How Much Focus Should Go Towards Optimizing Inherently Inefficient Compressed Air Systems vs Phasing Them Out?

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ABSTRACT

Compressed air systems represent about 10% of total U.S. industrial electricity usage, making them a popular focus for energy efficiency programs. These systems present big energy savings opportunities in generation equipment, distribution systems, and end-use applications. However, in a fully optimized compressed air system, the useful mechanical energy output is only 9% of the input energy. Furthermore, most end-uses can be met with non-compressed air solutions. For example, pneumatic valves, tools, and actuators can be replaced by electric motors. Many end-use applications or entire production lines can be redesigned to not use compressed air. These alternatives are not new technology and already exist in most industries.

This analysis finds a potential savings of nearly 68,000 GWh/year in the U.S. by switching away from compressed air. This represents 9% of total U.S. industrial sector electricity usage. When faced with a global timeclock to decarbonize, it is critical to reflect on our goals and strategies for compressed air. Should we optimize an inherently inefficient system, or try to phase it out completely? Is compressor-less manufacturing feasible? What impacts would this have on our electric grid, carbon goals, and manufacturing costs? This paper discusses these questions through use of compressed air energy audits, utility program M&V, and manufacturing databases. It provides analysis at both a zoomed in end-use-application level, as well as a big picture context level.

Introduction

Compressed air is one of the most expensive and widely used generated utilities in manufacturing. Some of the largest consumers of compressed air include chemical plants, iron and steel mills, and petroleum and coal product manufacturing (EIA 2018). While these are the most intensive users of compressed air, virtually all manufacturers have compressed air systems and often view it as a necessary utility, like electricity and natural gas. Common end-uses for compressed air include pneumatic controls and actuation, conveying and materials handling, pneumatic tools, cleaning and drying, mixing and agitation, dust collector shakedown, and cooling, to name a few.

Energy efficiency programs spend a lot of time, effort, and money on compressed air systems because they account for about 10% of the nation's industrial electricity consumption (EXERGY 2001). We work with several efficiency programs, mostly in Ohio. In the program we worked with most, the largest share of the efficiency program's industrial sector focus went to compressed air systems through incentivizing VFD compressor upgrades, sequence controllers, new dryers, distribution system upgrades, or continuous improvement efforts, such as strategic energy management (SEM). In addition to putting rebate incentive dollars into these projects, the efficiency program also had to invest in significant engineering efforts to subsidize system studies, metering for power, pressure, and flow, and third-party measurement and verification (M&V). For example, in this efficiency program, compressed air system projects accounted for about 18% of the program's total offered incentives for custom rebates, about 21% of the reported energy usage savings, and 15% of the reported peak demand reductions. Extrapolating from this case example for the point of argument, compressed air energy usage accounts for 10% of U.S. industrial electricity use, but it disproportionally consumes 18% of the available budget for incentives.

At face value, all this effort is worthwhile to the efficiency program because they were able to realize big savings and make their customers happy. Some of the largest industrial energy efficiency projects in the portfolio came from compressed air. However, the major problem with focusing so much effort on compressed air energy efficiency is that even most optimized compressed air systems are inherently and horribly inefficient. This is largely due to the heat of compression which results in nearly 80% of the input energy being lost to heat. Other losses that are present in all compressed air systems include leaks, losses from treating the air (drying, cooling, filtering, regulating, etc.), and pneumatic to mechanical conversion losses. After accounting for all these unavoidable losses, the useful energy output even in the most optimized compressed air systems is typically around 9% of the total electrical energy input (CEATI 2007).

All the best efforts to optimize these systems will ultimately only amount to small reductions to what is 10% of the U.S. industrial electricity consumption. If our end goal as an industry is to reduce our carbon emissions to zero, should we really be spending so much time and resources on a system that achieves 9% efficiency at best, or is there a more favorable alternative? The focus should instead be on phasing out compressed air systems and opening minds to compressor-less industries. As this paper will discuss, most compressed air end-use applications have non-pneumatic alternatives, or manufacturing processes can be redesigned to not need compressed air. Furthermore, the compressor-less technology ideas are not new advanced technologies. They already exist in most facilities, but they are not viewed as the default solution.

