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ORIGINAL ARTICLE

Optimizing Compressed Air Operations for Electrical Energy Savings: A Case Study in Pharmaceutical Packaging Manufacturing

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Abstract

This study in pharmaceutical packaging manufacturing focuses on improving compressed air efficiency through targeted strategies at both the source and user levels by establishing a baseline to analyze energy consumption patterns. Key measures, including minimizing air leaks, adjusting pressure, and optimizing compressor performance, aim to achieve a 20-50% increase in efficiency, thereby supporting environmental sustainability. The User Point and Source Point approaches are expected to lower Specific Power Consumption (SPC), with data collected from December 2020 to May 2022 providing insights into potential energy savings. Establishing this baseline, based on machine runtime and productivity, offers a solid foundation for evaluation. Results show a 23% reduction in compressor electricity usage and a 7-8% decrease in compressed air consumption. A structured improvement process and strong collaboration between engineering and management are essential for enhancing productivity and achieving sustainable energy efficiency in the industrial sector.

Introduction

The energy availability crisis poses a significant challenge to national development, driven by increasing costs and the depletion of traditional energy sources. The rapid growth in energy consumption has led to an imbalance between demand and supply, highlighting the need for a sustainable and efficient energy system to lessen reliance on fossil fuels [1].

Compressed air (CA) can be used in various industries, including the pharmaceutical packaging industry. The use of compressed air will vary depending on the size or volume of the product. In 2021, the electricity used by compressed air systems, CA, could account for 38% of total electricity consumption. Considering the significant energy consumption, it is important for industries to optimize the use of compressed air to reduce operational costs and improve overall energy efficiency [2].

The use of CA in industry is common, particularly in sectors like pharmaceutical packaging, where it plays a crucial role in supporting various manufacturing processes. However, generating compressed air requires substantial energy, making the cost of operating compressed air systems a significant portion of total energy expenses for many industries [3]. Given this high energy consumption, it is essential for industries to optimize compressed air usage to reduce operational costs and enhance overall energy efficiency. CA is one of the most expensive forms of energy used in industry due to its low efficiency. According to the Total Life Cycle Cost (LCC) model, initial investment and maintenance account for only a small portion of the total cost of compressed air equipment, with power requirements typically comprising 75 percent or more of the annual compression costs [4]. This often results in costs exceeding five times the initial equipment investment. Improvements in compressed air systems can achieve energy savings of 20 to 50 percent.

The high energy consumption required to generate compressed air is greatly influenced by the volume of air used and the pressure needed to operate machine components and ensure smooth production processes [5]. The two most critical factors affecting compressed air costs are the compressor control type/technology and the proper selection of compressor size. Large compressor units operating in inefficient control modes will incur high energy use and substantial annual operating costs. Modifications to the operational system have shown significant potential for savings and fast payback. Some effective adjustments include reducing air leaks, aligning supply with demand, and lowering system pressure. Additionally, if lower pressure is sufficient, using a smaller compressor at full load is more efficient than running a large compressor at partial load.

Implementing higher-efficiency motors is another impactful strategy for enhancing operational efficiency and generating economic benefits in a relatively short time [6]. Research indicates that energy efficiency measures in compressed air systems are often undervalued, despite many of these measures being low-cost and offering significant savings potential. However, the implementation of energy efficiency steps in compressed air systems (CAS) is often hindered by a lack of information, particularly regarding the high cost of electricity consumption.

Based on existing research, this study explores the analysis of the main energy efficiency measures that can be implemented in CAS. It also discusses how to calculate potential energy savings, costs of implementation, and return on investment. This tool is crucial for companies aiming to reduce energy consumption and greenhouse gas emissions. The research highlights the potential for energy savings in CAS through improvements or optimization of CAS [3,7,8]. Areas that can be optimized include compressor units, dryers, filters, receiver tanks, configurations, pressure differences/stability, leaks, misuse, and overheating. Therefore, taking concrete actions involving management elements is important, as these efforts require significant costs and time [9].

