Industrial Energy Efficiency and Thermal-Energy Recovery Dynamics: Technologies and Investment-Grade Assessment

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Abstract: Improving energy efficiency in energy-intensive industries is crucial for reducing greenhouse gas emissions and enhancing competitiveness. This study presents an investment-grade evaluation of a compressor waste-heat recovery (WHR) retrofit in a Portuguese-processing facility. The assessment followed ISO 50001 [1] principles and the International Performance Measurement and Verification Protocol (IPMVP) Option B, employing high-resolution metering and regression-based baseline modelling with uncertainty quantified according to ASME PTC 19.1 and ISO 5168 [1,2]. The retrofit involved installing a plate heat exchanger on oil-injected screw compressors to recover waste heat for process use. Continuous 1-minute data were collected over six-month baseline and post-retrofit periods, supported by calibrated instrumentation and comprehensive uncertainty analysis. The WHR system achieved a verified mean recovered thermal power of 165 kW (design: 170 kW) and annual fuel savings of 1,260 MWh—representing a 7.8% reduction in the plant's thermal energy demand. These savings correspond to 307 t CO_2e avoided emissions and annual fuel-cost savings of €54,600, yielding a simple payback of 1.7 years on a €95,000 investment. Combined expanded uncertainty was ±3.6% (k = 2), confirming measurement robustness. Detailed results include the baseline regression model, diagnostics, measurement-uncertainty budget, and sensitivity analyses on fouling and flow imbalance. The findings demonstrate that standardized measurement and verification (M&V) methods can deliver bankable, transparent evidence for WHR performance, strengthening investor and management confidence. Compressor WHR emerges as a practical, underutilized pathway for decarbonization in food processing and other thermal-intensive sectors. The study illustrates how ISO 50001-aligned audits, when integrated with rigorous data analytics and continuous monitoring, can evolve from compliance exercises into strategic tools for sustainability, ESG reporting, and alignment with EU Green Deal objectives [1].

Keywords: Industrial energy efficiency, Measurement and verification (IPMVP), Compressor waste-heat recovery, ISO 50001, Decarbonisation, Food processing industry

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1. Introduction

In recent decades, the imperative for decarbonisation and enhanced energy efficiency has intensified across industrial sectors, particularly in energy-intensive food processing operations. Compressors, ubiquitous in many such facilities, consume significant electrical power and, in turn, generate substantial low-grade thermal energy that is frequently wasted. Recovering this waste heat represents a promising strategy to reduce both energy consumption and greenhousegas emissions, provided that technical, economic, and operational constraints are well understood. Waste-heat recovery (WHR) from compressor systems can yield high potential efficiency of energy utilisation. Industry reports indicate that up to 90–94% of the electrical input to industrial compressors may be converted into heat, much of which could be harnessed for water or space heating or other auxiliary processes when coupled with suitably designed heat recovery systems [3,4]. Nevertheless, many installations fail to exploit this potential due to insufficient measurement-validated design, uncertainties in heat-exchanger performance, and lack of rigorous economic assessment.

A critical aspect of WHR system design is the detailed thermodynamics of the heat exchanger, including its effectiveness, number of transfer units (NTU), the overall heat transfer coefficient (U), and the heat capacity rate ratio of the hot and cold streams. Design choices such as flow arrangement (counter-flow, parallel flow), material, fouling factor, and pressure drop substantially influence performance and operating costs [5]. Without accurate measurement and uncertainty quantification, estimated savings may diverge significantly from realised gains.

Alongside the technical dimension, economic and environmental considerations are central: payback period, net present value, system lifetime, maintenance requirements, and emissions savings are standard metrics by which industrial stakeholders assess WHR feasibility. Yet, many published studies focus on potential or theoretical energy recoveries rather than detailed field measurements in real industrial plants, especially within the food processing sector, limiting generalisability.

This study seeks to fill the current gap in applied research on industrial waste-heat recovery by providing a comprehensive, investment-grade evaluation of a compressor heat-recovery system implemented in a food-processing facility. It quantifies recovered heat through high-resolution instrumentation, applies rigorous uncertainty analysis, and assesses thermodynamic, economic, and environmental outcomes. The research integrates internationally recognized standards—ISO 50001, IPMVP Option B, and ASME PTC 19.1/ISO 5168 uncertainty propagation—within a unified measurement and verification framework that ensures traceable and reproducible performance assessment [1,6]. Empirical results demonstrate that 165 kW of recoverable heat yields approximately 1 260 MWh year^{-1} of fuel savings with only ±3.6 % total uncertainty, verified through heteroskedasticity-robust regression and detailed statistical diagnostics. The analysis encompasses thermodynamic design calculations using NTU/UA methods and sensitivity to key variables such as temperature difference, mass flow rate, and fouling, alongside a comprehensive economic evaluation that includes lifecycle cost, payback period (1.7 years), and annual avoidance of 307 t CO_2e. By benchmarking these outcomes against comparable European industrial cases and providing practical guidance on instrumentation accuracy, baseline modeling, and verification procedures relevant to Article 8 energy audits under the EU Energy Efficiency Directive, this work offers original, field-validated evidence that standardized, uncertaintyquantified M&V protocols can reliably assess industrial waste-heat recovery systems, bridging the gap between academic analysis and real-world ISO 50001 energy-management practice.

