NATIONAL RENEWABLE ENERGY LABORATORY

Chapter X: Compressed Air Evaluation Protocol

The Uniform Methods Project: Methods for Determining Energy-Efficiency Savings for Specific Measures

Nathanael Benton, Nexant, Inc.
Subcontract Report: NREL/SR-&A30-53827, XXXX 2013

Chapter X – Compressed Air Evaluation Protocol

Nate Benton, Nexant, Inc.

Acknowledgements

The chapter author wishes to thank and acknowledge Jeff Bartels and Patrick Burns of Nexant for their thoughtful contributions.

Acronyms

ACFM	Actual cubic feet per minute
CAGI	Compressed Air and Gas Institute
CFM	Cubic feet per minute
ECM	Electronically commutated motor
psi	Pounds per square inch
psia	Pounds per square inch absolute
psig	Pounds per square inch gauge
RMS	Root mean square
SCFM	Standard cubic feet per minute
VSD	Variable-speed drive

Table of Contents

Page

List of Figures and

List of Tables

1 Measure Description

~~Industry widely uses compressed~~Compressed-air systems are used widely throughout industry for ~~a great~~ many operations, including~~:~~ pneumatic tools, packaging and automation equipment, conveyors, and other industrial process operations. Compressed~~-~~-air systems are defined as a group of subsystems~~,~~ composed of~~:~~ air compressors, air treatment equipment, controls, piping, pneumatic tools, pneumatically powered machinery, and process applications using compressed air. ~~Compressed~~A compressed-air ~~systems serve~~system has three primary functional subsystems: supply, ~~transmission~~distribution, and demand.

~~The~~ Air compressors are the primary energy consumers in a compressed-air system and are the primary focus of this protocol~~,~~[1] ~~air compressors primarily consume energy in compressed air systems. The protocol address the five following.~~[2] The two compressed~~-~~-air energy~~-~~-efficiency measures specifically addressed in this protocol are:

- High-efficiency/variable speed drive (VSD ~~compressors~~) compressor replacing ~~constant-speed compressors;~~modulating compressor
- ~~Compressor~~Compressed-air leak survey and repairs.
  - The general approach outlined for high-efficiency/VSD compressor ("VSD compressor") replacing modulating compressor can be applied, with some modifications, to other compressed-air energy conservation measures (ECMs), including compressor control system upgrades ~~and~~, optimization sequencing in ~~multi-compressor~~ multicompressor plants~~;~~

~~Optimization~~, and optimization of system air pressure set ~~points; and~~point.

- ~~Compressed air leak survey and repairs.~~

1.1 High-Efficiency/Variable-Speed Drive Compressor Replacing ~~a~~ Modulating Compressor

This measure ~~relates~~pertains to the installation of a rotary screw compressor with a ~~variable-speed drive (VSD) or variable-displacement capacity control.~~VSD. Most incentive programs and technical reference manuals use a baseline system definition of~~:~~ a standard modulating compressor with ~~a blow-down~~blowdown valve. ~~Energy~~The energy-efficient ~~compressors are~~ compressor is typically defined as~~:~~ an oil-flooded, rotary-screw ~~compressors~~compressor with variable-speed control.

~~[1] As discussed in *Considering Resource Constraints* in this UMP report's Introduction, small utilities (as defined under Small Business Administration regulations) may face additional constraints in undertaking this protocol. Therefore, alternative methodologies should be considered for such utilities.~~

[2] As discussed in "Considering Resource Constraints" in the introduction of this report, small utilities (as defined under the Small Business Administration regulations) may face additional constraints in undertaking this protocol. Therefore, alternative methodologies should be considered for such utilities.

http://www.sba.gov/category/navigation-structure/contracting/contracting-officials/small-business-size-standards

This measure is frequently ~~replaces~~offered for the replacement of an existing unit at the end of its useful life or ~~is installed in~~for the installation of a new system in a new building (i.e., time of sale).

~~Air~~Several control methods are available for air compressors ~~use several~~, and control methods~~, which~~ greatly affect ~~a compressor's~~the overall operating efficiency~~. Accurately estimating~~ of a compressor. In order to accurately estimate energy savings ~~requires understanding~~, it is important to know the baseline method of control ~~method~~. A brief description ~~follow~~ of each common control method is provided below.

1.1.1 Inlet Valve Modulation/Inlet Throttling

Inlet valve modulation throttles off ~~a compressor's ~~the air inlet to a compressor as discharge pressure rises above the set point pressure. ~~Modulating~~The part-load performance of modulating compressors ~~exhibit~~is relatively poor~~ part-load performance.~~. Some modulation-controlled machines may be adjusted to fully unload ~~or "blow down" ~~if capacity reduces to a certain level~~ (~~, such as 40~~%).~~%. This reduces energy consumption~~,~~ compared to modulation-only compressors but requires the use of air storage receivers to meet demand when in the fully unloaded state.

1.1.2 Load/No-Load (Dual) Control

Load/no-load or dual controls, also known as constant-speed controls, require storage receiver volume and operate a compressor at full capacity until the ~~line~~unload pressure ~~setpoint~~(cutout) set point is reached~~ at which time the ~~. The compressor ~~will cut-out. Variable Displacement Control~~then unloads and blows down the oil separator and operates at minimum power while producing no air.

1.1.3 Variable-Displacement Control

Variable-displacement controls change compressor capacity by opening ports in the compressor that limit the amount of the cylinder or air-end that is used for compression. This ~~often occurs~~can be implemented in either discrete steps (e.g~~.,~~., 50%, 75%, and 100~~%). This results in ~~%) or by continuously varying capacity. Compressor-specific power is typically good ~~efficiencies ~~within the variable displacement range, but these compressors ~~with variable-displacement controls~~ typically have a limited turndown range. At minimum turndown, the compressor commonly uses inlet modulation to further reduce flow, resulting in poor specific power (kW/CFM).

~~1.1.3~~1.1.4 Variable-Speed Control

VSD ~~(aka~~or variable-frequency drive~~)~~ compressor controls use an integrated variable frequency ~~AC~~alternating current or switched-reluctance ~~DC~~direct current drive to control the ~~frequency of the ~~electrical signal ~~sent ~~to the motor~~,~~ and, ~~hence~~in turn, vary the speed of the motor and compressor. Compressors equipped with VSD controls continuously adjust the drive motor ~~speeds~~speed to match variable demand requirements. ~~Variable speed ~~VSD compressors typically have an excellent turndown range~~.~~ and efficiently produce air over the entire range of operating speeds. Below the minimum turndown speed, the compressor typically cycles between off and minimum-load states. This method of control is typically the high-efficiency case and not the base case.

~~1.1 Compressor Control System Upgrades and Optimization Sequencing in Multi-Compressor Plants~~

~~Utility incentive and rebate programs offer two other common compressed air energy-saving measures (usually on a custom track rather than a prescriptive track): compressor control system upgrades; and optimization sequencing for plants with multiple compressors. These measures are typically implemented in concert with one another.~~

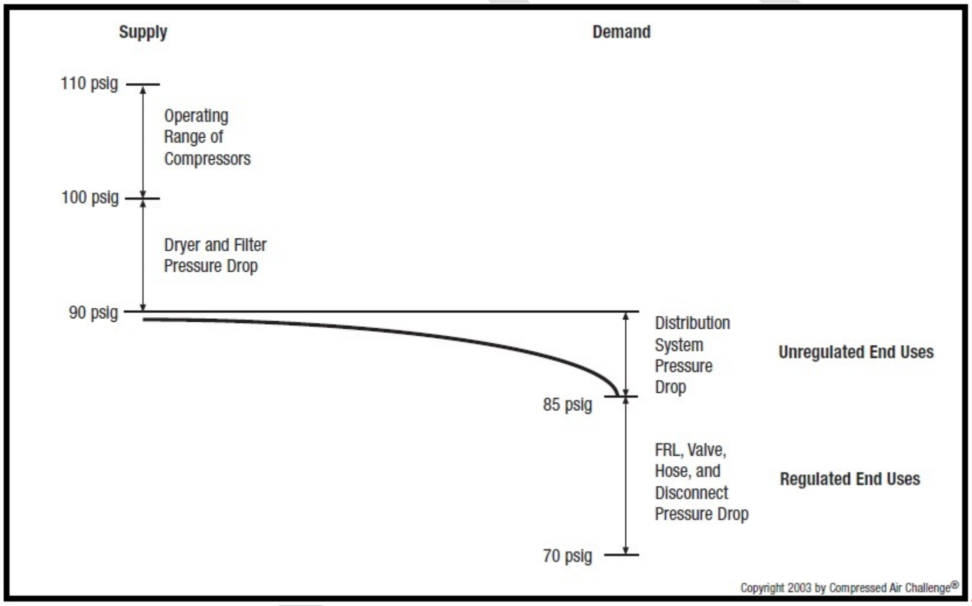
~~Systems with multiple compressors generally use more sophisticated controls to orchestrate compressor operations and air delivery to systems. An effective automatic system-control strategy seeks to match system demand with compressors operated at or near their maximum efficiency levels.~~

Significant energy savings can be achieved by upgrading to a centralized control systems. A common upgrade involves the conversion of system controls from local/network controls to central system master controls.

1.3 Optimization of a System Air Pressure Set point

One of the most common compressed-air energy-conservation measures (ECMs) reduces system operating pressures to reduce compressor energy consumption. Compressed-air systems commonly operate using a perceived pressure requirement, with a safety factor built in to account for transmission losses. Line pressure often is elevated to account for variability in demand.

Pressure at the compressor's discharge can be reduced by minimizing pressure losses across piping and air-treatment equipment in the distribution system. To minimize losses, a pressure profile must be developed, identifying pressure drops at individual components within a system, typically through using a calibrated pressure gauge or differential pressure gauge. Figure 1 shows a pressure profile in a system with excessive pressure drop.



1.2 Source: U.S. Department of Energy, Energy Efficiency and Renewable Energy Department, Compressed Air Challenge (November 2003). Compressed-Air Leak Survey and Repairs

"Improving Compressed Air System Performance: A Sourcebook for Industry." Page 21. http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/compressed_air_sourcebook.pdf

Figure 1: Pressure Profile at a Single Point in Time

1.4 Compressed Air Leak Survey and Repairs

Leaks significantly wasteare a significant cause of wasted energy in a compressed- air system, and can develop in many parts of a compressed air system, but the. The most common problem areas occur at:are couplings; hoses; tubes; fittings; pipe joints; quick disconnects; filters, regulators, and lubricators; condensate traps; valves; flanges; packings; thread sealants; and other point-of-use devices.