Although the use of CA in industry has been widely discussed, there remains a gap in understanding specific strategies for tackling the substantial energy efficiency challenges associated with it. Many studies highlight the potential for energy savings but often lack practical guidance on adapting these best practices across different industrial contexts, including the pharmaceutical packaging sector. Additionally, despite energy efficiency measures being seemingly straightforward and cost-effective, the lack of organized and accessible information on implementation impedes strategic adoption. This study aims to address these gaps by conducting in-depth research into operational modifications and control technologies that can enhance CA system efficiency. The objective is to identify, categorize, and systematize effective approaches for optimizing CA usage, thereby helping industries reduce operational costs and improve sustainability. This internal case study specifically aims to evaluate the outcomes of compressed air optimization in the pharmaceutical packaging industry.

Materials and Methods

The energy efficiency management process for a CA compressor system begins with the collection of primary data, which includes essential information required to analyze system performance, as illustrated in Figure 1.

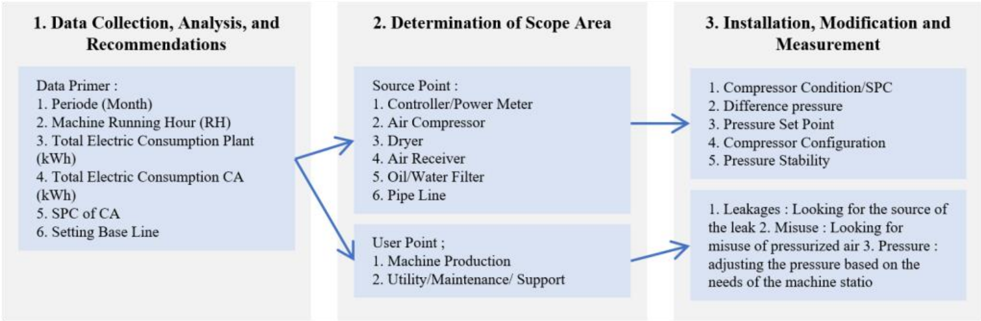


Figure 1. The energy efficiency management process.

The data collected includes the month to determine the observation time span; Machine Running Hour (RH) to calculate the total operating hours of the machine; Total Electric Consumption Plant (kWh), which shows the overall electricity consumption in the plant; Total Electric Consumption CA (kWh), to record the energy consumption of the compressor system; and SPC of CA (Specific Power Consumption), which is used to assess the energy efficiency of the compressor. After collecting the data, the next step is analysis and recommendations. This analysis aims to evaluate system performance and identify potential energy savings. The baseline is determined based on operating hours and total energy consumption, providing a reference for a more detailed efficiency evaluation [10,11].

Table 1 presents the SPC values, which measure the electrical consumption required by six compressor units per minute to produce one cubic meter of compressed air. The SPC value serves as an indicator of compressor efficiency; a lower SPC indicates higher compressor performance efficiency. At the bottom of the table, average values for each column offer an overall view of the system's performance.

Table 1. Specific Power Consumption (SPC) data (kW/m³/min).

Label Unit	C1	C2	C3	C4	C5	C6
Type	VSD	Fixed	Fixed	VSD	Fixed	Fixed
Power (kW)	75	120	160	160	160	160
Flow (m^3/min)	6 to 14	30	30	24 to 30	30	30
SPC	6.23	6.14	5.9	6.29	5.61	5.83

With the data presented, the next step is to analyze and gather recommendations from both internal and external sources. Internally, this analysis will involve collaboration between relevant departments, such as technical support and production. Externally, recommendations will be sought from experts and experienced practitioners in the field of CA to assist in reducing the SPC value.

The baseline for this case study involves comparing the total electricity consumption of all machines within a one-hour time frame and the resulting output. This can be calculated using Equation 1:

$$Rasio\ CA\ Power = \frac{Compressed\ Air(CA)\ Power(kWh)}{Machine\ Hour\ (Hour)} \tag{1}$$

This baseline will serve as a benchmark for assessing energy efficiency and provide valuable insights to identify areas needing improvement [12,13]. Additionally, we calculate the monthly electricity costs (IDR) for compressed air. Cost savings can be determined using Equation 2.

$$Monthly\ CA\ Cost\ (IDR) = CA\ Power\ Consumption(kWh)*1036\ (IDR/kWh) \tag{2}$$

Additionally, we will calculate the cost savings generated after the improvements using Equation 3:

$$Cost\ Saving\ (IDR) = Monthly\ CA\ Power\ Consumption(kWh)\ (Before - After) *1036(IDR/kWh)*12 \quad (3)$$

The next crucial step is to determine the coverage area and identify potential improvements for savings, focusing on both source and user points. Source points include components such as compressors, dryers, air receiver tanks, pipelines, and oil/water filters, while user points encompass production, maintenance, and utility machines that utilize compressed air.

