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## Response to Invitation to Submit Proposals - Compressors

*Additional submitted attachment is included below.*

# Compressors

## Codes and Standards Enhancement (CASE) Initiative
## For PY 2018: Title 20 Standards Development

Analysis of Standards Proposal for
**Compressors**
**18-AAER-05**

March 26, 2018

Prepared for:

PACIFIC GAS &
ELECTRIC COMPANY

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# 1. Purpose

The Codes and Standards Enhancement (CASE) initiative presents recommendations to support the California Energy Commission's (Energy Commission) efforts to update California's Appliance Efficiency Regulations (Title 20). The four California Investor Owned Utilities (IOUs) – Pacific Gas and Electric Company (PG&E), San Diego Gas and Electric (SDG&E), Southern California Edison (SCE), and SoCalGas® – sponsored this effort (herein referred to as the Statewide CASE Team). The program goal is to prepare and submit proposals that will result in cost-effective enhancements to improve the energy and water efficiency of various products sold in California. This report and the code change proposal presented herein is part of the effort to develop technical and cost-effectiveness information for potential appliance standards. This CASE Report covers a standard proposal for certain categories of commercial and industrial air compressors. This CASE Report also addresses a testing and reporting requirement for other categories of commercial and industrial air compressors.

# 2. Product/Technology Description

## 2.1 General Definition of Compressors

A compressor is defined as a mechanical device used to increase the pressure of gaseous media, with a minimum pressure ratio at full-load operating pressure of 1.3. Pressure ratio is defined as the ratio of absolute discharge pressure to the absolute inlet pressure at full-load operating pressure, determined using the test procedure from 10 CFR 431.344 (LBNL and RDC 2003; CFR 2017). See Section 2.5 for a complete scope of compressors covered by this CASE Report.

## 2.2 Uses

Compressors are primarily used to compress air in industrial facilities. Most industrial facilities have at least two compressors, and medium to large sized facilities may use compressed air in hundreds of operations (LBNL and RDC 2003). Examples of industrial sector uses for compressed air are shown below in Table 1.

**Table 1: Industrial Uses of Compressed Air**

| Industry | Example Compressed Air Uses |
|---|---|
| Apparel | Conveying, clamping, tool powering, automated equipment, controls, and actuators |
| Automotive | Tool powering, stamping, forming, conveying, control, and actuators |
| Chemicals | Conveying, controls, and actuators |
| Food | Dehydration, bottling, conveying, spraying coatings, cleaning, vacuum packing, controls, and actuators |
| Furniture | Air piston powering, tool powering, clamping, spraying, controls, and actuators |
| General Manufacturing | Clamping, stamping, tool powering, cleaning, controls, and actuators |
| Lumber and Wood | Sawing, hoisting, clamping, pressure treatment, controls, and actuators |
| Metals Fabrication | Assembly station powering, tool powering, injection molding, spraying, controls, and actuators |
| Petroleum | Process gas compressing, controls, and actuators |
| Primary Metals | Vacuum melting, hoisting, controls, and actuators |

|  |  |
|---|---|
| Pulp and Paper | Conveying, controls, and actuators |
| Rubber and Plastics | Tool powering, clamping, forming, mold press powering, injection molding, controls, and actuators |
| Stone, Clay, and Glass | Conveying, blending, mixing, glass blowing and molding, cooling, controls, and actuators |
| Textiles | Agitating liquids, clamping, conveying, automated equipment, loom jet weaving, spinning, texturizing, controls, and actuators |

Source: LBNL and RDC 2003.

In addition to industrial processes, compressors also play a key role in many non-industrial facilities. See Table 2 for examples of other compressor applications (LBNL and RDC 2003).

**Table 2: Non-Manufacturing Sector Use of Compressed Air**

| **Sector** | **Example Compressed Air Uses** |
|---|---|
| Agriculture | Farm equipment, materials handling, spraying of crops, and dairy machines |
| Mining | Pneumatic tools, hoists, pumps, controls, and actuators |
| Power Generation | Starting gas turbines, automatic control, and emissions controls |
| Recreation | Amusement parks - air brakes |
|  | Golf courses - seeding, fertilizing, and sprinkler systems |
|  | Hotels - elevators and sewage disposal |
|  | Ski resorts - snow making |
|  | Theaters - projector cleaning |
|  | Underwater exploration - air tanks |
| Service Industries | Pneumatic tools, hoists, air brake systems, garment pressing machines, hospital respiration systems, and climate control |
| Transportation | Pneumatic tools, hoists, and air brake systems |
| Wastewater Treatment | Vacuum filters and conveying |

Source: LBNL and RDC 2003.

## 2.3 Product Variations

There are two basic compressor types: positive-displacement and dynamic. Each of these two basic types can be broken down into a number of variations as described below in Figure 1 (LBNL and RDC 2003).

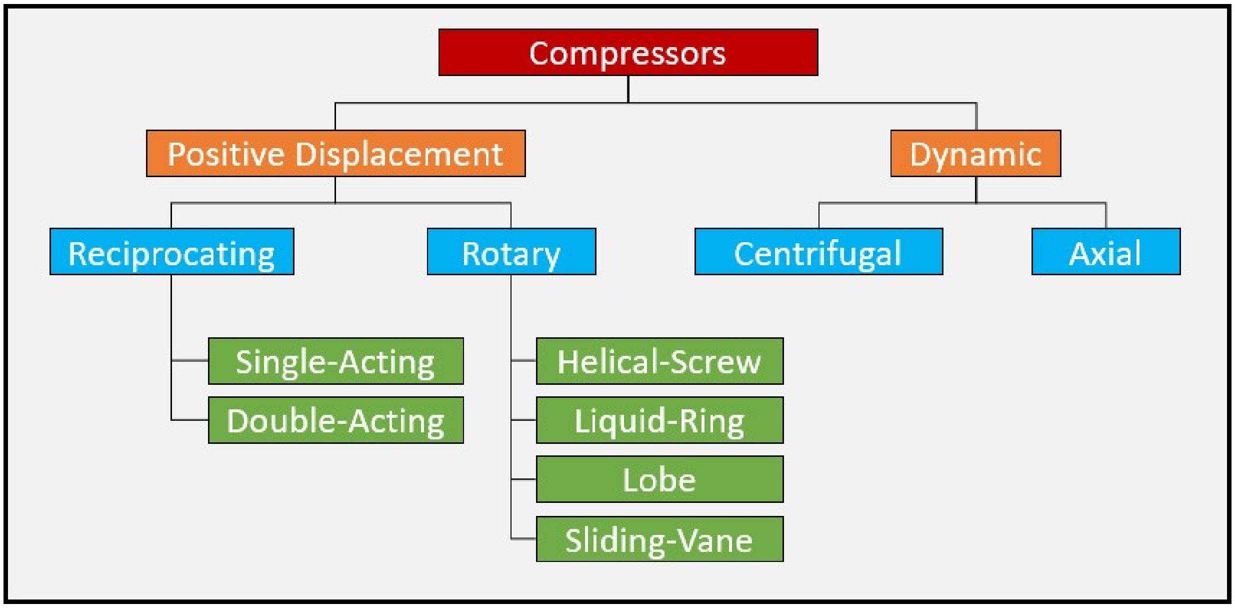

**Figure 1: Compressor type tree.**
Source: LBNL and RDC 2003.

### 2.3.1 Positive-Displacement Compressors

A positive-displacement compressor is a machine in which a volume of gaseous media is trapped in a compression chamber and that volume is mechanically reduced using displacement or a moving member. This forced discharge of the gaseous media into a high-pressure area causes a corresponding pressure rise prior to discharge from the chamber. In this type of compressor, the air flow remains essentially constant, with variations in discharge pressure (LBNL and RDC 2003; U.S. DOE 2017b).

#### 2.3.1.1 Rotary Compressors

Rotary compressors are a type of positive displacement compressor that operate by the cyclical rotation of one or several rotors in a compression chamber filled with a gaseous medium (U.S. DOE 2017b). There are many shapes of rotors, and therefore, a variety of rotary compressor types: helical screw, liquid-ring, sliding-vane, and lobe. Rotary compressors are considered the “workhorse” of American industry (LBNL and RDC 2003). See Figure 2 for an image of a rotary screw compressor.

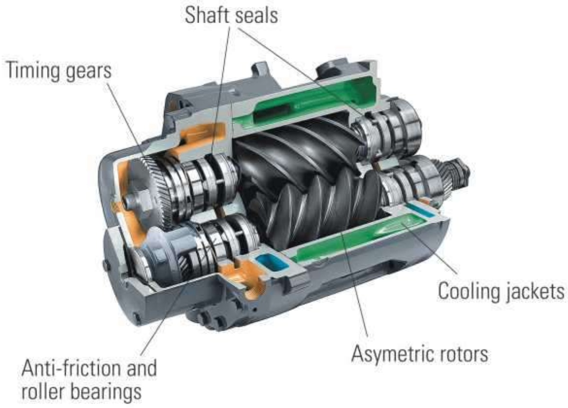

**Figure 2: Image of rotary screw compressor.**
Source: MachineDesign.com 2015.

#### 2.3.1.2 Reciprocating Compressors

Reciprocating compressors are a type of positive-displacement compressor that operate by a piston driven through a crankshaft and connected to a rod by a rotating prime mover (though the scope of this proposal excludes gas engines and focuses solely on electric motors as the prime mover). This mechanism reduces the volume in a compression chamber, which increases the pressure. There are two types of reciprocating compressors: single-acting and double-acting. Single-acting have a compression stroke in only one direction while double-acting have a compression stroke as the piston moves in each direction (LBNL and RDC 2003). See Figure 3 for an image of a reciprocating compressor.