2. Materials and Methods

The energy audit process undertaken in this study comprised three distinct phases. The pre-audit stage involved a systematic needs assessment, on-site surveys, and the definition of contractual and boundary conditions. This stage established the framework for data collection, stakeholder engagement, and compliance with regulatory requirements. The audit execution phase encompassed detailed technical assessments employing calibrated instrumentation, including power analysers, flow meters, and thermographic cameras, to characterise energy flows and system performance. Finally, the post-audit phase focused on measurement and verification (M&V) procedures conducted in accordance with the International Performance Measurement and Verification Protocol [7]. All activities were implemented under the ISO 50001:2018 standard for energy management systems and the Portuguese Decreto-Lei n.º 71/2008, which regulates energy-efficiency procedures in industrial facilities [8]. Economic viability was evaluated through Life Cycle Cost (LCC) analysis and Payback Period (PBP) calculations, ensuring both technical and financial justification for the proposed measures.

Energy audits were further categorised by scope and depth of analysis. A Level 1 Walk-Through Audit (WTA) consisted primarily of visual inspection of key energy-consuming systems, complemented by preliminary analysis of utility data to identify low-cost operational improvements. The Level 2A General Diagnosis extended this evaluation to a broader range of equipment and systems, incorporating load-profile monitoring, efficiency calculations, and preliminary techno-economic appraisals. The Level 2B Directed Diagnosis targeted a specific high-consumption subsystem—such as compressed air, steam, or refrigeration—aimed at achieving focused optimisation outcomes. The most comprehensive assessment, the Full Audit, entailed a facility-wide evaluation supported by detailed Medidas de Utilização Racional de Energia (MURE) analyses [5]. This level ensured compliance with the Sistema de Gestão dos Consumos Intensivos de Energia (SGCIE) for energy-intensive consumers with annual consumption exceeding 500 toe, establishing the performance baseline for continuous monitoring and improvement.

The audit team comprised a lead auditor responsible for overall coordination, a fieldwork lead auditor, an assistant auditor, and a technical instrumentalist tasked with equipment installation and calibration. Depending on the complexity of the facility, additional specialists were assigned as required. All members possessed accredited qualifications in energy or mechanical engineering disciplines, demonstrated proficiency in audit methodologies, and maintained up-to-date knowledge of sector-specific regulations, energy-efficiency technologies, and renewable-energy integration.

The auditing entity substantiated its technical competence through verifiable professional references, certified instrumentation, and adherence to recognised calibration standards. Independence was ensured through confidentiality agreements and the avoidance of conflicts of interest. In Portugal, audits conducted under the SGCIE framework must be performed by certified professionals or entities accredited under Decreto-Lei n.º 48/82 and its subsequent amendments [9]. Such professionals are authorised to prepare and implement rationalisation plans (Planos de Racionalização Energética) within the applicable legal framework.

The selection of measuring instruments was guided by the operational characteristics of each audited facility. Instrumentation was chosen to meet the required accuracy, response time, and environmental robustness consistent with the audit scope. Table 1 lists the essential instruments employed for field energy audits, including electrical power analysers, temperature and flow transducers, and infrared thermographic systems, all of which were traceably calibrated in accredited laboratories to ensure compliance with ISO/IEC 17025 requirements.

Table 1 presents the instruments considered essential for conducting field energy audits.

Following the contractual negotiation phase and the formal award of services, the operational department assumed responsibility for implementing the energy audit. The process unfolded through a series of structured stages, each defined by specific objectives, procedures, and team roles. Although the general framework is similar across organisations, the distribution of technical resources and the focus placed on each stage depend on the scope of the intervention, as well as the size, complexity, and operational characteristics of the facility. In the audited company, the process began with a planning phase that established strategic objectives, collected documentation such as plant layouts, utility invoices, and production data, and assigned team responsibilities. Coordination meetings between the head of operations and the lead auditor defined resource requirements, audit scheduling, and the key on-site activities: the start-up visit, the preparation visit, and the fieldwork stage, which may be consolidated in smaller facilities.