The final phase involves installation and modification to enhance system efficiency. This step includes several key actions: checking the compressor/SPC condition to ensure optimal operation; monitoring pressure differences to detect leaks [14,15]; setting ideal pressure levels; configuring the compressor; and ensuring pressure stability. By following these steps, energy efficiency is expected to increase, operational costs can be reduced, and operational sustainability in the industry can be effectively maintained [4,16].

Results and Discussion

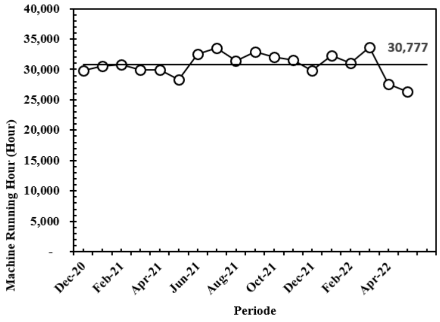
Data Collection, Analysis, and Recommendations

The data used in this research was collected from December 2020 to May 2022, covering important information related to energy usage. The data includes electricity consumption for production machines, specifically for the CAS, as well as the machine operating hours needed to analyze efficiency.

Table 2. Compressed Air Energy Consumption in Relation to Production Machine Operating Period (December 2020 to May 2022).

Period	Machine Hour (30 Machines)	Energy (kWh)			%CA	SPC (kW/m^3/min)
		TOTAL	CA	CA Power/Machine Hour		
Dec 2020	29,799	1,107,900	491,004	16.48	44%	-
Jan 2021	30,519	1,146,840	439,656	14.41	38%	-
Feb 2021	30,852	1,142,280	479,666	15.55	42%	-
Mar 2021	29,988	1,292,160	452,990	15.11	35%	-
Apr 2021	29,932	1,301,700	485,720	16.23	37%	-
May 2021	28,383	1,240,800	506,137	17.83	41%	-
Jun 2021	32,570	1,339,680	464,915	14.27	35%	-
Jul 2021	33,520	1,311,900	498,618	14.88	38%	-
Aug 2021	31,409	1,417,980	446,728	14.22	32%	-
Sep 2021	32,875	1,389,360	442,288	13.45	32%	-
Oct 2021	31,984	1,474,568	495,928	15.51	34%	5.93
Nov 2021	31,485	1,387,655	482,528	15.33	35%	5.87
Dec 2021	29,844	1,347,998	465,824	15.61	35%	5.87
Jan 2022	32,305	1,488,143	495,905	15.35	33%	5.92
Feb 2022	30,991	1,349,616	494,874	15.97	37%	5.98
Mar 2022	33,597	1,480,491	510,366	15.19	34%	5.89
Apr 2022	27,563	1,385,996	448,329	16.27	32%	5.89
May 2022	26,375	1,276,298	401,766	15.23	31%	5.72
AVG	**30,777**	**1,326,742**	**472,402**	**15.56**	**36%**	**5.88**

Table 2 displays Machine Hour data, which is a combination of a total of 30 production machines. Based on the established baseline formula, the ratio between electricity consumption used for CA and Machine Hour results in the amount of electricity consumption per hour used by each production machine. Meanwhile, the CA percentage column (%) indicates the proportion of energy consumption used to produce compressed air in the industry. This information is crucial for evaluating system efficiency and planning necessary improvement steps to enhance energy management [17].



