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# Cost-effectiveness Management of a Compressed-air System Using an Energy Analysis Application

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**Abstract.** This paper developed an application for a foundry enterprise to reduce the delay in fixing identified air leaks and decrease energy consumption in the compressed-air systems. In many instances, air leaks were detected, but the response towards correcting them is usually less expeditious by the various departments responsible. Perhaps, there is a lack of awareness about the opportunities to conserve energy either through prompt repairs of air leaks or by regulating the pressure setting to match demand per time. An energy analysis application was developed using Matlab®. It facilitated increased response to repairs of air leaks and improved supply-demand management of output pressures from compressed-air systems.

**Keywords:** *Air leaks, compressed-air, energy cost, waste energy, energy audit*

## 1. Introduction

Compressed air (CA) is an essential input requirement in process equipment including pneumatic-operated machine, cleaning machine, refrigeration, foundries, and more [1], [2]. Many manufacturing enterprises including sand casting industry require CA to perform a variety of tasks ranging from moulding, cleaning, blowing, and more. It is also used in some burners that generate heat for the preheating of ladle in sand casting. Also, compressed air is the most common energy source for control valve actuators [3]. The compressed air is usually supplied at a gauge pressure of between 0.55 to 1.0 MPa [4]. Some specific compressed-air systems require higher pressures in the range of 3.2 to 4.0 MPa [2]. Generally, increased energy cost is associated with CA supplied at high pressures. Perhaps, this explains why the cost of generating CA is relatively high, approximately 10 - 30% of the total electricity consumption in many industries around the world [1], [5]. Obviously, many manufacturers may be quick to identify low-pressure compressed-air systems as a conceivable low-cost alternative that may reduce energy consumption. But lower pressure of compressed air may not guarantee the desired pressures at the various points of end use. This is because the usual practice in many industries is to locate compressed-air systems in adjacent shelters specifically built outside the points of end use and then convey the compressed-air through pipe networks to various points of end use (Fig. 1) [6]. Consequently, pressure drops are not uncommon along the lines due to fittings, valves, filters and air leaks [1]. Several studies have identified methods for promoting energy savings and comprehensive optimisation decisions in compressed-air systems. They include supply-demand management technique, reducing output pressures to match demand per time, reducing leaks, prompt attention to leaks repair, and reducing average inlet temperature by installing intake duct [5], [7]. The comprehensive optimisation decisions involves the use of a combination of exergy and energy efficiencies as well as cost-effective analysis [6].



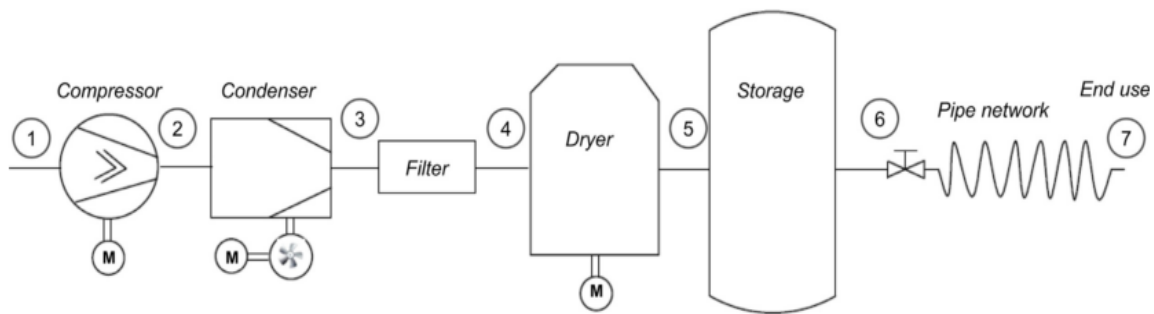


Fig. 1. Typical compressed-air system components, pipe network and points of end use (Source: [6])

Compressed air is more expensive to use than most users would probably want to admit [3]. This is because the general opinion about air is that it is free. Air is actually free of costs but not after it has been compressed. Huge electricity costs are required to filter, clean and raise the pressure of normal air to a status that is useful to operate many devices.

Air leaks have been identified to cause significant pressure drops and energy loss in compressed-air systems [4]. Similar to some accessories such as fittings and filters in the compressed-air lines, air leaks are difficult to avoid or totally eliminate. However, proactive measures are required to fixing identified air leaks. This paper developed an energy analysis application for compressed-air systems to demonstrate the energy savings potential when repairs are promptly carried out on identified air leaks in the system. This is to discourage the usual practice of waiting until the air leaks caused significant pressure losses that interfere with the normal operation of the equipment connected to the compressed-air lines.