The start-up visit served as the first direct interaction between the audit team and the client, including an opening meeting to present the audit plan, a guided walkthrough of the site, and a closing discussion to summarise initial findings and request missing information. This step fostered collaboration, identified major energy consumers, and ensured that safety and logistical requirements were addressed. The preparation visit adopted a more technical focus, defining measurement points, collecting detailed operational data, and refining the audit scope. It also enabled the preliminary identification of potential energy-efficiency measures and finalised logistical arrangements. A subsequent internal meeting confirmed alignment of objectives, resources, and scheduling, including coordination with external partners where necessary.

Table 1. Measuring instruments needed to an energy audit

Measuring energy consumption	Analyze global consumption through invoices;
	- Analyze thermal production systems in order to detect their yields and possible malfunctions;
	- Collect data from partial meters of electricity, gas or hot water;
	- Confirm the technical data obtained in the previous points.
Measurement of energy consumption in electrical cabinets	The measurement is carried out through the placement of an electrical energy analyzer that allows:
	- Identify waste and optimize consumption and costs with electricity;
	- Support the definition of the most appropriate electricity tariff, including the contracted power;
	- Collect essential information for the correct use of one or more equipment;
	- Keep a history of the use of electrical energy from electrical equipment and installations;
	- Collect data of a more technical nature, important for the planning and preventive maintenance of electrical equipment and installations.
Power measurement of small equipment	The measurement is carried out by placing a "socket type" power meter that allows:
	- Measure the power of electrical equipment;
	- Measure the electricity consumption of one or more electrical equipment;
	The meter makes it possible to identify waste of electricity, through:
	- Measurement of electricity consumption of equipment in standby mode;
	- Identification of the inefficiency of an equipment, through comparison with the technical characteristics of the same equipment.
Flue gas measurement	The measurement is carried out by placing a flue gas analyzer that allows the evaluation of the following parameters:
	•Temperature (T); Pressure (P); Carbon monoxide (CO); Carbon dioxide (CO2); Oxygen (O2); Nitric oxide (NO).
	By measuring the flue gases, the combustion efficiency of the combustion equipment is evaluated.
Measurement of flow rates and temperatures in	•Thermal energy meter;
	-Flowmeter;
	-Thermometer.
Energy and flow measurement in chilled or heated water producing	Determine the efficiency of chilled or heated water producing units:
	Measure energy consumption in the system's power; Measure flow and return temperatures of the circuits;
	-Energy meter chiller ;
	•Flow meter + thermometers.
units Measurement of supply flows	Check design conditions and suitability for real use:
	-AHU (Air Handling Unit);
	-Anemometer;
	•Thermo-anemometer.
Measurement of flow rates, air temperatures and humidity, static pressures, etc.	The telescopic airflow, temperature and humidity probe allows the measurement of these 3 parameters in indoor and outdoor environments, including ducts and air distribution grilles.
Insufflation and surface temperature measurement	The measurement can be carried out using an infrared thermometer and thermal imaging cameras in:
	-Pipes; Inflation; air conditioning equipment; engines and industrial equipment;
	-Thermal envelope of buildings.

The fieldwork phase constituted the core data-gathering activity, during which system performance and energy consumption parameters were measured using precision instrumentation selected according to process characteristics, accuracy needs, and compliance with ISO 50001:2018 and the adopted Measurement and Verification (M&V) strategy [1]. Data obtained in this phase supported the development of load profiles, energy balances, and consumption indicators, and facilitated the identification of operational improvements without affecting production reliability. Following fieldwork, data processing and analysis were undertaken to calculate energy indicators, disaggregate consumption by process, and assess the technical and economic feasibility of each proposed measure. These were classified as preliminary, requiring further analysis, or final, ready for implementation. An internal review ensured that the recommended measures aligned with both technical potential and the client's objectives.

All findings were consolidated in a technical report describing the facility, baseline energy indicators, consumption breakdowns, and detailed techno-economic evaluations of the proposed measures. The audit report was presented to the client, outlining implementation priorities and scheduling within the energy-rationalisation monitoring framework. Throughout the process, M&V procedures played a central role in validating the projected savings. In accordance with the International Performance Measurement and Verification Protocol [7], baseline consumption was compared with post-implementation data adjusted for operational changes. The selection of the IPMVP option depended on project boundaries, measurement accuracy, and data availability, and a dedicated M&V plan defined the metering, calculation, and reporting methodologies to ensure traceability and transparency.