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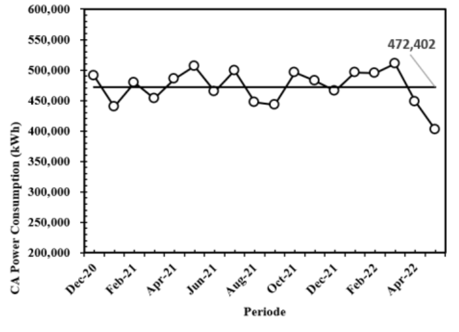

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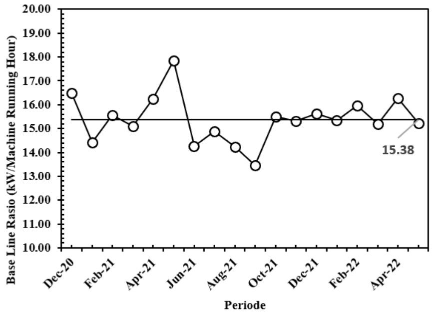

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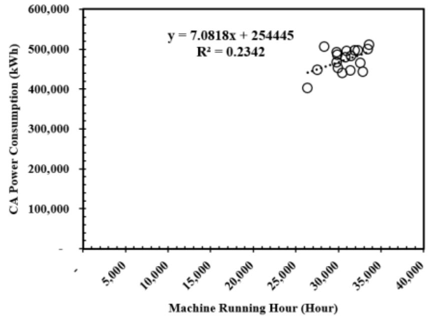


(d)

Figure 2. Baseline Development Illustrated in Four Graphs: (a) Equivalent Plant Power Consumption, (b) Compressed Air (CA) Electric Consumption, (c) Baseline Ratio of CA Energy Consumption to Production Machine Hour, and (d) Correlation Between Machine Hours and CA Power Consumption.

Figure 2 shows the basic development process illustrated in four graphs, based on the data in Table 1. Figure 2a displays fluctuations in the number of operating hours of machines from May 2021 to March 2022, with the increase in machine operating hours attributed to high market demand for COVID-19 vaccines [16]. Figure 2b illustrates fluctuations in electricity consumption for producing CA. The average value of 15.38 kW/Machine Hour for the ratio between electricity consumption to produce CA and the number of operating hours of machines is shown in Figure 2c, with a non-linear relationship and an R^2 value close to zero in Figure 2d. The variability in fluctuating production demand to meet market needs, along with inconsistent operational conditions of machines due to technical disruptions or unscheduled maintenance, highlights the importance of careful planning and readiness in machine operation to ensure optimal functioning of all systems. Optimizing these aspects is crucial not only for maintaining operational efficiency but also for reducing energy costs, ultimately enhancing the industry's competitiveness in a competitive market. The data presented offers insights for potential improvements, and the analysis of the graphs in Figure 2 provides detailed information for management to formulate more effective energy management and production resource strategies [18–20].

Replace the Unit with a Lower SPC and Reconfigure the Operational Sequence

The primary goal to reduce electricity consumption used to produce CA is by lowering the value of SPC. The following are some activities undertaken as efforts to reduce it, including: The first step taken is to replace the compressor unit with a lower SPC value. This is done by assessing all units and comparing the initial SPC value at the time of purchase with the current actual value. In addition to considering the lower SPC value, the age of the compressor is also an important factor to consider, as older compressors generally have higher SPC values compared to when they were newly purchased. In this case, the two units that are a priority for replacement are Compressor No. 2 and No. 3, which have SPC values of 5.3 kW/m³/minute each (Table 3).

Table 3. SPC configuration after replacement of compressor units No. 2 and 3.

Condition	C1	C2	C3	C4	C5	C6
Type	VSD	Fixed	Fixed	VSD	Fixed	Fixed
Before	6.23	6.14	5.90	6.29	5.89	5.83
After	5.95	5.47	5.33	6.02	5.61	5.50

Next, the system configuration is adjusted by giving priority to units with the lowest SPC value first, and by adding one unit with a Variable Speed Drive (VSD) type. This VSD unit helps to stabilize pressure even when the flow or consumption in the user/production area is highly fluctuating. This change in configuration is made on the control unit or CA Manager in order to enhance the system's performance and its ability to respond to changes in production requirements more effectively. By adopting this approach, it is anticipated that energy usage efficiency and operational performance can be enhanced overall.

Lowering the Main Pressure Setting

The next step in improving efficiency is to lower the main pressure setting. Table 4 outlines the process of reducing the main pressure setting, a change anticipated to lower the Specific Power Consumption (SPC). This adjustment is expected to enhance compressor system performance and significantly reduce energy consumption.