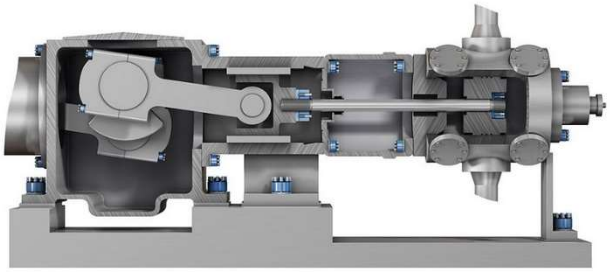

**Figure 3: Image of reciprocating compressor.**

Source: Nord-Lock.com 2016.

### 2.3.2 Dynamic Compressors

Dynamic compressors ("turbo compressors") increase pressure of a continuous flow of gaseous media through velocity energy by means of impellors rotating at very high speeds. This velocity energy is transformed into pressure energy both by impellers and the discharge volutes or diffusers. Dynamic compressors include centrifugal and axial types, which impart energy primarily in radial and axial planes, respectively (LBNL and RDC 2003). See Figure 4 for an image of a dynamic axial compressor.

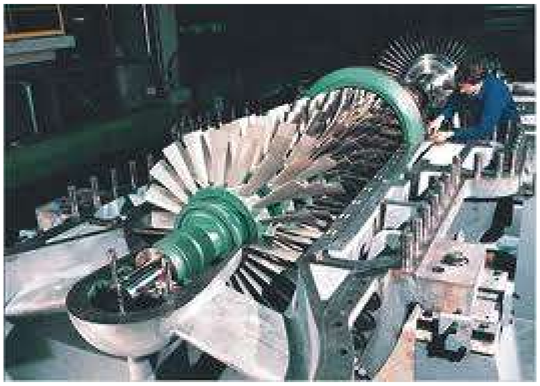

**Figure 4: Image of dynamic axial compressor.**

Source: AerMech.com 2015.

## 2.4 Speed Control

There are two compressor speed control types: fixed-speed and variable-speed.

### 2.4.1 Fixed-Speed

Fixed-speed compressors are the traditional industry standard. As compared with variable-speed compressors, fixed-speed compressors have higher parts availability, lower maintenance and repair costs, lower capital costs, and are generally most efficient in applications with full-load, constant demand (Fluid Aire Dynamics 2016).

#### 2.4.1.1 Fixed-Speed Controls

A variety of controls for fixed-speed compressors allow use for different applications: start/stop, load/unload, modulating controls, dual-control/auto-dual, and variable displacement.

**Start/Stop**

This is the most basic control available where the compressor's motor is switched on or off in response to pressure; the motor is switched on when more pressure is needed and shut off when sufficient pressure is achieved. This control strategy should only be used with compressors that do not cycle frequently. An advantage of this strategy is that the compressor uses no energy when stopped. Conversely, a disadvantage of this strategy is that air must be pressurized to a higher pressure receiver so that air can be drawn from the receiver while the compressor is stopped (LBNL and RDC 2003).

**Load/Unload**

The compressor's motor runs continuously, but unloads when the discharge pressure is adequate. The compressor can still consume 15-35 percent of full-load horsepower (hp) while delivering no useful work when unloaded, making load/unload a potentially inefficient control strategy (LBNL and RDC 2003).

**Modulating Controls**

Closing the inlet valve, which restricts inlet air to the compressor, varies output to meet flow requirements. This control scheme can be used with centrifugal and lubricated rotary screw compressors, but not reciprocating or lubricant-free rotary screw compressors. This control method is inefficient with lubricated rotary screw compressors, and the amount of capacity reduction achievable is limited by the possibility of the system entering "surge," or flow instability (LBNL and RDC 2003).

**Dual-Control/Auto-Dual**

Dual control includes either start/stop or load/unload to be chosen for small reciprocating compressors. For lubricated rotary screw compressors, auto-dual allows modulation to a preset reduced capacity, followed by unloading and an overrun timer that stops the compressor from running unloaded beyond a pre-set time (Compressed Air 2003).

**Variable Displacement**

Compressors' volumes are varied using sliding or turn valves and are typically used with modulating inlet valves (LBNL and RDC 2003).

### 2.4.2 Variable-Speed

Variable-speed compressors are most appropriate for applications with dynamic demand because they adjust the frequency and voltage supplied to the motor, thus changing the speed of the motor based on the demand for air. They are less efficient at full-load than fixed-speed compressors, but are more efficient at partial load. As compared with fixed-speed compressors, variable-speed compressors are quieter when running at a lower rotation per minute, have increased component lifetime, and reduce energy consumption when used in the proper application (Fluid Aire Dynamics 2016).

### 2.4.3 Combined

Fixed and variable compressors can be used in conjunction by using the variable-speed compressor as a “trim compressor” for any pressurization necessary that the fixed compressor cannot complete at full-load. This combined approach also allows for flexibility during maintenance, as one compressor can run while the other is repaired (Fluid Aire Dynamics 2016).

## 2.5 Scope of Products

### 2.5.1 Product Scope of Rulemaking

The proposed rulemaking applies to compressors that meeting the following criteria:[1]

- Are air compressors;
- Are rotary compressors;
- Are not scroll compressors;[2]
- Are not liquid ring compressors;
- Are driven by a brushless electric motor;
- Are lubricated compressors;
- Are not designed and tested to the requirements of The American Petroleum Institute (API) standard 619, “Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries”;
- Operate at a full-load operating pressure from 75 to 200 pounds per square inch gauge (psig); and
- Operate at a capacity of either:
  - ten to 200 motor nominal hp, or
  - 35 to 1,250 full-load volume flow rate (cubic feet per minute (cfm)).

### 2.5.2 Product Scope of Test-and-List Requirement

The Statewide CASE Team proposes an additional test-and-list requirement for the two independent scope criteria sets that fall outside of the rulemaking scope.

The first scope set is described by the following criteria:

- Are air compressors;
- Are reciprocating compressors;
- Are not scroll compressors;[3]

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[1] Please note that the proposed rulemaking closely mirrors U.S. DOE’s commercial and industrial air compressors rulemaking.

[2] U.S. DOE does not consider scroll compressors to be rotary compressors, and therefore are not included in the U.S. DOE rulemakings. The proposed rulemaking does not propose any efficiency standards for scroll compressors.

[3] U.S. DOE does not consider scroll compressors to be rotary compressors, and therefore are not included in the U.S. DOE rulemakings. The proposed rulemaking does not propose any efficiency standards for scroll compressors.

- Are not liquid ring compressors;
- Are driven by a brushless electric motor;
- Are not designed and tested to the requirements of API standard 619, "Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries";
- Operate at a full-load operating pressure from 75 to 200 psig; and
- Operate at a capacity of either:
    - one to 500 motor nominal hp, or[4]
    - 35 to 1,250 full-load volume flow rate cfm.

The second scope set includes the following criteria:

- Are air compressors;
- Are rotary compressors;
- Are not scroll compressors;
- Are not liquid ring compressors;
- Are driven by a brushless electric motor;
- Are either non-lubricated compressors that:
    - Are not designed and tested to the requirements of API standard 619, "Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries";
    - Operate at a full-load operating pressure from 75 to 200 psig; and
    - Operate at a capacity of either:
        - one to 500 motor nominal hp, or
        - 35 to 1,250 full-load volume flow rate cfm.
- Or are lubricated compressors that:
    - Are not designed and tested to the requirements of API standard 619, "Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries";
    - Operate at a full-load operating pressure from 75 to 200 psig; and
    - Operate at a capacity of:
        - Greater than or equal to one to less than ten motor nominal hp or greater than 200 to less than or equal to 500 motor nominal hp, and
        - Does not fall between 35 to 1,250 full-load volume flow rate cfm.

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[4] The test procedure would cover one to 500 motor nominal hp.

## 2.6 Efficiency Definition

The compressor efficiency in this document is defined by package isentropic efficiency $\eta_{Regr}$, which is equal to the ratio of the theoretical isentropic power to the actual package compressor power required for the compression process, and is a function of full-load actual volume flow rate (U.S. DOE 2016d). The expressions in Table 3 are used to calculate the package isentropic efficiency for rotary, lubricated, air cooled, fixed-speed, and variable-speed compressors, where $V_1$ represents the full-load actual volume flow rate of the compressor in cfm. These expressions represent the regression curves defined by U.S. DOE for each equipment class (U.S. DOE 2016d).