It is also believed that old compressed-air systems should be replaced to reduce energy consumption. But having old equipment changed to a new one is always not against the grain to waste energy [8]. Instead, the authors argued in favour of three elements that may be used to promote energy efficiency, viz: To identify and value waste energy. To encourage good practice for resource efficiency. In other words, to adopt supply-demand management technique to match output pressures to needs per time. To understand potential savings and set targets. The developed application may be used to facilitate the accomplishment of some aspects of the listed elements including estimating the energy cost of air leaks and computing the savings in energy cost due to prompt repairs of air leaks.

Furthermore, it is not a usual practice in many industries using compressed-air systems to have the time to study the cost involved in the operation of the utility system [5]. However, with the energy analysis application, energy analysts and maintenance crew may be alert on what better practice to adopt to reduce energy consumption and overall operating cost of a CA system. In this study, an energy analysis application is introduced to facilitate the best improvement decisions about air leakages and management of pressure supply-demand from compressed-air systems.

## 2. Literature Review

Different legislative and normative measures are usually adopted by various industries to reduce energy cost [9]. Similarly, with the advent of mechatronics measurement systems, many researchers have recently directed attention to developing new devices to retrieve information about air leaks and possible system inefficiencies [2].

Ming Yang [10] developed methodologies that served as a guide on how to analyse compressed-air system energy efficiency. It was found that the energy loss related to air leaks and non-optimised operations of compressed-air systems can be minimised. However, empirical data were largely utilized in the investigation and the conclusions were based on the outcome of the processed data. This approach can be extended to include a predictive analytical model to server as a forewarn to various departments

about the increased energy cost due to delay in air leaks repair and poor scheduling of output pressures from compress-air systems.

Optimization methods have also been suggested to improve energy efficiency and reduce cost of manufacturing compressed-air systems [2]. According to Jovanovic et al. [2], the method may be focused on different stages including modeling of the overall air supply capacity, capacity validation of all compressors used in a manufacturing line, compressor design optimization, and using simulation to evaluate multiple compressors at a station. The present research work is aimed at developing an application in consideration of stage one in addition to incorporating the analysis of air leaks to demonstrate the energy savings potential involved in promptly correcting air leakages.

Also, simulation of some fittings such as Tees and 90° elbows was carried out to determine the effects of pressure gradient across compressed-air pipe network [11]. The authors reported a reduction in compressor electricity consumption when the pipe junction geometry was redesigned. The redesign involved the replacement of Tees with branch lines of 46° from the main pipe and the substitution of 90° elbows with 150-mm fillet radii. However, replacing the existing pipe fittings with the new junction geometry may be difficult to implement in some orientations that are perpendicular to each other. Nevertheless, the pipe junction redesign may be considered alongside with the supply-demand management model proposed in the current work to maximize energy savings.

The use of mechatronic measurement systems to track, detect and increase the response to fixing air leaks, thereby increasing system efficiency, has recently become a focus of several studies [2]. But in developing countries including Nigeria, high-tech mechatronic systems are only gradually gaining attention and the inclusion of mechatronic devices in compressed-air systems is still being considered with caution. Also, substantial investment may be required to retrofit old compressed-air systems with mechatronic devices. By using energy analysis application to facilitate decision making about air leakages, substantial energy and cost may be saved.

On a general observation, it was stated that conservation measures be adopted in the use of energy in various energy intensive sectors [12]. Therefore, an energy analysis application is being developed for compressed-air systems to facilitate decision making about air leaks, and to substantially reduce energy consumption and cost associated with the use of the systems.

### 3. Materials and Method

Air leaks in compressed-air lines are considered. In addition, supply-demand management model of output pressure that meets air supply needs per time is incorporated.

#### 3.1 Thermodynamic analysis and energy application model

The higher the discharge pressure from a compressed-air system, the larger the work required for compression. On the contrary, when the discharge pressure,  $P_{disch(max)}$ , of the system is reduced to  $P_{disch(red)}$ , the power input requirements of the system is also reduced by a factor defined in Eq. 1 [4].

$$f_{red} = 1 - \frac{(P_{disch(red)}/P_{atm})^{(n-1)/n} - 1}{(P_{disch(max)}/P_{atm})^{(n-1)/n} - 1} \quad (1)$$

where  $n$  is ratio of specific heat,  $P_{disch(red)}$  is the reduced discharge pressure,  $P_{disch(max)}$  is the maximum discharge pressure possible,  $P_{atm}$  is the atmospheric pressure, and  $f_{red}$  is the power reduction factor.