Leakage rates are a function of the supply pressure, typically quantified in cubic feet per minute (CFM)SCFM, and proportional to the square of the orifice diameter (hole or crack size), as shown in Table 1.).

Table 1: Leakage Rates (CFM) for Different Supply Pressures and Approximately Equivalent Orifice Sizes[a]

Pressure (psig)	Orifice Diameter (inches)					
	1/64	1/32	1/16	1/8	1/4	3/8
70	0.3	1.2	4.7	18.6	74.4	167.8
80	0.3	1.3	5.2	20.8	83.1	187.2
90	0.4	1.5	5.7	23.1	92	206.6
100	0.40	1.6	6.3	25.2	100.9	227
125	0.5	1.9	7.7	30.7	122.2	275.5

Note: For well-rounded orifices, values should be multiplied by 0.97; they should be multiplies by 0.61 for sharp orifices.
[a]Source: U.S. Department of Energy Compressed Air Tip Sheet #3. "Minimize Compressed Air Leaks" – Compressed Air Challenge – Air Best Practices.Com. http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/compressed_air3.pdf

Compressed air leaks can be detected usingThere are three common methods of compressed-air leak detection: auditory and sensatory observations; usingobservation, soapy water; test, and ultrasonic leak detection (the. The industry standard and best practice). Ultrasonic is ultrasonic leak detection. This relies on the ability of specialized directional microphones and amplifiers to detect high-frequency noise generated by the turbulent flow of compressed air escaping a compressed--air system through an orifice or crack. The high-frequency sound produced by a compressed--air leak occursis both directionallydirectional and localized to the source.

Best practices use an ultrasonic leak detector capable of estimating the leakage volume (in CFM), based on a recorded decibel level. Leak volumes and flow can be approximated from decibel readings using conversion tables available from equipment manufacturers. 5 in Section 3.2 provides an sample conversion table for a UE Systems Ultraprobe Model 3000.

2 Application Conditions of Protocol

2.1 High-Efficiency/~~VSD~~ Variable-Speed Drive Compressor Replacement Measures

~~Rebate and incentive~~Demand-side management programs typically offer a prescriptive compressor replacement measure. Many~~ incentive~~ programs and technical reference manuals assume the baseline compressor system to be a modulating or constant-speed compressor~~ as a baseline compressor system.~~. New energy-efficient compressors ~~generally~~ are assumed to ~~use~~be VSD ~~controls~~controlled.

~~Air~~ Incentives for air compressor ~~replacement rebates or incentives~~ replacements are typically ~~make payments~~paid on a dollar-per-compressor-horsepower basis or ~~on~~ a fixed percentage of project ~~costs~~cost. Common eligibility requirements for compressor replacement measures include~~ the following~~:

- ~~Air compressors do not qualify is purchased or installed for back-up or redundant systems.~~
- The air compressor must be a primary system component and not a backup system component.
- Replaced equipment must be removed~~,~~ or ~~customers~~the customer must attest that the baseline system, if remained connected, will be used only for emergency ~~back-up~~backup purposes and will rarely (if ever) operate.
- Only one ~~VFD~~VSD compressor per system ~~qualify~~is eligible for ~~an~~ incentive.

This measure is commonly offered for retrofit (or early replacement) projects and new construction ~~(~~or replace on burnout/time-of-sale~~)~~ projects. For a new construction project or if ~~a~~the baseline unit has failed or is near the end of its useful life, ~~units must meet~~ the baseline efficiency ~~standards~~standard it must meet is generally ~~defined~~developed by the local ~~energy codes, federal manufacturing standards, ASHRAE 90.1, or International Energy Conservation Code~~jurisdiction or utility.

2.2 Compressed~~ air~~-Air Leak Surveys and Repairs

~~A~~Compressed-air leak surveys are typically performed by a program-approved third~~-~~ party or a trade ally~~ typically performs compressed air leak surveys.~~. Programs ~~commonly~~typically establish specific guidelines for conducting ~~surveys~~the survey and ~~presenting report~~reporting the findings.

Energy savings from compressed~~-~~ air system repairs are determined by multiplying the estimated reduction in compressed air loss in ~~standard cubic feet per minute (~~SCFM~~)~~ by the~~ rated~~ power input per CFM (also known as efficacy) of the air compressor serving the system for the range of loading experienced by the system.

Incentives are typically paid as the least of:

- A fixed dollar amount~~,~~ per rated compressor horsepower~~.~~

- Full reimbursement for the cost of the leak survey~~.~~
- A program-defined maximum, not-to-exceed dollar amount.

3 Savings Calculations

Annual energy savings resulting from installation of a high-efficiency air compressor, implementation of control upgrades or optimization sequencing, or optimization of a system air pressure set point can be determined by subtracting the post-retrofit case annual energy consumption from the base case system's annual energy consumption.

The calculation of compressed air system energy consumption can be considered the product of the following variables:

- Compressed air demand (CFM)

3.1 Package inputSavings Calculations for Installing a High-Efficiency Air Compressor

3.1.1 Compressor Power at Full Load

Energy use reduction for all compressor projects can be calculated by the difference between the energy consumed in the baseline operation minus the energy consumed in the post-retrofit operation. Generally, information is required for compressor capacity in both the baseline and post-retrofit scenarios. Appropriate adjustments are made to ensure the flow profile is equivalent between pre- and post-retrofit conditions unless demand improvements have been made that result in a change in the flow profile.

Compressor power at givenfull load(s) (kW/CFM) can be calculated as follows:

- Operating hours at given load(s)

The algorithms used to calculate package input power follow.

Equation 1: Package Input Power (kW/CFM) for a Constant Speed Compressor

$$kWFull\ Load\ kW_{rated} = \frac{(Compressor\ hp)\ x \times LF_{rated} \times (0.746\ kW/hp)\ x\ (\%\ Power}{(\eta_{motor})\ x\ (CFM\ Demand)} \quad (1)$$

Equation 2: Package Input Power (kW/CFM) for a VSD Compressor

$$kWFull\ Load\ kW_{rated} = \frac{(Compressor\ hp)\ x \times LF_{rated} \times (0.746\ kW/hp)\ x\ (\%\ Power)}{(\eta_{motor})\ x) \times (\eta_{VSD})\ x\ (CFM\ Demand)} \quad (2)$$

where:

Compressor hp	= compressor horsepower, nominal rating of the prime mover (motor)
0.746	= kW to horsepower to kW conversion factor
η_{motor}	= motor efficiency (%)
η_{VSD}	= variable-speed drive efficiency (%)
LF_{rated}	= load factor of compressor at full load (typically 1.0 to 1.2)

VSDs have losses, just like other electronic devices that transform voltage. VSD efficiency (%)decreases with decreasing motor load. The decline in efficiency is more pronounced with drives of smaller horsepower ratings. VSD efficiencies typically range from 94% to 97% depending on the load and compressor horsepower (DOE 2012).

Alternatively, full load power may be available from manufacturers or Compressed Air and Gas Institute (CAGI) performance sheet data. Measuring full- and part-load power is even more accurate for a specific site.

Air compressor full load performance values provided on CAGI data sheets are reported at standard atmospheric conditions (14.7 psia at sea level). Typically, air compressor operating conditions will differ from these standard values, so these values must be corrected to actual operating conditions. The full-load kW is influenced by site elevation and the compressor operating pressure.

The following expressions are used to correct the compressor full-load performance based on site-specific conditions.

$$kW_{adjusted} = \frac{\text{Full Load } kW_{rated} \times ((P_{discharge} + P_{alt})/P_{alt})^{((0.395/1.395)-1)}}{((P_{rated} + 14.7)/14.7)^{((0.395/1.395)-1)}} \qquad (3)$$

where:

Full Load kW_{rated}	= full-load kW of air compressor at full load capacity and pressure (per CAGI data sheet or manufacturer specifications)
$P_{discharge}$	= actual system discharge pressure (psig)
P_{alt}	= atmospheric pressure based on site elevation above sea level (psia)
P_{rated}	= pressure at rated flow (psig) per CAGI data sheet or manufacturer specified design inlet pressure
14.7	= standard atmospheric conditions (psia) at sea level
((0.395/1.395) -1)	= based on the ratio of specific heat for air at standard atmospheric conditions and isentropic compression with constant specific heats

A rule of thumb for systems in the 80 to 140 psig range is: for every 2 psi increase in discharge pressure, energy consumption will increase (decrease) by approximately 1% at full output flow. This rule of thumb closely approximates Equation 3 within this range. Outside this range, Equation 3 is preferred. Equation 4 demonstrates how the "rule-of-thumb" adjustment is calculated:

$$kW_{adjusted} = \text{Full Load } kW_{rated} \times [1 - (((P_{rated} - P_{discharge})/2) \times 0.01)] \qquad (4)$$

3.1.2 Compressor Power at Part Load

The rated full-load power of a compressor represents the energy use of the system when operating at full load. At part-load conditions, compressor power is generally lower with common control types. To determine power at part load, the part-load fraction, calculated as the supplied CFM divided by the rated CFM for a given compressor, is matched to the percent power using an appropriate table (see Table 1). The operating power can then be calculated at a given capacity using Equation 5:

$$kW_{operating} = kW_{adjusted} \times \% \text{ Power} \quad (5)$$

where:

$kW_{adjusted}$ = Adjusted full-load kW based on actual operating conditions or measured data

% Power = percent power input (%), ratio of the load that ~~a motor~~ the compressor is actually ~~draws,~~drawing relative to the rated full load

~~CFM Demand = compressed air demand of the system~~

~~The percent~~ Note: % power ~~input (% Power) of an air~~ is not a parameter that can be physically measured, although measuring power and then testing the compressor at full-load will ~~vary with fluctuations in system air demand (CFM) and~~ provide the ~~corresponding load on the equipment (% Capacity). The~~variables needed to calculate percent ~~capacity is the ratio of CFM demand over the rated full-load output of the compressor in CFM.~~ power.