**Table 3: Package Isentropic Efficiency by Equipment Class**

| Equipment Class | Package Isentropic Efficiency $\eta_{Regr}$ |
|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | $-0.00928*\ln^2(0.4719*V_1)+0.13911*\ln(0.4719*V_1)+0.27110$ |
| Rotary, lubricated, air-cooled, variable-speed | $-0.01549*\ln^2(0.4719*V_1)+0.21573*\ln(0.4719*V_1)+0.00905$ |
| Rotary, lubricated, liquid-cooled, fixed-speed | $-0.00928*\ln^2(0.4719*V_1)+0.21573*\ln(0.4719*V_1)+0.00905$ |
| Rotary, lubricated, liquid-cooled, variable-speed | $-0.01549*\ln^2(0.4719*V_1)+0.21573*\ln(0.4719*V_1)+0.00905$ |

Source: U.S. DOE 2016d.

Efficiency levels (EL) for each equipment class are defined by shifting the regression curves with specific "d-values." A positive d-value represents the percentage improvement from the market average package isentropic efficiency to theoretical 100 percent package isentropic efficiency. A negative d-value represents the losses from the market average package isentropic efficiency to the baseline efficiency. A d-value of 100 represents an efficiency level at 100 percent package isentropic efficiency, while 0 represents the average package isentropic efficiency on the market. The baseline efficiency is defined as the lowest efficiency equipment present in the market for each equipment class (U.S. DOE 2016d).

U.S. DOE establishes specific d-values and efficiency levels across all equipment classes, and are found in Table 4 below. See Table 5 for an example of a proposed d-value (proposed standard level) and set of expressions. Figure 5 shows all ELs plotted together for rotary, fixed-speed, lubricated, air-cooled compressors. This plot illustrates how the actual package isentropic efficiency value varies over the range of compressors flow rates, and shows the range of efficiencies from the base case (EL 0) up to max-tech (EL 6). See Section 4.3 for the full set of proposed standard levels.

**Table 4: Efficiency Levels and d-Values for all Equipment Classes**

| Efficiency Level (EL) | Rotary, lubricated, air-cooled, fixed-speed (d-Value) | Rotary, lubricated, air-cooled, variable-speed (d-Value) | Rotary, lubricated, liquid-cooled, fixed-speed (d-Value) | Rotary, lubricated, liquid-cooled, variable-speed (d-Value) |
|---|---|---|---|---|
| Baseline | -49 | -30 | -49 | -45 |
| EL 1 | -30 | -20 | -30 | -30 |
| EL 2 | -15 | -10 | -15 | -15 |
| EL 3 | 0 | 0 | 0 | 0 |
| EL 4 | 5 | 5 | 5 | 5 |
| EL 5 | 13 | 15 | 13 | 15 |
| EL 6 | 30 | 33 | 30 | 34 |

Source: U.S. DOE 2016d.

**Table 5: Example Proposed Standard Level with Applied d-Value Corresponding to EL 2**

| Equipment Class | Standard Level (package isentropic efficiency) | $\eta_{Regr}$ (package isentropic efficiency reference curve) | d-Value (percentage loss reduction) |
|---|---|---|---|
| Rotary, lubricated, air-cooled, variable-speed | $\eta_{Regr} + (1 - \eta_{Regr}) * (d/100)$ | $-0.01549 * \ln^2(0.4719 * V_1) + 0.21573 * \ln(0.4719 * V_1) + 0.00905$ | -10 |

Source: U.S. DOE 2016a.

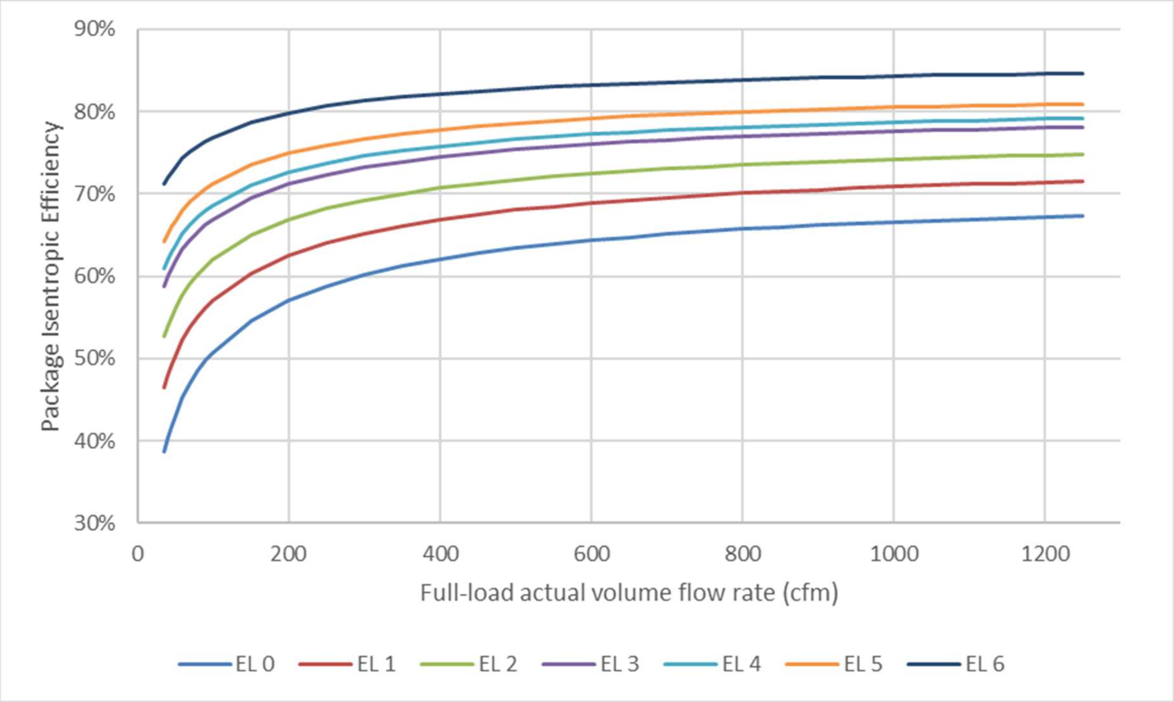

**Figure 5: ELs for rotary, fixed-speed, lubricated, air-cooled compressors.**
Source: U.S. DOE 2016a.

## 2.7 Relative Energy Use

Air compressors are used in a variety of industries and applications, have an assortment of sizes and types, and can be found at most industrial facilities (LBNL and RDC 2003). The Energy Commission's 2006 California Commercial End-Use Survey (Itron 2006) found that air compressors are responsible for roughly one percent of all commercial electricity consumption in California (CEC 2006). While electricity consumption for air compressors is less than other systems—such as lighting or heating, ventilation, and air-conditioning (HVAC)—it still represents a significant opportunity to increase efficiency and reduce electricity consumption. This is especially true since there are currently no federal or state efficiency standards for air compressors. See Figure 6 below for information on commercial electricity consumption in California.

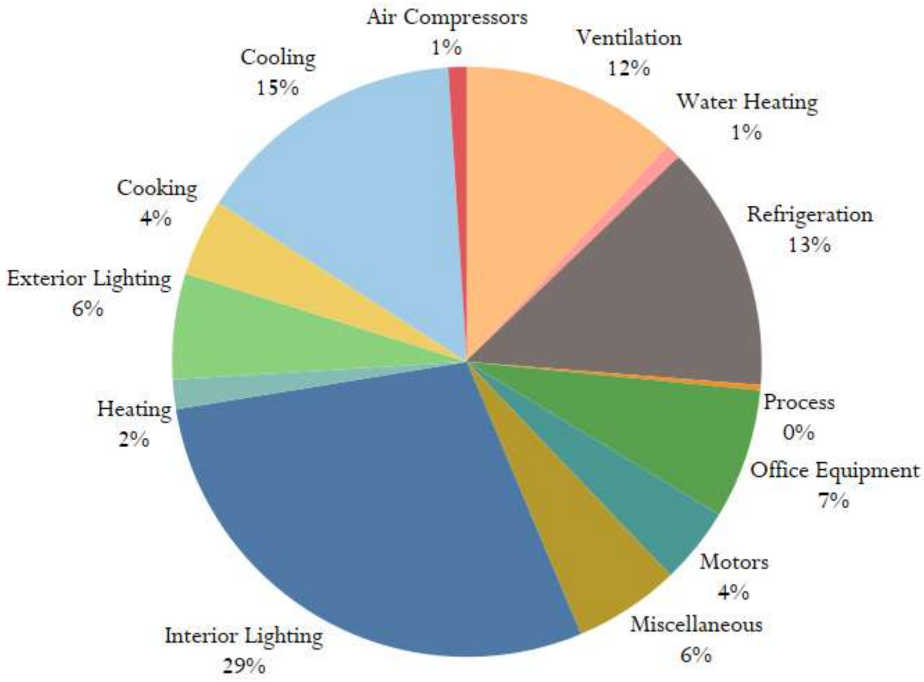

**Figure 6: Commercial electricity usage by end use.**
Source: CEC 2006.

## 2.8 Product Design Cycle

U.S. DOE originally began developing a standard and test procedure for compressors in 2012, giving stakeholders substantial time to provide feedback on the proposed changes as well as prepare for changes associated with the new standard. Given the ample time for preparation, the Statewide CASE Team proposes a one-year period between adoption of this standard and its effective date.