A unit mass of air that escapes through leaks on a compressed-air line usually wastes some amount of energy equivalent to the mechanical energy used in compressing it, and is determined in Eq. 2 [6], [13]–[15].

$$w_{comp,in} = \frac{n R T_{amb}}{n_{comp} (n-1)} \left[ \left( \frac{P_{disch}}{P_{atm}} \right)^{(n-1)/n} - 1 \right] \quad (2)$$

where  $w_{comp,in}$  is input energy to compressor,  $n_{comp}$  is the compressor efficiency,  $n$  is ratio of specific heat,  $R$  is the gas constant,  $T_{amb}$  is the ambient temperature,  $P_{atm}$  is the atmospheric pressure, and  $P_{disch}$  is the discharge pressure.

The unit mass of air usually has a mass flow rate as it escapes through a leak of minimum cross-section. This is determined using Eq. 3 [4].

$$\dot{m}_{air} = A C_{disch} \frac{P_{line}}{R T_{line}} \left(\frac{2}{n+1}\right)^{1/(n-1)} \sqrt{n R \left(\frac{2}{n+1}\right) T_{line}} \quad (3)$$

where  $\dot{m}_{air}$  is the mass flow rate,  $C_{disch}$  is the discharge or loss coefficient,  $A$  is the cross-sectional area of the leak hole,  $n$  is ratio of specific heat,  $R$  is the gas constant,  $P_{line}$  is the line pressure, and  $T_{line}$  is the line temperature.

The waste power when a leak is not repaired is determined as follow:

$$Power_{wasted} = \dot{m}_{air} \times w_{comp,in} \quad (4)$$

### 3.2 Analysis of data

Data were collected from a typical single-stage positive-displacement compressor from a foundry facility. The operating conditions of the compressor and the ambient environmental conditions of the air were recorded. The compressor rating including the mass flow rate and efficiency were obtained from technical book. The operating hours were estimated. The maximum discharge pressure of the compressed-air system is 1000 kPa. The highest-pressure requirement in the connecting points is 600 kPa. A gauge pressure to each of the points was between 640 – 720 kPa. An average 680 kPa was assumed for the line pressure. Table 1 shows the complete data used in the energy analysis.

Table 1: Compressed-air operating conditions data

Description	Unit	Value
Hole diameter	mm	2.50
Atmospheric pressure:	kPa	101.00
Ambient temperature:	C	24.00
Max. discharge pressure	kPa	10000.00
Reduced discharge pressure	kPa	780.00
Discharge temperature	C	43.00
Line pressure	kPa	680.00
Line temperature	C	32.00
Specific heat ratio		1.40
Hours per day	h	10.00
Discharge or loss coeff.		0.65
Motor efficiency	%	86.00
Compressor efficiency	%	72.00
Compressor mass flow rate	kg / s	3.00
Exchange rate	NGN / Dollar	364.00
Unit cost per kWh	\$/ kWh	0.0824

### 3.3 Application development

The application was developed using Matlab<sup>®</sup>. A typical single-stage positive displacement compression system was considered. The algorithms were based largely on the thermodynamics models for the compression systems. The assumptions made are: 1. The air is an ideal gas. 2. The compression system operates at a steady-state condition. 3. The losses at the fittings, filters and valves are negligible compared to energy lose due to air leaks.

## 4. Results and discussion

The energy analysis application can be used to facilitate decision making about energy management relating to compressed-air operation. The application revealed that air leaks caused substantial waste energy on compressed-air systems (Table 2). The waste energy increases with the increase in the diameter of hole as shown in Fig 2.

Table 2: Energy analysis result

Description	Unit	Value
Input energy to compressor	kJ / kg	1.1302 x10 <sup>3</sup>
Cost of electricity per year	\$	8.7190 x 10 <sup>5</sup>
Cost savings per year	\$ / yr	2.1768 x 10 <sup>8</sup>
Pressure reduced	kPa	9220
Wasted energy	kW	85.4317
Hole cross-sectional area	m <sup>2</sup>	4.9087 x 10 <sup>6</sup>
Mass flow rate	kg / s	0.0756
Wasted power per day	kWh / day	993.3920
Wasted power per year	kWh / yr	3.0994 x 10 <sup>5</sup>
Cost wasted per day	\$	77.4846
Cost wasted per year	\$	2.4175 x 10 <sup>4</sup>
Reduction factor		0.6859

