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Original research article

Impact of a High-Pressure Condensate Return System Upgrade on Boiler Fuel and Utility Consumption: A Case Study in a Corrugated Board Manufacturing Plant

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ABSTRACT

This study evaluates the technical and economic performance of a high-pressure condensate return system installed on an 8-ton industrial steam boiler at a corrugated board manufacturing plant in Samut Sakhon, Thailand. Before installation, surface temperatures at ten steam-trap points ranged from 129°C to 166°C, while the feedwater holding tank temperature was 50–60°C. A 15-kW high-pressure booster pump and 300-liter tank were installed to improve condensate recovery. Following installation, annual heavy fuel oil (HFO) consumption decreased by 58.5%, from 1,202,000 liters in 2022 to 498,500 liters in 2023, with comparable production output. Annual water consumption decreased by 28.9% (5,896,000 liters), and electricity consumption decreased by 10.3%. The feedwater holding tank temperature increased to approximately 150°C. Net annual monetary savings, after additional pump electricity costs, reached 21,197,558 THB. Over five years at a 6.25% discount rate, the project achieved an NPV of 86,187,810 THB, IRR of approximately 848%, and simple payback of approximately 43 days. However, fuel savings reflect both the pump upgrade and concurrent steam-trap repairs. High-pressure condensate recovery can improve resource efficiency, but site-specific assessment and further validation are recommended.

Keywords: Condensate recovery; Energy conservation; Heavy fuel oil reduction; High-pressure booster pump; Steam boiler efficiency

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1. Introduction

One of the most energy-intensive utilities in a process manufacturing plant is the industrial steam boiler system. Steam is the main energy carrier used in drying, pressing and forming processes in the paper and corrugated board industry [1, 2]. Geopolitical instability and post-pandemic demand recovery are pushing up global energy prices higher and higher, forcing industries to look for systemic improvement in thermal energy efficiency [3–5]. Heavy fuel oil (HFO) is a common fuel used in the boiler systems of Thailand's manufacturing sector because it has a high energy density. However, the increasing price of HFO poses a serious operational challenge for small and medium-sized enterprises [6]. In closed-loop configurations, steam boiler systems require careful handling of condensate, which is the water that is recovered after the steam has given up its latent heat to a process. The condensate contains a large amount of sensible heat usually 20–30% of the thermal energy supplied initially to generate the steam [7]. The recovery of this condensate and its return to the boiler as feedwater is generally recognized as one of the most effective energy conservation measures available in steam system management [8, 9]. However, many industrial plants in developing economies still dispose of condensate or do not attain maximum recovery efficiency due to inadequate pump infrastructure [10]. Condensate return systems directly determine the quality and thermal state of feedwater entering the boiler. When the feedwater temperature is low, for example in plants where condensate loses a lot of heat during transport, the boiler must spend more energy to heat the water to the temperature required to produce steam. This increases fuel consumption and operating costs [11, 12]. Research has indicated that a 5°C increase in the temperature of the feedwater will result in a 1% saving in fuel consumption [13]. Therefore, it is important for boiler efficiency to maintain condensate temperature during return transport. High pressure condensate recovery systems, known as booster pump assemblies, have been studied in various industrial environments to bridge the pressure difference between condensate collection points and the boiler feedwater tank [14]. These systems allow the transport of hot condensate under pressure, thereby avoiding flash steam losses and saving thermal energy which would otherwise be lost [15]. However, there is a lack of empirical evidence from actual corrugated board manufacturing plants, particularly in the Southeast Asian industrial context, in peer-reviewed literature [16].

This study is a case study of a large corrugated board manufacturing plant in Samut Sakhon Province, Thailand, operating an 8-ton, 8-bar steam boiler using heavy fuel oil. Before intervention, the facility experienced condensate temperatures falling to 50–60°C at the feedwater holding tank, far below the 150°C target, resulting in excessive fuel consumption. This study evaluates the technical performance and economic feasibility of implementing a high-pressure condensate booster pump system to enhance condensate recovery, decrease fuel consumption, and boost the overall productivity of the boiler system. The study also evaluates energy consumption across electrical power, water usage and thermal energy to provide a holistic evaluation of the intervention's impact [17–19]. Systematic energy management, supported by accurate assessment and forecasting of energy demand, can improve operational planning and enhance overall energy efficiency in industrial systems [20].

2. Materials and Methods

2.1 Study site and boiler system specifications

The facility for this case study is a corrugated board and carton box manufacturer in Samut Sakhon Province, Thailand. The plant has a nominal production capacity of 80,000 tons per year. The steam supply system consists of a single hybrid water tube and fire tube boiler with a capacity of 8 tons per hour (TPH) at 8 bar (800 kPa) operating pressure, producing saturated steam at around 170°C [18]. The primary fuel used is heavy fuel oil (HFO) with a net calorific value of 39,770 kJ/L. The total steam distribution piping is about 40 meters round trip from the boiler to the production equipment. The steam system is for the corrugated board production line, one-facer and double-facer. Steam traps (10 units) are provided at each major consuming equipment station. This steam trap discharge condensate is collected and returned through the condensate line to a feedwater holding tank where it is pumped back to the boiler. This study is focused on the condensate return system.