Calculating the Savings of Phasing Out Compressed Air

The simplified methodology used in this analysis can be summarized in four basic steps which will be expanded upon in the following sections. First, it is necessary to quantify how much electricity is currently being used for compressed air systems across the United States. Second, applying the ideal thermodynamic efficiency to this total electricity consumption results in the total amount of useful work generated by industrial compressed air systems in the U.S. Third, the efficiency of the replacement technology must be applied to see how much electricity would theoretically be used if all compressed air systems were replaced with more efficient alternatives. Finally, by comparing the difference between the number generated in step one to that generated in step three, a theoretical maximum savings can be quantified. The result is an estimate which assumes all compressed air can be converted to other technologies, which while not the most realistic assumption, is still useful as a starting point for comparison and can then be adjusted based on actual limitations. The analysis was conducted this way to first present the theoretical numbers as a best-case scenario to strive towards, and then introduce the nuances of the real-life constraints that exist to reduce this savings to something more practically achievable.

Step 1: Current Annual Electricity Usage for Compressed Air in the U.S. Industrial Sector

Determining how much electricity is consumed by U.S. industrial compressed air systems is estimated from two primary sources of information. The first is the 2018 Manufacturing

Energy Consumptions Survey, or MECS, which is prepared by the U.S. Energy Information Administration. The second is the Assessment of the Market for Compressed Air Efficiency Services, or CA Market Assessment, which was prepared for the U.S. Department of Energy.

MECS provides the best available estimate of how much total electricity is used by the industrial sector annually. The dataset is built mainly through web surveys and in its most recent poll, released in February 2021 and conducted in 2018, the sample size was approximately 15,000 establishments, representing 97%-98% of the manufacturing industry. The data shows total annual electricity purchases in million kilowatt-hours, or gigawatt-hours, summarized by industry group as defined by the North American Industry Classification System, or NAICS (EIA 2018). Figure 1 below represents this data visually in a bar chart.