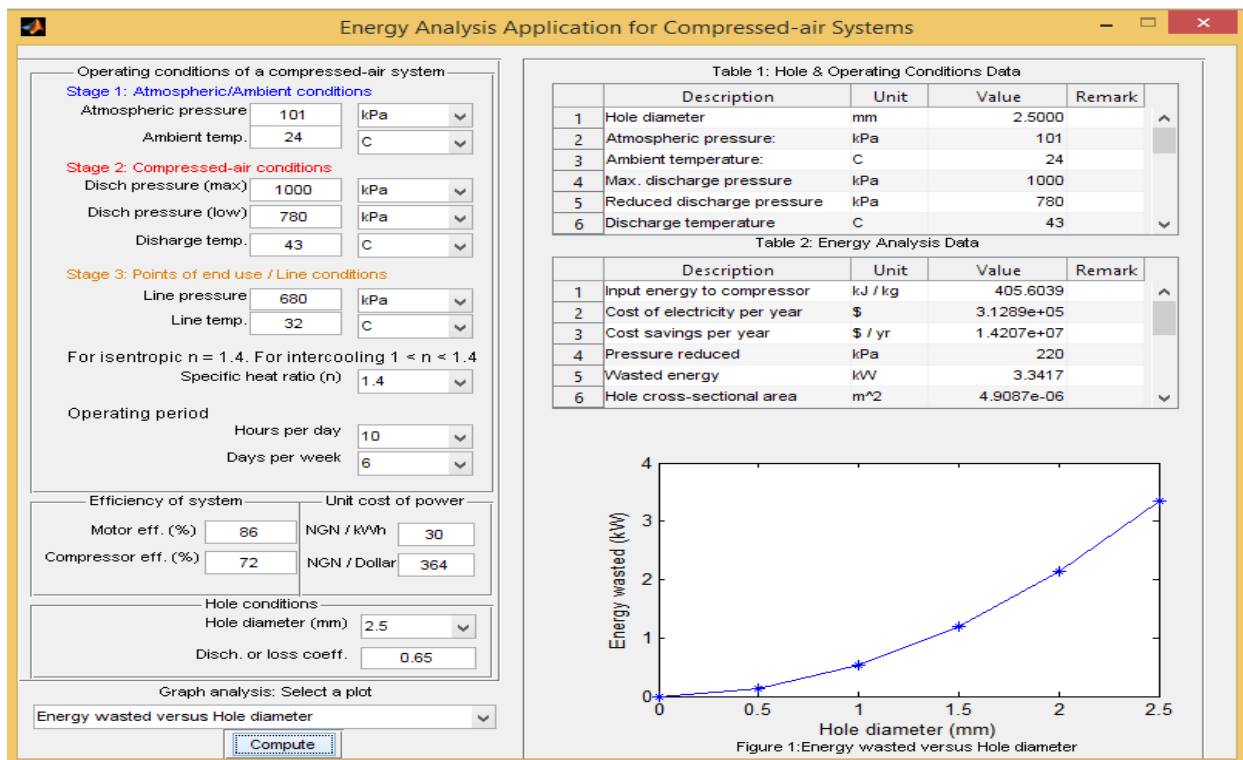


Fig 2: Analysis of waste energy against diameter of air leak

The minimum discharge pressure that can ensure that connecting points are not affected is 780 kPa. This pressure was used as the reduced pressure setting on the compressed-air system. That is, the system has an operating pressure range of 780 – 1000 kPa. For a pressure reduction of 220 kPa, cost of energy saved per annum is \$1.42 x 10<sup>7</sup>. The larger the pressure reduction without significantly affecting the operation of the connecting points, the higher the cost savings. As the discharge pressure increases to maximum, cost savings decreases as indicated in Fig 3.