Percent power is also influenced by ~~the~~ equipment type (~~e.g.,~~ reciprocating, rotary screw~~)~~, etc.) and ~~control~~ method ~~(e.g.,~~ of control (throttling, on/off, variable speed~~). Table 2~~, etc.). Table 1 presents typical % ~~Capacity~~power versus ~~% Power~~% capacity distributions for ~~various air compressor system types and~~ rotary screw compressors with multiple control methods. The data in Table 1 were developed from standard percent power versus percent capacity performance curves extracted from Scales and McCulloch (2013) and Smith (2012). Figure 1 shows examples of percent power versus percent capacity curves for lubricated rotary screw air compressors.

~~**Table 2: Average Percent Power vs. Percent Capacity for Various Air Compressor Control Methods and Systems[a]**~~

Table 1. Average Percent Power Versus Percent Capacity for Rotary Screw Compressors With Various Control Methods

(Scales and McCulloch 2013)

	% Power

% Capacity	On/Off Control	Load/-Unload (1 gal/CFM)	Load/-Unload (10 gal/-CFM)	Inlet Valve Modulation (w/o Blowdown)	Inlet Valve Modulation (w/Blowdown)	Variable Displacement	VSD w/Unloading	VSD w/Stopping
0%	0%	27%	27%	71%	26%	25%	12%	0%
10%	10%	~~42~~32%	~~33~~3 5%	74%	40%	34%	20%	12%
20%	20%	~~53~~63%	~~40~~4 2%	~~78~~76%	~~41~~54%	~~29~~4 4%	28%	24%
30%	30%	74%	52%	79%	62%	~~48~~5 2%	~~80~~3 6%	~~51~~3 3% ~~35%~~
40%	40%	~~71~~8 1% ~~57%~~ ~~83%~~	60%	~~47~~82%	82%	61%	45%	41%
50%	50%	~~80~~87%	~~65~~6 8%	86%	86%	63%	~~52~~5 3%	53%
60%	60%	~~85~~92%	~~73~~7 6%	~~90~~88%	~~70~~88%	~~63~~6 9%	60%	60%
70%	70%	~~91~~95%	~~80~~8 3%	~~93~~92%	92%	77%	~~73~~7 1%	71%
80%	80%	~~95~~98%	~~88~~8 9%	~~96~~94%	~~84~~94%	85%	80%	80%
90%	90%	~~98~~100%	~~95~~9 6%	~~99~~97%	~~92~~97%	~~95~~9 1%	89%	89%
100%	100%	100%	100%	100%	100%	100%	100%	100%

~~[a]Scales, B. and McCulloch, D.~~

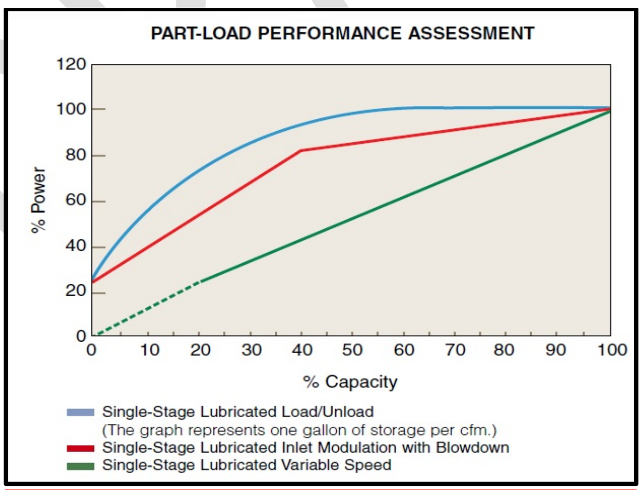


Figure 1. Example operation curve (% power versus % capacity curve) for lubricated rotary screw air compressor

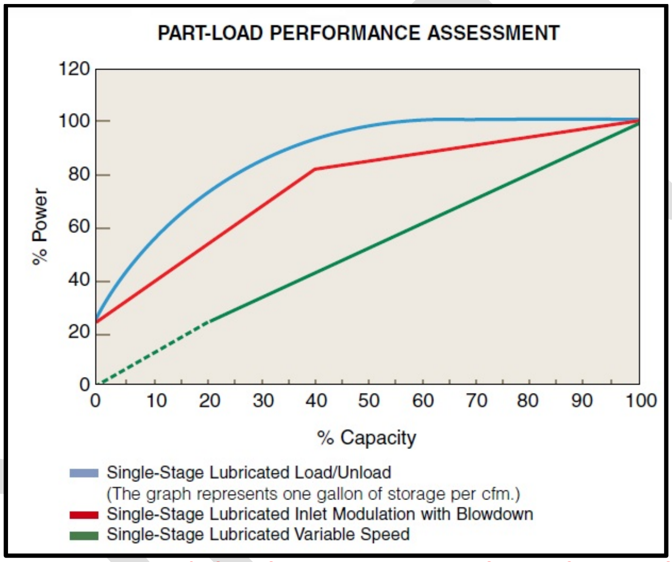
(Sullair 2014)

Inserted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Deleted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Deleted Cells
Deleted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Inserted Cells
Inserted Cells

The above methods for determining the instantaneous demand of an air compressor at a given load can be repeated for many bins of hour-CFM operation. This is commonly referred to as a CFM demand profile. A *Best Practices for Compressed Air Systems*. Compressed Air Challenge.

An air compressor's instantaneous kW demand can be determined from the product of the rated full-load kW of the compressor system and the % Power at the given load (% Capacity).

Table 2 data derived from standard fractional capacity (FC) versus fractional power (FP) performance curves extracted from the *Best Practices Manual for Compressed Air Systems*. Figure 2 shows examples of FC versus FP curves for a lubricated rotary screw air compressor.



Source: Product brochure for Sullair S-Energy Lubricated Rotary Screw Air Compressor.Online. http://www.sullairinfo.com/Downloads/LIT_S-energy_LS14EN.pdf

Figure 2: Example Operation Curve (FC/FP Curve) for Lubricated Rotary Screw Air Compressor

Best practices recommend determining compressed air demand (CFM Demand) from metered air flow or from trended data from an energy management system (EMS). During compressed air energy-efficiency project evaluations, a common issue often arises from a lack of information regarding baseline energy consumption. In the absence of measured or trended CFM data, parameters such as load profile or operating hours must be developed by an evaluator, based on: interviews with on-site facility personnel; reviews of historic operations/production levels; and reported operating schedules. In many instances, baseline consumption must be derived usingthe aforementioned resources.

As compressed air demand rarely remains constant within a given system, a demand profile must be developed to provide accurate estimates of annual energy consumption. A demand profile typically consists of a CFM-bin hour table, summarizing hours of usage under all common loading conditions throughout a given year. Table 3Table 2 provides an example of a Compressed Air CFM-Bin Hour Profile. The table also includes: the corresponding fractional input power, energy demand, and annual energy consumption for eachcompressed air CFM-bin, calculated using Equation 3. hour profile based on the following assumptions:

Table 3: Compressed Air CFM-Bin Hour Table

CFM Demand	Hr/Yr	% Power	Input Power (kW)	kWh
525	130	60%	128.7	16,563
475	2,640	53%	117.5	310,200
425	300	52%	116.0	34,800
150	170	16%	74.3	12,631
0	1,130	0%	61.6	69,608
Off	4,390	-	0.0	0.0
Total Hours	8,760	Annual Consumption		443,802

- The base-case compressor system consisted of a 75-hp rotary screw compressor with inlet valve modulation (w/blowdown) controls, an adjusted full-load power of approximately 65.5 kW, and a rated flow of approximately 360 ACFM.
- The post-retrofit case compressor system consists of a 75-hp rotary screw compressor with VSD (w/stopping) controls, an adjusted full-load power of approximately 67.5 kW, and a rated flow of approximately 360 ACFM.

The annual CFM load profile is used to determine base case and proposed case demand and energy use. For both, compressor electricalelectricity demand for each CFM--bin should be determined from actual metering data, spot power measurements, or CFM-to-kW lookup tables, developed from Compressed Air and Gas Institute (CAGI) performance data sheets or FC versus FP performance curves.

Table 2. Sample Compressed Air CFM-Bin Hour Table—Base and Post Cases

CFM-bin #	CFM Load Profile	Base Case: Rotary Screw Compressor With Inlet Valve Modulation (w/Blowdown)				Post Case: VSD Rotary Screw Compressor w/Stopping			
		% Power	H/Yr	Input Power (kW)	kWh	% Power	H/Yr	Input Power (kW)	kWh
CFM-bin 1	324	97%	200	63.5	12,707	89%	200	60.1	12,015
CFM-bin 2	288	94%	2,440	61.6	150,231	80%	2,440	54.0	131,760
CFM-bin 3	216	88%	170	57.6	9,799	60%	170	40.5	6,885
CFM-bin 4	180	86%	430	56.3	24,222	53%	430	35.8	15,383
CFM-bin 5	144	82%	1,100	53.7	59,081	41%	1,100	27.7	30,443
CFM-bin 6	0 idling *	26%	770	17.0	13,113	0%	0	0.0	0.0
CFM-bin 7	0 shutdown	0%	3,650	0.0	0.0	0%	4,420	0.0	0.0
Total kWh/yr		269,153				196,486			

The ~~annual~~difference in energy consumption between an air compressor operating in idling mode and being physically shut down can be significant depending on the base case and post-retrofit case methods of system control (as demonstrated by CFM-bin6 where base case consumption includes 13,113 kWh when the inlet valve modulation (w/blowdown) compressor is operating in idling mode for approximately 770 hours per year; whereas the post-retrofit case VSD-controlled system (w/stopping) has zero energy consumption for the same bin-hours. It is also common to differentiate between compressor systems operating in "timed-out" mode versus "shut-down" mode. "Timed-out" mode is generally determined from metering. "Shut-down" mode is typically determined from staff interviews and is verified from metering.