# 3. Standards Proposal Overview

This CASE Report is based heavily on the U.S. DOE commercial and industrial air compressors energy conservation standard and test procedures. The U.S. DOE began its investigation into a potential air compressors standard in 2012 and, over the subsequent four years, engaged with industry stakeholders and efficiency advocates in developing a framework, test procedure, and energy conservation standard. The Statewide CASE Team's proposal builds upon this work.

The Statewide CASE Team proposes a scope for compressors subject to an energy conservation standard identical to the scope in the U.S. DOE pre-published final rule from December 2016 (U.S. DOE 2016a). This includes rotary, lubricated, fixed-speed, and variable-speed compressors within size boundaries established in the U.S. DOE test procedure for air compressors (U.S. DOE 2017b). The Statewide CASE Team proposes minimum package isentropic efficiency requirements at efficiency level (EL) 3 for all compressor equipment classes subject to an energy conservation standard. Additionally, the Statewide CASE Team proposes testing and reporting (test-and-list) requirements for reciprocating, non-lubricated, and rotary compressors that fall outside of the input motor hp bounds, subject to energy conservation standards. Further details on scope can be found in Section 2.5.

The Statewide CASE Team estimates that adoption of this standard would result in 538 gigawatt hours per year (GWh/yr) of electricity savings after stock turnover, a statewide net present value (NPV) of $477 million after stock turnover, and a benefit-to-cost (B/C) ratio of 5.5 (total present value (PV) of benefits divided by total PV of costs). Stock turnover will occur in 2031 if the standard is adopted in 2019.

**Table 6: Summary of Proposal**

| Topic | Description |
|---|---|
| Description of Standards Proposal/Framework of Roadmap | The Statewide CASE Team proposes to require that all compressors covered by the scope in Section 2.5 are tested using the full-load or partial-load package isentropic efficiency test procedures described in Section 4.3.2 and meet the minimum EL 3, as defined by product type. Additionally, the Statewide CASE Team proposes that reciprocating compressors, non-lubricated rotary compressors, and rotary compressors from one to ten and 200 to 500 hp be subjected to the test procedure described in Section 4.3.2 and report package isentropic efficiency to be eligible for sale in California. |
| Technical Feasibility | Product efficiency opportunities are described in depth in Section 5.2. In summary, opportunities include compressor staging, air-end improvement (e.g., manufacturing precision, surface finish, mechanical design clearances, and aerodynamic efficiency), and auxiliary component improvement (e.g., valves, piping system, drive motor, capacity controls, fans, fan motors, filtration, drains, and driers). |
| Energy Savings and Demand Reduction | This proposal will yield 538 GWh/yr and 84 megawatts (MW) of demand reduction after stock turnover in 2031. |
| Environmental Impacts and Benefits | This proposal will yield savings of 8,033 metric tons of carbon dioxide equivalent (MTCO2e) per year and a total 88,341 MTCO2e total after stock turnover in 2031. These figures are based on the projected carbon intensity of the California electricity supply over the coming years (see Section 5.6.1). |

| | |
|---|---|
| Economic Analysis | This proposal will lead to significant cost savings for consumers with $33 million in first-year savings and over $477 million NPV after stock turnover in 2031. Additionally, on a shipment weighted basis there is a lifecycle B/C ratio of 5.5. |
| Consumer Acceptance | The commercial and industrial air compressors market is mature. Customers are typically sophisticated and will understand the benefits that a higher efficiency product will bring. However, it should be noted that no air compressor energy conservation standard has existed in the past, and the concept of package isentropic efficiency may be unfamiliar to certain segments of the market. Therefore, some customer education efforts may be required to prepare the market for this new standard (CAGI 2015; Van Elburg and van den Boorn 2014a). |
| Other Regulatory Considerations | This energy conservation standard, testing, and reporting requirement will not interfere with other local, state, or federal regulations. California Title 24, Part 6 does include standards for air compressors and associated controls, but there is no conflict between the established building code standard and the proposed standard. Title 24, Part 6 standards regulate air compressor systems, while the proposed Title 20 standards will regulate compressor energy consumption (CEC 2016b). See Section 5.11.2 for more details. The U.S. DOE initiated (but did not complete) an energy conservation standard. The U.S. DOE did complete a test procedure final rule, enforced as of December 30, 2017 (U.S. DOE 2017a). The Statewide CASE Team proposes that the Energy Commission reference this test procedure in Title 20 with additional equipment classes subject to testing and reporting. |

Source: Statewide CASE Team 2018.

# 4. Proposed Standards and Recommendations

## 4.1 Proposal Description

U.S. DOE analyzed European Union (EU) Lot 31 and information provided by Compressed Air and Gas Institute (CAGI) to understand the package isentropic efficiency of compressors currently sold into the marketplace. It was determined that airflow is the primary variable that drives efficiency variations within a single equipment class. Therefore, compressor efficiency standards are described as a function of full-load airflow (U.S. DOE 2016c). The Statewide CASE Team proposes standard levels for identical equipment classes that were in the U.S. DOE energy conservation standard final rule, but at EL 3. Compressors have not been subject to energy conservation standards in the past, necessitating a new section for such in Title 20.

## 4.2 Proposal History

No energy efficiency requirements for compressors currently exist in the United States. In 2012, U.S. DOE began the process of developing standards for compressors. U.S. DOE issued a framework document in 2014, and a notice of proposed rulemaking in 2016. U.S. DOE pre-published a final rule in December 2016, but did not finalize the rule in the Federal Register. U.S. DOE finalized a test procedure for compressors in January 2017, which took effect in December 2017. The EU completed Lot 31 in 2014 and finalized compressor standards in 2015, to take effect in 2018 (Tier 1) and 2020 (Tier 2, which is the same as EL 3) (ECEEE 2014). U.S. DOE decided to set standards for rotary, lubricated compressors only. Furthermore, there are lower and upper bounds on airflow, motor hp, and outlet pressure, which limit the number of compressors subject to the efficiency standard.

Compressors have never been considered in previous Title 20 rulemakings. However, Title 24, Part 6 (CEC 2016b) requires that trim compressors must be variable-speed (see Section 5.11.2).

## 4.3 Proposed Changes to the Title 20 Code Language

The proposed changes to the Title 20 standards are provided below. Changes to the 2017 standards are marked with underlining (new language) and ~~strikethroughs~~ (deletions).

The text below was adapted from the U.S. DOE final rule with modifications to make the text more appropriate for Title 20 Section 1605 (DOE 2016a). The standard would reside in Section 1605.3: State Standards for Non-Federally Regulated Appliances.

References to Table 1Table 7 in the text below refer to the relative position of the table within this standards proposal document, but the table label would require adjustment to match the relative position of the table in Title 20 Section 1605 if the proposed language is adopted.

**Air Compressor Energy conservation standards and effective dates.**

(a) Each compressor that is manufactured starting on January 1, 2019, and that:

(1) Is an air compressor,

(2) Is a rotary compressor,

(3) Is not a liquid ring compressor,

(4) Is not a scroll compressor,

(5) Is driven by a brushless electric motor,

(6) Is a lubricated compressor,

(7) Has a full-load operating pressure greater than or equal to 75 pounds per square inch gauge (psig) and less than or equal to 200 psig,

(8) Is not designed and tested to the requirements of The American Petroleum Institute standard 619, "Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries,"

(9) Has full-load actual volume flow rate greater than or equal to 35 cubic feet per minute (cfm), or is distributed in commerce with a compressor motor nominal horsepower greater than or equal to 10 horsepower (hp),

(10) Has a full-load actual volume flow rate less than or equal to 1,250 cfm, or is distributed in commerce with a compressor motor nominal horsepower less than or equal to 200 hp,

(11) Is driven by a three-phase electric motor,

(12) Is manufactured alone or as a component of another piece of equipment, and

(13) Is in one of the equipment classes listed in the Table 7, must have a full-load package isentropic efficiency or part-load package isentropic efficiency that is not less than the appropriate "Minimum Package Isentropic Efficiency" value listed in Table 7 of this section.

**Table 7: Energy Conservation Standards for Certain Compressors**

| **Equipment Class** | **Standard Level (minimum package isentropic efficiency)** | **$\eta_{Regr}$ (package isentropic efficiency reference curve)** | **d-Value (percentage loss reduction)** |
|---|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | $\eta_{Regr} + (1-\eta_{Regr}) * (d/100)$ | $-0.00928 * \ln^2(0.4719 * V_1) + 0.13911 * \ln(0.4719 * V_1) + 0.27110$ | 0 |
| Rotary, lubricated, air-cooled, variable-speed | $\eta_{Regr} + (1-\eta_{Regr}) * (d/100)$ | $-0.01549 * \ln^2(0.4719 * V_1) + 0.21573 * \ln(0.4719 * V_1) + 0.00905$ | 0 |
| Rotary, lubricated, liquid-cooled, fixed-speed | $0.02349 + \eta_{Regr} + (1-\eta_{Regr}) * (d/100)$ | $-0.00928 * \ln^2(0.4719 * V_1) + 0.13911 * \ln(0.4719 * V_1) + 0.27110$ | 0 |
| Rotary, lubricated, liquid-cooled, variable-speed | $0.02349 + \eta_{Regr} + (1-\eta_{Regr}) * (d/100)$ | $-0.01549 * \ln^2(0.4719 * V_1) + 0.21573 * \ln(0.4719 * V_1) + 0.00905$ | 0 |

Source: U.S. DOE 2016a.