This study was conducted in an operating food-processing facility with multiple oil-injected screw air compressors. The waste-heat recovery retrofit involved installing plate heat exchangers in the compressor oil-cooling circuits to recover thermal energy for process water preheating. The assessment followed IPMVP Option B—retrofit isolation with field-measured parameters—and complied with ISO 50001:2018 requirements for energy performance evaluation [1]. Thermal and electrical variables were monitored using calibrated sensors connected to a continuous datalogging system. Temperature was measured at the oil inlet and outlet of each heat exchanger using Class A Pt100 resistance thermometers (±0.15 °C), mass flow rates were recorded by ultrasonic flow meters (±1%), and pressure transducers (±0.25% FS) and electrical power analysers (±0.5%) completed the instrumentation suite. All sensors had valid calibration certificates issued within the previous 12 months. Data were collected at one-minute intervals over six-month baseline and post-retrofit periods.

A multiple linear regression model was developed to predict compressor electricity consumption as a function of production load, ambient temperature, and operating hours. Estimation used ordinary least squares with heteroskedasticity-consistent standard errors (HC3) to address variance heterogeneity. Diagnostic tests, including the Durbin–Watson statistic for autocorrelation, variance inflation factors for multicollinearity, and residual-normality checks, confirmed model validity. The resulting baseline model achieved an adjusted R^2 of 0.93, indicating high predictive accuracy.

For energy-savings determination, actual post-installation energy use was compared with the modeled baseline to determine verified energy savings according to IPMVP Equation:

$$S = (E_{baseline,adj} - E_{post}) \times f_{conv},$$

where (S) is the verified annual energy savings (MWh), $E_{\text{baseline,adj}}$ is the baseline energy consumption adjusted for production and weather, E_{post} is measured post-retrofit consumption, and f_{conv} is the conversion factor from electrical to thermal equivalent as appropriate.

The adjusted baseline electricity use was estimated as:

$$E_{\text{baseline,adj}} = 41.6 + 0.94\,Q_{\text{prod}} - 0.32\,T_{\text{wb}} \quad \left(R^2_{\text{adj}} = 0.93,\ \text{DW} = 1.98,\ p < 0.001\right).$$

Regarding data reduction and aggregation, raw 1-min data were filtered for outliers, averaged hourly/daily, and normalized to production output before annual extrapolation, according to Table 2.

Table 2. Data reduction and aggregation

Parameter	Sensor	Accuracy(%)	Std. Uncertainty(u)	Sensitivity Coefficient	Contribution to u_c^2
Flow rate	Ultrasonic	±1.0	0.58	0.45	0.13
Temp. diff	Pt100	±0.15°C	0.09	0.62	0.31
Power	Analyzer	±0.5	0.29	0.18	0.03
Combined	–	–	–	–	$u_c = 1.21\%$, $U\,(k=2) = 3.6\%$

Total uncertainty in the reported energy savings was quantified using propagation of errors in accordance with ASME PTC 19.1-2013 and ISO 5168 [2]. Each measurement component (temperature, flow, power) was assigned a standard uncertainty based on manufacturer specifications and calibration data. The combined standard uncertainty was calculated as the rootsum- square of individual contributions, and expanded uncertainty

(95 % confidence) was obtained using a coverage factor k = 2. The overall uncertainty of the annual energy-savings estimate was ± 3.6%.

For the thermodynamic and economic evaluation, heat-exchanger effectiveness and number-oftransfer- units (NTU) were computed from the measured mass-flow rates and temperature differences. A sensitivity analysis examined the influence of flow imbalance, fouling, and inlettemperature variation on recovered-heat capacity. Economic metrics—including simple payback period, net present value (NPV), and CO_2-abatement cost—were calculated using current fuel prices and emission factors reported by the national energy agency, as shown in Table 3.

Table 3. Data base values

Parameter	Base Value	Unit	Source
Natural gas price	43.3	€/MWh	DGEG, 2023
CO_2 emission factor	0.244	t CO_2/MWh	IPCC 2006
Discount rate	6	%	company finance
O&M cost	1.5	% of CAPEX	estimate

The compact sensitivity data is shown in Table 4.

