Compressed Air End-Use Management

Final Report

ET22SWE0045

Prepared by:

M M Valmiki, ASK Energy

David Moell, AESC

December 8, 2025

Acknowledgements

ASK Energy and AESC would like to acknowledge the host site staff and management for their trust, voluntary participation, and for welcoming our research team into their buildings. Energy efficiency and their greenhouse gas emission impacts depend on adventurous, forward-thinking building owners and operators who believe in a more sustainable energy future. Thank you to the manufacturer, vendors, and subject matter experts who made this project and technology possible.

The project was conducted through the CalNEXT program under the auspices of Southern California Edison and the Emerging Technologies Program. The CalNEXT program is a statewide California electrical energy efficiency emerging technology initiative, focusing on a variety of technology priorities.

Disclaimer

Executive Summary

Compressed air energy systems operate in 82 percent of industrial facilities and account for about 10 percent of all manufacturing electrical energy use. This ubiquity and the inherent inefficient use of energy in compressed air systems make them a high-value target for new efficiency measures and program support. Compressed air systems convert high-value electrical energy into usable motive energy at pneumatic end-uses at an efficiency of only 10 to 20 percent. Many opportunities for improvement and energy savings remain, especially in the controls, management, and monitoring of these systems. Despite the large energy footprint of compressed air systems, leaks, artificial loads, and inappropriate uses remain a persistent source of energy waste. One particularly unaddressed opportunity is control and monitoring of loads at large end-use machinery. Manufacturers and vendors in the compressed air industry have acknowledged this market need and new technologies are becoming available.

One such new product is a monitoring and control technology known as an air management system, that can be installed conveniently in both new and retrofit applications. Air management systems augment or replace existing filter-regulator-lubricator assemblies which are nearly always installed upstream of large pneumatic end uses. These large end-use machines often have internal air leaks, losses, inefficiencies, and unproductive loads whether production is active or not. Remedying these losses is oftentimes prohibited or too costly if the interiors of these machines are difficult to access. The new technology can address this issue. The thoughtful design includes features that can be commissioned to reduce supply pressure and completely cut off airflow to these machines when they are idle and unproductive. These control features will generate dependable, reliable energy savings by reducing the load on the air compressors. Additionally, monitoring at these machines can give facility staff insight into their plant and machine health that would otherwise be unavailable.

Savings for this technology were calculated on a per-unit basis for both a packaged frozen food production host site and across a range of flow and runtime conditions that could be observed across the market. The results for the host site are shown in Table 1. These results were dependent entirely on the operating conditions and airflows of the individual packaging lines at which the product was installed.

Table 1: Per-unit air management system savings at the host site.

Parameter	Value
Annual Savings (kWh/yr)	1,223
Annual Energy Cost Savings ($/yr)	432
Installed Cost ($)	4,567
Estimated Customer Payback Time (yr)	10.6
GHG Emissions Reduction (tons/yr)	0.1

Impacts were also calculated for a range of operating conditions to determine savings and payback for extrapolation to other plants and end uses. Across a range of conditions that would be seen in various plants, payback can be well under five years with savings exceeding 3,000 kWh per installed unit, depending on the end-use flowrate and idle time. In machinery with open pipe blowing and large idle flowrates in comparison to the working flow, payback can easily be under one or two years in ideal applications. These observations and savings present an uncommon and useful opportunity to develop a new workpaper and deemed measure for energy efficiency program portfolios.

New plug-and-play widget technologies rarely come to market, especially in the industrial sector, but the emerging technology's calculated savings and impacts set the stage for further opportunities such as workpaper development. In parallel with such an effort, air management systems could be further validated in a laboratory or additional field demonstration setting, if necessary. The product has a wide training and technical support network for early adopters and installation is generally straightforward for any typical industrial facility with knowledgeable maintenance staff. The findings suggest that the emerging technology is broadly applicable across the industrial sector and is well-suited for rebate program support that could benefit both utilities and their customers.

Abbreviations and Acronyms

Acronym	Meaning
AMS	Air management system
CFM	Cubic feet per minute
FRL	Filter-regulator-lubricator
GHG	Greenhouse gas
IOU	Investor-owned utility
kW	Kilowatt
kWh	Kilowatt-hour
psig	Pounds per square inch gauge
TSB	Total System Benefit
VDC	Volts direct current

Table of Contents

List of Tables

List of Figures

Introduction

This work is an assessment of air management system (AMS) technology, a new compressed air management product that measures, monitors, and controls airflow to pneumatic end uses. It is designed to replace filter-regulator-lubricator (FRL) assemblies - or subsets of FRLs - and can be easily installed in both existing and new machinery applications. Although AMS is marketed primarily toward industrial and manufacturing customers with large pneumatic machinery, the technology is modular, has a range of sizes for various applications, is highly customizable to match air treatment and plant needs, and can be commissioned with a variety of control parameters.

The AMS has two primary benefits for the user: monitoring and energy savings. Monitoring airflows to important pneumatic machinery gives plant operators insight into their production and machine health that would otherwise be invisible. These data streams can be integrated with existing plant controls and management systems for ongoing monitoring, alerts, observation, and trends. Additionally, reducing airflow rates and pressures during machine downtime or idle production times - such as during product changeout, between production shifts, or after hours, if airflows are not otherwise valved off - offers energy savings. The device can also be commissioned to drop pressures or completely turn off airflow with an electronic regulator and control valve, reducing air compressor loads and again, saving energy. In general, energy savings will increase with larger machines, higher pressures, more production downtime, and when machines have large leak loads or open blowing.

This project funded the installation of four AMS units at a food manufacturing facility in Santa Rosa, California. The intent was to gather in situ performance and user feedback. However, complications at the plant ended the field demonstration before energy savings features could be commissioned. The project team opted to calculate savings across a range of conditions, instead. This should set the stage for a deemed measure development. Energy savings for the AMS measure on a per-unit basis were calculated. These were used to calculate cost-effectiveness, greenhouse gas (GHG) impacts, and total system benefits (TSB). If necessary, a lab or field demonstration could be used to validate the product benefits before integration into the California energy efficiency (EE) programs portfolio.

Background

Compressed air is sometimes called the “fourth utility,” alongside natural gas, electricity, and water due to its widespread, distributed use in industrial and manufacturing facilities. Compressed air is often piped throughout industrial buildings for driving a broad spectrum of end uses including pneumatic hand tools, conveyors, automation, and large, custom machinery. It is so ubiquitous that 82 percent of industrial buildings have compressed air systems, accounting for about 10 percent of all industrial sector electrical energy use (Xenergy 2001) (Greenstone, et al. 2019) (Beneditti, et al.

2016). Based on the market size calculations for a recent Title 24[1] effort, total energy use for compressed air in California is about 9,800 gigawatt hours per year (Valmiki, et al. 2020).

However, the generation, distribution, and use of compressed air is often inefficient and requires large amounts of electrical energy. The benefits of using versatile, convenient, and safe pneumatic tools comes at a cost: they can use up to 10 times as much energy as electrically driven counterparts (U.S. Department of Energy 2016). Only about 10 to 20 percent of the input energy to a compressed air system is converted to useful work at the end-use (Saidur, Rahim and Hasanazzaman 2010). While there are ways to optimize the generation of compressed air through compressor selection, design, and controls, there are large sources of inefficiency and waste across plants that cannot be addressed at the air compressors. Common sources of inefficiency and waste in compressed air systems include leaks, artificial loads, and inappropriate end uses.

All three of these sources of inefficiency can occur within large end uses. Large pneumatic machines can contain many potential points of pressure drop, leaks, open blowing, diaphragm pumping, vacuum venturis, and other components that are suboptimal with respect to compressed air and energy usage. Furthermore, even appropriate and well-purposed components within pneumatic machines can use compressed air unnecessarily during production downtime or gaps. For instance, a packaging machine can consume high-cost compressed air for no purpose if it is left on during breaks or gaps between production shifts.