The energy consumption for each CFM-bin ~~can be~~is determined from the product of the average compressor demand and the number of hours in each bin~~.~~ (Equation 6). The sum of the kWh bin values ~~provides~~gives the annual consumption~~.~~ (Equation 7).

$$\Delta kWh_{bin1} = (\text{Base } kW_{operating\_bin1} - \text{Post } kW_{operating\_bin1}) \times \text{CFM-bin 1 H} \qquad (6)$$

$$\Delta kWh_{binN} = (\text{Base } kW_{operating\_binN} - \text{Post } kW_{operating\_binN}) \times \text{CFM-bin N H}$$

where:

Base $kW_{operating\_bin1}$ = baseline demand at part-load associated with CFM-bin 1

Post $kW_{operating\_bin1}$ = post demand at part-load associated with CFM-bin 1

Base $kW_{operating\_binN}$ = baseline demand at part-load associated with CFM-bin N

Post $kW_{operating\_binN}$ = post demand at part-load associated with CFM-bin N

Total Energy ~~savings equals base case usage minus the energy-efficient case usage.~~Reduction

$$(kWh/yr) = \sum_{o\text{-}n} [\ \Delta kWh_{bin1} + \Delta kWh_{bin2} + \ldots + \Delta kWh_{binN}\ ] \qquad (7)$$

~~*Equation 3: General Equation for Compressor Energy Savings (kWh)*~~

~~$$\text{kWh Saved} = (kW/CFM_{base} - kW/CFM_{eff}) \times (\text{CFM Demand}) \times (\text{CFM-bin Hours}) \times (1 - 0.005 \times (psig_{Rated} - psig_{Actual}))$$~~

where:

kWh Saved	= kilowatt-hours saved per year
kW/CFM_{base}	= package input power of base case compressor at the given CFM demand (for each bin)
kW/CFM_{eff}	= package input power of efficient case compressor at the given CFM demand (for each bin)
CFM Demand	= compressed air demand (for each bin)
CFM-bin Hours	= annual operating hours of compressor (for each bin)
$psig_{Rated}$	= pressure at rated flow (psig)
$psig_{Actual}$	= actual system pressure (psig)
Operating Pressure Adjustment Factor	= $(1\text{-}0.005 \times (psig_{Rated} - psig_{Actual}))$ Apply this adjustment factor when the rated (max) operating pressure differs from the actual system pressure.

Equation 3 can also be restated as follows.

Equation 4: [insert title]

$$kWh\ Saved = [((kW_{FLbase}) \times (\%\ Power_{base})) - ((kW_{FLeff}) \times (\%\ Power_{eff}))] \times (CFM\text{-}bin\ Hours) \times (1\text{-}0.005 \times (psig_{Rated} - psig_{Actual}))$$

where:

ΔkWh_{bin1}	= energy reduction for CFM-bin 1
ΔkWh_{binN}	= energy reduction for CFM-bin N

3.1.3 Addressing Uncertainty

During compressed air energy efficiency project evaluations, a common issue arises from a lack of information about baseline energy consumption and lack of airflow data. In the absence of measured or trended CFM data, parameters such as load profile and operating hours must be developed by the evaluator, based on interviews with on-site facility personnel, reviews of historical operations/production levels, reported operating schedules, and short-term (2 weeks or more) individual compressor power recordings.

One common method is to measure compressor power. The percent power can be correlated to percent flow using the appropriate compressor curve for the given type of control type. In this way, a load profile can be developed that can be used to compare the baseline and post systems at equivalent flow.

For systems with load and unload compressors, timing the load/unload cycles can be an effective way of determining percent capacity. A load/unload compressor either produces full flow or no flow; thus, the percent of

where:

kW_{FLbase}	= full load kW of base case system
$\%\ Power_{base}$	= % Power of base case at the given CFM demand (for each bin)
kW_{FLeff}	= full load kW of the energy-efficient case system

~~% Power$_{eff}$ = % Power of the efficient case at the given CFM demand (for each bin)~~

~~Whenever possible, measured and/or trended data should be used to support pre- and post-installation energy consumption calculations. If performing metering, amperage (coupled with spot power measurements) or true power should be~~ measured ~~for a minimum of two weeks.~~time when the compressor is loaded is equivalent to percent capacity.

~~3.1~~3.2 Savings Calculations for Compressed ~~air-~~Air Leak Surveys and Repairs

~~3.1.1~~3.2.1 Quantifying ~~Amount of~~the Compressed ~~air-~~Air Leakage

Before ~~conducting~~ a compressed-air leak survey is conducted, a system ~~bleed~~leak-down test should be performed to estimate the combined loss (CFM) of compressed ~~air leaks. A bleed-~~air leaks. Leak-down tests are best performed at the air receiver by isolating the receiver from the supply side of the system. The basic procedures for conducting a leak-down test ~~uses the following basic procedures~~are:

- Estimate the total storage volume of the compressed-~~-~~air system, receivers, main headers, ~~and so on,~~etc., in cubic feet.
- During ~~non-production~~nonproduction hours, start the system ~~should be started~~ and ~~allowed~~allow it to reach normal operating system ~~pressures~~pressure.
- ~~All~~Turn off all production loads ~~should be turned off~~.
- ~~Compressors should be shut~~Shut off~~.~~ the compressor(s).
- ~~The~~Allow the system ~~should "bleed~~to "leak down" to approximately ~~one-~~half ~~of~~ the full-load pressure (psig) and record the time ~~required~~it takes to reach this point.
- Use the following formula ~~below.~~:

~~*Equation 5: [insert title]*~~

Leak ~~Volume CFM~~Flow SCFM (Free Air) = [(V ~~x~~× ΔP~~) / ()~~/(Time ~~x 14.7)] x~~ × P_{alt})] × 1.25 (8)

where:

V = total storage volume of compressed-~~-~~air system in cubic feet

ΔP ($P_1 - P_2$) = drop in line pressure during ~~bleed~~leak down test in psig

~~14.7~~ P_{alt} = atmospheric pressure (psia) corrected for local altitude (elevation)

T = time ~~required~~it takes for ~~the~~ line pressure to drop by 50% from ~~the~~ normal system operating pressure (minutes)

The 1.25 multiplier corrects leakage to normal system pressure, allowing for reduced leakage~~,~~ with system pressure falling to 50% of the initial reading.

Best practices suggest performing power measurements during a bleed-down test to collect and calibrate the actual rated power input to CFM output for the air compressor system. Load/unload cycles also should be timed (if applicable).

In many cases, a leak-down test is impractical or critical users must have air at all times. In these instances, flow should be estimated by measuring compressor power and correlating to flow (reference table/methods above). This should be done during a nonproduction period, such as a weekend. During this test, it is important to identify any nonleak users of air. The measured compressor flow should be reduced by the total air use of the nonleak applications to determine the actual leak volume.

Leakage is expressed in terms of the percentage of compressorsystem capacity lost; that. The percentage lost to leakage should be less than 10% in a well-maintained system.[3] (Marshall 2013). Poorly maintained systems can experiencehave losses as high as 20%–30% of air capacity and power.%.

3.1.23.2.2 Compressed air Air Leak Survey and Repairs

Significant energy Energy savings can resulting from repairing the repair of compressed--air leaks. Estimating can be significant. The algorithm used to estimate the energy savings of a leak repair uses the following algorithm.is:

Equation 6: Energy Savings from Compressed air Leak Repair (kWh)

kWh Saved = (# leaks) x (leakage rate, CFM) x(repaired leak volume) × (kW_{FL}) x (% Power) x (CFM-bin Hours) x OPAF× CCAF / CFM_{rated} (9)

where:

kWh saved = kWh Saved = kilowatt-hours saved per year

# of leaks = quantity of leaks repaired

leakage rate leak volume = rate of air loss from leak (CFMleaks repaired (SCFM)

kW_{FL} = rated full- load kW of air compressor

% Power = percent power input of the compressor at givenaverage system CFM demand (for each bin)

CFM-bin Hours = annual operating hours of air compressor (for each CFM-bin)

OPAF = operating pressure CCAF = compressor control type adjustment factor

Similar to the algorithms used to estimate annual energy consumption of an air compressor, annual energy savings resulting from compressed air leak repairs may need to be determined

---

[3] Marshall, R. (2013). "Finding and Fixing Leaks" Compressed Air Challenge – Air Best Practices.com. Online. http://www.airbestpractices.com/system-assessments/leaks/finding-and-fixing-leaks

based on multiple iterations of Equation 6, if the compressed air system experiences variable demand.

CFM_{rated} = rated CFM output of air compressor

The operating pressure adjustment factor will vary, based on the method of system control. Table 4Table 3 presents typical adjustment factors for common control strategies. Use of anAn adjustment factor ensures achieving conservative should be used to ensure that energy savings estimates. Vendors commonly accurately represent savings. It is common for vendors to use an average measured kW/CFM value, which frequently results in overestimated savings.

Table 3~~:~~. Recommended Adjustment Factors for Determining Energy Savings ~~from~~From Compressed~~-~~-Air Leak Repairs

Control Method	Operating Pressure Adjustment Factor
Reciprocating—~~On/Off Control~~on/off control	4 1.00
5 Reciprocating—~~Load/Unload~~load/unload	6 0.74
7 Screw—~~Load/Unload~~load/unload	8 0.74
9 Screw—~~Inlet Modulation~~inlet modulation	10 0.30
11 Screw—~~Inlet Modulation~~inlet modulation w/ ~~Unloading~~unloading	12 0.30
13 Screw—~~Variable Displacement~~variable displacement	14 0.83
15 Screw—~~VFD~~variable frequency drive	16 0.97

The following basic procedures should be followed when quantifying energy savings resulting from leak repairs:

- ~~1.~~ Impacts from leaks should be supported with formal documentation. ~~Whenever possible, the~~ The rated power input to CFM output (air compressor ~~efficiency~~specific power) should be supported by trended system data~~.~~ whenever possible.

~~2. The air loss rate (CFM) for each repaired leak should be approximated using: decibel readings taken in the field; and a manufacturer-supplied decibel-to-CFM conversion table, associated with the instrumentation used to conduct the survey. Table 5 provides a sample decibel-to-CFM conversion table.~~

Table 5: Compressed air Loss Estimator for Digital Ultraprobes[a]

- The leakage rate (CFM) from a compressed-air leak can be estimated based on the system line pressure and approximate orifice diameter of the crack or leak identified. Leakage rate is proportional to the square of the measured orifice diameter. Table 4 shows the leakage rates for various line pressures (psig) and leak orifice diameters (inches). Correction factors for well-rounded versus sharp orifice shapes must be applied to the leakage rates to ensure estimates are conservative.