(b) Instructions for the use of Table 7 of this section:

(1) To determine the standard level a compressor must meet, the correct equipment class must be identified. The descriptions are in the first column ("Equipment Class"); definitions for these descriptions are found in Title 20 Section 1602.

(2) The second column ("Standard Level (minimum package isentropic efficiency)") contains the applicable energy conservation standard level, provided in terms of package isentropic efficiency.

(3) For "Fixed-speed compressor" equipment classes, the relevant Package Isentropic Efficiency is Full-load Package Isentropic Efficiency. For "Variable-speed compressor" equipment classes, the relevant Package Isentropic Efficiency is Part-load Package Isentropic Efficiency. Both Full and Part-load Package Isentropic Efficiency are determined in accordance with the air compressors test procedure at 10 C.F.R. §431.344.

(4) The second column ("Standard Level (minimum package isentropic efficiency)") references the third column ("$\eta_{Regr}$ (package isentropic efficiency reference curve)") and the fourth column ("d-Value (percentage loss reduction)").

(5) The third column is a function of $V_1$, the full-load actual volume flow rate, described in terms of cubic feet per minute ("cfm") and determined in accordance with the air compressors test procedure at 10 C.F.R. §431.344.

### 4.3.1 Proposed Definitions

The Statewide CASE Team proposes that the Energy Commission use the definitions contained within the Code of Federal Regulations (10 C.F.R. §431.342), the federal rulemaking framework (U.S. DOE 2014), and the pre-published energy conservation standard final rule (U.S. DOE 2016a) in a new "Compressors" subsection to Title 20 Section 1602 "Definitions". For convenience, the definitions are reproduced here (in alphabetical order, combined from the two sources):

"Actual volume flow rate" means the volume flow rate of air, compressed and delivered at the standard discharge point, referred to conditions of total temperature, total pressure, and composition prevailing at the standard inlet point, and as determined in accordance with the test procedures prescribed in 10 C.F.R. § 431.344.

"Air compressor" means a compressor designed to compress air that has an inlet open to the atmosphere or other source of air, and is made up of a compression element (bare compressor), driver(s), and mechanical equipment to drive the compressor element, and any ancillary equipment.

"Air-cooled compressor" means a compressor that utilizes air to cool both the compressed air and, if present, any auxiliary substance used to facilitate compression, and that is not a liquid-cooled compressor.

"Ancillary equipment" means any equipment distributed in commerce with an air compressor but that is not a bare compressor, driver, or mechanical equipment. Ancillary equipment is considered to be part of a given air compressor, regardless of whether the ancillary equipment is physically attached to the bare compressor, driver, or mechanical equipment at the time when the air compressor is distributed in commerce.

"Auxiliary substance" means any substance deliberately introduced into a compression process to aid in compression of a gas by any of the following: Lubricating, sealing mechanical clearances, or absorbing heat.

"Bare compressor" means the singular machine responsible for the change in air pressure and is sometimes referred to as an "air end," which is the compression chamber where air is compressed. ISO 12942 refers to this level of equipment as the "mechanical compressor." This term is inclusive of auxiliary devices required for performing the gas compression process (e.g. inlet and outlet valves, seals, lubrication system, and gas flow paths) but exclusive of the following:

(1) The driver;

(2) Speed-adjusting gear(s);

(3) Gas processing apparatuses and piping; and

(4) Compressor equipment packaging and mounting facilities and enclosures.

"Basic model" means all units of a class of compressors manufactured by one manufacturer, having the same primary energy source, the same compressor motor nominal horsepower, and essentially identical electrical, physical, and functional (or pneumatic) characteristics that affect energy consumption and energy efficiency.

"Brushless electric motor" means a machine that converts electrical power into rotational mechanical power without use of sliding electrical contacts.

"Compressor" means a machine or apparatus that converts different types of energy into the potential energy of gas pressure for displacement and compression of gaseous media to any higher-pressure values above atmospheric pressure and has a pressure ratio at full-load operating pressure greater than 1.3.

"Compressed air system (CAS)" means the compressor inclusive of all componentry attached, including components from the air intake to the final 'point-of-use." This system boundary includes the many configuration packages that could be attached such as the distribution (piping) network, air-treatment systems, sequencers, storage tanks, and any end-use equipment (e.g., pneumatic tools).

"Compressor motor nominal horsepower" means the motor horsepower of the electric motor, as determined in accordance with the applicable procedures in subparts B and X of 10 C.F.R. § 431, with which the rated air compressor is distributed in commerce.

"Driver" means the machine providing mechanical input to drive a bare compressor directly or through the use of mechanical equipment.

"Fixed-speed compressor" means an air compressor that is not capable of adjusting the speed of the driver continuously over the driver operating speed range in response to incremental changes in the required compressor flow rate.

"Full-load actual volume flow rate" means the actual volume flow rate of the compressor at the full-load operating pressure.

"Liquid-cooled compressor" means a compressor that utilizes liquid coolant provided by an external system to cool both the compressed air and, if present, any auxiliary substance used to facilitate compression.

"Liquid ring compressor" means a compressor that utilizes a rotating impeller with protruding blades eccentrically mounted in a stationary round housing or centrally mounted in a stationary elliptical housing. Liquid ring compressors are a type of rotary compressor.

"Lubricant-free compressor" means a compressor that does not introduce any auxiliary substance into the compression chamber at any time during operation.

"Lubricated compressor" means a compressor that introduces an auxiliary substance into the compression chamber during compression.

"Maximum full-flow operating pressure" means the maximum discharge pressure at which the compressor is capable of operating, as determined in accordance with the test procedure prescribed in 10 C.F.R. § 431.344.

"Mechanical equipment" means any component of an air compressor that transfers energy from the driver to the bare compressor.

"Package compressor" means the compressor inclusive of ancillary equipment. This option includes a driver, such as an electric motor, and may include other equipment, such as gears, drains, air treatment (filtering) equipment, onboard controls, etc. This configuration is considered the single largest piece of equipment brought to market by an individual manufacturer.

"Package isentropic efficiency" means the ratio of power required for an ideal isentropic compression process to the actual packaged compressor power input used at a given load point, as determined in accordance with the test procedures prescribed in 10 C.F.R. § 431.344.

"Package specific power" means the compressor power input at a given load point, divided by the actual volume flow rate at the same load point, as determined in accordance with the test procedures prescribed in 10 C.F.R. § 431.344.

"Positive displacement compressor" means a compressor in which the admission and diminution of successive volumes of the gaseous medium are performed periodically by forced expansion and diminution of a closed space(s) in a working chamber(s) by means of displacement of a moving member(s) or by displacement and forced discharge of the gaseous medium into the high-pressure area.

"Pressure ratio at full-load operating pressure" means the ratio of discharge pressure to inlet pressure, determined at full-load operating pressure in accordance with the test procedures prescribed in 10 C.F.R. § 431.344.

“Reciprocating compressor” means a positive displacement compressor in which gas admission and diminution of its successive volumes are performed cyclically by straight-line alternating movements of a moving member(s) in a compression chamber(s).

“Rotary compressor” means a positive displacement compressor in which gas admission and diminution of its successive volumes or its forced discharge are performed cyclically by rotation of one or several rotors in a compressor casing.

“Rotor” means a compression element that rotates continually in a single direction about a single shaft or axis.

“Scroll compressor” means a positive displacement compressor in which gas admission and diminution of its successive volumes or its forced discharge are performed cyclically by nutating (or orbiting) one or several rotors in a compressor casing. Scroll compressors are not considered rotary compressors because they nutate (or orbit) instead of rotating continuously in a single direction around an axis.

“Variable-speed compressor” means an air compressor that is capable of adjusting the speed of the driver continuously over the driver operating speed range in response to incremental changes in the required compressor actual volume flow rate.

“Water-injected lubricated compressor” means a lubricated compressor that uses injected water as an auxiliary substance.

### 4.3.2 Proposed Test Procedure

The Statewide CASE Team proposes that the Energy Commission use the compressors test procedure contained within the Code of Federal Regulations (10 C.F.R. § 431.344) as the test procedure for this equipment standard. The U.S. DOE test procedure incorporates ISO 1217:2009(E) (including Amendment 1: 2016, “Calculation of isentropic efficiency and relationship with specific energy”) by reference with modifications. The U.S. DOE test procedure modifications include the full and part-load isentropic efficiency metrics, clarifications to ISO 1217:2009(E), which specify operating ranges, the types of compressors subject to the standard, sampling plans, representations requirements, and enforcement provisions.