2.2 Identification of the problem

Before installation of the upgraded pump system, infrared thermometry measurements were made at all 11 condensate monitoring points (10 steam trap discharge points and the feedwater holding tank). Measurements were performed using a FLUKE 62 MAX infrared thermometer (range: -30°C to 500°C). Because pipe-surface rather than fluid temperature was measured, the reading depends on the emissivity setting used. The instrument was set to $\varepsilon = 0.95$ for all measurements, consistent with the aluminum-jacketed insulation cladding covering the condensate piping, and the same instrument and setting were used consistently across all three years. No separate contact-thermocouple cross-check was performed. Individual steam trap readings indicated condensate temperatures from 129°C to 166°C. However, at Point 11 (feedwater holding tank), condensate temperature was always found to be only 50–60°C indicating severe heat loss during transport attributable to inadequate pump head pressure and insulation losses.

Calculations of mass and energy balance showed that the boiler consumed 17.36 liters of HFO in each heating cycle (5 minutes) to raise the temperature of the feedwater from 60°C to the operating temperature of 170°C. The existing condensate pump (5.5 kW, 100 liters capacity, flow rate 44 liters/min) was not able to maintain the condensate pressure and temperature in the return line. Infrared imaging [21, 22] showed steam trap leakage in several locations, contributing to energy loss. Steam-trap leaks identified during the baseline inspection were repaired concurrently with the condensate return system upgrade in January 2023. Because the steam-trap repair and booster-pump replacement were implemented together, their individual contributions to the observed fuel savings could not be separated.

2.3 System upgrade: high-pressure booster pump

Systematic engineering analysis of the heat and mass balance deficiencies identified in Section 2.2 led to the design, procurement and installation of a dedicated high-pressure condensate booster pump system to replace the original low-capacity return pump. The upgraded system is equipped with a high temperature water pump (booster pump) driven by a 15 kW, 20 HP electric motor, which can pump condensate with a flow rate of 69.5 liters/min

against the back-pressure of the boiler feedwater circuit. All steam trap points discharge to the primary condensate collection and separation tank (first stage), where steam-water separation occurs before the condensate is transferred under pressure to the feedwater holding tank (300-L capacity, second stage). The system architecture, illustrated schematically in Fig. 1(A) and as physically installed in Fig. 1(B), incorporates the following major components: (i) a strainer at the condensate inlet from steam trap discharge; (ii) a primary condensate collection and separation tank; (iii) a pressure gauge and check valve assembly on the condensate line; (iv) a 300-liter feedwater holding tank equipped with liquid-level sensors for automated level control; (v) a pressure diaphragm tank to dampen hydraulic transients and maintain system pressure stability; (vi) a pressure switch for cut-in/cut-out control of the booster pump; (vii) a pneumatic three-way (T-pattern) valve governing condensate routing; (viii) the 15 kW high-pressure booster pump with motor; (ix) a vapor pressure eliminator (cavitation eliminator) to prevent pump cavitation caused by high-temperature condensate; (x) a pre-filter protecting the pump from particulate contamination; and (xi) a control panel (400 × 570 × 200 mm) housing the electric cabinet, relay logic, and indicator lights. The assembly is mounted on a common base plate and powered from a three-phase, 380 V electrical supply. The sequence of automated pump operation is shown in Fig. 1. In the event liquid-level sensors detect the condensate in the feedwater holding tank to be below the low-level set-point, the control panel activates the high-temperature booster pump. Condensate from the steam trap discharge network passes through the strainer and enters the primary collection and separation tank where bulk steam-water separation occurs, and residual flash steam is vented. The separated condensate then passes through the check valve to the feedwater holding tank. When condensate level in the holding tank reaches the high-level set-point, the pneumatic three-way valve changes position, directing pressurized condensate through the vapor pressure eliminator and pre-filter to the boiler feedwater system. This pressurized closed-loop return path avoids flash evaporation losses along the return piping, and ensures that the condensate is received at the boiler feedwater inlet at temperatures above 150°C, the design goal versus 50–60°C observed before the upgrade [23]. The physical installation (Fig. 1B) also includes an additional siphoning pump to assist priming and initial transfer of condensate from the low-lying collection points where gravity-driven flow is insufficient. The condensate/steam piping was measured on site with a BOSCH GLM40 laser distance meter as a total round-trip distance of 40 m between the boiler and the production equipment (Section 2.1), at a nominal 2-inch pipe diameter (Table 1, measured with a vernier caliper) unchanged between the original and upgraded systems. The system operates at the boiler's rated 800 kPa (8-bar) working pressure at 170°C; a separately measured return-line pressure at an intermediate point along the route was not recorded. The piping carries standard mineral-wool insulation, approximately 50 mm thick, with aluminum sheet cladding, typical for 2-inch pipework operating in the 150–170°C range. This insulation was unchanged by the pump upgrade, which replaced only the condensate booster pump, tank, and control components.