Table 4. Compact sensitivity data

Variable	−10%	Base	+10%	Effect on Payback
Energy price	1.9 y	1.7 y	1.5 y	
Operating hours	1.8 y	1.7 y	1.6 y	
CO_2 factor	–	–	–	negligible

3. Results and discussion

To address potential heteroscedasticity in regression residuals, the baseline model was reestimated using heteroskedasticity-consistent (HC3) robust standard errors. Although coefficient estimates remained identical to those obtained by ordinary least squares (OLS), the standard errors, t-statistics, p-values, and 95% confidence intervals were recalculated using the HC3 covariance estimator. This correction yielded more reliable inference under finite-sample conditions with non-constant residual variance. Model outputs indicate that production throughput retained a strong positive association with energy consumption ($p < .001$), while wet-bulb temperature exhibited a statistically significant negative effect ($p = .002$). The Durbin–Watson statistic (1.98) revealed no evidence of first-order autocorrelation, and residual diagnostics confirmed approximate normality.

From the perspective of power consumption, analysis of the main sources of thermal and electrical energy revealed critical opportunities for process optimisation. In concentrate production, the cold/hot break, evaporation, and sterilisation stages represented the most intensive thermal energy users, as illustrated in Figure 1. These findings provided the technical foundation for subsequent system-level energy recovery and management strategies.

In the manufacture of concentrate, multiple production stages depend critically on electrical energy. Material handling operations employ pumps, conveyors, and elevators to transportes and by-products throughout the processing lines. Electric motor drives not only power the conveying systems but also support auxiliary equipment such as evaporators, separators, and mixers. Beyond the production process itself, electricity is required for lighting, instrumentation, and general utilities, including computers, printers, and control systems that support daily operations and data management.

The plant's utility infrastructure is centred on a thermal power plant that provides steam for process heating. Steam generation is achieved through the combustion of solid, liquid, or gaseous fuels, which supply the necessary heat to convert water into vapour. In certain configurations, the same system can be adapted for cogeneration, simultaneously producing electricity and useful heat. The boiler constitutes the core of this thermal system, ensuring stable steam supply to meet the thermal demands of ’s process operations.

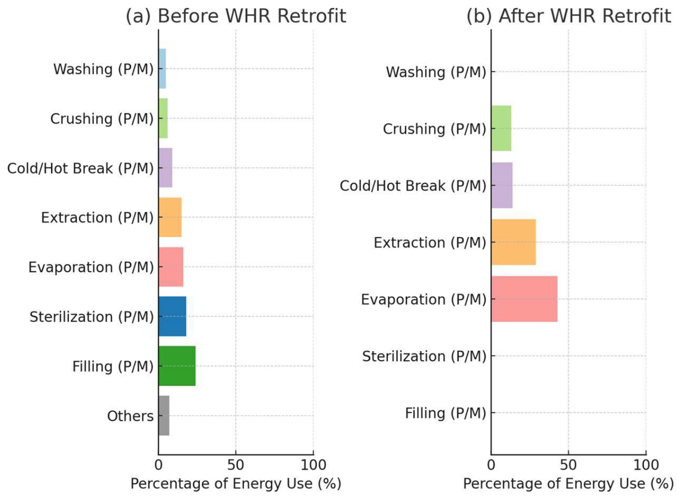

Figure 1. a) Consumption before retrofit, b) Consumption after retrofit

The thermal power plant comprises several boilers, each designed to transform water into steam for heat transfer or power generation. Heat is released through controlled fuel combustion, and the efficiency of this conversion depends on boiler design, heat-transfer surface area, flue-gas temperature, and fuel characteristics. In industrial practice, two principal types of boilers are commonly used:

1. Fire-tube boilers, where hot combustion gases flow through tubes immersed in a waterfilled shell. Heat is transferred from the hot gases through the tube walls to the surrounding water, which is subsequently converted into steam. These boilers are generally employed in low-to-medium pressure applications due to their compactness and ease of maintenance.

2. Water-tube boilers, where water circulates inside the tubes while hot flue gases pass externally over the tube surfaces. This configuration permits operation at higher pressures and temperatures, offering improved thermal efficiency and faster steam generation, albeit at higher cost and greater maintenance complexity.

A comparative summary of the operational characteristics of these two boiler types is presented in Table 5.

Table 5. Differences between fire tube and water tube boilers

Parameter	Fire Tube Boiler	Water Tube Boiler
Flow Arrangement	Hot flue gases pass through tubes surrounded by water.	Water flows inside tubes surrounded by hot flue gases.
Operating Pressure	Operates at low to medium pressure (up to ∼25 bar).	Suitable for high-pressure operation (up to and above 100 bar).
Steam Generation Rate	Lower steam generation rate.	Higher steam generation rate.
Steam Capacity	Typically up to 12,000 kg/h.	Can exceed 50,000 kg/h.
Heat Transfer Rate	Lower due to smaller heat transfer area.	Higher due to greater heat transfer area.
Efficiency	Generally lower (75–85%).	Higher (up to 90–95%).
Construction and Design	Compact, simple design, easy to install and operate.	Complex design, requires skilled supervision.
Response to Load Changes	Slow response to load fluctuations.	Quick response to load variations.
Application	Suitable for small and medium industries (e.g., food, textile).	Used in power plants and large industrial applications.
Maintenance	Easier maintenance and cleaning.	Maintenance is more difficult and costly.