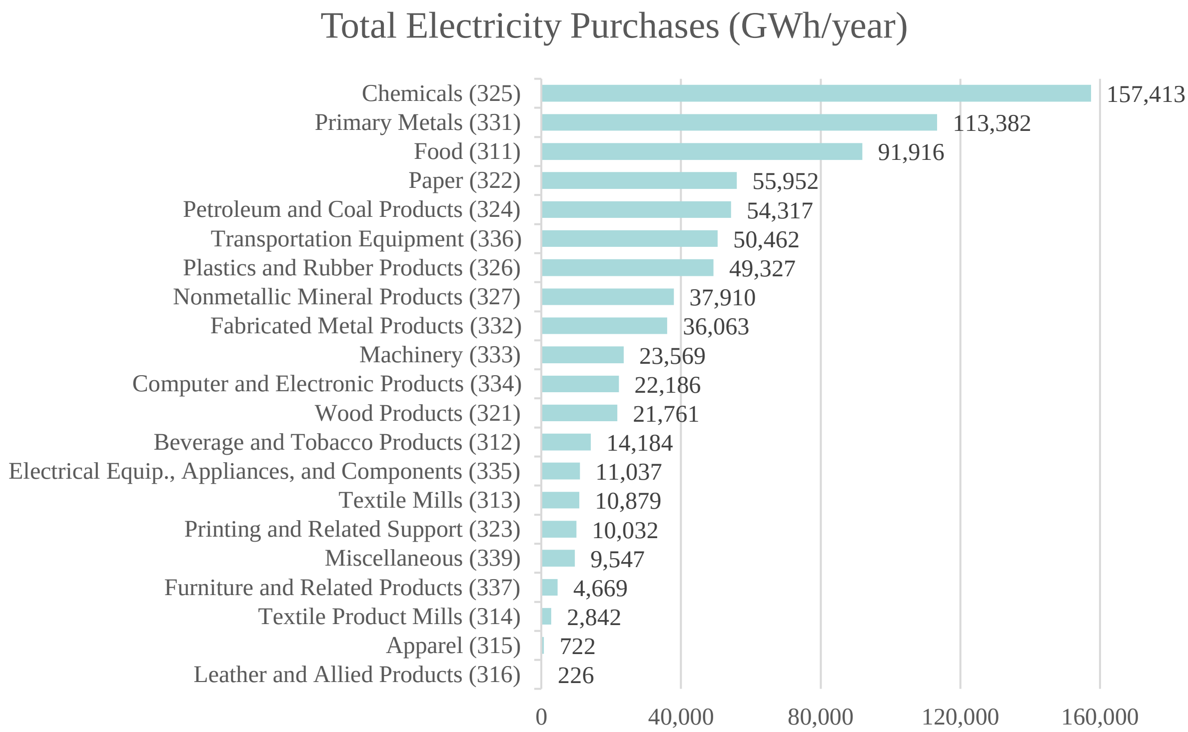

Figure 1. Total U.S. electricity purchases in gigawatt-hours per year, summarized by industry group (NAICS number), in descending order from most to least electricity purchases. *Source:* EIA, 2018.

For the purposes of this analysis, electricity purchases are considered to be equal to electricity consumption and will be referred to as such. On-site electricity generation can offset the total amount of purchased electricity, and therefore underrepresent total electric consumption. By not accounting for on-site generation in baseline calculations, the resulting savings calculation is smaller and therefore more conservative, making this a more conservative approach. Summing all the industry groups together results in the total electricity consumption of 778,396 GWh/year for the U.S. industrial sector. In order to use this number to calculate annual U.S. industrial compressed air usage, it is necessary to introduce the second source of information used in this analysis, the CA Market Assessment.

The CA Market Assessment was commissioned by the U.S. Department of Energy in 2001 and prepared by XENERGY Inc. with help from the Compressed Air Challenge. Similar to the MECS, the information in this report was sourced through voluntary participation of many individuals and organizations, which allowed XENERGY Inc. to conduct interviews and inventories of their industrial motor systems. In this assessment, compressed air system electricity usage is given as a percentage of total electric usage by industry group, only the industry groups are summarized by Standard Industrial Classification, or SIC. Table 1 below summarizes this data and it also shows which NAICS codes correspond to each SIC code for use in this analysis.

Table 1. Compressed Air Electricity Usage as a Percentage of Total Electricity Usage

SIC	NAICS	Industry Group	Comp. Air as % of Total Electric Use (%)
28	325	Chemicals (325)	20.1%
33	331	Primary Metals (331)	8.3%
20	311	Food (311)	4.5%
26	322	Paper (322)	3.7%
29	324	Petroleum and Coal Products (324)	15.9%
37	336	Transportation Equipment (336)	14.0%
30	326	Plastics and Rubber Products (326)	10.9%
32	327	Nonmetallic Mineral Products (327)	1.6%
34	332	Fabricated Metal Products (332)	5.2%
35	333	Machinery (333)	3.6%
38	334	Computer and Electronic Products (334)	4.9%
24	321	Wood Products (321)	8.7%
20	312	Beverage and Tobacco Products (312)	4.5%
36	335	Electrical Equip., Appliances, and Components (335)	9.1%
22	313	Textile Mills (313)	7.2%
27	323	Printing and Related Support (323)	2.5%
	339	Miscellaneous (339)	
25	337	Furniture and Related Products (337)	6.9%
22	314	Textile Product Mills (314)	7.2%
23	315	Apparel (315)	5.1%
31	316	Leather and Allied Products (316)	0.2%
Total			**10.0%**

Annual compressed air electricity usage as a percentage of total industry group electricity usage, summarized by industry group, in descending order from most to least electricity purchases. Source: EXERGY, 2001.

Note that the CA Market Assessment does not have a line item that corresponds to NAICS Industry Group 339-Miscellaneous. This does not affect the analysis, as a value of 10.0% is given for the total industrial sector. Additionally, SIC Code 20 appears twice in Table 1 above, as the SIC combines Food (NAICS 311) with Beverage and Tobacco Products (NAICS 312) into one category called Food and Kindred Products (SIC 20). This is a similar case for SIC Code 22 which combines Textile Mills (NAICS 313) with Textile Product Mills (NAICS 314) into a single category called Textile Mill Products (SIC 22). This analysis continues to summarize data by NAICS Code in order to remain consistent across its visual representations of data.

Total U.S. industrial compressed air electricity usage can now be easily calculated by multiplying the data in Figure 1, total annual electricity usage, by the data in Table 1, compressed air as a percentage of total annual electricity usage.