To enable the “test-and-list” requirements that the Statewide CASE Team is recommending for categories of compressors not subject to the energy conservation standard, the Energy Commission will need to amend the U.S. DOE test procedure by expanding its scope to include non-lubricated rotary compressors, reciprocating compressors, and all compressor motor input power ratings from one to 500 hp.

### 4.3.3 Proposed Standard Metrics

The Statewide CASE Team proposes that the standard metric be package isentropic efficiency. Package isentropic efficiency is the ratio of the theoretical isentropic power required for a compression process to the actual power required for the same process (DOE 2016a). A package isentropic efficiency rating of 100 percent implies that the compression process did not result in any increase in entropy in the air stream between the inlet and discharge of the compressor, and is impossible in practice. The package isentropic efficiency rating of a fixed-speed compressor is calculated differently than that of a variable-speed compressor. For a fixed-speed compressor, “package isentropic efficiency” refers to “full-load package isentropic efficiency” ($\eta_{isen,FL}$) and is calculated at full-load operating pressure and 100 percent of the full-load actual volume flow rate of air. For a variable-speed compressor, “package isentropic efficiency” refers to “part-load package isentropic efficiency” ($\eta_{isen,PL}$), and is a weighted composite of performance at three load points (100, 70, and 40 percent of full-load). Full-load package isentropic efficiency is described in Equation 1, and part-load package isentropic efficiency is described in Equation 2.

**Equation 1. Full-load Package Isentropic Efficiency**

$$\eta_{isen,FL} = \frac{P_{isen,100\%}}{P_{real,100\%}}$$

where $\eta_{isen,FL}$ is the package isentropic efficiency at full-load operating pressure, $P_{isen,100\%}$ is the isentropic power required for compression at full-load operating pressure, and $P_{real,100\%}$ is the packaged compressor power input at full-load operating pressure.

**Equation 2. Part-load Package Isentropic Efficiency**

$$\eta_{isen,PL} = \sum_{i} \omega_i \frac{P_{isen,i}}{P_{real,i}}$$

where $\eta_{isen,PL}$ is the part-load package isentropic efficiency, $\omega_i$ is the weighting factor for rating point i, $P_{isen,i}$ is the isentropic power required for compression at rating point i, $P_{real,i}$ is the packaged compressor power input at rating point i, and i is the load points at 100, 70, and 40 percent of full-load actual volume flow rate.

The package isentropic power is the power that is theoretically required to compress an ideal gas under constant entropy, from a given inlet pressure to a given discharge pressure, in multi-stage compression. Further, the package isentropic power at any operating point is described in Equation 3 (U.S. DOE 2017b)

**Equation 3. Package Isentropic Power at Any Operating Point**

$$P_{isen} = \dot{V}_{1\_m3/s} \cdot P_1 \frac{\kappa}{(\kappa - 1)} \cdot \left[ \left( \frac{P_2}{P_1} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]$$

In Equation 3, $\dot{V}_{1\_m3/s}$ is the volumetric flow rate, $P_1$ is the inlet pressure (atmospheric in this case), $P_2$ is the discharge pressure at the tested operating point (determined in accordance with Section 5.2 of ISO 1217:2009(E)), and $\kappa$ is the isentropic exponent of air (ratio of specific heats, set at a value of 1.400). The actual package specific power at any test point is calculated in accordance with ISO 1217:2009(E).

The part-load package isentropic efficiency weighting factors for each of the three load points are 25 percent at 100 percent full-load, 50 percent at 70 percent full-load, and 25 percent at 40 percent full-load. The proposed weighting factors are aligned with the EU Lot 31 draft standard, due to a lack of industry weighting factors or real-world load profile data as rationale for the proposed weights. At each part-load point, it is the volumetric flow rate of air that is reduced, and the pressure remains at full-load operating pressure (Van Elburg and van den Boorn 2014b).

### 4.3.4 Proposed Reporting Requirements

The Statewide CASE Team proposes the following pieces of information be included for each compressor entry in the Energy Commission Modernized Appliance Efficiency Database System (MAEDBS):

- Manufacturer;
- Brand;
- Model Number;
- Add Date;

- Regulatory Status (subject to energy conservation standard or “test-and-list”);
- Compressor motor nominal horsepower;
- Compressor Type (reciprocating or rotary);
- Speed Control (fixed or variable-speed);
- If fixed-speed, which Control Type: start/stop, load/unload, modulating controls, dual-control/auto-dual, or variable displacement;
- Lubricant Presence (lubricated or non-lubricated);
- Full-load Operating Pressure (psig);
- Maximum Full-flow Operating Pressure (psig);
- Pressure Ratio at Full-load Operating Pressure;
- Full-load Rated Airflow (cfm);
- Isentropic Efficiency Rating (full or part-load package) (as applicable);
- Minimum Isentropic Efficiency (required full or part-load package).

# 5. Analysis of Proposal

## 5.1 Scope/Framework

### 5.1.1 Scope Overview

This scope of compressors subject to the efficiency standard is identical to the scope in the U.S. DOE pre-publication Final Rule for compressor energy conservation standards. In addition, the Statewide CASE Team proposes that the Energy Commission subject other categories of compressors to test-and-list requirements. The compressors subject to the rulemaking and the test-and-list requirement are found in Section 2.5.

### 5.1.2 Package Compressor Level Scope Justification

The Statewide Case Team evaluated the possibility to regulate compressors at the following system boundary levels: "bare" compressor, package compressor, of compressed air system (CAS) as defined in Section 4.3.1.The scope is defined at the package compressor-level, rather than the compressed air system (CAS)-level for the following reasons:

- Each CAS is unique to installation site;
- Each CAS includes equipment from several manufacturers; and
- A single CAS may contain multiple compressors that operate at different full-load operating pressures.

The scope is defined at the package compressor-level, rather than bare compressor-level, because of the greater opportunity for energy savings through proper component selection and package design.

### 5.1.3 Compression Principle Classification

Rotary and reciprocating compressors were analyzed for standard feasibility. The compressors are classified by equipment class because of the differential utility and ability to reach greater efficiencies between rotary and reciprocating compressors. The scope was limited to rotary compressors because standards for reciprocating compressors were not found to be economically justified. The available reciprocating compressors data set is very limited, which suggests a potential risk in implementing standards without more information. The Statewide CASE Team recommends test-and-list for reciprocating compressors to enable regulators to gain data and information to consider include reciprocating compressors in a future energy conservation standard (U.S. DOE 2016a).

### 5.1.4 Exclusion of Scroll Compressors

"Scroll compressor" is defined as a positive displacement compressor in which gas admission and diminution of its successive volumes or its forced discharge are performed cyclically by nutating (or orbiting) one or several rotors in a compressor casing. Scroll compressors are explicitly excluded from the scope of the proposed rulemaking because they nutate (or orbit) instead of rotating continuously in a single direction around an axis, and therefore are not considered rotary compressors (U.S. DOE 2016a).

### 5.1.5 Exclusion of Liquid Ring Compressors

"Liquid ring compressor" is defined as a machine with a rotating impeller with protruding blades eccentrically mounted in a stationary round housing or centrally mounted in a stationary elliptical housing. Liquid ring compressors are a type of rotary compressors. Liquid ring compressors are explicitly excluded from the scope of the proposed rulemaking because they are used in unique applications that require a durable compressor tolerant of dirty input air and ingested liquid. Therefore, they require different test methods from those proposed in the test procedure (U.S. DOE 2016a).

### 5.1.6 Motor Scope Justification

Non-electric drivers were excluded from the scope because they have differing utility from electric compressors and are covered under the U.S. Environmental Protection Agency's Tier 4 emissions regulations. Additionally, limited test data is available to verify suitability to the test procedure.

Brushed motors were excluded from the scope because they serve a niche role in the market and have low market penetration. Brushed motors are rarely used in applications with significant operating hours due to their higher maintenance costs, short operating lives, significant acoustic noise, and electrical arcing. They are therefore not a substitution risk to compressors within the scope of this report (U.S. DOE 2016a).

### 5.1.7 Lubricant Scope Justification

Compressors are manufactured in either lubricated or lubricant-free configurations. "Lubricated compressor" is a compressor that introduces an auxiliary substance into the compression chamber during compression. Under this definition, compressors would be considered "lubricated" if any auxiliary substance of any sort were introduced into the compression chamber, including oil and water (water is not typically described as a lubricant within the compressor industry). "Lubricant-free compressor" is a compressor that does not introduce any auxiliary substance into the compression chamber at any time during operation. Lubricant-free compressors may still use lubricant within other portions of the compressor, as long as the lubricant does not enter the compression chamber at any point during operation.

Lubricant-free compressors are excluded from the scope for the following reasons:

- The test method and metric are not directly applicable to lubricant-free compressors.

- An opportunity exists to universalize the efficient market scope for manufacturers and consumers by harmonizing with the EU regulatory process, which does not include lubricant-free compressors.
- A substitution risk—whereby consumers substitute unregulated technologies, such as dynamic compressors, for regulated lubricant-free compressors—is avoided.

Additionally, lubricant-free compressor data is scarce; it is difficult to create an accurate independent test procedure for this application. The limited dataset provides a strong justification for including lubricant-free compressors in the test-and-list scope (U.S. DOE 2016a).