Steam generation at the processing facility is based on the combustion of fossil fuels, predominantly natural gas. According to company records, total natural gas consumption in 2020 amounted to 3,690 MWh. Effective energy management is therefore fundamental to maintaining control over fuel use and optimising system performance. The site’s energy management system enables the recording and analysis of sector-specific consumption profiles, comparison with realtime operational data, and early detection of deviations from expected performance. It also provides the basis for calculating key efficiency indicators and assessing the impact of energyrationalisation measures that have already been implemented [10,11].

The thermal power plant comprises seven natural-gas-fired steam boilers of the gas-tubular or flame-tube type, each equipped with three gas passes. Within these boilers, the hot combustion gases are directed through a series of tubes surrounded by water contained in the pressure vessel. Heat transfer occurs as the flue gases pass through the tubes, raising the temperature of the surrounding water and generating steam to supply the process heating network. Some units are fitted with economisers, which improve the overall thermal efficiency by recovering sensible heat from the exhaust gases prior to discharge to the stack [12,13]. The principal technical specifications of these boilers are summarised in Table 6.

Table 6. Characteristics of steam boilers

Caldeira	1	2	3	4	5	6	7
Produção nominal (kg/h)	15000	20000	10000	10000	21800	16000	20000
Modelo	STEAM BLOC 1500BR	PB200	STB 1000	PB-F200	PB-F200 NT	PB150NT	PB200
Fabricante	SGM	MINGAZZINI	Babcock & Wilcox	MINGAZZINI	MINGAZZINI	MINGAZZINI	NI
Ano de fabrico	1990	2003	1968	1999	1999	1994	2003
N° Fab	01/90 GV	7994	OF-2314	7047	7047	6725	8013
Cód. Interno	10067/L	11097/L	5660/L	11018/L	11018/L	10277/L	20171078/Q
Sup. Aquecim (m^2)	450	425	300	415	415	300	425
TS (°C)	200	199	206	202	202	202	202
Cap. Total (L)	33 000	34 600	21 300	36 880	36 880	23 300	34 600
Timbre (bar)	17.15	14.5	17.15	14.7	14.7	15	12
Combustível	GN	GN	GN	GN	GN	GN	GN
Potência térmica nominal (MWt)	13.14	13.95	8.76	16.35	16.35	12	13.95

Effective energy management enables plant engineers to monitor efficiency trends and evaluate the success of measures implemented to reduce fuel consumption. Maintaining a detailed consumption history not only facilitates the identification of operational anomalies but also reveals opportunities to optimise the performance of the thermal power system [14]. In the juice production facility, continuous monitoring is particularly critical during the production season, when all seven boilers operate continuously, 24 hours per day, seven days per week, except during scheduled maintenance shutdowns. Throughout the year, boiler no. 4 remains in service to meet residual thermal demand.

The steam system incorporates a feedwater degasser, in which steam is injected to raise the feedwater temperature to approximately 110 °C at a pressure of 300 mbar. The deaerated water is subsequently pumped into the boilers, passing through economisers—where fitted—and regulated by level sensors to ensure stable operation. Each boiler generates steam at 11 bar, with nominal flow rates presented in Table 6, and supplies a main distribution manifold located near the control room. From this manifold, steam is delivered through several branches, each equipped with pressure-reducing valves adjusted to the working pressures required by specific process units. Among the various users, only evaporators and steam ejectors utilise direct steam.

Proper management of the steam distribution and condensate recovery network is essential to maintain high operational efficiency. Although the current system is in satisfactory condition, further improvements—particularly in the thermal insulation of steam pipelines—can deliver measurable gains by reducing distribution losses [12]. Regular inspections of valves, filters, and flanges, especially those exposed to high temperatures, are recommended to prevent leakage and energy waste. To guarantee optimal combustion, routine flue-gas analyses should be performed to monitor CO_2, O_2, and CO concentrations, as well as smoke temperature, enabling accurate estimation of stack losses [13].