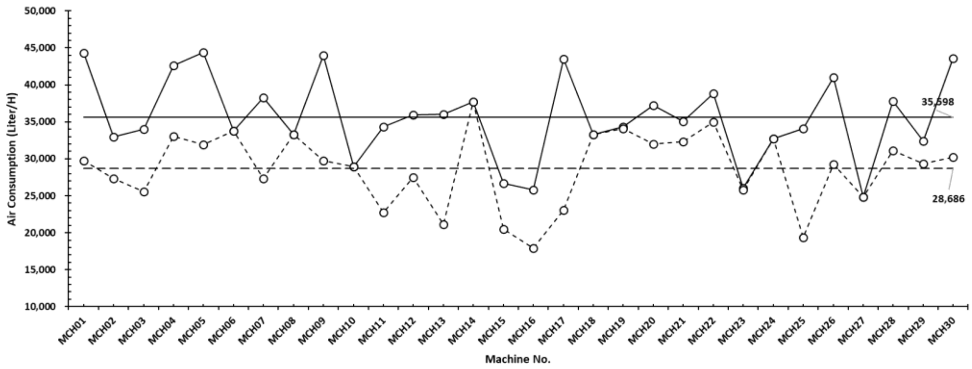
Table 4. Process of reducing main pressure setting to improve efficiency.

Step	Pressure (Bars)	SPC (kW/m^3/min)
1	6.65	5.71
2	6.55	5.66
3	6.40	5.55

Optimizing Flow and Consumption and Pressure at the User Point

Optimizing at the user level involves measuring the consumption and compressed air pressure in all machine units using a flow measurement tool. The best machine out of a total of 30 identical machines is chosen as a pilot project. The optimization results from the pilot project machine are then applied to the other machines. Figure 3 illustrates the results of measuring consumption and CA pressure before and after the optimization process. By following these steps, it is anticipated that energy usage efficiency in all machine units will see a significant improvement [21].

Figure 3 depicts the results following optimization at the user point, including the resolution of leaks, adjustment of pressure, and reduction of errors in compressed air (CA) usage. The average consumption of compressed air decreased from 35,598 liters per hour to 28,686 liters per hour, reflecting a decrease of 19.4%. Additionally, the average pressure at the user point decreased from 6.04 bar to 5.43 bar, representing a 10% decrease. This is in contrast to the pressure setting at the source point, which remains at 6.4 bar, showing a difference of approximately 0.4 bar. The reduction in consumption and pressure validates the effectiveness of the actions taken to enhance the efficiency of compressed air utilization.



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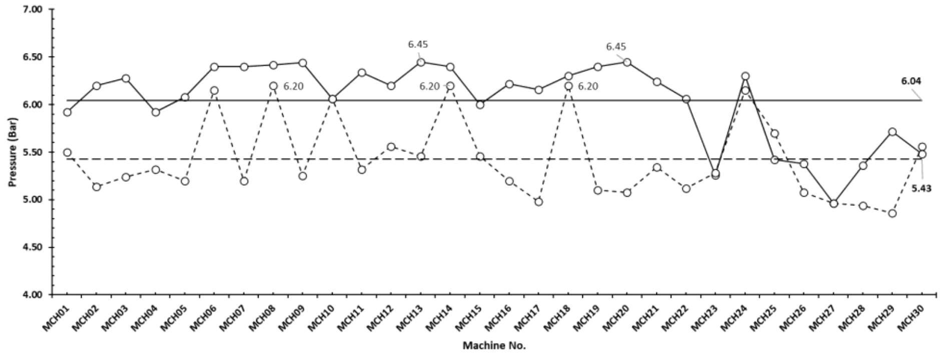

(b)

Figure 3. Results of optimizing CA consumption and pressure settings.

Table 5. Energy Consumption Data for Compressed Air in Production Machines (June 2022 to July 2023).