### 5.1.8 Operating Pressure Scope Justification

The pressure range scope of 75 to 200 psig is used because:

- Isentropic efficiency is approximately independent of pressure in the range specified.
- Most compressors operate in the 80 to 125 psig range, and some operate in the 125 to175 psig range, so the pressure scope would include almost all commercially available compressors, eliminating a substitution risk.

### 5.1.9 Operating Capacity Scope Justification

The lower end of the capacity range (ten hp) is defined in order to avoid substitution risk of scroll and reciprocating compressors for regulated rotary compressors. The upper capacity limit (200 hp) is defined by the upper limit of the CAGI Performance Verification Program. Data is not readily available for ELs and trial standard levels (TSLs) above 200 nominal hp because of this limit. Limited data provides a good justification for including small (one to ten hp) and large (200 to 500 hp) compressors in the test-and-list scope (U.S. DOE 2016a).

### 5.1.10 Flow Rate and Capacity Coupling

The scope definition couples the compressor capacity with the actual volume flow rate as suggested by Sullair and CAGI in their letters to the U.S. DOE (Sullair, LLC 2016; CAGI 2016). This coupled capacity/flow rate prevents manufacturers from altering hp ratings to add a nominally larger hp motor in order to circumvent standards. CAGI performance data sheets were used to determine the flow rate range of ten to 200 hp nominal hp motors, and a 35 to 1,250 cfm inclusive range was determined to encompass the range of compressor capacity specified. The flow rate range is broader than the capacity range by approximately nine percent for fixed-speed compressors and three percent for variable-speed compressors, ensuring that the range does not further shrink the scope (U.S. DOE 2016a).

### 5.1.11 Customized Compressors Exclusion

The scope is limited to compressors that are not are not designed and tested to the requirements of the API standard 619, “Rotary-Type Positive-Displacement Compressors for Petroleum, Petrochemical, and Natural Gas Industries”. The standard specifies certain minimum requirements for compressors used in the petroleum, gas, and chemical industry. It also requires that customers specify many design requirements themselves, and thus compressors designed to meet API 619 are inherently customized compressors. API 619 requires rigorous testing, data reporting, and data retention requirements. Therefore, customized compressors that are regulated under API 619 are distinguished from general-purpose compressors, and are not included in the scope because the compressors cannot be compared one-to-one with the general-purpose compressors in the scope (U.S. DOE 2016a).

## 5.2 Product Efficiency Opportunities

U.S. DOE consulted with manufacturers, design engineers, and other interested parties in their analysis of technology options to improve compressor efficiency. U.S. DOE identified three package redesign categories that would improve the overall package efficiency of air compressors, and determined which are technologically feasible (U.S. DOE 2016a).

The first technology available is multi-staging. A multi-stage compressor has a series of cylinders of different diameters, each representing a different stage. Between each compression stage, the air is cooled using a heat exchanger, which reduces the total amount of work needed to compress the air for its final use (Quincy Compressor 2016). In a letter submitted to U.S. DOE's Proposed Determination For Commercial And Industrial Compressors As Covered Equipment, Ingersoll Rand noted that two-stage compression improves efficiency by approximately 12-15 percent as compared to single-stage compression (Ingersoll Rand 2013). U.S. DOE also performed an analysis on pairs of single and two-stage lubricated rotary screw compressors that had CAGI performance data sheets, and found that adding a stage improved specific power by 11 percent over their single-stage counterparts (U.S. DOE 2016d). **Figure 7**a shows the total work required for single-stage compression while **Figure 7**b shows the total work required for dual-stage compression. As shown, the total work, or the area under the curve, for a compressor with multiple stages is less than the total work for a compressor with a single stage.

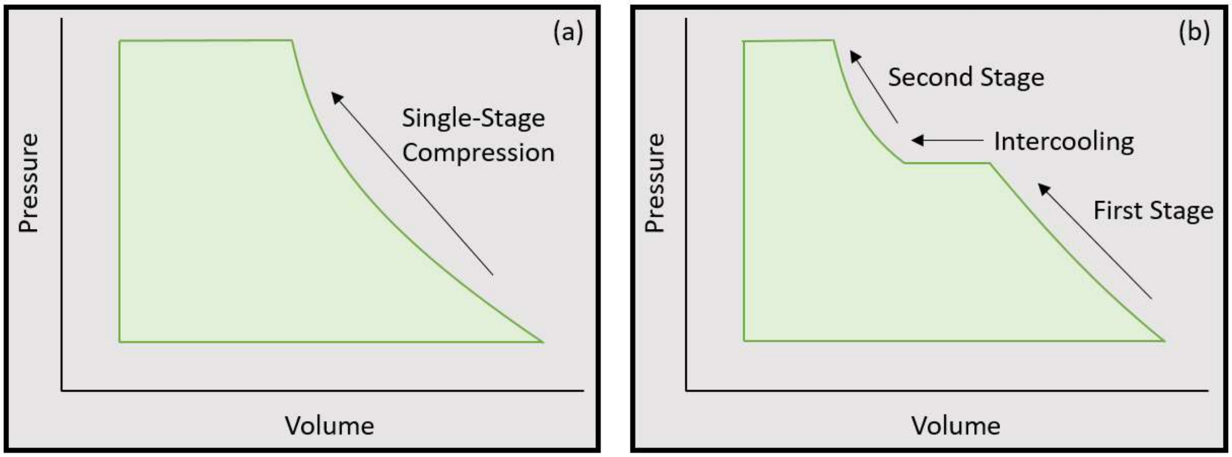

**Figure 7: Work required for (a) single-stage and (b) dual-stage compression.**
Source: Statewide CASE Team 2018.

The second technology U.S. DOE considered was air-end improvement. An air-end is defined as the compression element without the prime mover or transmission (Van Elburg and van den Boorn 2014a) and air-end efficiency depends on a number of factors including: rated compressor output capacity; compression chamber geometry; operating speed; surface finish; manufacturing precision; and designed equipment tolerances. Since air-ends can operate at multiple flow rates, manufacturers often use a single air-end in multiple packages by changing the operating point, frame size of the package, or the package configuration. This simplifies the number of compressors manufacturers need to provide across the market, but reduces the package efficiency of the compressors. There are two ways manufacturers can increase efficiency through air-end improvement. The first is improving design properties of the air-end that affect efficiency, including manufacturing precision, surface finish, mechanical design clearances, and overall aerodynamic efficiency. The second is to match air-ends and applications more appropriately by building a larger number of air-end designs. This would allow each air-end to operate more closely to its optimal operating point (U.S. DOE 2016a).

Third, U.S. DOE analyzed auxiliary component improvement. This technology involves improving the operating characteristics of the auxiliary parts of the compressor package, such as valves, piping system, motor, capacity controls, fans, fan motors, filtration, drains, and driers, which could all affect the overall package efficiency. However, it is important to remember that the design process involved in implementing higher efficiency auxiliary components is more nuanced than simply replacing a less efficient part for a more efficient one. These parts are often complementary, thus requiring careful design of the overall package in order for the parts to properly work together. This could potentially increase design costs for manufacturers, but is nevertheless an important consideration in increasing compressor package efficiency (U.S. DOE 2016a).

## 5.3 Technical Feasibility

All three technology options described in Section 5.2 were deemed implementable by U.S. DOE based on: technological feasibility; practicability to manufacture, install, and service; impact on equipment utility or equipment availability; and potential adverse impacts on health or safety (U.S. DOE 2016a). Additionally, in their analysis, U.S. DOE concluded that the standards they proposed would not reduce the utility or performance of any of the covered products (U.S. DOE 2016a). Given that this rulemaking is proposing a very similar standard, it can be concluded that this proposal will likewise not reduce utility or performance of covered products.

Table 8 below from U.S. DOE's analysis shows the percentage of qualifying products available in the market today.

**Table 8: Percentage of Qualifying Products Available in the Market Today**

| Trial Standard Level (TSL) | Fixed-Speed | Variable-Speed |
|---|---|---|
| 1 | 88% | 88% |
| 2 | 72% | 72% |
| 3 | 56% | 56% |
| 4 | 39% | 39% |
| 5 | 33% | 33% |
| 6 | 22% | 22% |

Source: U.S. DOE 2016d.

The Statewide CASE Team recommends adopting TSL 3, resulting in a total of 56 percent of the currently available products already meeting the standard. In order to meet the standard, manufacturers may focus their product offering on products that already meet the efficiency standard. Alternatively, they may alter the design of their products to include multiple compression stages, improve the air-end efficiency, or improve performance of the auxiliary components.

In summary, the Statewide CASE Team believes this proposal is technically feasible given U.S. DOE's previous analysis and recommendations.

### 5.3.1 Future Market Adoption of Qualifying Products

To estimate current base-case efficiency distribution, U.S. DOE used the frequency of efficiencies from CAGI's voluntary testing program data and the distribution of efficiencies of shipments used in the pumps rulemaking (U.S. DOE 2016d). These numbers were scaled for the capacity range of compressors and adjusted for the fact that pump shipment efficiencies were skewed towards higher efficiencies. Based on these numbers, U.S. DOE reported the base case efficiency distribution for all equipment classes covered under this standard, as shown in Table 9.