While it is beneficial to see the raw data summarized by industry group, for the purposes of this analysis, the calculated value of greatest interest is the total U.S. industrial sector compressed air electricity usage as a whole. This calculation is presented in the equations below.

Total CA Electricity Usage = Total Electricity Usage x CA as Percentage of Total Usage (%)
= 778,396 GWh/year x 10.0% = 77,840 GWh/year

In summary, it is calculated that the U.S. industrial sector uses approximately 77,840 GWh/year in electricity for its compressed air systems alone. This was calculated using MECS data and the CA Market Assessment.

Consider the climate context. Applying the national average of 889.2 lbs CO_2e / MWh of generated electricity (EPA 2019) results in 34.6 million tons of CO_2e annual emissions directly attributed to compressed air in U.S. industrial manufacturing.

Step 2: Annual Useful Work for Compressed Air in the U.S. Industrial Sector

Now that an estimate for annual electricity usage has been calculated for the U.S. industrial compressed air systems, the next step is to estimate how much of this is actually useful thermodynamic work. A common rule of thumb for 100-psig class compressed air states that for every 100-hp of input electricity, there is 80-hp of input energy that is lost to the heat of compression and only 20-hp of useful work can continue through the compressed air system. In other words, according to the rule of thumb, a 100-psig system has a theoretical maximum efficiency of 20%.

The underlying principle driving this unavoidable loss is the thermodynamic relationship between the volume, pressure, and temperature of a gas. In short, temperature rises proportionally to pressure. As raising the pressure is the primary function of air compressors, the temperature also rises and this increase in thermodynamic energy in the form of heat must be paid for by the input electrical energy source. Some compressed air systems can capture a portion of this waste heat and use it for desiccant purge cycles, or to reclaim it as “free” heating for other processes at the facility. Unfortunately, this is simply an attempt to gain back a small portion of the inherent inefficiencies of compressed air systems. To illustrate this point, no one has ever opted to purchase a compressed air system to heat process water over a high efficiency condensing boiler system. Therefore, while reclaiming the lost heat is a best practice, what if one simply opted to purchase a more efficient system that did not require heat to be reclaimed? While it may be referred to as “free” heating, it could not be further from the truth.

Although it is the largest loss, heat of compression is not the only loss present in compressed air systems. Compressed air systems also have losses attributed to drying the air, filtering the air, losses to leaks, and losses in pneumatic to mechanical conversion. In a study by CEA Technologies for the Canadian Department of Natural Resources, losses for typical compressed air systems were calculated and summarized to show relative magnitude when compared to a 100-hp system. The data from that study is summarized in Figure 2 below.

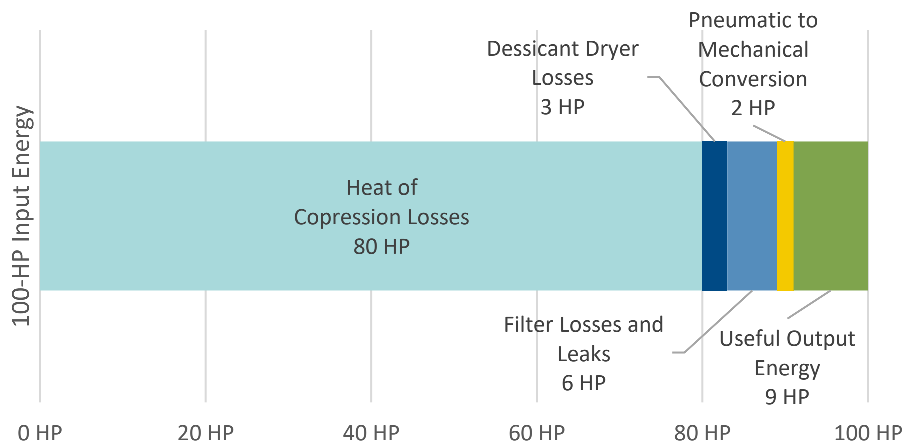

Figure 2. Relative breakdown of losses in a typical compressed air system assuming 100-hp of input energy. *Source*: CEATI, 2007.