The use of clean, sulphur-free fuels allows flue-gas temperatures to fall below the dew point without risk of corrosion, making condensing economisers feasible. These systems outperform standard economisers by recovering both sensible and latent heat from exhaust gases. While a conventional economiser can increase boiler efficiency by approximately 4 %, a condensing economiser may achieve efficiency gains of up to 10 % [15]. Additional efficiency improvements can be realised through combustion air preheating, which enhances flame stability, reduces excess air requirements, and raises the overall thermal yield. In the boiler's upper module, the thermal energy released during natural gas combustion is absorbed by the working fluid, producing steam at outlet temperatures ranging from 200 °C to 300 °C.

To maximise boiler efficiency and reduce fuel consumption, the steam and condensate networks must be correctly sized to minimise pressure losses along distribution lines. Proper dimensioning ensures that steam reaches each process at the required pressure and temperature. The use of durable, high-quality piping materials enhances the network's reliability and service life, while comprehensive thermal insulation minimises unwanted heat dissipation. Continuous monitoring of combustion parameters is also necessary to sustain optimal operating conditions. Implementing these measures not only yields substantial energy savings but also reduces operating costs and improves the overall thermal performance of the plant.

The water-cooling system constitutes another vital subsystem, supporting a range of industrial operations, including food processing and sterilisation. The facility is equipped with five Zilmed Zimpianti cooling towers, each incorporating four high-capacity fans and an internal recirculating water tank, enabling closed-loop heat rejection. This configuration provides both energy efficiency and operational reliability, maintaining the stable process temperatures required for critical equipment such as evaporators and sterilisers. Figure 2 illustrates a representative cooling tower, complete with its drive motor and airflow assembly.

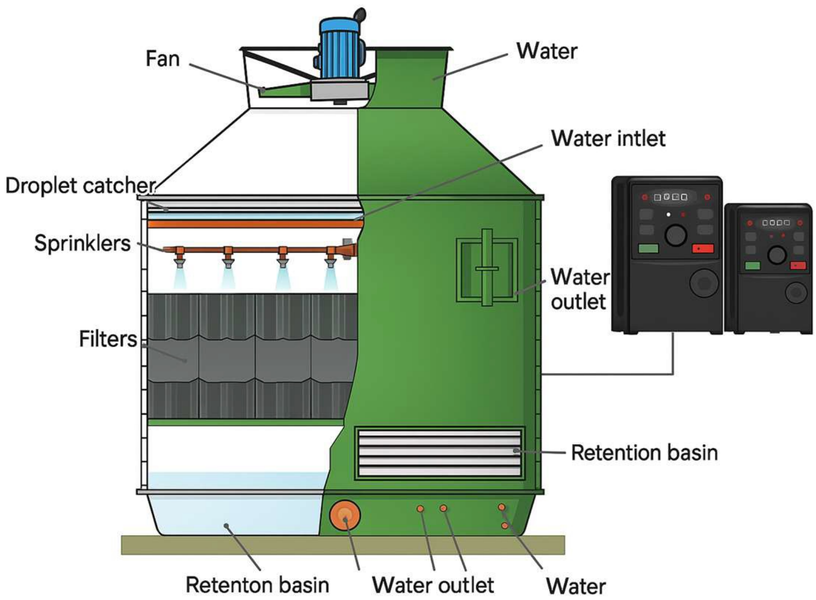

Figure 2. Adapted cooling tower

Energy efficiency within the cooling system can be substantially enhanced through the integration of variable-speed drives (VSDs) on the cooling-tower fan motors. VSDs regulate motor rotational speed in response to real-time process demand, thereby minimising unnecessary power consumption and reducing electrical loading on the distribution network [16]. By maintaining operation only at the speed required to meet the prevailing thermal load, VSDs diminish mechanical stress on the drivetrain, decrease wear on moving components, and extend overall motor service life. This control strategy not only lowers energy use but also contributes to improved system reliability, reduced maintenance requirements, and enhanced operational safety [17]. Consequently, the adoption of VSD technology represents a cost-effective and sustainable measure for optimising the performance of industrial cooling installations.

The verified results show that compressor waste-heat recovery systems can deliver measurable and bankable energy savings when properly designed, monitored, and maintained. From a practitioner's perspective, several operational insights emerge from this assessment. Continuous, high-resolution monitoring at one-minute intervals proved crucial for detecting short-term load fluctuations and compressor sequencing effects that lower-frequency data would have obscured. Effective metering architectures should combine synchronized electrical and thermal measurements, use calibrated flow and temperature sensors, and include redundant channels for validation. Regular calibration—preferably once a year or after around 4,000 hours of operation— helps maintain measurement traceability and prevents drift that could distort verified savings. Thermal recovery performance depends strongly on the cleanliness of heat-exchange surfaces and the quality of control logic coordinating compressors and recovery loops. Preventive maintenance addressing fouling, oil carry-over, and air entrainment in condensate circuits is essential to sustain long-term efficiency. Integrating a clear maintenance checklist within the plant's computerised maintenance management system allows operators to track tasks and ensure consistent performance over the equipment life cycle.