Table 4. Leakage Rates (CFM) for Different Supply Pressures and Approximately Equivalent Orifice Sizes

(DOE 2013)

dB ReadingPressure (psig)				150 PSIOrifice Diameter (inches)	125PSI	100 PSI	75 PSI	50 PSI	25 PSI	10 PSI
				1/64	1/32	1/16	1/8	1/4	3/8	
10			0.70	0.6029	0.501.16	0.304.66	0.1518.62	0.1074.4	0.05167.8	
20	1.40	1.20	0.80	0.9032	0.501.26	0.305.24	0.1520.76	83.1	187.2	
3090				1.850.36	1.6546	1.405.72	23.1.10	0.8092	0.50206.6	0.40
40100				20.40	1.9055	1.706.31	1.4025.22	1.10100.9	0.80227	0.50
50				3.90	3.40	2.00	2.80	2.20	2.00	1.90
60				4.50	4.10	3.60	3.00	2.80	2.60	2.30
70				6.80	6.40	5.20	4.90	3.90	3.40	3.00
80				10.20	9.10	7.70	6.80	5.60	5.10	3.60
90125				11.000.48	10.301.94	8.40	7.7066	7.1030.65	6.80122.2	275.5.30
100Values should be multiplied by 0.97 for well-rounded orifices and by 0.61 for sharp orifices.				12.90	12.50	10.60	10.00	9.60	7.30	6.00

[a] http://www.uesystems.com/new/resources/charts-and-graphs/compressed-air-loss-guesstimator-for-digital-ultraprobes/

3. The leakage rate (CFM) from a compressed air leak can be estimated based on system line pressure and the approximate orifice diameter of the crack or leak identified. The leakage rate is proportional to the square of the measured orifice diameter. Table 1 in Section 1.3 shows leakage rates for various line pressures (psig) and orifice diameters (inches). Correction factors for well-rounded versus sharp-orifice shapes must be applied to the leakage rates to ensure conservative estimates.

- Once leak repair work is complete the combined air loss (CFM) of the logged leaks that were repaired should be summed and compared to the total leakage determined from the preliminary bleed-down test. Identifying all leaks in a compressed-air system is nearly impossible, so it is appropriate to allocate a portion of the bleed-down test CFM to "undetected leakage." A post-repair bleed-down test should also be performed to quantify leak reduction.

4 Measurement and Verification Plan

The When choosing an option, consider the following factors should be considered in choosing a measurement and verification plan:

- The equation variables used to calculate savings;
- The uncertainty in the claimed estimates of each parameter;
- The cost, complexity, and uncertainty in measuring each of those variables; andvariable
- The interactive effects of concurrently implementing multiple compressed--air efficiency measures.

4.1 IPMVP Option

Obtain CAGI standard data sheets for the air compressor system to accurately estimate the package input power.

Use one of the equations provided in Section 3.1, with manufacturer-rated values for: compressor brake horsepower; motor efficiency; VFD/VSD efficiency (if applicable); the rated power input (kW) at maximum design pressure (psig) or rated CFM; and load operation curves for the air compressor motors

Incorporate program-specific measured values for the operating hours, load factors, and load profiles. This approach most closely resembles IPMVP Option A: Partial Retrofit Isolation/Metered Equipment.

4.1 IPMVP: Option B (International Performance Measurement and Verification Protocol Option

The preferred approach for evaluating compressed air ECMs is International Performance Measurement and Verification Protocol Option A: Retrofit Isolation (Key Parameter Measurement). Options B, C, and D can be used in limited applications, but Option A is the preferred approach. Discussions on the feasibility and applicability of the other approaches are provided below.

4.1.1 Option A: Retrofit Isolation) could be applicable in one of two cases: (Key Parameter Measurement)—Preferred Approach

- First, Option B could be used if amperage cannot be measured as a proxy variable and be reliably converted to power, although this would apply in few cases.
- Second, Option B should be used if equipment loading cannot be captured by short-term sampling.

Evaluators also commonly use Option D: Calibrated Simulation upon concurrent implementation of ECMs.

International Performance Measurement and Verification Protocol Option A (Retrofit Isolation Key Parameter Measurement) offers the best approach for measuring the energy consumption of compressed-air system. Option A relies on field measurements of key performance parameters and estimates of key parameters not selected for field measurements. Field measurements are typically collected for compressor load current (amps) or true root mean square (RMS) power (Watts).

Parameters such as airflow, line pressure, compressor specific power, part-load performance, and operating hours are typically determined from a combination of one-time spot measurements, historical production data, manufacturers' specifications, CAGI standard data sheets, and interviews with the customer. Using Option A, the measurement boundary is established on the line side of the power supply feeding the air compressor or VSD.

Interval field measurements of compressor load current (amps) coupled with spot power measurements or true RMS power (Watts) measurements are used to determine the instantaneous operating load of an air compressor and to develop trends of energy consumption over time (minimum metering period of 2 weeks). Equation 10 is used to convert interval measurements of load current (amps) and one-time spot measurements of line voltage and power factor into operating load ($kW_{operating}$) for three-phase motors.

$$kW_{operating} = \sqrt{3} \times Amps \times Volts_{RMS} \times PF \qquad (10)$$

where:

Amps = measured load current

$Volts_{RMS}$ = measured True RMS phase-to-phase voltage

PF = measured power factor

True RMS voltage, load current, and power factor should be measured with the system operating under all common loading conditions. Each "common loading condition" should correlate with an established bin of hour-CFM operation. The derived operating load for each CFM-bin is then inserted into Equation 7 (most commonly as the parameter "Post $kW_{operating\_binN}$") to determine annual consumption and energy reduction.

4.1.2 Option B: Retrofit Isolation (All Parameter Measurement)

The savings created by compressed air ECMs can be determined using Option B (Retrofit Isolation – All Parameter Measurement); however, the degree of difficulty and costs associated with enhanced measurement and verification will increase. By definition Option B requires "field measurement of all key performance parameters which define the energy use of the ECM-affected system." This implies that in addition to measuring load current or true RMS power, the evaluator is required to measure airflow (SCFM) and operating hours. Option B also requires pre-retrofit metering before the measure is implemented.

4.1.3 Option C: Whole Facility

Typically, Option C is not applicable because compressed air is generally not more than 10% of a typical facility's energy consumption.

4.1.4 Option D: Calibrated Simulation

Option D can be used in circumstances where multiple ECMs are concurrently implemented; however, this approach can be cost prohibitive and is less common when evaluating ECMs only affecting compressed air systems.

4.2 Verification Process

~~The~~In accordance with Option A, the first step of the protocol ~~first~~ entails verifying key data collected on typical program application or rebate forms~~. These can include~~, including information on the baseline compressor system. This typically includes:

- Number of shifts per day, shift-hours per week, weekend hours per week, and estimated total operating hours per year~~.~~
- Average air demand ~~in~~ (SCFM) for each shift.
- Baseline equipment use pre- and post-retrofit (~~e.g.,~~ lead, trim, or ~~back-up~~backup compressor).
- Baseline compressor system type (~~e.g.,~~ reciprocating, screw oil-less/oil-flooded, two-stage, centrifugal, vane~~).~~, etc.).
- Baseline compressor system control ~~types (e.g.,~~ type (load/no load, inlet modulating dampers, other).
- Baseline compressor system operating ~~pressures~~pressure (psig) at rated SCFM.
- Manufacturer, model number, system type, control method, nominal horsepower, rated SCFM, operating pressure at rated SCFM, and installation date for the new energy-efficient air compressor.

~~Compressed~~ For compressed-air leak survey and repair projects ~~often frequently require~~, the following information is also frequently requested:

- Whether the facility currently has a formal compressed-air leak detection program in place~~.~~
- An estimate of total plant air leakage as a percentage of total use~~.~~
- Type and model of leak detection instrument used by the trade ally to conduct the survey.

Some of these data can be verified using a desk review of~~:~~ invoices~~;~~, manufacturer ~~specification~~specifications sheets (which are typically required for rebate/incentive payments~~);~~), compressed-air survey reports~~;~~, or an on-site audit of a sample of participants to verify the quality of self-reported information. If efficiency and unit capacity ~~cannot be~~are not collected for each participant, program application requirements should be modified to include these important data.

4.3 Data Requirements

~~Plant production levels typically govern the~~ The energy use of a compressed-air system~~.~~ is typically governed by plant production levels. The actual recommended metering duration for any given compressed~~-~~-air project should be established to represent all ~~of a facility's~~ operating modes~~.~~ of the facility. This period should span two full operating cycles~~,~~ from maximum energy use (e.g., weekday production) to minimum~~,~~ (e.g., weekend nonproduction) to confirm the ~~reoccurrence~~ rate of recurrence in the metered data. This ~~allows evaluation of operational~~is also done to evaluate the consistency of operations on a cycle-to-cycle basis and ~~avoids~~avoid circumstances where data collected during a single cycle coincided with abnormal operations. For most ~~non-weather~~nonweather-dependent compressed~~-~~-air applications, a ~~one month or less~~ metering period ~~proves~~of 1 month or less is acceptable.

~~Though sampling~~ Sampling intervals of 30–60 seconds ~~to 1 minute~~ are recommended, although sampling ~~must~~should occur at a ~~frequency~~ high enough frequency to avoid aliasing errors associated with rapidly fluctuating system demand. In general, the sampling frequency should be at least twice the frequency of ~~system events~~events in the system, such as compressor load and unload cycles. In most applications a sampling interval of 30–60 seconds satisfies this requirement.

~~Evaluating~~The minimum data required to evaluate a high~~-~~-efficiency air compressor replacement project ~~requires the following minimum data~~are:

- Equipment manufacturer, model, and serial number~~.~~
- Compressor system type (e.g., ~~positive displacement,~~ reciprocating, oil-flooded rotary screw, centrifugal~~).~~)
- Prime mover (motor) efficiency~~.~~
- Rated compressor shaft horsepower (bhp) or rated compressor horsepower (hp) and prime mover (motor) load factor~~.~~
- Rated fully loaded SCFM output.
- Rated input power of the compressor in ~~kilowatts~~kW over output flow rate in CFM~~.~~ (at rated pressure).
- Annual operating hours of constant speed or modulating compressors~~.~~ at a range of loadings
- Load factor of baseline constant speed or modulating compressor~~.~~
- ~~Load profile~~Percent CFM versus percent kW curve of new variable displacement capacity or VSD compressor~~.~~
- Type of control system (~~e.g.,~~ modulation, load/no-load, VSD, variable displacement~~).~~, etc.).