According to the results of that study, only 9-hp of useful output energy is created at the cost of 100-hp of input electrical energy. Note that this breakdown did not even account for inefficient control strategies, inappropriate end uses, or neglectful maintenance strategies. Explicitly stated, the most well-maintained and efficiently run compressed air systems can only achieve around a 9% efficiency at best. This number can vary slightly case-by-case, but for the purposes of this analysis, this can act as a general average.

Thus, the total amount of useful work from industrial compressed air systems in the U.S. can be calculated by multiplying the value determined for annual electricity usage in the previous section of this analysis by 9%, as shown in the equation, below.

$$\textit{Total CA Useful Work} = \textit{Total CA Electricity Usage x CA Efficiency of Useful Work}$$
$$= 77{,}840 \textit{ GWh/year x } 9.0\% = 7{,}006 \textit{ GWh/year.}$$

In summary, it is calculated that the U.S. industrial sector uses approximately 7,006 GWh/year in useful output energy for its compressed air systems alone, while paying for 77,840 GWh/year in electricity usage, as calculated in step one.

Step 3: Proposed Annual Electricity Usage for Compressed Air in the U.S. Industrial Sector

The next step of the analysis is to see how much annual electricity would be reduced if the U.S. industrial sector swapped out compressed air systems for more efficient technologies, while achieving the same quantity of useful work. As described in the opening to this section, there are some physical limitations that must be considered when deciding whether a compressed air system can be swapped for a different technology. This will be addressed in subsequent sections of this analysis, but this section will assume all compressed air work can be swapped out, providing a theoretical maximum savings. Additionally, there will be several types of replacement technologies with differing efficiencies. For example, pneumatic controls would be replaced with direct digital control, or DDC devices. DDC sensors typically operate with low voltage circuits, requiring little power draw, although the controllers may use 24-V power and require slightly more power to operate. This being said, when compared to operating a compressed air system for pneumatic controls, DDC uses less energy. It is difficult to estimate exactly how much savings could be applied in this case, as it would have to be considered on a case-by-case basis, or enough data would need to be generated to provide typical estimates. Other more complicated examples include process drying and cooling, spraying, and dehydrating, among others.

A simple, conservative, and more all-encompassing strategy to estimate the efficiency of replacement technology is to consider conveying and materials handling, pneumatic hand tools, agitation, and any other end use that could be replaced with electric motors. Because there is a large variation in the size of motors that must also be considered for this analysis, it is best to remain conservative in selecting the proposed efficiency. With modern, high efficiency motors and technologies like electrically commutated, or EC motors, common efficiencies range from 70% to 85% in the fractional horsepower range (Roth 2004). For larger motors, which are less likely to be used in a compressed air to motor replacement, efficiencies are even greater. The lower end of the efficiency range, 70%, will conservatively be used for this analysis. The proposed annual electricity usage for U.S. industrial compressed air systems can be calculated by dividing the value determined for the total amount of useful work from compressed air systems, as calculated in step two, by 70%, as shown below.

Total Proposed CA Electricity Usage = Total CA Useful Work / Proposed CA Efficiency
= 7,006 GWh/year / 70.0% = 10,008 GWh/year.

In summary, it is calculated that the U.S. industrial sector could use approximately 10,008 GWh/year in electricity for its compressed air systems alone. This was calculated assuming 100% of compressed air end uses could be replaced with direct motor applications with an assumed motor efficiency of 70%.

Consider the climate context. Applying the national average of 889.2 lbs CO_2e / MWh of generated electricity (EPA 2019) results in 4.4 million tons of proposed CO_2e annual emissions directly attributed to compressed air in U.S. industrial manufacturing.

Step 4: Annual Electricity Savings for Compressed Air in the U.S. Industrial Sector

The final step is to compare the current annual electricity usage for compressed air in the U.S. industrial sector to the proposed value calculated in the section above.

Total CA Elec. Savings = Current CA Elec. Usage - Proposed CA Elec. Usage
= 77,840 GWh/year - 10,008 GWh/year = 67,832 GWh/year.

In summary, it is calculated that the U.S. industrial sector could save approximately 67,832 GWh/year, or 87%, in electricity for its compressed air systems alone. This was calculated assuming 100% of compressed air end uses could be replaced with direct motor applications with an assumed motor efficiency of 70%. This translates to a savings of 8.7% for the total U.S. industrial sector electricity usage.