Accurate data analysis and verification further enhance system credibility. The use of IPMVP Option B regression models enabled robust baseline reconstruction and formal uncertainty quantification. Model inputs should include all relevant load drivers—such as ambient temperature, production throughput, and compressor set-points—to capture realistic variations in operation. Diagnostic tests of residuals and autocorrelation confirm statistical soundness before results are reported. Applying established methods like ISO 5168 and ASME PTC 19.1 for uncertainty propagation strengthens confidence in the findings and ensures that results remain verifiable and audit-ready [2].

Presenting outcomes in investment-grade terms—annual energy recovered, CO_2 emissions avoided, and payback period—helps communicate benefits effectively to financial decisionmakers. Including sensitivity analyses for energy-price volatility or varying operating hours reinforces the business case and demonstrates the project's resilience to market changes. When the same standardised approach is replicated across multiple industrial sites, it can support benchmarking and guide capital allocation at a corporate level.

Embedding such projects within an ISO 50001 energy-management framework promotes continuous improvement and helps companies meet European energy-audit obligations under Directive 2012/27/EU [10]. Integrating measurement and verification data into the facility's energymanagement information system enables ongoing performance tracking and early detection of deviations. Although this study focuses on a single food-processing facility, the approach is transferable to other industrial settings with substantial compressed-air or refrigeration loads. The combination of granular metering, standards-based uncertainty analysis, and investment-grade evaluation offers a replicable pathway for advancing industrial decarbonisation and energy efficiency at scale.

4. Conclusions

This study contributes original evidence that a standardized, uncertainty-quantified M&V protocol can validate industrial waste-heat recovery systems with high accuracy, bridging the gap between academic analyses and real-world ISO 50001 energy-management practice. This study has demonstrated that compressor waste-heat recovery (WHR) represents a technically robust and economically viable solution for enhancing industrial energy efficiency. Field implementation at the food-processing facility showed that the recovered thermal capacity of 165 kW closely matched the 170 kW design expectation. The system delivered verified annual energy savings of approximately 1,260 MWh of natural gas—equivalent to 7.8 % of the plant's total thermal-energy demand—and avoided about 307 t CO_2e emissions. The retrofit achieved annual fuel-cost savings of €54,600 and a simple payback period of 1.7 years, supported by a positive net present value across multiple sensitivity scenarios.

Methodologically, the research advances investment-grade measurement and verification (M&V) practices in industrial energy auditing. Application of the IPMVP Option B within an ISO 50001-aligned framework, supported by calibrated high-resolution metering and regression-based baseline modelling, achieved a quantified savings uncertainty of only 3.6%. Such transparent treatment of uncertainty remains rare in published field studies yet is essential for generating reliable, bankable evidence of energy-efficiency performance. The proposed framework provides a replicable structure for cross-sector adoption, strengthening the credibility of energy-savings assessments and enabling integration with corporate energy-management and ESG reporting systems.

Beyond plant-level benefits, the verified results underline the strategic relevance of compressor WHR as a scalable decarbonisation measure. In the European context—where manufacturing accounts for a major share of total energy consumption and emissions—such retrofits can make a measurable contribution to policy objectives under the EU Green Deal and national energyefficiency action plans. Coupling WHR with continuous monitoring, predictive analytics, and thermodynamic modelling can further enhance operational reliability, maintenance planning, and long-term performance optimisation.

The methodology presented here is inherently transferable. Clear boundary definition, permanent metering infrastructure, and statistically robust verification ensure reproducibility across diverse industrial settings, including food processing, pulp and paper, dairy, and brewing. Adopting such rigorously verified approaches transforms regulatory energy audits into strategic instruments for improving sustainability, competitiveness, and industrial resilience. Future research should broaden this framework to multi-site and multi-year analyses, employ stochastic models for uncertainty propagation, and integrate wider sustainability indicators such as water consumption, material efficiency, and lifecycle costs.

Overall, compressor WHR is confirmed as both a cost-effective retrofit and a model of how standards-based verification can bridge the gap between engineering feasibility and investmentgrade assurance. By uniting technical performance, economic soundness, and environmental benefit, this study contributes to the advancement of industrial energy management and supports the transition of energy-intensive sectors toward a more sustainable and decarbonised future.

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