Leaks throughout distribution piping, connections, and end uses are one of the largest, most pervasive sources of waste in the compressed air world. Leaks typically account for 20 percent to 30 percent of air loads in most systems without proactive leak management programs (U.S. Department of Energy 2016), while the typical cost-effective target is to limit leaks to 5 percent to 10 percent of the total load (U.S. Department of Energy 2004) (CEA Technologies 2007) (Marshall 2018). The total energy wasted on compressed air leaks in California has been estimated to be 2,000 to 3,000 gigawatt-hours per year (Valmiki, et al. 2020). Despite near continuous, vocal advocacy for leak management best practices and their cost-effective benefits, regular remediation is uncommon and low priority for most industrial facilities (Xenergy 2001).

Leak management continues to be poorly implemented and difficult to support through incentives outside of strategic energy management programs. Measures to address leak loads are labor intensive, behavioral, difficult to verify, and tend to have relatively short effective useful lives. Compressed air leaks and their impacts are physically and operationally invisible, with little-to-no impact on production if the air compressors have capacity to overcome them. Therefore, there is a need for technological measures that can help move the needle on leak load management through more guaranteed, reliable, verifiable, user-friendly monitoring and controls. One recent publication stated that leak management is the single largest, most widespread compressed air savings opportunity in the typical industrial plant, and correct handling of compressed air energy requires the management of energy performance indices for the continuous evaluation process (Hernandez-Herrera, et al. 2020). The Compressed Air Gas Institute states, "the first step to reduce compressed

[1] Title 24, Part 6 is the Building Energy Efficiency Standards and Energy Code for California.

air energy costs is to measure and monitor your compressed air system's energy consumption, flow rates, and operating air pressure" (CAGI n.d.).

Manufacturers and the compressed air industry have taken note of this need and developed various whole-system monitoring products that measure and trend total plant usage at the air compressors. This evolution in compressed air system monitoring, control, and analytics has been driven by the development of cost-effective smart sensors, cloud manufacturing products, and convenient, versatile communication protocols such as OPC UA (Abela, Refalo and Francalanza 2019). These products are extremely valuable in characterizing overall plant health, total leak loads, system performance, and encouraging maintenance actions when systems trend towards inefficiency. Recent changes to Title 24, Part 6 require air compressor monitoring to take advantage of those benefits. However, there remains a market gap in end-use management, especially for high-flow end uses, such as large, custom machines. Monitoring and control products implemented at end uses would allow for targeted measures, load reduction, and management of compressed air waste in machines that cannot otherwise be remedied. End-use air monitoring and control measures could be an easily verifiable, reliable program offering that could reduce leak loads and avoidable air consumption with a large market potential.

Leaks within the confines of complicated, large pneumatic machines are particularly difficult to remedy. Locating, accessing, and repairing them is more troublesome than those machines at distribution piping or hand tool connections. They are often behind safety barriers and buried in tangles of interior components or cannot be addressed without costly pauses in production. Leaks within these machines may also be early indicators of component failures. Technologies that can reduce these losses and provide data on end-use air consumption would fill a glaring market need. This is especially true for retrofits of legacy machines that are not easily monitored, have outdated documentation, long histories of use, and are costly to integrate into plant control systems.

Emerging Technology: Air Management System

A major international manufacturer of pneumatic components has recently released a product that includes monitoring and controls of the compressed air supply for end-use locations. The product can stand alone, augment or replace existing FRL assemblies as a drop-in measure on any end use with flows up to 141 cubic feet per minute (CFM). FRLs are air treatment assemblies that are virtually ubiquitously installed upstream of end uses to ensure that the delivered air is clean, lubricated, and at the correct pressure. Note that these assemblies may also have just one or two of the three components, depending on end-use needs. The new product is modular and can be arranged from a variety of size ranges and optional components, including filters, lubricators, regulators, control valves, and an AMS that adds monitoring and controls capabilities. This thoughtful design allows manufacturing facilities to retrofit a multitude of existing end uses with an FRL that incorporates monitoring and energy saving features.

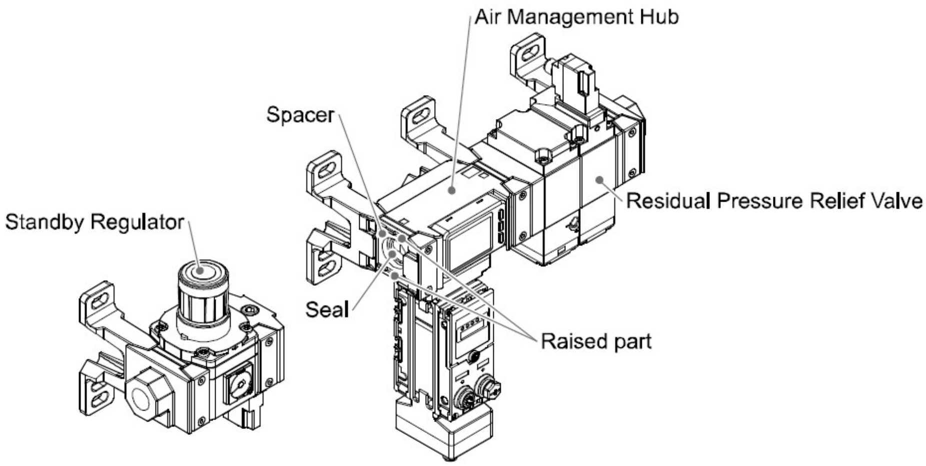


Figure 1: AMS components.

Each AMS requires 24 Volts DC (VDC) power - typically directly from the host machine - and can be selected for a “normally open” configuration, so that if power is ever lost, the device will supply constant air at the operating pressure without any interruption to production. The physical installation is relatively non-invasive and straightforward. The physical installation simply requires shutting air supply to the FRL location via an upstream valve which will always be present, matching the tubes or piping to the inlets and outlets of the AMS, and securing the components to whatever support the FRL was located. Any plant and their maintenance staff will have the tools, extra parts, and expertise to physically install the AMS without training. No permitting is necessary for FRLs or the replacement AMS.

Programming, commissioning, and controls integration of the AMS, however, does have a learning curve. Since it has controls, input/output signals, and commissioning that any typical, analog FRL does not, additional training and labor is involved above and beyond the standard baseline equipment. The manufacturer has knowledgeable representatives across California – and the country – that can assist the early adopters of this technology. Extensive documentation and manuals are readily available. Training and virtual support from the manufacturer is also available. Most plants will have an onsite controls engineer who is familiar with the ins and outs of such technology and can relatively easily learn how to use the product. Regardless, there is some learning and initial labor that is necessary to take full advantage of the product’s energy saving features.

The AMS can be programmed in a variety of ways and integrated into either a cloud-based monitoring suite or into existing plant controls, monitoring, and data collection. In either case, the AMS can give facility management visibility into the air consumption, pressure, and health of the downstream end uses. Each AMS is built with onboard flow, temperature, and pressure measurement that can be sent to the cloud or plant monitoring systems through a variety of communication protocols. The AMS networking architecture with optional satellite monitoring sensors is shown in Figure 2. Every hub AMS requires an ethernet connection and can accommodate up to 40 remote AMS units, each of which wirelessly transmits data to the hub.