Consider the climate context. Applying the national average of 889.2 lbs CO_2e / MWh of generated electricity (EPA 2019) results in 30.2 million tons of CO_2e annual emissions saved.

How Zero Air Compressor Manufacturing Could Look

As mentioned at several points throughout the analysis, achieving 100% of these savings would likely be impossible for a number of reasons. For example, some industries, like chemical manufacturing, require compressed air as an input to their product. That said, even if it were assumed that only 50% of all current compressed air uses could be eliminated and replaced with an alternative technology, this would result in 33,916 GWh/year in electricity savings, 15.1 million tons/year in CO_2e savings, 44% of U.S. industrial compressed air savings, and 4.4% of total U.S. industrial electricity savings. Table 2 below summarizes a range of potential savings resulting from 50% to 100% of U.S. industrial compressed air being eliminated and replaced with alternative technologies.

Table 2. Compressed Air Electricity Usage as a Percentage of Total Electricity Usage

Percent Savings Achieved (%)	CA Electricity Savings (GWh/year)	CO2e Savings (million tons/year)	Percent Savings of Industrial Sector CA (%)	Percent Savings of Total Industrial Sector (%)
100%	67,832	30.2	87%	8.7%
90%	61,048	27.1	78%	7.8%
80%	54,265	24.1	70%	7.0%
70%	47,482	21.1	61%	6.1%
60%	40,699	18.1	52%	5.2%
50%	33,916	15.1	44%	4.4%
**CA = Compressed Air*				

Range of annual savings achieved if 50% to 100% of U.S. industrial compressed air was swapped for alternative technologies, in increments of 10%.

The vast majority of compressed air applications we have observed across hundreds of Ohio and Midwest facilities are for pneumatic valves, actuators, tools, and processes that could be replaced with electric motor alternatives, suggesting that the 50% scenario is easily technologically feasible. So, it is worth noting that even the 50% savings are enticing enough to bear the question: could we have industrial manufacturing plants without any compressed air on-site?

It is not common, but for many facilities the technology does exist to make it possible. In a way, some of this work has already been started with energy efficiency program pushes to reduce inappropriate uses of compressed air. This is a good starting point, but it could be taken a step further. The following sections discuss the most common uses of compressed air and the relative difficulty of replacing them with alternative technologies. The industrial compressed air end uses have been grouped into four distinct tiers, starting with the simplest for replacement and ending with applications which cannot be replaced with an alternative technology. Table 3 below summarizes these categories.

Table 3. Common Compressed Air End Uses and Proposed Alternatives

Category	End Use Description	Sample Pneumatic End Uses	Proposed Alternatives
Tier 1	Easily Imagined One-for-One Retrofit to Electric Motors	Pneumatic tools, materials handling and conveying, air mixing and agitation	Electric power tools, motor-driven conveyors, mechanical mixing/agitating
Tier 2	Retrofit with Blowers, Vacuums, Fans, etc.	Low-pressure blowing, product moving, cleaning, drying, padding, or vacuum generation	Dedicated low-pressure blowers, fans, or vacuum pumps
Tier 3	Replaced with System Redesign	Diaphragm pumps, bag house shakedowns, lifts, cabinet cooling, aspiration, and atomizing, vortex cooling	Redesigned mechanical equivalents for filter shaking, lifts, cooling coil cooling, localized atomization systems, etc.
Tier 4	Must be Pneumatic and Require Small, Dedicated Systems	Product input, safety concerns, some painting equipment, many niche or specialized applications	Avoid large central systems that serve all needs, moving to smaller more localized systems

Tier 1: Easily Imagined One-for-One Retrofit to Electric Motors

Tier 1 is comprised of any industrial compressed air end use that can be directly replaced, one-for-one, with an electric motor-driven alternative. This tier represents some of the most common industrial compressed air end uses. Some of the end uses in this category originated as motor-driven technologies in the first place, making this category very simple to phase out compressed air. In fact, many manufacturers we have studied already have a mixture of pneumatic and electric applications within their processes. However, in these cases the electric motor alternatives were not typically selected with efficiency in mind, but rather used because the compressed air distribution system could not easily serve a certain location, or a component to a process was added as an afterthought and not tied into the pneumatic system.