To provide visual confirmation of the liquid level in the main storage tank, a sight glass (viewing mirror) is fitted that is in-

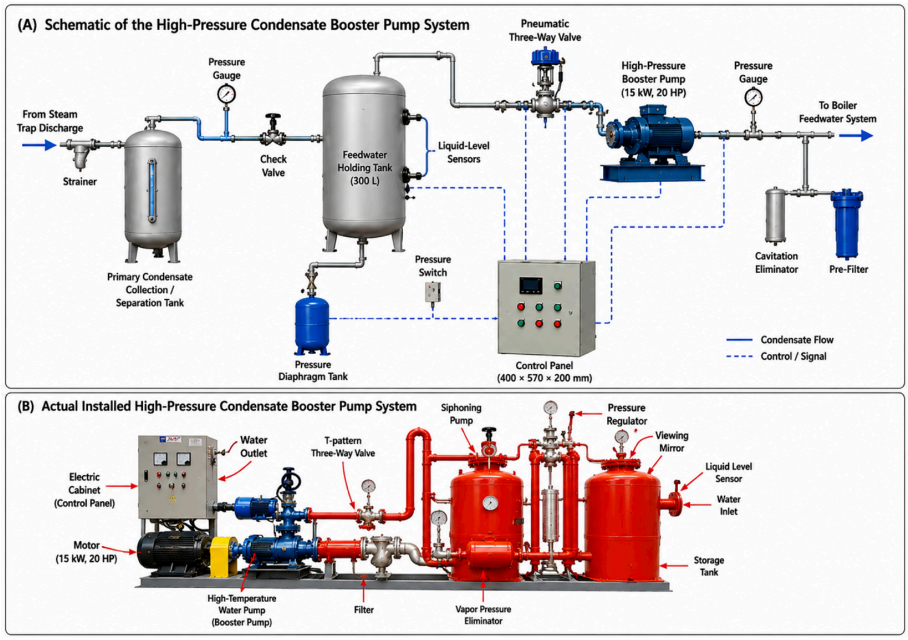


Fig. 1. High-pressure condensate return system: (A) system schematic and (B) installed system showing the booster pump, separator, storage tank, sensors, valves, and control cabinet.

Table 1. Specifications of the original and upgraded condensate return pump systems.

Parameter	Original Pump	Upgraded Pump
Type	Booster Pump (Single)	Booster Pump (High-Pressure)
Motor Power (HP / kW)	7.5 HP / 5.5 kW	20 HP / 15 kW
Tank Capacity	100 L	300 L
Flow Rate	44 L/min	69.5 L/min
Pipe Size	2 inches	2 inches
Electrical Supply	3P, 380 V	3P, 380 V

dependent of electronic sensors. Installation and commissioning were completed at the beginning of January 2023 with full production-load testing undertaken over the following month to confirm stable condensate return temperatures and pump performance. The total capital investment for all equipment, piping, electrical works and installation labor was 2,500,000 Thai Baht (THB). The economic viability of the project was assessed for a service period of five years using a discount rate of 6.25% per year.

2.4 Data collection

Baseline energy consumption data were collected retrospectively for the years 2021 and 2022 (24 months), covering monthly records of: (i) electrical energy consumption (kWh); (ii) heavy fuel oil consumption (liters); and (iii) water (tap water) consumption (liters). Post-installation data were collected for January–December 2023. Production output (tons of corrugated board) was recorded monthly across all three years for productivity comparison.

Condensate temperature measurements were repeated after pump installation at all 11 monitoring points using the same FLUKE 62 MAX instrument under equivalent production load conditions. Monthly productivity ratios (output per unit fuel consumed) were computed for statistical comparison using standard deviation and mean calculations [24].

2.5 Economic analysis

The economic viability assessment was carried out using three standard engineering economic measures: Net Present Value (NPV), Internal Rate of Return (IRR), and Simple Payback Period (SPP). The gross annual monetary saving was estimated from the reduction in HFO consumption. The incremental electricity cost associated with the larger pump motor was then deducted to obtain the net annual saving used in the NPV, IRR, and SPP calculations. Water savings were reported as a resource-saving benefit but were not monetized because sufficiently documented water-cost data were not available. NPV was calculated using standard discounted cash-flow analysis over a five-year project life at a discount rate of 6.25%, assuming uniform annual net savings [25, 26].

3. Results and Discussion

3.1 Condensate temperature recovery

Prior to high-pressure pump installation, condensate temperatures at the ten steam trap discharge points varied from 129±3°C (lowest at Point 8) to 166±2°C (Point 1) as recorded with the FLUKE 62 MAX infrared thermometer (accuracy: ±1.5°C or ±1.5% of reading, whichever is greater; n = 3 repeated measurements per point). Points 1, 2 and 3, which are closest to the boiler and the start of the production line, had relatively high condensate temperatures (160–166°C), which is in line with short transport distances and low heat dissipation. The points 5, 6, 7, 8 and 10, situated at the mid-to-far positions along the production line, showed progressively lower temperatures (129–149°C before the upgrade), thus suggesting cumulative thermal losses along the return piping. However, by the time the condensate arrived at Point 11 (the feedwater holding tank), the temperature had dropped to just 55±5°C, a drop of more than 100°C from the steam trap discharge temperatures [27]. The observed thermal loss was likely associated with insufficient pump delivery pressure, extended condensate residence time, flash-steam losses, and heat dissipation at pipe joints and fittings. The 15-kW high-pressure booster pump system installation resulted in an increase in the condensate temperature at point 11 (feedwater holding tank) to 150±2°C, which is a net increase of 95°C over the baseline measurement equivalent to 172.7% relative increase. This shows that the closed loop return system under pressure was able to keep condensate in the liquid phase throughout the return piping, avoiding flash evaporation losses and therefore retaining sensible heat up to the boiler feedwater inlet. Fig, 2 shows the before and after comparison of the condensate temperature for all eleven monitoring points. Error bars reflect the accuracy of the instruments and repeatability of the measurements (n = 3).