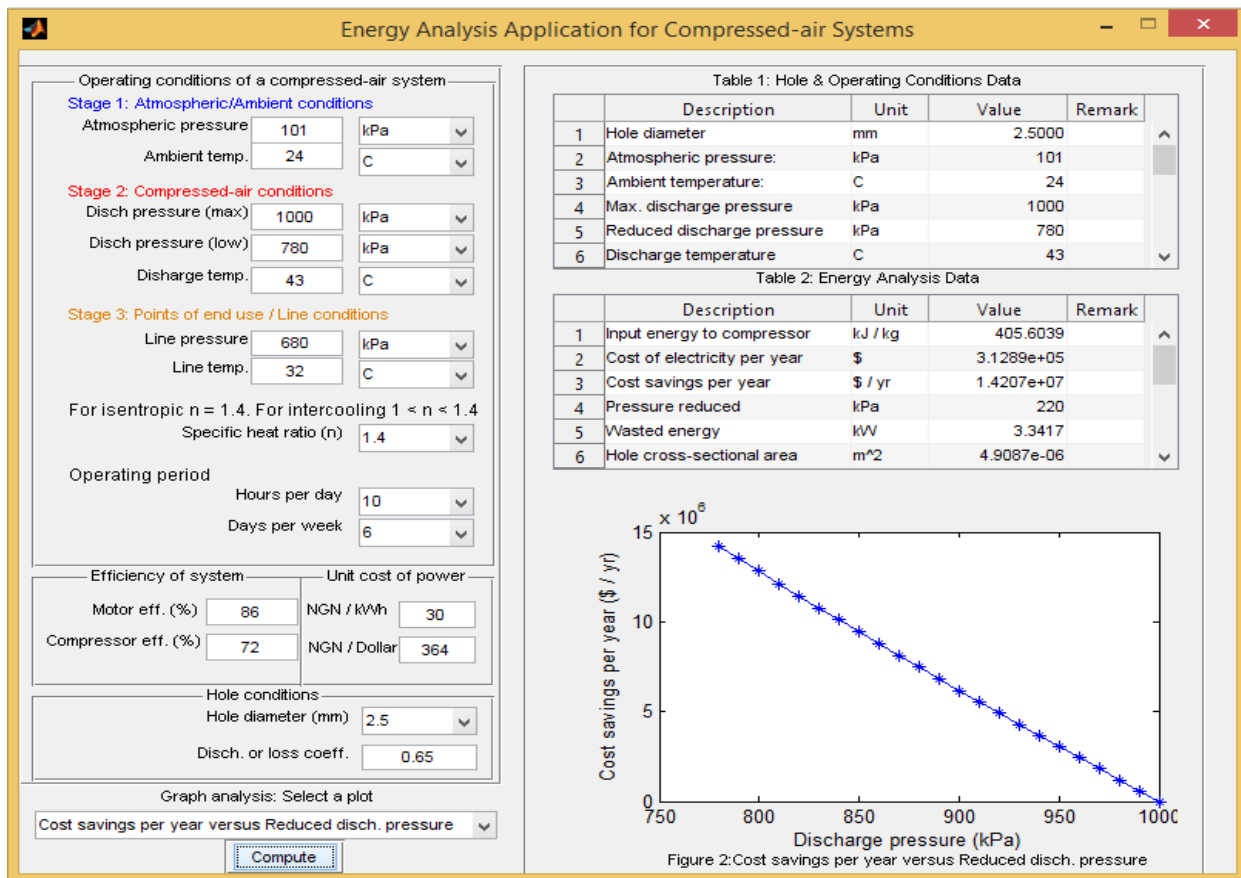


Fig 3: Analysis of the cost savings per year by reducing discharged pressure

This study presents a different cost-effective management technique of energy analysis for the operation of compressed-air system based on the utilization of energy application to demonstrate the energy savings potential associated with quick-fix of identified air leaks and in using reduced pressures at low demand periods Fig 2 and 3. Air is free of costs but only before it is compressed. From the moment of compression, any compressed air has several cost implications including production, distribution and equipment wear costs. Every unit mass of air that escapes through leaks has wasted some amount of mechanical energy used in compressing it. Therefore, when air is allowed to leak due to a general lack of awareness about its negative impact, a considerable portion of the energy or money is wasted. In many industries, this lack of awareness is more rooted in the non-technical departments that are usually responsible for funding maintenance request from the technical crew to correct faulty equipment. Also, both the technical and non-technical teams are usually too occupied to have the time to study the cost associated with air leaks and the cost savings associated with reducing air pressure setting.

**5. Conclusion**

Supply-demand management of compressed air to match production needs per time is one of the main goals of every compressed-air system to achieve better energy efficiency. Also, prompt repairs of air leakages can have significant energy savings on a compressed-air system. Planning engineers and maintenance crew may have to include air leakages in emergency maintenance records. More importantly, prompt attention is required by various departments involved to reduce energy or money losses. The application was considered for a single-stage compressed-air system. It may be further developed to include multi-stage compressed-air systems. Other elements of the compressed-air system that may be included in the energy analysis model to further increase energy savings are filters, fittings and valves.

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