One common example is pneumatic hand tools which typically employ pneumatic technology used to mimic small electric, motor-driven power tools. This is one of the simplest applications for phasing out compressed air. Another example is materials handling and conveying. For dry bulk products, pneumatic conveyor systems are utilized to move the product throughout each phase of manufacturing and out to shipping or storage. This is an application which can be easily replaced with motor-driven conveyors. Finally, compressed air mixing and agitation can be easily substituted with a one-for-one motor replacement. Using compressed air for agitating liquid product is particularly inefficient as the addition of compressed air to liquid product can change the dew point and result in product being wicked away by the dry air.

Tier 2: Retrofit with Blowers, Vacuums, Fans, etc.

Tier 2 is comprised of any industrial compressed air end use that relies on low pressure air flow or vacuum pressure. Rather than using high pressure compressed air systems to provide this end-use, localized or centralized blowers, fans or vacuum pumps can be used instead, with inherently much higher efficiencies at two to six time more efficient. Examples of this type of end use application include product movement, like moving sand in die casting, or moving paper cups in a coffee cup line, or creating suction to remove waste or hold a product. Additionally, low-pressure blowers can very often replace compressed air to meet demands such as liquid aeration, mixing or cooling. We often observe compressed air being used to do the work of a vacuum pump or blower because a central compressed air system already exists and it is an easier option compared to a separate blower or vacuum. However, it is not necessarily the lower maintenance or superior option, and it is definitely not the higher efficiency option. It is just the status quo option.

Tier 3: Replaced with System Redesign

Tier 3 is comprised of any industrial compressed air end use that requires a bit more effort and redesign when considering phasing out compressed air. In many cases retrofits are difficult once the systems exist. The best time to make this changeout is during a new construction or major process overhaul. Some of the end uses in Tier 1 or Tier 2 may be bumped into this category if they are very large systems that require significant redesign to ensure cost effectiveness. Other end uses in this category may be a one-for-one replacement but are not a simple retrofit motor-driven technology. The combination of Tiers 1, 2, and 3 make up virtually all compressed air end uses except for those that still require compressed air which have been reserved for Tier 4. Tier 3 end uses can still be phased out of compressed air, but the savings will be dependent on a case-by-case basis and may not be as closely reflected in the best-case savings calculations in the previous sections of this analysis.

Examples of compressed air end uses in this category include baghouse filters that use compressed air to purge or shakedown the filters. There typically does not exist an obvious one-to-one retrofit, but it is not difficult to imagine redesigning a baghouse system that can shake down, scrape or clean filters mechanically. Another example could be electric cabinet cooling, or even colder, vortex cooling applications. These end uses could be met more efficiently with direct expansion, or chilled water cooling coils, but this would require additional cooling systems and equipment to be installed. A third example might be diaphragm pumps used in many chemical applications. Non-pneumatic alternatives exist for most diaphragm pump applications, however, making this changeout will often require a case-by-case analysis to account for any needed system design or operation changes.

Many existing compressed air applications fall into the Tier 3 bucket, where more engineering analysis and system selection is needed. For these applications, the best time to make these changes may be when a system is built and selected. We performed a compressed air system study or a large automotive plant in Ohio with over 14,000-hp of compressed air. This plant was adding new lines to one of their aluminum casting departments and trying to anticipate the added compressed air demand on their system. It was found by studying the already existing lines, that each line used around 1,000 cfm of air on average. Virtually all of the air was used for pneumatic valves, actuators and some cooling. In light of the study, the plant engineers were considering compressed air-less line design options and expressed appreciation for the benefits of reduced air system distribution and leak load maintenance.

Tier 4: Must be Pneumatic and Require Small, Dedicated Systems

Tier 4 is the catch-all category which includes any end use that still requires compressed air generation. For example, this can be because compressed air is an actual product ingredient or input, as may be the case for some chemical industries, or because of safety concerns which require a diaphragm pump or motor to keep an explosion proof environment. This final category represents the smallest fraction of compressed air end uses and it obviously is not representative of the savings calculations laid out in the previous sections of this analysis.

However, for manufacturers that require compressed air, it is still important to consider a mindset shift away from viewing compressed air as centralized catch-all utility system that serves many needs, and instead view it as a valuable niche system that can be localized and minimized to only meet the necessary applications.