Temperatures at Points 1, 2, and 3 remained the same (166°C, 164°C, and 160°C, respectively) at the individual steam trap discharge points, as these points were already at or near the saturation temperature corresponding to the 8-bar system pressure and were not affected by the return pump upgrade. Further down the line the points showed measurable improvement: Point 4 from 158°C to 170°C (+12°C; +7.6%), Point 5 from 149°C to 168°C (+19°C; +12.8%), Point 6 from 138°C to 168°C (+30°C; +21.7%), Point 7 from 147°C to 167°C (+20°C; +13.6%), Point 8 from 129°C to 159°C (+30°C; +23.3%), Point 9 from 150°C to 158°C (+8°C; +5.3%) and Point 10 from 133°C to 163°C (+30°C; +22.6%). The improvements at Points 4–10 may be associated with (i) reduced low-

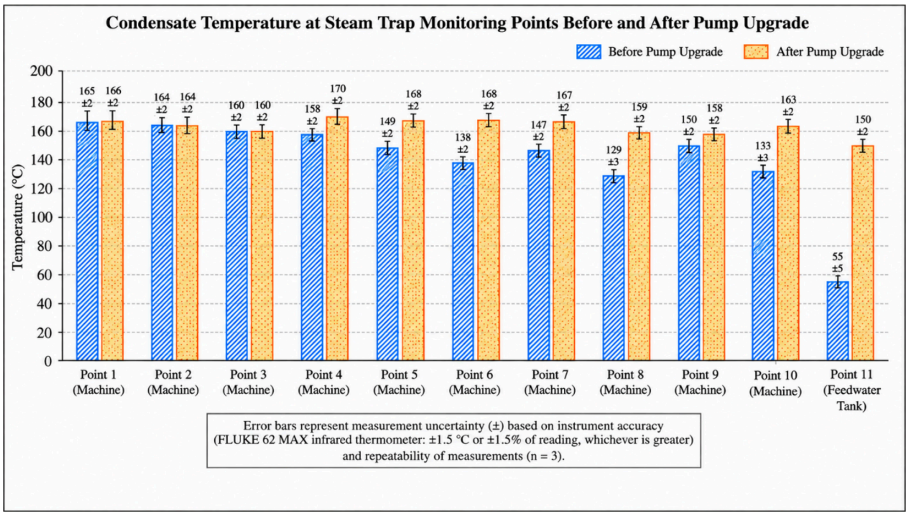


Fig. 2. Measured surface temperatures at 11 condensate monitoring points before and after the pump-system upgrade. Error bars indicate measurement uncertainty.

pressure stagnation in the condensate return line, (ii) higher condensate flow under the increased pump head, and (iii) improved steam-trap operating conditions after system re-pressurization. Table 2 gives a complete quantitative before-and-after comparison for all monitoring points.

The temperature recovery achieved at Point 11 (95°C) is much larger than that predicted by the standard rule-of-thumb relating feedwater temperature to fuel savings (approximately 1% fuel reduction per 5°C increase in feedwater temperature), which would suggest an 18–19% fuel saving from the feedwater temperature gain alone. The discrepancy demonstrates that additional energy savings result from not having to heat the cold feedwater from 55°C to the steam-generating temperature (170°C), by reducing the frequency of boiler cycling due to a steadier feedwater supply, and by eliminating condensate dumping from leaky steam traps identified in the baseline audit. These results are in agreement with the results reported in similar studies of condensate recovery optimization in industrial process heating applications where integrated pump upgrades led to feedwater temperature improvements of 50–80°C and corresponding fuel saving far in excess of that attributable to feedwater preheating alone [27].

Table 2. Measured surface temperatures at 11 condensate monitoring points before and after the pump-system upgrade.

Monitoring Point	Before Upgrade (°C)	After Upgrade (°C)	ΔT (°C)	Relative Change (%)
Point 1 (Machine)	166±2	166±2	0	—
Point 2 (Machine)	164±2	164±2	0	—
Point 3 (Machine)	160±2	160±2	0	—
Point 4 (Machine)	158±2	170±2	+12	7.6%
Point 5 (Machine)	149±2	168±2	+19	12.8%
Point 6 (Machine)	138±2	168±2	+30	21.7%
Point 7 (Machine)	147±2	167±2	+20	13.6%
Point 8 (Machine)	129±3	159±2	+30	23.3%
Point 9 (Machine)	150±2	158±2	+8	5.3%
Point 10 (Machine)	133±3	163±2	+30	22.6%
Point 11 (Feedwater Tank)	55±5	150±2	+95	172.7%