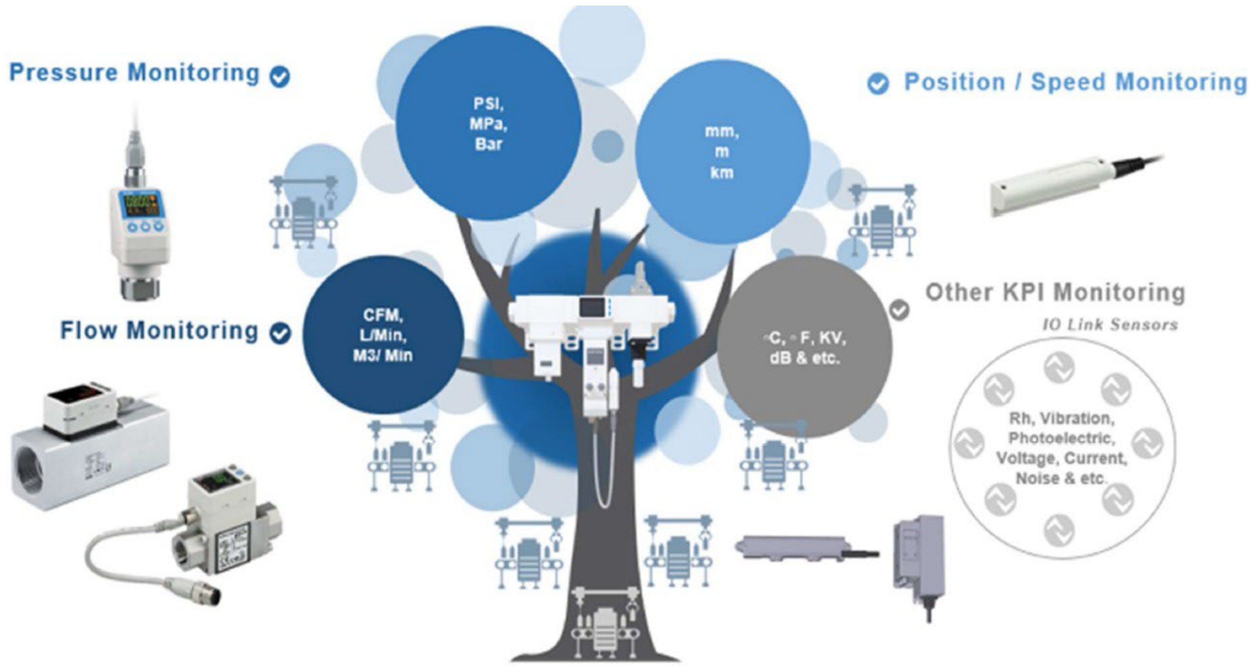


Figure 2: AMS networking tree and optional sensors.

An AMS can be programmed to reduce pressure to a specified lower value ("standby mode") or completely close the control valve and stop air flow ("isolation mode") in the absence of demand. The air demand signal input to the AMS can be as simple as a 24-VDC on/off switch within the end use, an external control signal from the plant's supervisory control and data acquisition system, or from other external inputs, such as a photoeye pointed at product throughput. In all these cases, this signal is meant as a proxy for compressed air load and serves as a control input to the AMS, telling it when compressed air is not needed.

Standby and isolation modes can be programmed with specified timed delays, starting when the air demand control signal is turned off. In other words, the plant operators can specify how long the AMS should wait after the absence of demand before going into one of the energy saving modes. Figure 3 shows the control sequence for standby and isolation modes with flow rate as in lieu of a proxy control signal, pressure drop response, timed delays, and pressure ramp up and ramp down.

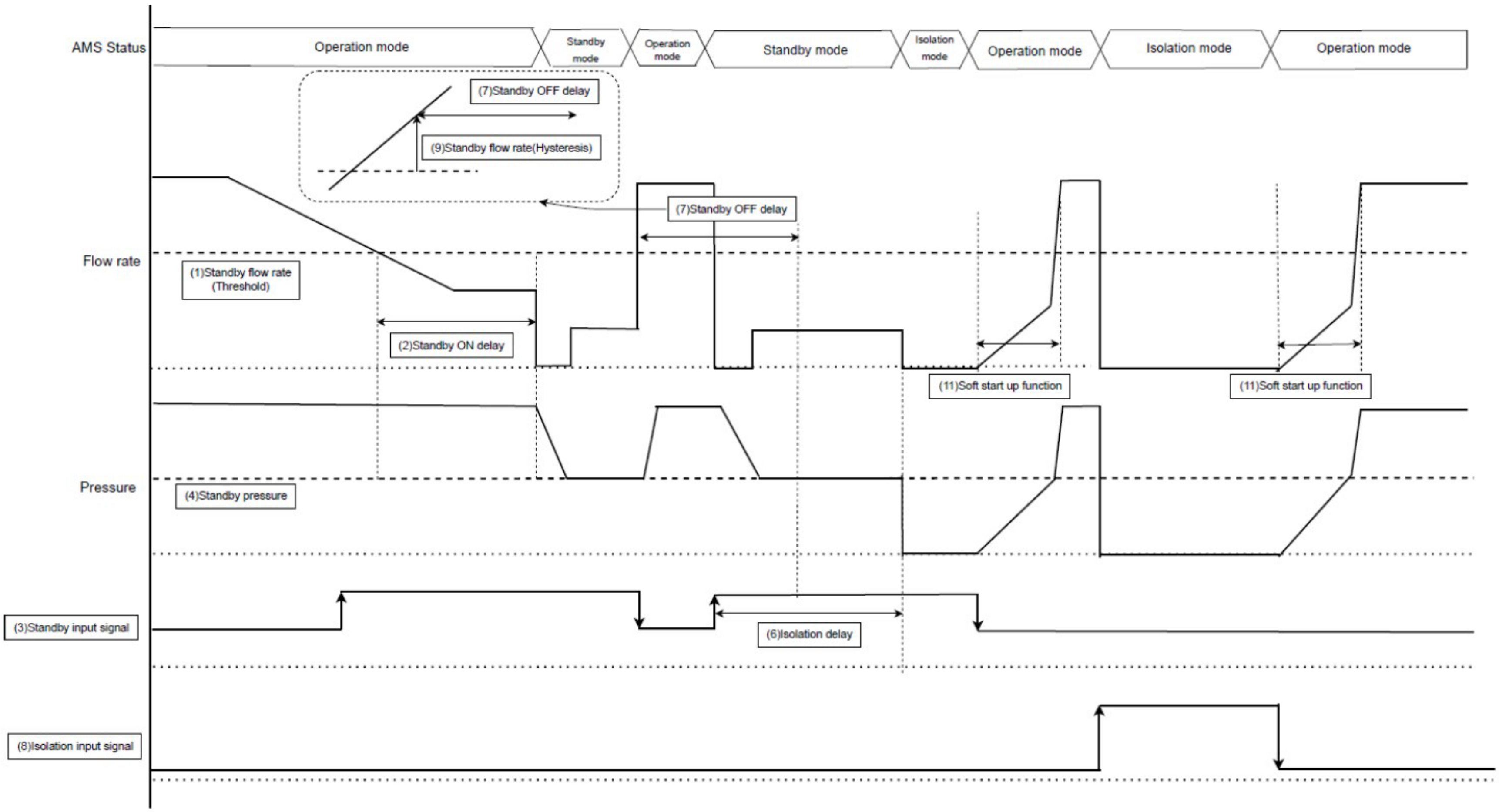


Figure 3: Standby and isolation mode control sequencing.

Standby and isolation modes will generate savings by reducing the load on the air compressors. Reduced pressure in standby mode will lower the flow through various orifices, artificial loads, and leaks throughout the end use, while isolation mode will completely turn off the air supply. Assuming aggregate effect is great enough across multiple AMS units, these modes will result in reduced speed in variable speed compressors, or reduced cycling in constant speed air compressors. While there are other factors that influence an air compressor's response to load variation (like storage volume and total system regulation), enough reduced load and a responsive air compressor can achieve reliable savings.

This is particularly true with variable speed rotary screw compressors, which are by far the most common type of trim air compressor in industrial facilities. Mandated code in Title 24 virtually ensures this is the case, and industry standard practice is to rely on variable speed rotary screw compressors for the variable load trim in most cases, excluding high-pressure and some other infrequent conditions. Thus, it is reasonable to assume that reduced airflow and pressure at the AMS end uses would typically result in savings at the air compressor.

The magnitude of energy and cost savings from any given AMS installation will depend on several factors:

- Runtime of the impacted, downstream end use(s).
- Percent production downtime during the operating times (e.g., lunch, production shift changes, and other periods of downtime or pauses between product throughput).
- Whether air compressors are left on between production shifts (e.g., overnight) and whether the end uses have any automatic shut-off valves already in place.
- Air compressor efficiency, controls, and specific power, such as kilowatts (kW) and CFM.
- Operating supply pressure and minimum standby pressure.
- Programmed AMS settings for the standby pressure and timed delays.
- End-use airflow, leak magnitude, and unproductive airflow magnitude.
- Utility rates.

The technology has been installed in a several plants internationally, including a case study demonstration at a bottling plant with 10 AMS retrofits on existing machines (Jensen, Eisel and Sanike 2023). This demonstration installed two AMS hub units and eight remote units on machines that operated between 94 and 109 pounds per square inch gauge (psig), with air consumption between 2 and 37 CFM. The AMS implementation at this site was able to achieve 26 percent energy savings, as shown in Table 2. The average installed cost and savings per AMS in this case study were $3,000 and 5,985 kWh per year, respectively.