~~Note:~~ All of the above listed parameters should be gathered for both the baseline and energy-efficient equipment.

Parameters to be spot-measured during the ~~evaluation~~verification include ~~the following~~:

- ~~Line voltage; and~~

- Integrated~~,~~ true ~~root mean square (~~RMS~~)~~ kW~~,~~ three-phase power~~,~~ under all common compressor loading conditions.

Parameters to be metered or trended:

- ~~•~~ Preferred ~~Method~~method: True poly-phase RMS ~~Power~~power (kW~~)~~
-): This protocol prefers a trend log of true poly-phase RMS power for the circuit powering the VSD compressor. The selected sampling interval should be at a ~~frequency~~ high enough frequency to avoid aliasing errors and at least twice the frequency of ~~system~~ events~~.~~ in the system. In general, ~~-~~a sampling interval of once~~-~~ per~~-~~ minute ~~interval sample~~ is preferred.
- ~~•~~ Alternative ~~Method~~method of ~~Power Measurement:~~
- power measurement: In lieu of true power metering, trending of current (amperage~~),~~) combined with several one-time true power measurements~~,~~ can be used for base-loaded/ constant speed systems. This ~~is not, however, not recommended for VSD~~method can also be used with variable frequency drive compressors ~~due to difficulties arising from simulating part-load conditions (varying amps/flow) for VSD compressors by taking a few spot power factor measurements, and then applying those values to the entire spectrum of collected amperage measurements. This may not be representative of~~ as long as true ~~loading conditions as power factors vary with system load/amps~~ RMS current transducers are used.
- ~~Generation pressure (psig).~~
- ~~Flow (SCFM).~~

~~Evaluating~~Additional data required to evaluate compressed air leak survey and repair projects include ~~the following additional data~~:

- Compressed~~-~~-air system ~~efficacy~~ specific power (kW/CFM), including compressors, dryers, and significant end~~-~~ uses~~.~~ over a range of CFM loadings
- Supply and demand~~-~~ side~~,~~ one-line ~~diagrams~~diagram showing all generation equipment and ~~-~~significant end uses~~.~~
- Presence of intermediate pressure and/or flow controllers~~.~~
- ~~System pressure profiles of the supply and demand-side, noting points of measurement referenced in the system diagram.~~
- Delivery pressure~~.~~
- Historical production data for systems affecting compressed~~-~~-air consumption (~~e.g., the~~ number of products produced, active equipment, etc. as appropriate for facility). Production data should be collected for both the pre-and post-retrofit measurement period and appropriate production adjustments should be made to the collected data.

Data to be collected and utilized, when available:

- Measured or trended airflow (SCFM) data can be quite advantageous when evaluating compressed-air ECMs; however, this information can be difficult to obtain and is not generally collected unless the existing compressed-air system controls already have the capability. In the absence of measured or trended CFM data, the evaluator must develop parameters such as load profile and operating hours, based on interviews with on-site facility personnel; reviews of historical operations/production levels; reported operating schedules, and short-term (2 weeks or more) individual compressor power recordings.

5 Data Collection Methods

5.1 Metering

~~Measuring~~ The typical metering equipment used to measure and ~~trending~~trend the energy consumption of a VSD ~~compressor's energy consumption typically requires the following equipment~~compressor are:

- Handheld (or portable) power meters to measure true RMS ~~volts, amps, watts~~voltage, current, power, and power ~~factors~~factor at all common loading conditions.
- Current ~~transducersfor~~transducers for measuring load ~~currents~~current while metering (preferably with a linearity accuracy of ±1.0% of the reading). Recording amp loggers are acceptable as long as spot measurements of compressor power are performed with a handheld kW meter at various loadings.
- Watt-hour transducers to measure true power (kW) of ~~1, 2~~one, two, or ~~3 system~~three phases of a system.
- Meter recorders (data loggers) with adequate storage capacity to match logging interval and measurement ~~frequencies~~frequency.
- ~~In-line air-flow meters (for use with data loggers).~~

~~Selected~~The selected measurement equipment should always be installed on the line side of a VSD compressor, not on the load side. Measurements from the ~~VSD~~ output of a VSD compressor can lead to significant data errors. ~~During~~In the pre- and post-retrofit measurement periods, all regularly operating compressors serving a common system should be logged simultaneously~~,~~ regardless of ~~compressor quantities.~~quantity of compressors. Compressors ~~only~~that are used only for ~~back-up~~backup purposes do not need ~~not~~to be logged~~.~~, although it is good practice to do so to validate that the equipment was never used. Often post-retrofit only measurements are taken and the pre-retrofit power profile is estimated using the post-retrofit CFM (from kW to CFM conversions) and generic control curves for the baseline control method.

5.2 Ultrasonic Leak Detectors for Compressed Air Leak Surveys

~~Ultrasonic~~An ultrasonic leak ~~detectors~~detector with a frequency response of 35–45 kHz should be used to conduct compressed air leak surveys. ~~An instrument capable of measuring and recording decibel frequency readings will allow determination of the approximate air loss associated with each identified leak. To get a more reliable and accurate decibel reading, best practice suggests using a flexible scanning module or rubber focusing probe once a leak has been identified. Using~~ It is also beneficial to use a set of noise~~-~~ attenuating headphones~~,~~ designed to block ~~the~~ intense sounds that often ~~found~~occur in industrial environments~~, also proves useful;~~ so that the user may easily hear the sounds ~~detected~~received by the instrument.

~~Discussion of~~

6 Methodology

6.1 General Discussion

The primary energy savings verification method ~~monitors, via~~is to monitor, by metering, energy use over a time period ~~reflecting~~that reflects a full or complete range of the underlying operations within a specific industrial facility. Monitoring for periods of less than ~~a~~1 year, ~~which~~as is most often ~~occurs~~the case, will require ~~approximation of~~that annual energy use~~,~~ be approximated based on the results of short-term metering and ~~historic~~historical production data.

~~Compressed~~ A common issue encountered during compressed-air energy~~-~~ efficiency project evaluations ~~often encounter~~is a lack of information ~~regarding~~about baseline energy consumption. In many instances, baseline consumption must be derived ~~from:~~based on pre-retrofit production levels~~;~~, reported equipment performance~~; or~~, as well as equipment and component specifications. Key parameters to be determined include~~:~~ motor efficiencies, load factors, load profiles, operating hours,~~ and~~ total system SCFM and compressor efficacies (kW/CFM). Often, this information must be gathered through interviews with the program participant, implementer, or ~~the~~ energy advisor directly involved with ~~a~~the project.

Other resources frequently used to inform baseline assumptions include:

- Equipment tags~~.~~[4]
- ~~Historic~~Historical trending from an EMS~~.~~
- Engineering reports and calculations~~,~~ generated during ~~a project's~~the design and application phases~~.~~ of the project
- Rebate or incentive program application forms.

When determining energy savings for VSD compressors, production data must be normalized to an independent normalizing variable. A unit indicating a relative level of production ~~level~~ should be obtained from the site, often provided as~~:~~ units produced, hours of machine operation, or labor hours, depending on the site and the availability of information.

Preferably, the independent variable would be collected with sufficient granularity ~~to allow correlations~~so a correlation can be developed between the measured compressed air energy consumption and the independent variable. ~~To be considered valid, the~~The correlation should have a coefficient of determination (R^2) value of at least 0.75~~.~~ to be of value to the analysis. The pre- and post-~~period then~~ retrofit periods should then be normalized to an annual variable for units of production~~, determining~~ to determine the ~~system improvement's~~ annual effect~~.~~ of the system improvement. If an annual value ~~cannot be procured~~is unavailable, using an average of production ~~average~~ between the pre- and post-retrofit periods can ~~prove~~be acceptable.

[4] ~~———~~It is common for baseline compressor systems to be salvaged or kept in service and converted to an emergency ~~back-up~~backup role. This provides an opportunity for the evaluator to observe and collect information from equipment tags.

Many sites may not be able to provide an independent variable for normalization. In ~~such~~these cases, normalizing to flow ~~offers~~is an acceptable alternative. ~~Depending~~Two methods are used depending on the type of ECM implemented~~, two different methods are used~~:

- ECMs that reduce system flow (~~**e.g.,**~~ leaks, air nozzles, condensate drains): For ~~such upgrades~~this type of upgrade, the ~~individually~~individual installed components should be inspected and ~~the~~ CFM reduction confirmed. ~~Flow~~The flow reduction can then be modeled via a bin table approach using the measured compressor data and simulating the decrease in energy consumption ~~due to~~caused by the decrease in flow.
- ECMs that improve system ~~**efficacy (e.g.,**~~specific power (new air compressors, compressor controls): For ~~such upgrades~~this type of upgrade, the system CFM should be determined at each measured point for both the baseline and the installed ~~system~~systems. The CFM ~~then~~ should then be compared. The pre- and post-~~period~~retrofit periods should be normalized to an annual CFM demand profile. The system should then be simulated via a bin table approach at the normalized CFM level using the correlation between flow and power for the respective system.

~~For~~In a new construction~~,~~ situation where past process production ~~volumes~~volume and past energy consumption data are unavailable, ~~determining~~ the determination of energy use per unit of production ~~derives from a~~ will have to be based on some form of comparable site~~,~~ such as a similar process~~,~~ in-house or in-company at another facility. For new construction or normal end-of-life replacement projects the baseline system efficiency is determined from the minimum allowed by current local jurisdictions.

~~Equation 3 includes the following~~The key parameters~~:~~

- ~~'% Power'~~
- ~~'ΔkW'~~
- ~~Annual~~ from Equation 3 are: % Power, ΔkW, and annual operating hours

. Each ~~parameter~~ will fluctuate~~,~~ based on the operating load profile of the VSD compressor. Actual post-retrofit consumption can be determined from the sum of multiple iterations of ~~Equation 3,~~Equation 3, where a unique calculation must be performed for each common loading condition~~.~~ (i.e., using a bin table method). The compressor load profile dictates the number of iterations. Metering generally provides this information.

6.2 Step-by-Step Procedures for Evaluating High-Efficiency/Variable-Speed Drive Air Compressor Installation Projects

This section of the protocol summarizes the basic step-by-step procedures to be performed when evaluating a high-efficiency/VSD compressor replacing a modulating compressor measure.