3.2 Heavy fuel oil consumption

The high-pressure condensate pump installation was accompanied by a considerable decrease in heavy fuel oil (HFO) consumption. Annual HFO consumption was 1,407,000 liters in 2021, with monthly values from 102,500±5,125 liters to 145,500±7,275 liters. Total HFO consumption decreased slightly to 1,202,000 liters in 2022, mainly due to changes in operating schedules rather than modifications to the condensate return system. After the installation of the high-pressure booster pump in January 2023, the annual HFO consumption was reduced to 498,500 liters, thus a reduction of 703,500 liters (58.5%) compared to 2022 and 908,500 liters (64.6%) compared to 2021. The observed reduction in HFO consumption is consistent with previous assessments of industrial steam systems, which demonstrate that improving steam-system performance and reducing energy losses can substantially enhance overall energy efficiency [28]. Fig. 3 shows the monthly HFO consumption profiles for the three years. Monthly HFO consumption ranged from 11,000±550 liters in April to 26,500±1,325 liters in June during January–June 2023 compared with 115,500±5,775 liters and 124,000±6,200 liters, respectively, in 2022. This corresponds to reductions of 104,500 liters (90.5%) in April and 97,500 liters (78.6%) in June. January and February 2023 recorded HFO consumption of 18,000±900 liters and 14,000±700 liters, respectively, compared with 123,000±6,150 liters and 83,500±4,175 liters in the corresponding months of 2022. Similarly, March consumption declined from 133,000±6,650 liters in 2022 to 13,500±675 liters in 2023 (89.8% reduction). HFO consumption grew with increasing production loads from 49,000±2,450 liters in July to 85,000±4,250 liters in December 2023. Still, consumption generally stayed below the 2022 equivalents: July (49,000±2,450 vs. 105,000±5,250 liters), August (55,000±2,750 vs. 92,000±4,600 liters), September (62,000±3,100 vs. 80,500±4,025 liters), October (68,000±3,400 vs. 75,500±3,775 liters), and November (72,000±3,600 vs. 79,000±3,950 liters). However, HFO consumption increased in December to 85,000±4,250 liters compared to 62,500±3,125 liters in 2022.

Fig. 3 identifies 2021 and 2022 as pre-installation periods and 2023 as the post-installation period. The HFO consumption data were acquired from the plant's routine utility records and supplier delivery tickets, as opposed to dedicated research-grade instruments. Calibration records for the existing HFO meters were not available, so the error bars always reflect an assumed ±5% measurement uncertainty based on typical commercial/custody-transfer meter tolerances rather than standard deviations based on repeated measurements. This definition is applied consistently to all three data sets shown in Fig. 3. The corresponding statistics for the year and month are presented in Table 3.

Normalized specific fuel consumption (SFC) dropped from 28.32 liters/ton in 2022 to 11.57 liters/ton in 2023, a fall of 59.1%. Compared with the 2021 baseline of 30.68 liters/ton the drop is 62.3%. These normalized reductions are very similar to the reductions shown in Table. 3 which list 58.5% and 64.6%. They are slightly larger because production in 2023 was 1.5% higher than in 2022. This suggests that the observed fuel saving was associated with the post-installation interven-

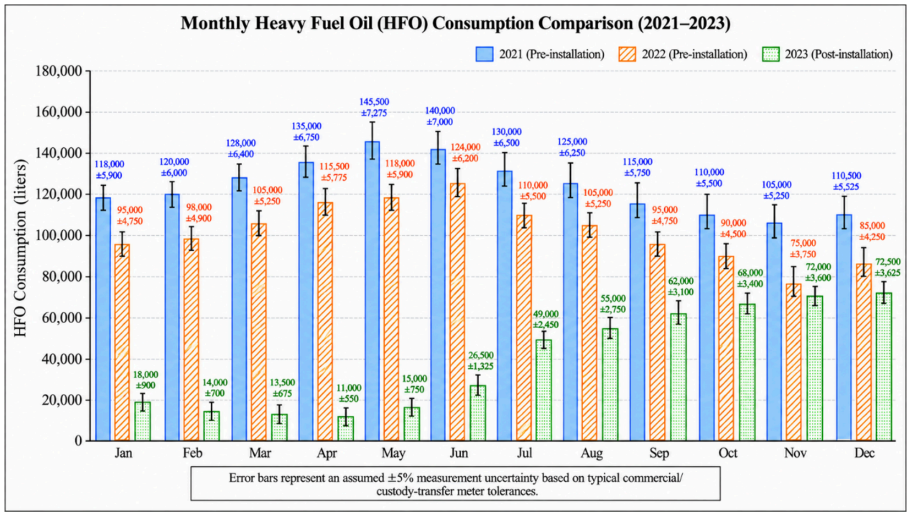


Fig. 3. Monthly HFO consumption during 2021–2023. The largest reductions occurred during January–June 2023 compared with 2022.

Table 3. Annual HFO consumption before and after the condensate return system upgrade, 2021–2023.

Parameter	2021	2022	2023 (Post-Install)
Total HFO (liters)	1,407,000	1,202,000	498,500
Monthly Average (liters)	117,250 ±5,863	100,167 ±5,008	41,542 ±2,077
Monthly Range (liters)	102,500 –145,500	62,500 –133,000	11,000 –85,000
Std. Deviation (liters)	12,985	24,187	26,464
Reduction vs. 2022 (%)	—	—	58.5%
Reduction vs. 2021 (%)	—	—	64.6%

tion rather than with a reduction in production volume; however, the individual contributions of the pump upgrade and concurrent steam-trap repair cannot be separated.

The observed reduction magnitude of HFO (58.5% compared to 2022) is much greater than the theoretical prediction based only on the improvement of feedwater temperature. The usual approximation of 1% fuel saving per 5°C increase in feedwater temperature would imply that the 95°C gain at Point 11 would correspond to as much as 19% fuel saving due to the feedwater preheat. The additional savings are attributed to three compounding mechanisms: (i) elimination of the need for the supplementary fuel energy that was previously required to heat cold feedwater (55°C) to boiler operating temperature (170°C) within each boiling cycle (17.36 liters HFO per 5-minute cycle prior to the upgrade); (ii) reduction in boiler start-up cycling frequency due to the more stable and thermally consistent feedwater supply enabled by the pressurized return system; and (iii) elimination of uncontrolled condensate discharge at steam traps identified as leaking during the baseline audit that resulted in a direct loss of thermal energy and water. The compounded efficiency gain is in line with the results of integrated condensate management studies in paper mill and food processing applications, where system level interventions led to fuel savings well beyond those predicted by single-parameter analyses [29, 30].