Table 2: Bottling plant case study results (Jensen, Eisel and Sanike 2023).

Study Datapoint	Value
Number of AMS	10
Total Connected Load	157 CFM
Operating Hours	8,760
Standby Mode Time	38%
Isolation Mode Time	2%
Baseline Energy Consumption	230,570
Energy Savings	59,851 (26%)
Installed Cost	$30,000
Simple Payback	1.25 years

Objectives

The purpose of this project is to evaluate the savings and cost-effectiveness of AMS, and to develop recommendations for future projects, programs, and adoption. To this end, the study has the following objectives:

- Field installation of the AMS product at a packaged food production facility.
- Estimate savings dependence on driving conditions (airflow and idle runtime) through a calculation approach.
- Estimate or comment upon statewide potential.
- Document installed product costs and payback.
- Provide recommendations for product use, best applications, future installation, product improvement, and rebate or incentive program pathways.

Methodology and Approach

A packaged food production facility located in Santa Rosa, California served as the host site, with products that include macaroni and cheese, rice bowls, and burritos. The plant operates five days per week year-round on a two-shift schedule, from 6:00 a.m. to 11:00 p.m., and produces meals starting from raw input materials - e.g., tortillas and rice - to the final packaged, sealed boxed product ready for freezing and shipping. Compressed air loads follow roughly the same 6:00 a.m. to 11:00 p.m. schedule, with load troughs during breaks, between shifts, at nights, and on weekends.

However, the air compressors are always at least partly loaded and are never turned off to maintain pressure throughout the plant.

Compressed air is supplied by two air compressors at a common, outside location, as shown in Figure 4 and Figure 5. Both compressors are rotary screw models, each with its own cycling refrigeration air dryer, a common regulator, and single storage volume upstream of the plant distribution loop. The two compressors operate in a lead/lag configuration, although the lag compressor is primarily a backup. The single lead variable speed compressor installed in 2023 exclusively satisfies total plant air demand, while the second compressor operates as backup with only sporadic, as-needed operation.

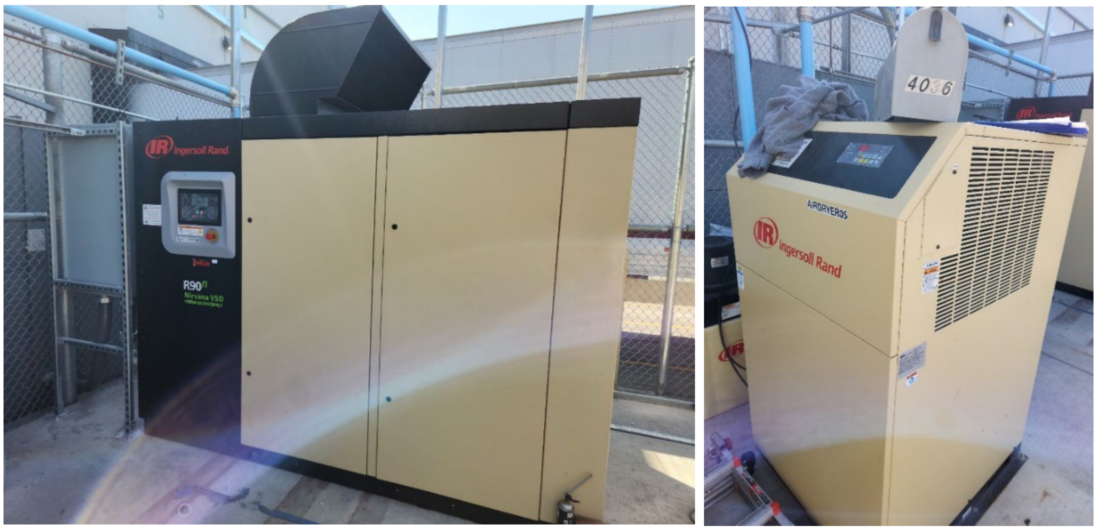


Figure 4: Lead air compressor (Ingersoll Rand R90n) and dryer.

Figure 5: Lag air compressor (Quincy QSi-500i) and dryer.

The team selected six locations for AMS installation in the plant during site walkthroughs and audits with host site staff and the manufacturer, based on feasibility, host site preference, and suitability for AMS features. These included five packaging lines and one conveyor oven, and each of these locations had an existing FRL that would be replaced by the AMS assembly, as shown in Figure 6.

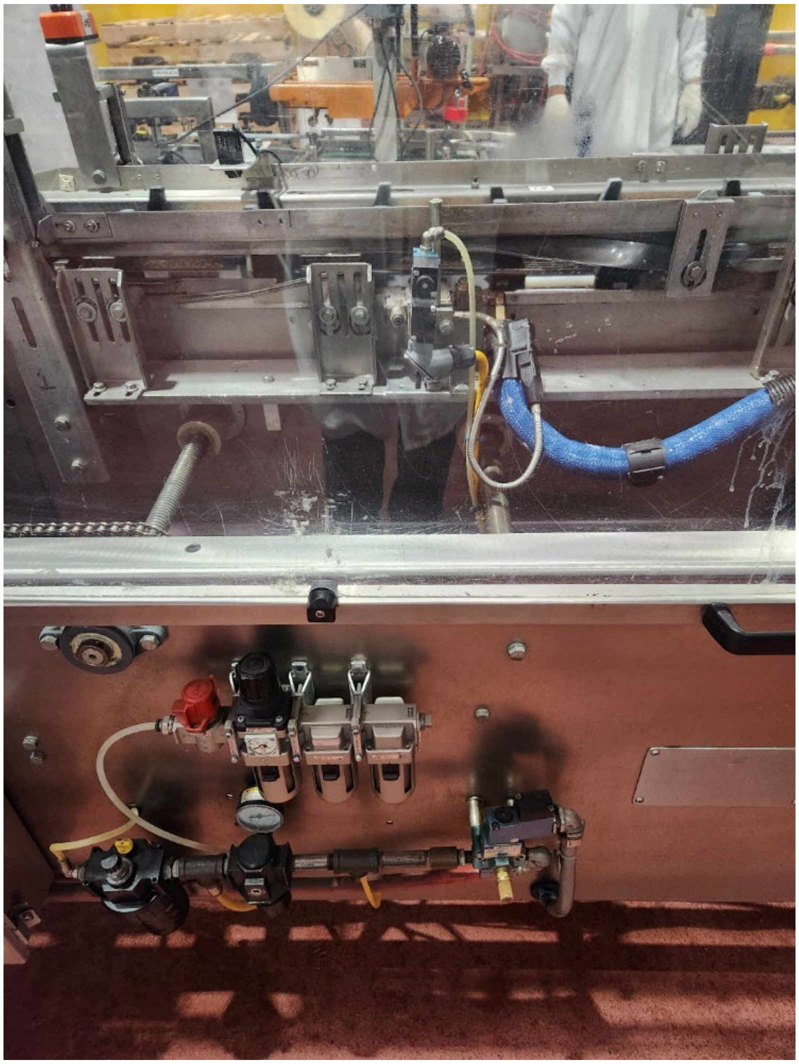


Figure 6: Typical packaging machine selected for AMS installation, with FRL and compressed air supply piping.

The measurement plan included measurement and monitoring of all necessary datapoints for calculating energy usage, savings, and normalization to typical annual conditions, as listed in Table 3. Flow and pressure at each AMS were originally included in the measurement plan but could not be gathered due to complications at the plant that ended the field work effort before the AMS energy savings features could be commissioned. Each data point in Table 3 was measured on one-minute intervals between January 9, 2024, and April 29, 2024.

Table 3: Monitored data points.

Measurement Point	Unit	Instrumentation
Total Plant Airflow	CFM	CDI Meter 5400-20C
Plant Supply Pressure	psig	CDI Meter 5400-20C
Air Compressor Power	kW	Dent ElitePro Power Meter

Figure 7 shows the installed airflow and pressure metering of the compressed air flow in the supply pipe to the plant and power metering at the air compressor electrical disconnect.

Figure 7: Air compressor supply airflow and pressure meter and power metering.