Period	Machine Hour	Energy (kWh)			%CA	SPC (kW/m³/min)
		TOTAL	CA	CA Power/Machine Hour		
Jun 2022	33,483	1,342,101	464,917	13.89	35%	5.76
Jul 2022	28,630	1,308,477	424,594	14.83	32%	5.71
Aug 2022	24,898	1,26,5474	390,939	15.70	31%	5.70
Sep 2022	20,244	996,017	297,747	14.71	30%	5.68
Oct 2022	28,734	1,320,161	399,735	13.91	30%	5.68
Nov 2022	27,099	1,230,803	367,891	13.58	30%	5.66
Dec 2022	31,380	1,286,902	409,366	13.05	32%	5.71
Jan 2023	29,643	1,286,792	411,289	13.87	32%	5.71
Feb 2023	24,920	1,131,061	361,858	14.52	32%	5.69
Mar 2023	26,246	1,252,246	357,238	13.61	29%	5.55
Apr 2023	15,922	794,063	216,733	13.61	27%	5.56
May 2023	24,753	1,314,245	339,640	13.72	26%	5.58
Jun 2023	22,745	1,177,200	330,155	14.52	28%	5.56
Jul 2023	22,500	1,183,041	332,253	14.77	28%	5.59
AVG	**25,800**	**1,183,041**	**364,597**	**14.16**	**30%**	**5.65**

Table 5 presents electricity consumption data during the repair process that took place from June 2022 to July 2023. Based on the analysis shown in Figure 4a, the Machine Running Hour experienced a decrease from 30,777 to 25,800 per month, due to a decrease in market demand after the COVID-19 cases subsided.

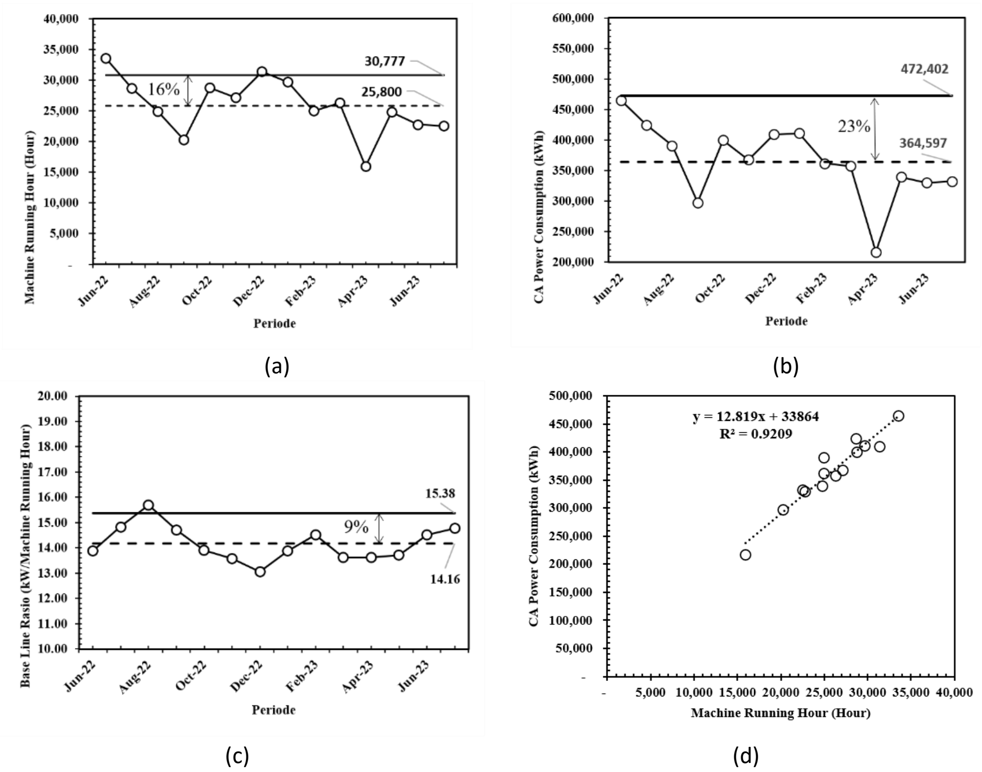

Figure 4. Baseline Development in four Graphs: (a) Equivalent Plant Power Consumption, (b) Compressed Air (CA) Electric Consumption, (c) Baseline Ratio of CA Energy Consumption per Production Machine Hour.