Step 1: Collect product performance data for baseline and new high efficiency/VSD air-compressor equipment. If product literature is not available, data should be collected from the equipment nameplate. Product literature may be obtainable online after leaving the site using the manufacturer and model number. A sample data collection form is shown Table 5. Note that the data fields shown in Figure 2 should be collected for both the baseline and new equipment.

Table 5. General On-Site Data Collection Form for Air Compressor

Air Compressor General Data Collection Form			
Manufacturer:		Rated Flow (ACFM):	
Model Number:		Pressure at Rated Flow (psig):	
Nominal Horsepower (HP):		Full Load kW_{rated}:	
Drive Motor Efficiency:		Fan Motor HP and Efficiency (if applicable):	
Air-Cooled/Water-Cooled:	❒Air-cooled ❒Water-cooled		
Duty:	❒Lead (Primary) ❒Trim (Secondary) ❒Back-up		
Compressor Type:	❒Rotary Screw (oil-flooded) ❒Rotary Screw (oil-less) ❒Centrifugal ❒Other _______		
Control Type (Screw Compressors)	❒On/Off		
	❒Load/Unload Total Storage Volume (gallons): ________		
	❒Inlet Modulating Dampers ❒w/blowdown ❒w/o blowdown		
	❒Variable Speed Drive (VSD) ❒w/unloading ❒w/stopping		
	❒Variable Displacement ❒Other		

Step 2: Determine compressor power at full load for baseline and new high efficiency/VSD air-compressor units using either CAGI performance sheet data, metered full-load and fully unloaded kW data, or derived using Equations 1 and 2. On projects involving the replacement of an older air-compressor system, the evaluator may encounter some difficulty in locating CAGI data sheets, product literature, or manufacturer specifications for the baseline system. In the absence of historical metering data or product literature, the full-load kW for an air compressor system can be derived using Equation 1 or 2:

$$\text{Full Load } kW_{rated} = \frac{(\text{Compressor hp}) \times LF_{rated} \times (0.746\ kW/hp)}{(\eta_{motor})} \qquad (1)$$

$$\text{Full Load } kW_{rated} = \frac{(\text{Compressor hp}) \times LF_{rated} \times (0.746\ kW/hp)}{(\eta_{motor}) \times (\eta_{VSD})} \qquad (2)$$

where:

Compressor hp = compressor horsepower, nominal rating of the prime mover (motor)

0.746 = horsepower to kW conversion factor

η_{motor} = motor efficiency (%)

η_{VSD}	= variable-speed drive efficiency (%)
LF_{rated}	= load factor of compressor at full load (typically 1.0 to 1.2)

Typically the compressor horsepower will be known by the customer or on-site personnel. Motor efficiency and load factor may or may not be known by on-site personnel and may need to be estimated using engineering judgment informed by known parameters such as system type, method of control, and age.

Step 3: Once rated compressor power at full load for the baseline and new high efficiency/VSD air compressor have been determined, correct these values for site-specific conditions using Equation 3 or the "rule-of-thumb" approach (Equation 4). The two primary adjustments that must be made pertain to atmospheric pressure based on site elevation above sea level and actual system discharge pressure (psig).

Preferred Approach

$$kW_{adjusted} = \frac{\text{Full Load } kW_{rated} \times ((P_{discharge} + P_{alt})/P_{alt})^{((0.395/1.395)-1)}}{((P_{rated} + 14.7)/14.7)^{((0.395/1.395)-1)}} \qquad (3)$$

where:

Full Load kW_{rated}	= full load kW of air compressor at full load capacity and pressure (per CAGI data sheet)
$P_{discharge}$	= actual system discharge pressure (psig)
P_{alt}	= atmospheric pressure based on site elevation above sea level (psia)
P_{rated}	= pressure at rated flow (psig) per CAGI data sheet
14.7	= standard atmospheric conditions (psia) at sea level
((0.395/1.395) -1)	= ratio of specific heat for air at standard atmospheric conditions (Ideal Gas Law)

Alternate "Rule-of-Thumb" Approach for Correcting for Discharge Pressure

Although not the preferred approach, a general rule of thumb for air compressors with a rated pressure capacity of 100 psig is: for every 2 psi increase or decrease in discharge pressure, energy consumption will increase ordecrease by approximately 1% at full output flow. A sample calculation is shown below:

$$kW_{adjusted} = \text{Full Load } kW_{rated} \times [1+ (((P_{rated} - P_{discharge})/2) \times 0.01)] \qquad (4)$$

Step 4: Once the rated compressor power at full load for the baseline and new high efficiency/VSD air-compressor equipment have been adjusted for site-specific conditions, develop a CFM demand profile. A demand profile consists of a CFM-bin hour table, summarizing hours of usage under all common loading conditions throughout a given year for the base and post-retrofit case conditions.

Table 6 provides an example of a Compressed Air CFM-bin Hour Profile. The base and post-retrofit case profiles shown in Table 6 were developed based upon the following assumptions:

- The base-case compressor system consisted of a 75-hp rotary screw compressor with inlet valve modulation (w/blowdown) controls, an adjusted full-load power of approximately 65.5 kW, and a rated flow of approximately 365 ACFM.
- The post-retrofit case compressor system consists of a 75-hp rotary screw compressor with VSD (w/stopping) controls, an adjusted full-load power of approximately 69.2 kW, and a rated flow of approximately 365 ACFM.

Table 6. Example Compressed Air CFM-Bin Hour Table—Base and Post Cases

CFM-bin Number	Air Demand Load Profile (ACFM)	%Capacity *	Base Case Hours per Year	Post Case Hours per Year
CFM-bin 1	324	90%	2,640	2,640
CFM-bin 2	288	80%	150	150
CFM-bin 3	216	60%	170	170
CFM-bin 4	180	50%	430	430
CFM-bin 5	144	40%	1,130	1,130
CFM-bin 6	0 idling	26%	770	0
CFM-bin 7	0 shut-down	0%	3,650	4,420
	Total Hours		**8,760**	**8,760**

* Percent flow (part-load fraction) values were determined assuming a rated output flow of 365 ACFM.

Step 5: Once the base and post-retrofit case CFM demand profiles have been developed, calculate the base case and proposed case energy usage. For both base and post-retrofit cases, compressor electricity demand for each CFM-bin should be determined from actual metering data, spot power measurements, or CFM-to-kW lookup tables (refer to Sections 4.3 and 5.1 for guidance on measurement and verification data requirements and data collection methods).

When actual meter or spot power measurement data are unavailable, the percent power at part-load for each CFM-bin is typically determined using the calculated percent flow values and generic CFM-to-kW lookup tables (see Table 1 in Section 3.1). Percent power is influenced by equipment type and method of control. Percent capacity versus percent power profiles pertinent to the example project for the base and post-retrofit cases are provided in Table 7.

Table 7. Average Percent Power Versus Percent Capacity for Base Case and Post Case for Example Project

(Scales and McCulloch 2013)

% Capacity	Base Case: Rotary Screw w/Inlet Valve Modulation (w/Blowdown)	% Power for Post Case: VSD Rotary Screw Compressor w/Stopping
0%	26%	0%
10%	40%	12%
20%	54%	24%
30%	62%	33%
40%	82%	41%
50%	86%	53%
60%	88%	60%
70%	92%	71%
80%	94%	80%
90%	97%	89%
100%	100%	100%

Using the percent power values from Table 7 and the percent capacity values calculated in Step 4, the power at part load (kW) for each CFM-bin is determined using Equation 5:

$$kW_{operating} = kW_{adjusted} \times \% \text{ Power} \qquad (5)$$

where:

$kW_{adjusted}$ = Adjusted full load kW

% Power = percent power input (%), ratio of the load that a motor is actually drawing relative to the rated full load.

Note: % Power is not a parameter that can be physically measured.

Revisiting the example problem introduced in Step 4, the part-load power (kW) for each CFM-bin is calculated below and is shown in Table 8.

Table 8. Percent Power and Operating Load or Base Case and Post-Retrofit Case for Example Project

CFM-bin Number	CFM Load Profile	% Capacity	Base Case		Post Case	
			% Power	$kW_{operating}$	% Power	$kW_{operating}$
CFM-bin 1	324	90%	97%	63.5	89%	60.1
CFM-bin 2	288	80%	94%	61.6	80%	54.0
CFM-bin 3	216	60%	88%	57.6	60%	40.5
CFM-bin 4	180	50%	86%	56.3	53%	35.8
CFM-bin 5	144	40%	82%	53.7	41%	27.7
CFM-bin 6	0 idling	0%	26%	17.0	0%	0.0
CFM-bin 7	0 shutdown	0%	0%	0.0	0%	0.0

Obtaining an actual percent power versus percent capacity performance curve for the specific air compressor system being evaluated is recommended (if available). A system-specific curve can also sometimes be developed based on information provided on CAGI data sheets. The data presented in Tables 1 and 7 within this protocol could also be used to chart percent power versus percent capacity in a spreadsheet platform (MS Excel) and develop polynomial fit curves to better estimate part-load values as opposed to using lookup tables.

