
36. KEY ESG. The top 10 sustainability software providers. London, UK: KEY ESG; 2026.
37. SAI360. Environmental, social and governance (ESG) software. Chicago, IL, USA: SAI360; 2025.
38. Taler J, Trojan M, Dzierwa P, Kaczmarek K, Węglowski B, Taler D, et al. The flexible boiler operation in a wide range of load changes with considering the strength and environmental restrictions. *Energy*. 2023;263:125745. doi:10.1016/j.energy.2022.125745.
39. Park JS, Lee SJ, Kim KH, Kwon KW, Jeong JW. Estimating thermal performance and energy saving potential of residential buildings using utility bills. *Energy Build*. 2016;110:23–30. doi:10.1016/j.enbuild.2015.10.038.
40. Golman B, Yermukhambetova A. An excel VBA-based educational module for simulation and energy optimization of spray drying process. *Comp Applic Eng*. 2019;27(5):1103–12. doi:10.1002/cae.22139.
41. Abisoye BO, Abisoye OA. Simulation of electric power plant performance using excel[®]-VBA. *Int J Inf Eng Electron Bus*. 2018;10(3):8–14. doi:10.5815/ijieeb.2018.03.02.
42. Chowdhury NI, Gopalakrishnan B, Adhikari N, Li H, Liu Z. Evaluating electrification of fossil-fuel-fired boilers for decarbonization using discrete-event simulation. *Energies*. 2024;17(12):2882. doi:10.3390/en17122882.
43. Postma TJB, Liebl F. How to improve scenario analysis as a strategic management tool? *Technol Forecast Soc Change*. 2005;72(2):161–73. doi:10.1016/j.techfore.2003.11.005.
44. Duinker PN, Greig LA. Scenario analysis in environmental impact assessment: improving explorations of the future. *Environ Impact Assess Rev*. 2007;27(3):206–19. doi:10.1016/j.eiar.2006.11.001.
45. Witt T, Dumeier M, Geldermann J. Combining scenario planning, energy system analysis, and multi-criteria analysis to develop and evaluate energy scenarios. *J Clean Prod*. 2020;242:118414. doi:10.1016/j.jclepro.2019.118414.