The team calculated savings for an individual AMS using the observed whole-plant compressed air performance, instantaneous spot measurements of per-machine idle airflow, and observed idle time. Electrical demand savings for each minute of the observed operation were calculated with the following formula, where the air compressor specific power is the measured efficiency in kW per 100 CFM and the dryer-specific power is the rated value of 0.7 kW per 100 CFM:

$$Savings\left[\frac{kWh}{yr}\right] = Operating\ Hours\ [hr] * Percent\ Idle\ Time * Idle\ Flow\ [CFM] * \left(Compressed\ Air\ Specific\ Power + Dryer\ Specific\ Power\ \left[\frac{kW}{100CFM}\right]\right) * 100$$

The observed idle time of the packaging lines was about 25 percent during production hours. This idle time accounted for staff breaks and stoppage time for tasks such as changeout of boxes, trays, and ingredient inputs. Spot measurements at the six packaging lines showed that the average idle airflow was about 5 CFM.

Findings

Installation and Measure Cost

The project team worked closely with the host site staff, manufacturer, service providers, and distributors to install the AMS units, as shown in Figure 8. The project team installed four AMS before the field work was cut short.

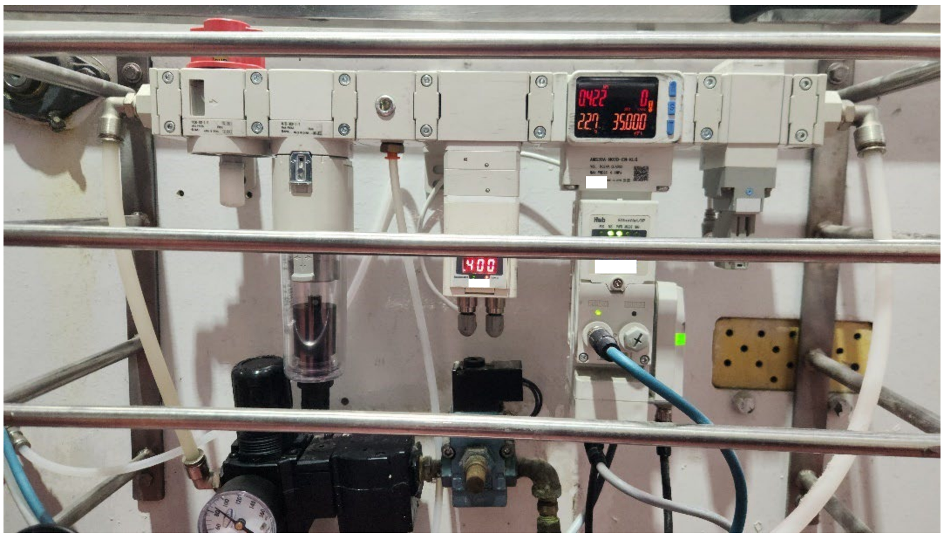


Figure 8: AMS installation.

The AMS hardware cost was $3,967 per unit, including all necessary accessories. The implementation also required the installation of two industrial-grade, shielded ethernet cable runs for connectivity at the two hub AMS end uses, as well as the use of knuckle booms to access the overhead, congested channels where the conduit was routed - an unexpected cost addition that would not usually be present in most cases. The AMS installation labor was provided at no cost by the host site, which would be typical of most industrial facilities who regularly employ in-house industrial controls engineers and staff capable of replacing FRL components. The team estimates that about four hours of labor is needed for the physical installation and controls integration per AMS. At a fully burdened labor rate of $150/hour, the total measure cost for hardware and installation labor is about $4,567.

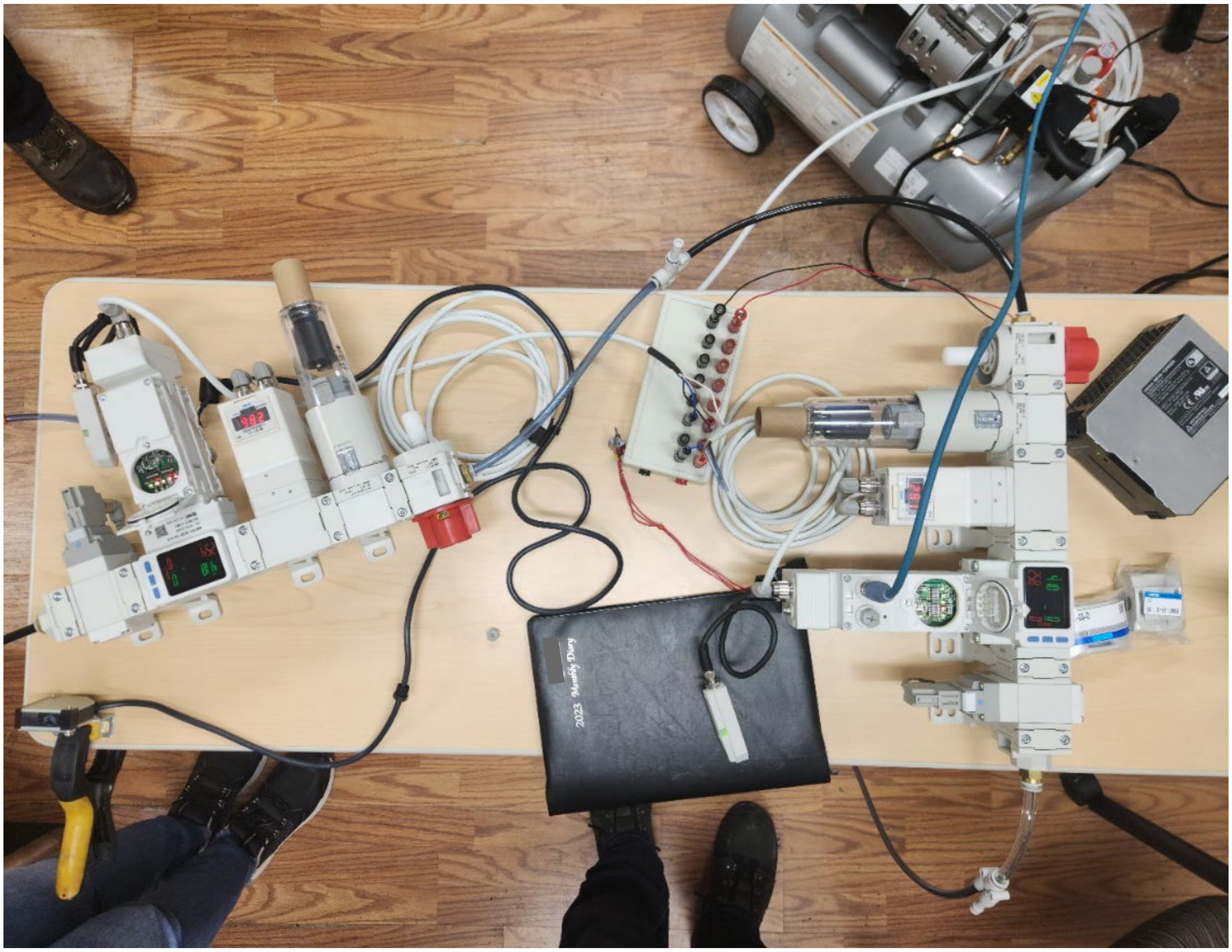


Figure 9: AMS demonstration at host site.

Air Compressor System Performance

The project team established the compressed air system load and efficiency by logging whole-plant baseline data over four months in early 2024; Figure 10 shows the measured load profile. The first monitored week was during an annual plant downtime, which afforded the opportunity to install air compressor metering without production disruption, and the regular production loads ramped back up on January 15, 2024. After-hours minimum loads demonstrated a significant leak load and airflow necessary to maintain system pressure during non-production times. Pressure to the plant was maintained at a consistent 100 psig.