3.3 Electrical energy and water consumption

Overall, plant electricity consumption decreased after installation of the upgraded pump motor, despite the increase in motor rating from 5.5 to 15 kW. Total electricity consumption was 2,422,848 kWh in 2021 (monthly average 201,904 kWh, standard deviation 18,443 kWh/month). In 2022, it dropped to 2,161,896 kWh (average monthly: 180,158 kWh; standard deviation: 29,119 kWh/month), and this was due to changes in production scheduling not related to the pump intervention. After the pump was installed (January 2023), electrical consumption was 1,939,274 kWh (monthly average 161,606 kWh; standard deviation 35,035 kWh/month), a 10.3% reduction from 2022 and a 19.9% reduction from 2021. During the year 2023, the monthly electrical consumption was always lower than the two profiles of previous years (Fig. 4A). The annual moving average dropped from 201,904 kWh in 2021 to 180,158 kWh in 2022 and 161,606 kWh in 2023. The theoretical incremental electricity cost of the larger pump motor, calculated at 9.5 kW additional draw × 24 h/day × 30 days = 6,840 kWh/month, valued at approximately 33,148 THB/month, was more than offset by the reduction in HFO cost averaging approximately 1,799,612 THB/month (based on average 2023 monthly HFO savings versus 2022). The net electricity consumption per metric ton of corrugated board produced also decreased in 2023, indicating that the overall energy intensity has not been displaced between vectors.

Similarly, the use of tap water for boiler feedwater makeup also showed a positive trend. The total water consumption in 2021 was 21,868,000 liters (average per month: 1,822,333 liters; standard deviation: 281,085 liters/month). Consumption in 2022 was 20426000 liters (average monthly consumption: 1702167 liters; standard deviation: 334792 liters/month). Water consumption in 2023, since the installation of the pumps, was 14,530,000 liters (average per month: 1,210,833 liters, standard deviation: 50,972 liters/month) which is 5,896,000 liters (28.9%) less than in 2022 and 7,338,000 liters (33.6%) less than in 2021. The monthly water usage profiles for 2022 and 2023 are shown in Fig. 4B (2021 data is marked N/A due to no sub-monthly water metering records for that time period). Importantly, the 2023 profile is flat with all monthly values clustered closely around the annual mean of 1,210,833 liters, compared to the wide seasonal swings in 2022 (range: 1,276,000–2,189,000 liters/month). The standard deviation of monthly water consumption in 2023 was substantially lower (50,972 liters/month; coefficient of variation: 4.2%) than in 2022 (334,792 liters/month; coefficient of variation: 19.7%), indicating a more stable pattern of feedwater makeup demand. Normalized to production output (Section 3.2, Table 4), electrical energy intensity fell from 50.94 kWh/ton (2022) to 45.01 kWh/ton (2023), an 11.6% reduction, and water intensity fell from 481.26 liters/ton (2022) to 337.23 liters/ton (2023), a 29.9% reduction — both consistent with the absolute reductions reported above, confirming the improvements are not an artifact of the small year-to-year change in production volume. Table 5 shows the consolidated three years comparison of all the electrical energy and water consumption metrics.

The simultaneous reduction in electrical energy and water use in 2023, despite using a higher-rated pump motor, indicates that the high-pressure condensate return system was associated with improve-

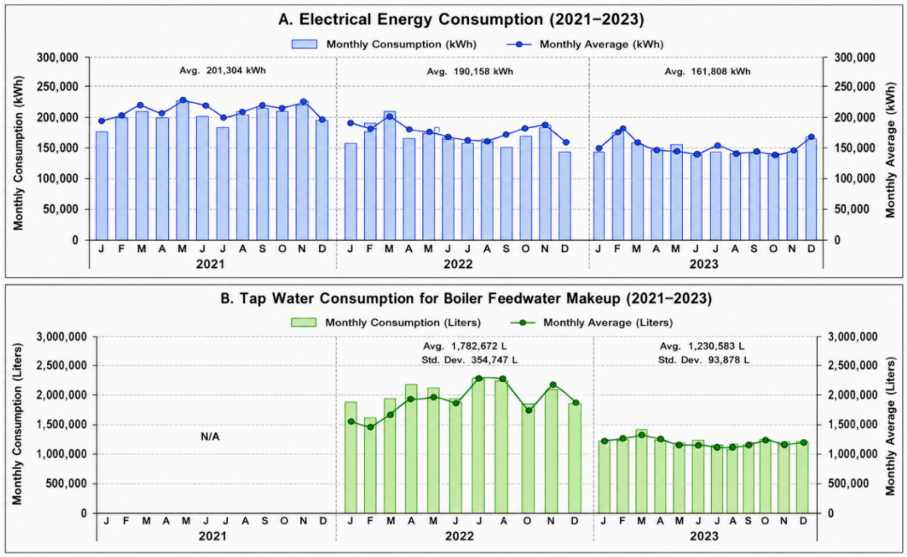


Fig. 4. Monthly electricity and water consumption during 2021–2023: (A) electricity consumption and (B) boiler feedwater makeup.