In Figure 4b, the electricity consumption for compressors averaged 364,597 kWh, showing a significant decrease of 23% after the repair steps were implemented. The average Machine Running Hour also decreased by 16%. With this condition, the energy usage for compressed air decreased relatively by 7%, with the average electricity consumption for compressed air per machine per hour decreasing by 8%. The baseline value also decreased to 14.16 kW/Machine Hour, from the previous 15.38 kW/Machine Hour.

The linear regression value approaches one, indicating a correlation between the number of machines running hours and electricity consumption to produce compressed air [22,23]. With energy savings ranging from 7% to 8%, these results reflect the success of targeted efficiency strategy implementation. The decrease in machine running hours is also influenced by market demand fluctuations, showing a close relationship between production and energy needs.

Table 6. Summary of savings from June 2022 to July 2023.

Parameter Description	Before	After	Dev	%
SPC	5.88	5.65	0.23	4%
CA Power Consumption	472,402	364,597	107,805	23%
Machine Running Hour	30,777	25,800	4,977	16%
Ratio CA Power Consumption vs Machine Running Hour	15.56	14.16	1.4	9%
Cost Saving per month (kWh Price IDR 1,036) (Mio IDR) [24]	-	111.6	-	-
Cost Saving per Annual (Mio IDR)	-	1,340.2	-	-

Table 6 provides a summary of the optimization results, highlighting the differences between conditions before and after implementing improvements. At the bottom of Table 6, the total cost savings achieved is calculated.

Discussion

Based on the results presented, three key points merit discussion. First, the success level, measured by the ratio of Compressed Air Power to Machine Running Hours, is influenced by factors such as fluctuating demand, product variations, and machine conditions. Management must anticipate these variations to ensure optimization aligns with expectations. Second, for sustained optimization, continuous monitoring and measurement of consumption and pressure are essential to maintain efficiency levels. Third, adopting alternative renewable energy sources can reduce reliance on fossil fuels and help lower electricity costs [25,26].

This case study offers comprehensive insights into optimizing compressed air systems and achieving energy savings, especially in reducing fossil fuel use. Key actions include replacing units with lower SPCs as aging and outdated technology contribute to higher SPC levels; reducing operational pressure to align with minimum pneumatic equipment requirements and product variations; and standardizing compressed air consumption and pressure across machines. The success level, as measured by the Compressed Air Power to Machine Running Hours ratio, indicates improved efficiency even with fluctuating machine capacity.

This case study provides valuable insights for management, particularly for sales and production planners. The variability in machine running hours due to fluctuating demand, product variations, and machine conditions need to be anticipated by management to ensure optimization meets expectations. Additionally, to sustain optimization efforts, continuous monitoring and measurement of consumption and pressure must be implemented to maintain efficiency.

Energy savings in compressed air systems through optimization have proven effective. However, further energy conservation, particularly in reducing fossil fuel dependence, can be achieved through other means. At the case study facility, installing photovoltaic (PV) panels on building rooftops could provide an alternative electricity source. The ample roof space and sufficient sunlight availability are ideal for generating alternative energy through PV. The capacity of the alternative energy produced can be tailored to meet the needs of compressed air system equipment, such as compressed air motors or dryers. In this regard, smart technology is essential to align the energy generated by PV with the requirements of the compressed air system.

Conclusions

Achieving energy consumption savings for CA production requires focusing on two main areas: Source Point and User Point. This approach involves accurate data collection from both primary and secondary sources to ensure relevance, with energy consumption and machine operating time data serving as essential benchmarks for evaluating efficiency. Improvement strategies in both areas have proven effective, reducing electricity consumption by 8 to 9%, surpassing initial targets and achieving levels below previous averages. These efforts not only enhance energy efficiency but also positively impact resource management. Furthermore, incorporating technologies designed to reduce or eliminate the need for compressed air significantly enhances efficiency, while active employee participation, including from machine operators and maintenance technicians, is essential to implement energy-saving practices and foster a culture of sustainable energy awareness. Thus, sustainable energy savings hinge on a blend of technical improvements, new technologies, and engaged employees, enabling companies to improve energy performance and advance their sustainability goals

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