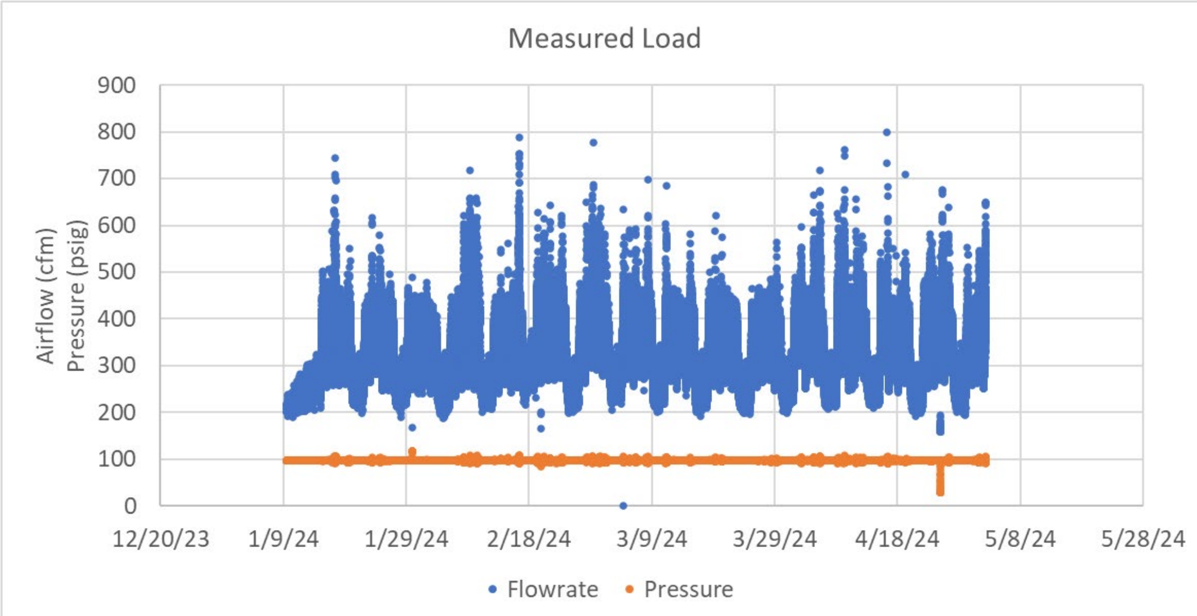


Figure 10: Measured total plant load profile.

With these measured loads and simultaneous power metering, the project team established total air compressor system efficiency (in specific power), as shown in Figure 11. The performance curve and specific power matched expectations for a variable speed rotary screw compressor operating at constant supply pressure and variable load. The minute-by-minute specific power for the main lead compressor supplied air at an average of 19 kW per 100 CFM.

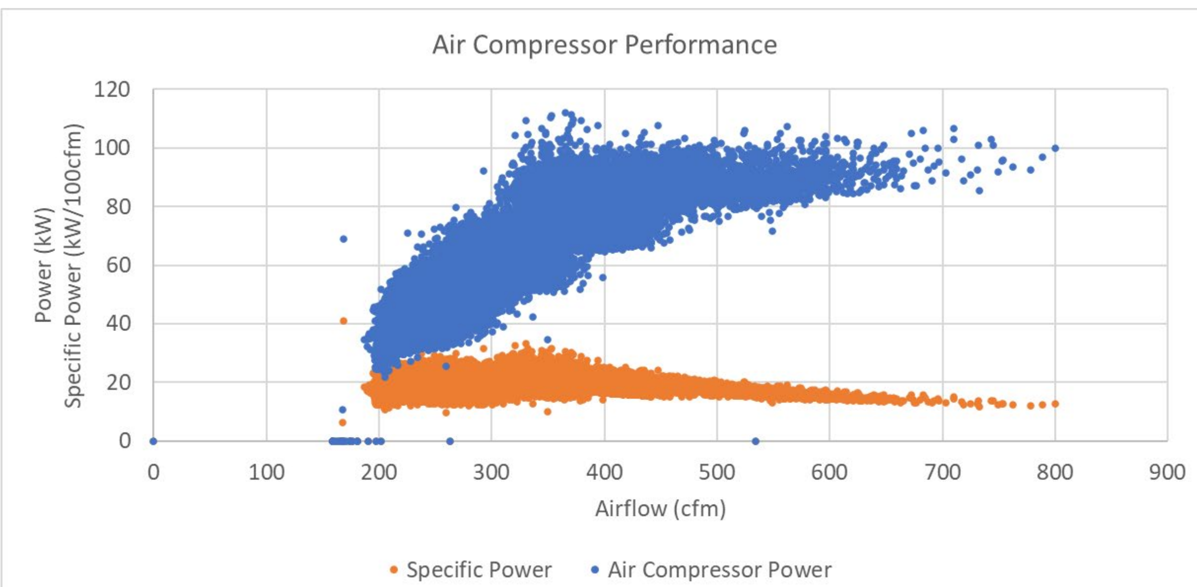


Figure 11: Measured air compressor performance.

Figure 12 shows the plant air load and compressed air efficiency collapsed to an averaged, representative typical weekly profile.

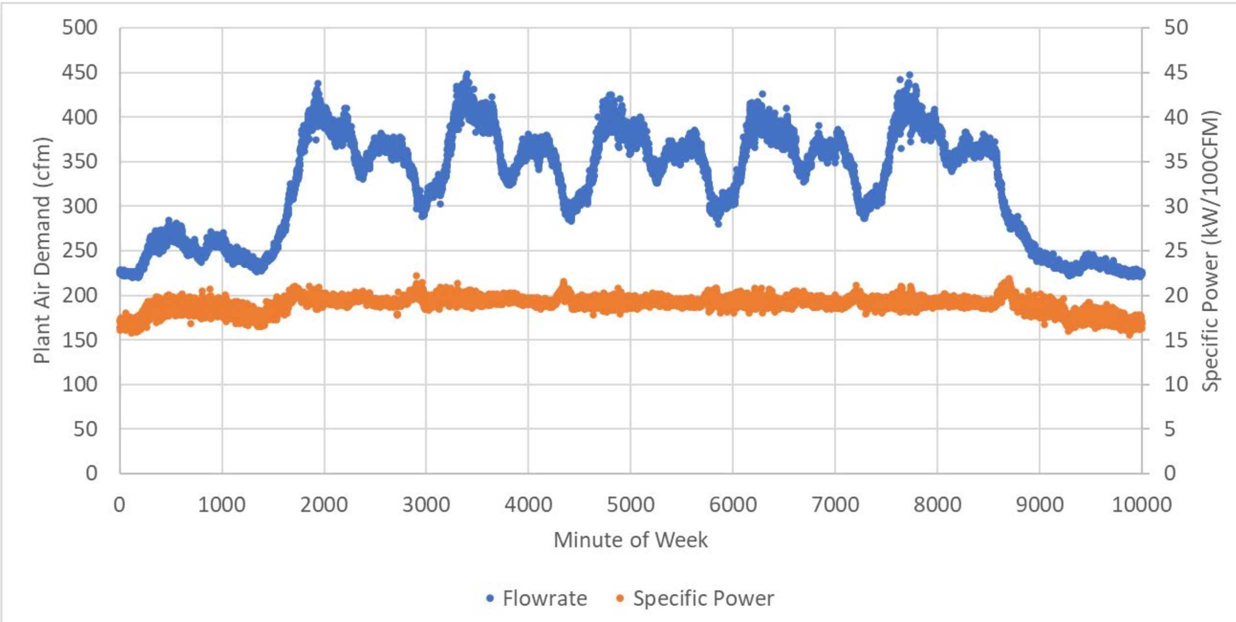


Figure 12: Average host site weekly load profile.

Host Site Energy Savings

The project team calculated energy savings on a per-unit basis for an individual AMS. The isolation mode of the AMS would eliminate airflow during idle machine times by opening and closing the supply control valve, depending on the photoeye signal monitoring product throughput. Spot measurements showed that the average idle airflow for the installed packaging lines was 5 CFM. The machines were idle about 25 percent of the time during production hours. This airflow reduction, combined with the measured compressed air-specific power, enables an easy savings calculation for each minute of the representative weekly load profile.

Table 4 lists the calculated savings per installed AMS. Customer energy cost savings are based on Pacific Gas and Electric's B-19 Time-of-Use rate schedule, which has a typical blended rate of $0.35 per kWh. GHG and TSB impacts are calculated on an hourly basis using established factors for the host site's climate zone (California Energy Commission 2022) (California Public Utilities Commission 2024).

Table 4: Savings per AMS.