Table 4. Specific HFO, electricity, and water consumption normalized by production output, 2021–2023.

Parameter	2021	2022	2023 (Post-Install)
Production output (tons)	45,860.74	42,443.00	43,086.74
Specific HFO consumption (L/ton)	30.68	28.32	11.57
Specific electricity consumption (kWh/ton)	52.83	50.94	45.01
Specific water consumption (L/ton)	476.83	481.26	337.23
SFC(HFO) reduction vs. 2022 (%)	—	—	59.1%
SFC(HFO) reduction vs. 2021 (%)	—	—	62.3%

Table 5. Annual electricity and water consumption, 2021–2023.

Parameter	2021	2022	2023 (Post-Install)
Total Electricity (kWh)	2,422,848	2,161,896	1,939,274
Monthly Average (kWh)	201,904	180,158	161,606
Std. Deviation (kWh/month)	18,443	29,119	35,035
Reduction vs. 2022 (%)	—	—	10.3%
Total Water (liters)	21,868,000	20,426,000	14,530,000
Monthly Average (liters)	1,822,333	1,702,167	1,210,833
Std. Deviation (liters/month)	281,085	334,792	50,972
Reduction vs. 2022 (%)	—	—	28.9%

ments across three resource and utility categories: thermal fuel, electricity, and water. Additional operational implications are related to the significant reduction of monthly water consumption variability (coefficient of variation was reduced from 19.7% in 2022 to 4.2% in 2023): a more stable supply of feedwater is associated with fewer interventions for boiler level control, reduces blowdown losses and decreases the need for chemical treatment dosing to maintain boiler water quality within the specified parameters. While not directly quantified in the present study, these secondary benefits additionally contribute to the overall cost-reduction profile of the intervention and are consistent with the multi-benefit framework for condensate recovery systems recommended in industrial steam management guidelines [13, 26].

3.4 Production output

The total production output was maintained in all three years: 2021 (45,860.74 tons), 2022 (42,443.00 tons) and 2023 (43,086.74 tons). Monthly production averages were 3,821.73 tons (2021), 3,536.92 tons (2022) and 3,590.56 tons (2023). Production in 2023 was in fact 1.5% higher than in 2022 on average, but with strong shared seasonality (both years peak in March–April and trough in October–December), so the 12 matched calendar-month pairs were compared with a paired-samples t-test ($\alpha = 0.05$): $t(11) = 1.17$, $p = 0.267$ - not statistically significant. An independent two-sample (Welch) t-test on the same data gives the same conclusion: $t(21.9) = 0.08$, $p = 0.936$, supporting the conclusion that the fuel, water and electricity savings were not achieved by curtailing production. No adverse effect on steam supply to the production equipment was observed during the post-installation operating period.

3.5 Economic analysis

The annual energy saving was monetized at 21,595,340 THB/year, corresponding to the 703,500-liter reduction in HFO consumption (2023 vs. 2022) at an implied fuel price of approximately 30.70 THB/liter (21,595,340 THB ÷ 703,500 liters). The energy content of this saving is 703,500 liters × 39,770 kJ/liters = 27,978,195 MJ (the figure 47,803,540 MJ instead represents the energy content of the full 2022 HFO consumption of 1,202,000 liters). NPV is calculated using the standard annuity-based formula in Eq. (3.1), assuming a 5-year project horizon, a 6.25% discount rate, and uniform annual savings:

$$NPV = A_{net} \times \left[\frac{1-(1+i)^{-n}}{t}\right] - P, \tag{3.1}$$

where A_{net} is an annual monetary saving (THB/year). i is a discount rate. n is a project lifetime (years). P is an initial investment cost (THB).

The annual saving used in the analysis is net of the incremental electricity cost of the larger pump motor (33,148.50 THB/month × 12 = 397,782 THB/year), giving A_{net} = 21,595,340 − 397,782 = 21,197,558 THB/year. Substituting $A_{net} = 21,197,558$ THB/year, i = 6.25%, $n = 5$, and $P = 2,500,000$ THB into Eq. (3.1):

$$\begin{aligned} NPV &= 21,197,558 \times \left[\frac{1-(1+1.0625)^{-5}}{0.0625}\right] \\ &\quad - 2,500,000 \\ &= 21,197,558 \times 4.18392,500,000 \\ &\approx 86,187,810 \text{ THB}. \end{aligned}$$

The corresponding internal rate of return is IRR ≈ 848%, and the simple payback period is $P/A_{net} = 2,500,000/21,197,558 = 0.118$ years (≈ 43 days). The very high IRR is a direct consequence of the sub-year payback period: the plant recovers the 2,500,000 THB capital cost from the net annual savings within approximately six weeks. Table 6 provides the year-by-year discounted cash flow for independent verification.

Table 7 uses the pre-O&M base case for clarity of the HFO-price and discount-rate sensitivity. Including the illustrative O&M estimate from Table 6 would further reduce the NPV in each scenario, with the magnitude of the reduction depending on the applicable discount rate. The qualitative conclusion remains unchanged.

The economic performance of this intervention is comparable to, but far exceeds, reported payback periods for condensate recovery systems in similar industrial settings, which are generally in the range of 0.5 to 2 years [17, 18]. The rea-

Table 6. Five-year discounted cash flow for the economic analysis of the condensate return system upgrade, including an illustrative O&M cost.