Step 6: Once the percent power and operating load for each CFM-bin have been determined, calculate the corresponding energy consumption using the product of the average compressor demand and the number of hours in each bin for the base and post cases (Equation 6). The sum of the kWh bin values gives the annual consumption (Equation 7).

$$\Delta kWh_{binN} = (\text{Base } kW_{operating\_binN} - \text{Post } kW_{operating\_binN}) \times \text{CFM-bin N H} \qquad (6)$$

where:

Base $kW_{operating\_binN}$ = baseline demand at part-load associated with CFM-bin N

Post $kW_{operating\_binN}$ = post demand at part-load associated with CFM-bin N

$$\text{Total Energy Reduction (kWh/yr)} = \sum [\, \Delta kWh_{bin1} + \Delta kWh_{bin2} + \ldots + \Delta kWh_{binN} \,] \qquad 970$$

where:

ΔkWh_{bin1} = energy reduction for CFM-bin 1

ΔkWh_{binN} = energy reduction for CFM-bin N

Using the data from our example project (summarized in Table 9) and Equation 6, the CFM-bin level energy reduction for each bin would be as follows:

$$\Delta kWh_{bin1} = (63.5 \text{ kW} - 60.1 \text{ kW}) \times 200 \text{ h} = 692 \text{ kWh}$$

$$\Delta kWh_{bin2} = (61.6 \text{ kW} - 54.0 \text{ kW}) \times 2{,}440 \text{ h} = 18{,}471 \text{ kWh}$$

ΔkWh_{bin3} = (57.6 kW – 40.5 kW) × 170 h = 2,914 kWh

ΔkWh_{bin4} = (56.3 kW – 35.8 kW) × 430 h = 8,839 kWh

ΔkWh_{bin5} = (53.7 kW – 27.7 kW) × 1,100 h = 28,639 kWh

ΔkWh_{bin6} = (17.0 kW – 0.0 kW) × 770 h = 13,090 kWh

ΔkWh_{bin7} = (0.0 kW – 0.0 kW) × 4,420 h = 0 kWh

Table 9. Example Project Compressed-Air CFM-Bin Hour Table and Consumption—Base and Post-Retrofit Cases

		Base Case: Rotary Screw Compressor with Inlet Valve Modulation (w/Blowdown)				Post Case: VSD Rotary Screw Compressor w/Stopping			
CFM-bin #	**CFM Load Profile**	**% Power**	**H/Yr**	**Input Power (kW)**	**kWh**	**% Power**	**H/Yr**	**Input Power (kW)**	**kWh**
CFM-bin 1	324	97%	200	63.5	12,707	89%	200	60.1	12,015
CFM-bin 2	288	94%	2,440	61.6	150,231	80%	2,440	54.0	131,760
CFM-bin 3	216	88%	170	57.6	9,799	60%	170	40.5	6,885
CFM-bin 4	180	86%	430	56.3	24,222	53%	430	35.8	15,383
CFM-bin 5	144	82%	1,100	53.7	59,081	41%	1,100	27.7	30,443
CFM-bin 6	0 idling	26%	770	17.0	13,090	0%	0	0	0
CFM-bin 7	0 shutdown	0%	3,650	0.0	0.0	0%	4,420	0.0	0.0
Total kWh/yr					**269,153**				**196,486**

Using Equation 7 the Total Energy Reduction resulting from the example project would be:

Total Energy Reduction (kWh/yr) =

$= \sum_{0\text{-}7} [\Delta kWh_{bin1} + \Delta kWh_{bin2} + \Delta kWh_{bin3} + \Delta kWh_{bin4} + \Delta kWh_{bin5} + \Delta kWh_{bin6}]$

$= \sum_{0\text{-}7} [692 + 18{,}471 + 2{,}914 + 8{,}839 + 28{,}639 + 13{,}090 + 0]$ kWh

= 72,644 kWh

7 Sample Design

Evaluators will determine the required targets for confidence and precision levels, subject to specific regulatory or program administrator requirements. In most jurisdictions, the generally accepted confidence levels should be designed to estimate operating hours and load profiles~~,~~ with a sampling precision of 10% at the 90% confidence interval.

In addition to sampling errors, errors in measurement and modeling ~~errors~~ can also occur. ~~Generally~~In general, these errors ~~tend to be less~~ are lower than the sampling error; thus, sample sizes are commonly ~~are~~ designed ~~simply~~ to meet sampling precision levels alone.

Sample sizes for achieving ~~the necessary~~this precision level should be determined by estimating the coefficient of variation ~~(CV),~~, calculated as the standard deviation divided by the mean. ~~CVs~~These generally range from 0.5 to 1.06 for compressed~~-~~-air measures, and the more homogeneous the population, the lower the likely ~~CV.~~coefficient of variation. After ~~completing~~ the study~~, the CV~~ is completed, it should be recalculated to determine the actual sampling error of the metered sample. See Chapter 11: Sample Design for further guidance.

7.1 Program Evaluation Elements

To ensure the validity of data collected, establish procedures at the ~~study's~~ beginning of the study to address the following issues:

- Quality of an acceptable regression curve fit (~~e.g.,~~ based on R^2, missing data~~).~~, etc.).
- Procedures for filling in limited amounts of missing data.
- Meter failure (the minimum amount of data from a site ~~data~~ required for analysis).
- High and low data limits (~~e.g.,~~ based on meter sensitivity, malfunction~~).~~, etc.).
- ~~Metered units~~Units to be metered not operational during the site visit ~~(i.e.,~~; for example, determine whether this should be brought to the owner's attention or whether the unit should be metered as is~~).~~.
- Units to be metered malfunction during the mid-metering period and have (or have not) been repaired at the customer's instigation.

~~Including an~~An additional 10% of the number of sites or units ~~will aid in accounting~~should be put into the sample to account for data attrition.

At the beginning of each study, determine whether metering efforts should capture short-term measure persistence. That is, decide how the metering study should capture the impacts of ~~non-operational~~nonoperational rebated equipment (~~e.g.,~~ due to malfunction, equipment never installed~~). Non-operational~~, etc.). For nonoperational equipment, these could be treated as equipment with zero operating hours, or a separate assessment of the in-service rate could be conducted.

7.2 Net-to-Gross Estimation

The cross-cutting chapter, *Estimating Net Savings: Common Practices*, discusses various approaches for determining net program impacts~~A separate cross-cutting~~~~crosscutting~~ ~~protocol for determining~~~~to determine~~ ~~applicable net-to-gross~~ ~~is~~ ~~currently is under development~~~~being developed~~.

References

U.S. Department of Energy (November 2003). "Improving Compressed Air System Performance: A Sourcebook for Industry." Energy Efficiency and Renewable Energy Department, Compressed Air Challenge. Page 20. Online. http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/compressed_air_sourcebook.pdf

DOE (2013). Compressed Air Tip Sheet #3, "Minimize Compressed Air Leaks." Compressed Air Challenge – Air Best Practices.com. www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/compressed_air3.pdf

Product brochure forDOE (2012). Motor Systems Tip Sheet #11, Adjustable Speed Drive Part-Load Efficiency. Accessed June 2014. www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/motor_tip_sheet11.pdf.

Marshall, R. (2013). "Finding and Fixing Leaks." Compressed Air Challenge – Air Best Practices.com. www.airbestpractices.com/system-assessments/leaks/finding-and-fixing-leaks

Scales, William, and David M. McCulloch. "Appendix 2.A.2." Best Practices for Compressed Air Systems. 2nd ed. Alexandria, VA: Compressed Air Challenge, 2013. 123. Print.

Sullair (2014). Sullair S-Energy Lubricated Rotary Screw Air Compressor. Online. http://Product Brochure. www.sullairinfo.com/Downloads/LIT_S-energy_LS14EN.pdf

Marshall, R. (2013). "Finding and Fixing Leaks"." Compressed Air Challenge – Air Best Practices.com. Online. http://www.airbestpractices.com/system-assessments/leaks/finding-and-fixing-leaks

http://www.uesystems.com/new/resources/charts-and-graphs/compressed-air-loss-guesstimator-for-digital-ultraprobes/

U.S. Department of Energy.DOE (2013). Compressed Air Tip Sheet #3, "Minimize Compressed Air Leaks" Compressed Air Tip Sheet #3.." Compressed Air Challenge. Air Best Practices.com. Online. http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/compressed_air3.pdf

Resources

U.S. Department of Energy. (November 2003). "Improving Compressed Air System Performance: A Sourcebook for Industry." – Energy Efficiency and Renewable Energy Department. – Compressed Air Challenge. "Improving Compressed Air System Performance: A Sourcebook for Industry." Online. November 2003. http://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/compressed_air_sourcebook.pdf

Kleinhenz, P., Seryak, J., Sever, F., Brown, S. (2013)., and Go Sustainable Energy, LLC. "Comparison of Metering and Verification Methodologies of Compressed Air Systems for Utility-Based Energy-Efficiency Programs: A Case-Study." ACEEE Summer Study on Energy Efficiency in Industry. 2013.

Scales, B., McCulloch, D. *Best Practices for Compressed Air Systems – Second Edition.* Compressed Air Challenge – Air Best Practices.com. https://www.compressedairchallenge.org/

Compressed Air Challenge Internet Resources

Marshall, R. (March 2011). "VSD Compressor Control" ." March 2011.Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2011-03-CABP.pdf

Marshall, R. (August 2013). "Innovative Dual Pressure Control Improves Efficiency." August 2013. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2013-08-CABP.pdf

Smith, D.E. (April 2012). "Eliminating Pressure Problems in Compressed Air Systems." April 2012. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.airbestpractices.com/system-assessments/pressure/eliminating-pressure-problems-compressed--air-systems

Ghislain, J. (April 2012). "ASME EA-4-2010 – Energy Assessment for Compressed Air Systems." *Compressed Air Challenge – Air Best Practices.com.* Online. http://www.compressedairchallenge.org/library/articles/2012-04-CABP.pdf

van Ormer, H. (2013). "Drive Down Your Energy Costs with Heat of Compression Recovery." 2013. Plant Services.com. Online. http://www.plantservices.com/articles/2013/03-heat-of-compression-recovery.html?page=full

Perry, W. (August 2012). "Optimizing the Supply Side with Intelligent Controls." August 2012. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2012-08-CABP.pdf

Moskowitz, F. (September 2010). "Heat Recovery and Compressed Air Systems." September 2010. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2010-09-CABP.pdf

Wilson, B. (April 2011). "Matching the Supply and Demand in a Compressed Air System." April 2011. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2011-04-CABP.pdf

Fox, T.J. (November 2011). "Cycling Refrigerated Air Dryers— – Are Savings Significant?" November 2011. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2011-11-CABP.pdf

Marshall, R. (November 2012). " "How's the Weather in Your Pipes?" November 2012. Compressed Air Challenge— – Air Best Practices.com. Online. http://www.compressedairchallenge.org/library/articles/2012-11-CABP.pdf.www.compressedairchallenge.org/library/articles/2012-11-CABP.pdf

Scales, B. and Marshall, R. (July 2010). "Baseline and Monitor Efficiency of Compressed Air Systems" ." July 2010. PlantServices.com. Online. http://www.plantservices.com/articles/2010/07MonitorCompressorEfficiency.html

Scales, William, and McCulloch, D.M. (2013). *Best Practices for Compressed Air Systems*. 2nd ed. Alexandria, VA: Compressed Air Challenge, Appendix 2.A.2.

Marshall, R. ~~(2013).~~ "Finding and Fixing Leaks" 2013. Compressed Air Challenge~~—~~ – Air Best Practices.com. ~~Online. http://~~www.airbestpractices.com/system-assessments/leaks/finding-and-fixing-leaks