Parameter	Value
Nonproductive Load Reduction (CFM)	5.0
Percent Idle Time	25%
Production Time (hours/year)	4,848
Annual Savings (kWh/yr)	1,223
Annual Energy Cost Savings ($/yr)	432
Per Unit Installed Cost ($)	4,567
Estimated Customer Payback Time (yr)	10.6
GHG Emissions Reduction (tons/yr)	0.1
TSB ($/yr)	128

Note that the savings and cost effectiveness for this application are entirely dependent upon the flowrates and operating times for the end-use machines selected at the host site. Since savings and cost effectiveness are so dependent upon these factors which will vary across applications, the team conducted a parametric analysis to these variables, as shown in the next section.

Parametric Energy Savings

To estimate benefits across a range of machine sizes and idle time, the project team calculated savings for a representative industrial load profile and varying assumed conditions. Title 24 has prototype compressed air load profiles, which were used as a basis for savings calculations typical to the industrial market (Valmiki, et al. 2020). These Title 24 load profiles have an operating time of 4,000 weekday hours per year - equivalent to two-shift, five-day industrial operations. Assuming that idle time is evenly distributed across these annual operating hours, savings can be calculated for a range of flowrates and idle time fractions. Table 5, Table 6, and Table 7 show the energy savings, customer energy cost payback, and GHG emissions reductions for the range of applicable conditions that the AMS may be used in the field. These impacts are not climate dependent, as compressed air energy usage is largely weather agnostic in most industrial facilities.

These results are shown for an assumed end-use machine size, based on a 20 percent leak and artificial load rate that would be eliminated during the isolation mode function of the AMS. Note that idle flowrate can be much higher in certain instances. Machines with open pipe and nozzle blowing can have idle flowrates far exceeding 20 percent of the working flow. These savings are also slightly conservative since some industrial facilities will also have weekend operation and may employ the standby function of the AMS controls which could increase savings slightly.

Table 5: Energy savings in kWh per year for varying flowrate and idle time.

	Machine Size ->	10	20	30	40	50	60	70	80	90	100	110	120	130	140
	Idle Flowrate ->	2	4	6	8	10	12	14	16	18	20	22	24	26	28
Idle Time (%)	5%	75	150	224	299	374	449	524	598	673	748	823	898	972	1,047
	10%	150	299	449	598	748	898	1,047	1,197	1,346	1,496	1,646	1,795	1,945	2,094
	15%	224	449	673	898	1,122	1,346	1,571	1,795	2,020	2,244	2,468	2,693	2,917	3,142
	20%	299	598	898	1,197	1,496	1,795	2,094	2,394	2,693	2,992	3,291	3,590	3,890	4,189
	25%	374	748	1,122	1,496	1,870	2,244	2,618	2,992	3,366	3,740	4,114	4,488	4,862	5,236
	30%	449	898	1,346	1,795	2,244	2,693	3,142	3,590	4,039	4,488	4,937	5,386	5,834	6,283
	35%	524	1,047	1,571	2,094	2,618	3,142	3,665	4,189	4,712	5,236	5,760	6,283	6,807	7,330
	40%	598	1,197	1,795	2,394	2,992	3,590	4,189	4,787	5,386	5,984	6,582	7,181	7,779	8,378
	45%	673	1,346	2,020	2,693	3,366	4,039	4,712	5,386	6,059	6,732	7,405	8,078	8,752	9,425
	50%	748	1,496	2,244	2,992	3,740	4,488	5,236	5,984	6,732	7,480	8,228	8,976	9,724	10,472

Table 6: Payback in years for varying flowrate and idle time.

	Machine Size ->	10	20	30	40	50	60	70	80	90	100	110	120	130	140
	Idle Flowrate ->	2	4	6	8	10	12	14	16	18	20	22	24	26	28
Idle Time (%)	5%	172.9	86.5	57.6	43.2	34.6	28.8	24.7	21.6	19.2	17.3	15.7	14.4	13.3	12.4
	10%	86.5	43.2	28.8	21.6	17.3	14.4	12.4	10.8	9.6	8.6	7.9	7.2	6.7	6.2
	15%	57.6	28.8	19.2	14.4	11.5	9.6	8.2	7.2	6.4	5.8	5.2	4.8	4.4	4.1
	20%	43.2	21.6	14.4	10.8	8.6	7.2	6.2	5.4	4.8	4.3	3.9	3.6	3.3	3.1
	25%	34.6	17.3	11.5	8.6	6.9	5.8	4.9	4.3	3.8	3.5	3.1	2.9	2.7	2.5
	30%	28.8	14.4	9.6	7.2	5.8	4.8	4.1	3.6	3.2	2.9	2.6	2.4	2.2	2.1
	35%	24.7	12.4	8.2	6.2	4.9	4.1	3.5	3.1	2.7	2.5	2.2	2.1	1.9	1.8
	40%	21.6	10.8	7.2	5.4	4.3	3.6	3.1	2.7	2.4	2.2	2.0	1.8	1.7	1.5
	45%	19.2	9.6	6.4	4.8	3.8	3.2	2.7	2.4	2.1	1.9	1.7	1.6	1.5	1.4
	50%	17.3	8.6	5.8	4.3	3.5	2.9	2.5	2.2	1.9	1.7	1.6	1.4	1.3	1.2

Table 7: GHG reduction in tons per year for varying flowrate and idle time.

	Machine Size ->	10	20	30	40	50	60	70	80	90	100	110	120	130	140
	Idle Flowrate ->	2	4	6	8	10	12	14	16	18	20	22	24	26	28
Idle Time (%)	5%	0.01	0.01	0.02	0.02	0.03	0.04	0.04	0.05	0.05	0.06	0.07	0.07	0.08	0.08
	10%	0.01	0.02	0.04	0.05	0.06	0.07	0.08	0.10	0.11	0.12	0.13	0.14	0.16	0.17
	15%	0.02	0.04	0.05	0.07	0.09	0.11	0.13	0.14	0.16	0.18	0.20	0.22	0.23	0.25
	20%	0.02	0.05	0.07	0.10	0.12	0.14	0.17	0.19	0.22	0.24	0.26	0.29	0.31	0.34
	25%	0.03	0.06	0.09	0.12	0.15	0.18	0.21	0.24	0.27	0.30	0.33	0.36	0.39	0.42
	30%	0.04	0.07	0.11	0.14	0.18	0.22	0.25	0.29	0.32	0.36	0.40	0.43	0.47	0.50
	35%	0.04	0.08	0.13	0.17	0.21	0.25	0.29	0.34	0.38	0.42	0.46	0.50	0.54	0.59
	40%	0.05	0.10	0.14	0.19	0.24	0.29	0.34	0.38	0.43	0.48	0.53	0.57	0.62	0.67
	45%	0.05	0.11	0.16	0.22	0.27	0.32	0.38	0.43	0.48	0.54	0.59	0.65	0.70	0.75
	50%	0.06	0.12	0.18	0.24	0.30	0.36	0.42	0.48	0.54	0.60	0.66	0.72	0.78	0.84

Conclusions and Recommendations

The AMS product presents a unique opportunity for addressing one of the most common and impactful sources of energy waste in industrial facilities. Compressed air leaks and wasteful uses, such as open-pipe blowing, continue to be a persistent source of inefficiency and wasted costs across all industrial sectors. While measures at the air compressors and distribution piping are effective, there has often been no easy way to address these sources of waste inside large pneumatic machinery, until now. The AMS is demonstrably easy to install, effective in its control algorithms with proper commissioning, and a dependable, self-contained plug-and-play measure that is well suited to rebate programs.

The team estimated savings across a range of expected site conditions on an individual, per-AMS basis, which can serve as a foundation for establishing a deemed measure for industrial applications. In some settings, the savings and payback can be dramatic. For instance, pneumatic machinery with open pipe blowing can have idle flow rates close to the active production flowrate. Machines with open pipe and nozzle blowing is an excellent target for AMS installs. A new workpaper effort should use these results to set boundaries of cost effectiveness and define the typical conditions or tiered impacts based on end-use machine size. If necessary, the AMS product could be further validated with laboratory testing or additional field demonstration in parallel with a workpaper to justify inclusion in energy efficiency program portfolios.