Year	Net annual saving (THB)	O&M cost (THB)	Discount factor @6.25%	Discounted cash flow (THB)	Cumulative NPV (THB)
0	− 2,500,000 (capital)	—	1.0000	− 2,500,000	− 2,500,000
1	21,197,558	125,000†	0.9412	19,832,996	17,332,996
2	21,197,558	125,000†	0.8859	18,666,349	35,999,345
3	21,197,558	125,000†	0.8338	17,568,328	53,567,673
4	21,197,558	125,000†	0.7847	16,534,897	70,102,570
5	21,197,558	125,000†	0.7385	15,562,256	85,664,827

†Illustrative O&M assumption of 125,000 THB/year, corresponding to 5% of the initial capital cost. This assumption is included to examine the sensitivity of the economic conclusion to an annual maintenance allowance.

Table 7. Sensitivity analysis of NPV, IRR, and payback period under varying HFO prices and discount rates, based on the pre-O&M case.

Scenario	NPV (THB)	IRR (%)	Payback (days)
Base case (HFO price as reported, i = 6.25%)	86,187,810	848%	43
HFO price −20%	68,117,395	675%	54
HFO price +20%	104,258,226	1,021%	36
Discount rate 10%	77,855,422	848%	43
Discount rate 15%	68,557,502	848%	43

son for the quick payback in this instance is the high initial fuel cost, the severity of the original heat loss problem and the relatively low capital cost of the booster pump system.

3.6 Limitations

This study has several limitations that should be considered when generalizing the results.

3.6.1 Co-intervention (confounded treatment effect)

Steam-trap leak repair was performed at the same time as the booster-pump replacement, as described in Section 2.2. The 58.5% reduction in heavy fuel oil (HFO) therefore reflects the combined effect of the steam-trap repair and booster-pump replacement. Because there was no period in which the two interventions were implemented separately, their individual contributions cannot be separated using the available data.

3.6.2 Single-site case study

All data came from one boiler and one production facility. The amount of savings, which is higher than the 10–30% that is usually reported in the literature (see Section 1), is partly due to the poor initial condition of this plant's original pump and return line. Because of that, the results may not apply directly to plants that have severe initial problems. It is recommended to repeat the study at other sites before using the 58.5% figure as a general benchmark for this technology.

3.6.3 Uncontrolled seasonal and production-mix effects

Data from the baseline period (2021 to 2022) and from after the installation (2023) were compared across calendar years. The comparison was not made under a counterbalanced design. As a result, seasonal temperature changes, variations in production mix, and other year-to-year operational differences cannot be completely separated from the effect of the intervention, despite the production-output check performed in Section 3.4.

3.6.4 No long-term durability or reliability data

The post-installation dataset covers one operating year (2023). No data are available yet on pump wear, seal life, maintenance frequency, or unplanned downtime of the upgraded 15 kW system over a multi-

year horizon; these factors could affect both the technical durability and the economic analysis.

3.6.5 Operating and maintenance costs

The bigger booster pump, which is 15 kW compared with 5.5 kW is expected to cost more for maintenance than the pump during the five-year life of the project. Table 6 gives an illustrative allowance of 125,000 THB/year, corresponding to 5% of the initial capital cost. This assumption is included to examine the sensitivity of the economic conclusion to potential annual maintenance costs. Because the maintenance cost is small compared with the savings it changes the net present value by less than 1% and does not change the main conclusion.

4. Conclusion

A study was conducted in which the addition of a high-pressure condensate return booster pump to an 8-ton industrial steam boiler system provided significant and measurable improvements in thermal energy efficiency, fuel economy and total production cost for a corrugated board manufacturing plant. The principal results are:

1. The measured temperature at the feedwater holding tank increased from approximately 50–60°C to 150°C after installation, corresponding to an increase of about 95°C. This result is consistent with improved pressurized condensate return and reduced thermal losses along the return path.

2. The annual consumption of heavy fuel oil was decreased by 58.5% (1,202,000 liters to 498,500 liters) and saved 21,595,340 THB per year without reducing the production output.

3. Water consumption for boiler feedwater makeup decreased by approximately 28.9% (5,896,000 liters/year), while electrical energy consumption decreased by 10.3%, demonstrating improvements across multiple resource and utility categories.

4. The economic analysis based on net annual savings after accounting for the incremental electricity cost of the larger pump motor yielded an NPV of 86,187,810 THB, an IRR of approximately 848%, and a simple payback period of about 43 days for a capital investment of 2,500,000 THB. An illustrative O&M allowance of 125,000 THB/year reduced the five-year NPV to 85,664,827 THB (Table 6).

The findings support consideration of high-pressure condensate recovery as an energy-conservation option in industrial boiler operations where condensate return is suboptimal, subject to site-specific assessment. Future work should include predictive maintenance of steam traps and automated monitoring of condensate quality to optimize system performance. Also, it would be interesting apply this methodology to larger multi-boiler facilities and natural gas or biomass fueled boilers so as to generalize these findings to the wider manufacturing sector. As discussed in Section 3.6, the magnitude of the saving reported here also reflects the unusually poor baseline condition of this plant and a concurrent steam-trap repair, so replication at other sites under a design that separates the two interventions is recommended before generalizing the 58.5% figure.

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