Case Study Example

In an effort to compare the magnitude of electricity savings resulting from efficiency programs to this theoretical approach of phasing out compressed air as a whole, a real-world case study will be used. This case study is based on a multi-year utility program engagement study of a large compressed air system at a Midwest automotive glass manufacturer. The study involved ongoing metering, analysis, identification of efficiency opportunities, project rebates, and M&V of implementation, similar to SEM efforts in some efficiency programs. This facility had three separate compressed air loops that ran at three distinct pressures, served by a total of seventeen compressors. The system consumed 9.38 GWh/year in annual electricity usage. Several energy efficiency recommendations were identified, including optimizing system pressures, repairing faulty capacity controls, repairing leaks, reducing inappropriate end uses, optimizing compressor sequencing, and upgrading sequencing controls. The total summation of calculated savings was 1.47 GWh/year, or 15.7% system savings. According to the DOE's *Evaluation of the Compressed Air Challenge Training Program*, implementing compressed air efficiency measures results in 7.5% system savings on average, and experts agree that 30% system savings can typically be achieved cost-effectively (2001). At 15.7% system savings, this case example falls within the expected range of 7.5% to 30% system savings from efficiency programs.

In smaller, less maintained systems, this range can increase a bit, but the distinction should also be made between calculated savings and realized savings. Efficiency programs offer some incentives for the study and for project implementation, but this does not guarantee project implementation. For the sake of comparison, let us conservatively assume that all 1.47 GWh/year in savings from our case study are implemented and realized. Let us also conservatively assume that every single manufacturing facility in the U.S. received a similar study and implemented the 15.7% system savings at their individual facilities. This would result in 12,221 GWh/year in savings for the industry as a whole. How does this number compare to phasing compressed air out and replacing it with alternative technologies?

Using the methodology described in the previous sections, it would only require 18% of the current U.S. industrial compressed air systems to be replaced with motor-driven equivalents. Which path is more achievable and realistic? Path 1 requires an engineering study be conducted at 100% of all manufacturing facilities that have compressed air systems on-site. Additionally, energy savings projects must be implemented and must save 15.7% of system energy usage on average, over double the quoted average of 7.5% from the DOE. This path also requires all energy savings projects do not diminish in their saving year after year. Path 2 requires a targeted approach to only 18% of manufacturing facilities with compressed air on-site, where incentives can be used on system redesign. While there are obvious limitations in the ability of certain facilities to eliminate compressed air completely, the potential savings of an approach like this are tempting. If it would be possible to convince less than 20% of all manufacturing facilities to retire or reduce their compressed air systems and opt for alternative technologies, the savings are approximately equivalent to an idealized, perfect case scenario implementation of efficiency programs.

This analysis is meant to act as a high-level look at the numbers, and to see if an approach like this is feasible and advantageous. If our end goal as an industry and as a society is to limit our energy waste and resulting carbon emissions, then the results of this analysis show that phasing out and eliminating compressed air technology cold be both feasible and advantageous to reaching our goal.

Conclusions

In conclusion, a theoretical maximum savings of 67,832 GWh/year, or 87% savings, could be achieved for U.S. industrial compressed air systems if 100% of all compressed air systems could be replaced with a 70% efficient motor. This corresponds to 8.7% energy savings for total U.S. industrial electricity usage. While achieving 100% of these savings is a fictitiously idealized scenario, achieving a portion of these savings is still significant and should be considered as a viable alternative to spending resources on optimizing compressed air systems.

Additionally, as shown in the final case study example, energy efficiency programs could significantly increase energy savings and carbon reductions by pursuing air compressor system phase out programs rather than focusing on energy efficiency alone. The results of the case study showed that a perfect 100% implementation of energy efficiency programs resulted in equivalent savings of an 18% implementation of compressed air phase out programs. Furthermore, the case study used a conservative 15.7% system savings estimate. If the DOE's assumed average of 7.5% savings were used, then only a 9% implementation of compressed air phase out programs would result in equivalent savings. The numbers point to the fact that a compressed air phase out approach could result in more energy and carbon savings for the U.S. industrial sector and may be a better way to focus our energy efficiency programs for industrial compressed air.

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