Workpaper development would likely need to identify a single set of representative idle flow and idle time per machine size. The project team suggests 25 percent idle time as an assumed, representative idle time but some confirmation through additional market surveying may be warranted. The effective useful life of the AMS would also need to be defined. The team suggests drawing on approved lifespan of controls measures since the electronics and mechanical valving system is equivalent in terms of longevity. The workpaper should also make note that there are various manufacturers of pneumatic end use monitoring systems and off-the-shelf valving but, thus far, only one offers the measure as a packaged, plug-and-play product with flow controls.

If included in rebate programs, the inspection process would also be relatively straightforward, as observation of the product’s standby and isolation functionality of the product can be conducted during a site visit or in exported data. Control parameters can be exported or captured from the AMS control portal to further validate measure implementation, if necessary. No permitting is necessary for the measure.

One observed barrier to implementation is the relative complexity in comparison to baseline FRL assemblies. Typical baseline FRLs have no controls or network needs, and are simple, analog devices that require little training and no controls engineering knowledge. In contrast, the AMS requires controls knowledge, a voltage supply, and commissioning - an increase in technical complexity that could be daunting to certain plant or maintenance staff. While most plants will have their own dedicated controls staff or service providers, this element would present new, added maintenance work and knowledge.

This concern could be ameliorated by highlighting both the benefits of energy savings and the operational maintenance impact of having visibility into plant metrics through the monitoring of end-use compressed air characteristics. Visibility into otherwise unknown plant operations could prove to be additional motivation for staff to take on the new complexity in their FRL needs. Furthermore, manufacturers of AMS products should continue to streamline and simplify the specification and programming process where possible, which would help the product gain market traction and reduce friction during early adoption.

To address the added complexity that AMS presents over incumbent, analog FRL products, there is comprehensive training and manual documentation for plant staff to refer to. After the initial learning curve for the first installation, subsequent units will be much easier. Distributors and manufacturer representatives are also widely available to provide support for both the physical and controls installation process. Incentive and rebate programs such as the Industrial Incentive Solutions in Southern California Edison territory can market the new measure and provide materials and information to both gain market traction and ease the learning curve for early adopters. Potential workpaper limits around eligible conditions can also ensure that customers realize the energy efficiency benefits of the product, thereby avoiding the lower-value applications that could potentially slow the adoption curve. All this combined suggests that the AMS is a rare and valuable opportunity for a new, deemed energy efficiency measure broadly applicable across the industrial sector.

References

Abela, Kyle, Paul Refalo, and Emmanuel Francalanza. 2019. "Design and Implementation of an Energy Monitoring Cyber Physical System in Pneumatic Automation." *CIRP Conference on Intelligent Computation in Manufacturing Engineering.* Gulf of Naples, Italy.

Beneditti, Miriam, Ilaria Bertini, Francesca Bonfa, Silvia Ferrari, Vito Introna, Domenico Santino, and Stefano Ubertini. 2016. "Assessing and Improving Compressed Air Systems' Energy Efficiency in Production and Use." *ICAE.* Beijing, China.

CAGI. n.d. *10 Steps to Savings.* https://www.cagi.org/working with compressed air/benefits/10-steps-to-savings.aspx.

California Energy Commission. 2022. *2025 energy Code Date and Hourly Factors.* https://www.energy.ca.gov/files/2025-energy-code-date-and-hourly-factors.

California Public Utilities Commission. 2024. *DER Cost-Effectiveness.* https://www.cpuc.ca.gov/dercosteffectiveness.

CEA Technologies. 2007. "Compressed Air Energy Efficiency Reference Guide."

Greenstone, Michael, Christopher Knittel, Catherine Wolfram, Andrew Campbell, Karen Notsund, and Kathy Nagel. 2019. *Unlocking Industrial Energy Efficiency Through Optimized Energy Management Systems.* California Energy Commission.

Hernandez-Herrera, Hernan, Jorge Silva-Ortega, Vicente Diaz, Zaid Sanchez, Gilberto Garcia, Sandra Exorcia, and Habid Zarate. 2020. *Energy Savings Measures in Compressed Air Systems.* International Journal of Energy Economics and Policy.

Jensen, Jon, Nathan Eisel, and Sahith Sanike. 2023. *Smart and Sustainable Monitoring Solutions for Pneumatically-Driven Machines.* SMC Corporation of America.

Marshall, Ron. 2018. *Money in your pocket: Fix your compressed air system leaks.* Plant Services.

Saidur, R., N.A. Rahim, and M. Hasanazzaman. 2010. "Review on Compressed-Air Energy Use and Energy Savings." *Renewable and Sustainable Energy Reviews* 1135-1153.

U.S. Department of Energy. 2004. *Energy Tips - Compressed Air Tip Sheet #3.* Industrial Technologies Program.

U.S. Department of Energy. 2016. *Improving Compressed Air System Performance: A Sourcebook for Industry.* Office of Energy Efficiency and Renewable Energy.

Valmiki, M M, Joseph Ling, Keith Valenzuela, Regina Caluya, and Kiri Coakley. 2020. *Pipe Sizing, Monitoring, and Leak Testing for Compressed Air Systems.* California Energy Codes & Standards Enhancement Program.

Xenergy. 2001. *Assessment of the Market for Compressed Air Efficiency Services.* US Department of Energy.

Appendix A: Host Site Air Compressor Data Sheet

Ingersoll Rand

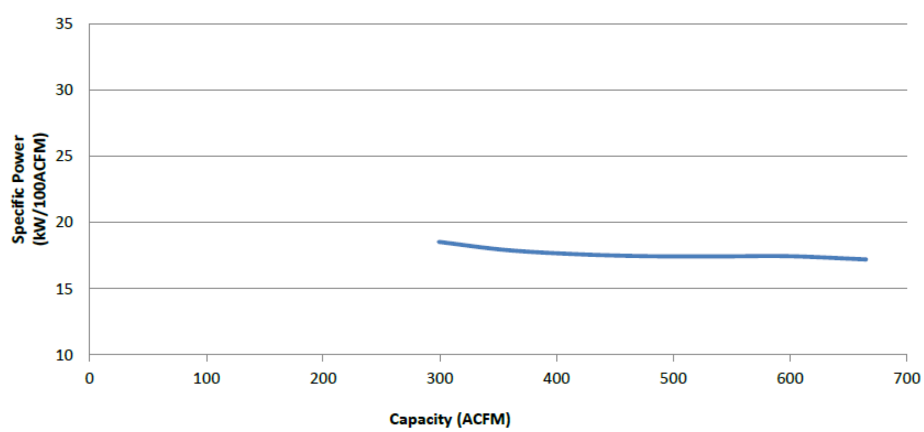
COMPRESSOR DATA SHEET

In Accordance with Federal Uniform Test Method for Certain Lubricated Air Compressors

Rotary Compressor: Variable Frequency Drive

MODEL DATA - FOR COMPRESSED AIR			
1	Manufacturer: **Ingersoll Rand**		
2	Model Number **R90N-A145**	Date:	**8/18/2020**
	[X] Air-cooled [ ] Water-cooled	Type:	**Screw**
		# of Stages:	**1**
3*	Full Load Operating Pressure [b]	**100**	psig[b]
4	Drive Motor Nominal Rating	**125**	hp
5	Drive Motor Nominal Efficiency	**95.4**	percent
6	Fan Motor Nominal Rating (if applicable)	**5.4**	hp
7	Fan Motor Nominal Efficiency	**88.6**	percent
8*	Input Power (kW)	Capacity (acfm) [a,d]	Specific Power (kW/100 acfm)[d]
	114.4	**665.0**	**17.20**
	104.3	**597.7**	**17.45**
	93.8	**538.2**	**17.43**
	83.4	**478.0**	**17.45**
	73.5	**417.7**	**17.60**
	63.9	**356.7**	**17.91**
	55.4	**299.0**	**18.53**
9*	Total Package Input Power at Zero Flow[c, d]	**0.0**	kW
10	Isentropic Efficiency	**74.8**	percent

11



Note: Graph is only a visual representation of the data in section 8

Note: Y-axis scale 10 to 35, +5kW/100acfm increments if necessary above 35

X-Axis Scale, 0 to 25% over maximum capacity

* For models that are tested in the CAGI Performance Verification Program, these are the items verified by the third party program administrator