**Table 9: Base-Case Efficiency Distribution for all Equipment Classes**

| Efficiency Level (EL) | Air-Cooled | Liquid-Cooled |
|---|---|---|
| 0 | 12% | 12% |
| 1 | 16% | 16% |
| 2 | 16% | 16% |
| 3 | 18% | 18% |
| 4 | 6% | 6% |
| 5 | 11% | 11% |
| 6 | 22% | 22% |

Source: U.S. DOE 2016d.

The data collected indicate that, without a standard, this distribution will remain constant over time because there is no trend towards market adoption of higher efficiency products (U.S. DOE 2016d).

As shown in Table 8, 56 percent of compressors currently meet TSL 3. Given that the majority of products in the market that currently meet the proposed standard level, the Statewide CASE team does not see a barrier for products to meet the proposed standard.

## 5.4 Statewide Energy Savings

### 5.4.1 Per Unit Energy Savings Methodology

This section describes the methodology the Statewide CASE Team used to estimate energy and environmental impacts. The Statewide CASE Team calculated the impacts of the proposed code change by comparing non-qualifying products to qualifying products.

The Statewide CASE Team drew heavily from the U.S. DOE analysis for information regarding per unit energy consumption by efficiency level, product lifetime, shipments, and cost data by efficiency level. The per unit energy consumption data came from the Final Rule TSD Chapter 7: Energy Use Analysis (U.S. DOE 2016d). The product lifetime data came from the Final Rule Technical Support Document Chapter 8: Life-Cycle Cost and Payback Period Analysis (U.S. DOE 2016d). The shipments data and cost data by efficiency level came from the Final Rule National Impact Analysis (U.S. DOE 2016b).

The analysis assumes a standard effective year of 2019. The Statewide CASE Team chose efficiency level (EL) 3. This was done to align with EU standards and to deliver significant, cost-effective savings for California electricity users.

The Statewide CASE Team has provided the unit energy consumption, incremental measure costs, energy savings, and cost-effectiveness outputs for a potential compressors standard at EL 2 for the Energy Commission's reference. This information is contained in Appendix C: EL 2 Results. The savings and cost-effectiveness are still significant at EL 2 but not as significant as EL 3. Furthermore, EL 3 has the benefit of aligning California with the EU. However, because U.S. DOE decided to pursue EL 2, the Statewide CASE Team is showing these results for California for reference.

#### 5.4.1.1 Annual Per Unit Energy Use Methodology

As mentioned in 5.4.1, the per unit energy use originated from the U.S. DOE analysis. These figures were obtained by product class and EL (ranging from 0 to 6). However, the per unit energy use does not refer to a specific capacity due to the U.S. DOE analysis, wherein the lifecycle cost sample used to derive the energy use results contained a wide range of capacities. Across the entire spectrum of compressors, the energy use is representative of average compressor energy consumption at each EL.

#### 5.4.1.2 Peak Demand Methodology

Peak demand was calculated by multiplying daily electricity use by an assumed load factor. A load factor is the ratio of average annual load to coincident peak load. The Statewide CASE Team obtained end-use load factors through consultations with the Energy Commission. The load factors used in this report were developed by the Energy Commission using an Hourly Energy and Load Model (HELM) developed by Brown and Koomey (2002) on 2013 utility-level energy demand data. A complete table of updated values for several end uses is included in Appendix B: Load Factors.

### 5.4.2 Summary of Per Unit Energy Use Impacts

Annual per unit energy impacts are presented in Table 10, Table 11, and Table 12 below.[5,6] Baseline products are the current distribution of products in the marketplace (EL 0) and qualifying products are products that meet the proposed standards (EL 3). The methodology used to calculate these estimates is presented above in Section 5.4.1.

**Table 10: Per Unit Energy Use for Baseline Products (EL 0)**

| Compressor Equipment Classes | Size and Application Weighted Electricity Use (kWh/yr) | Peak Demand (W) |
|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 147,820 | 23,116 |
| Rotary, lubricated, liquid-cooled, fixed-speed | 283,157 | 44,279 |
| Rotary, lubricated, air-cooled, variable-speed | 131,497 | 20,563 |
| Rotary, lubricated, liquid-cooled, variable-speed | 226,302 | 35,388 |
| Shipment Weighted Average | 170,262 | 26,625 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

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[5] Annual electricity use values are directly from the U.S. DOE analysis.

[6] To arrive at peak demand, the Statewide CASE Team adapted U.S. DOE derived annual energy data to California using an Hourly Energy and Load Model (HELM) (Brown and Koomey 2002).

**Table 11: Per Unit Energy Use and Potential Savings for Qualifying Products (EL 3)**

| Compressor Equipment Classes | Size and Application Weighted Electricity Use (kWh/yr) | Peak Demand (W) |
|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 139,611 | 21,832 |
| Rotary, lubricated, liquid-cooled, fixed-speed | 269,791 | 42,189 |
| Rotary, lubricated, air-cooled, variable-speed | 125,899 | 19,688 |
| Rotary, lubricated, liquid-cooled, variable-speed | 214,598 | 33,558 |
| Shipment Weighted Average | 161,296 | 25,223 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

**Table 12: Annual Per Unit Energy Savings**

| Compressor Equipment Classes | Size and Application Weighted Electricity Use (kWh/yr) | Peak Demand (W) |
|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 8,209 | 1,284 |
| Rotary, lubricated, liquid-cooled, fixed-speed | 13,366 | 2,090 |
| Rotary, lubricated, air-cooled, variable-speed | 5,598 | 875 |
| Rotary, lubricated, liquid-cooled, variable-speed | 11,704 | 1,830 |
| Shipment Weighted Average | 8,965 | 1,402 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

### 5.4.3 Stock

Air compressors are installed in a wide variety of applications and end-uses. A few of the most popular uses of air compressors are for pneumatics, packaging and automation equipment, and conveyors (LBNL and RDC 2003). Any industrial or commercial setting where pneumatic tools are used, pneumatic controls are employed, or even requires compressed air as an oxidizer for a combustion process will have a need for an air compressor.

The Statewide CASE Team estimated the California compressors stock based on U.S. DOE's analysis of shipments, and was then subsequently weighted for California's proportion of the national population. See Section 5.4.4 for more information on how shipments were estimated.

The California compressors stock is based on product lifetime and annual compressor shipments. It was assumed that each year's shipments would remain in service for the product's average lifetime. The shipment weighted average lifetime for compressors is 13.0 years. The U.S. DOE analysis dates to 2014. As a result, for any year prior to 2027, shipments from years prior to 2014 would be required to estimate the compressors stock for that given year. For the purposes of this analysis, years prior to 2014 are assumed to have shipments equal to 2014.

### 5.4.4 Shipments

The U.S. DOE shipments were estimated from confidential shipments data from manufacturers, U.S. Census Bureau data, and the Energy Information Administration's Annual Energy Outlook to project shipments out into the future (U.S. DOE 2016d).

Table 9 shows the distribution of products across ELs for all equipment classes. U.S. DOE determined that the distribution of ELs did not vary by equipment class.

Shipments are unevenly distributed among the four equipment classes as well as whether equipment is used in a commercial or industrial setting. Of the four equipment classes for which a standard is proposed, most shipments are for rotary fixed-speed, lubricated, air-cooled compressors going to industrial applications. See Table 13 for a full breakout of shipments by market sector and equipment class.

**Table 13: Compressor Shipments by Equipment Class and Market Sector**

| Compressor Equipment Classes | Commercial Shipments | Industrial Shipments | Total Shipments |
|---|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 3.2% | 73.5% | 76.8% |
| Rotary, lubricated, liquid-cooled, fixed-speed | 0.1% | 16.3% | 16.3% |
| Rotary, lubricated, air-cooled, variable-speed | 0.1% | 5.3% | 5.4% |
| Rotary, lubricated, liquid-cooled, variable-speed | N/A | 1.5% | 1.5% |
| Total Shipments | 3.4% | 96.6% | 100% |

Source: U.S. DOE 2016b

### 5.4.5 Current and Future Shipments

U.S. DOE's analysis projects a roughly three percent annual growth rate in shipments in 2019. U.S. DOE data has been converted into California-specific data in Table 14 (scaled shipments with California's share of national population from U.S. Census Bureau, Population Division 2015). Full stock turnover will occur in 2031, assuming a weighted average 13.0-year lifetime across all product classes and a standard effective year of 2019.

**Table 14: California Shipments and Stock**

| Year | Annual Shipments | Stock[7] |
|---|---|---|
| 2019 (standards take effect) | 3,053 | 37,909 |
| 2031 (after stock turnover) | 4,676 | 52,762 |

Source: U.S. DOE 2016b; Statewide CASE Team 2018.

### 5.4.6 Statewide Energy Savings - Methodology

This section presents the statewide energy savings and environmental impacts of the proposed code change for the first year that the 2019 Standards take effect, and 2031 when the stock turns over. This includes the amount energy that will be saved by California owners and operators, and impacts on material. Statewide savings estimates were calculated by applying the per unit energy savings to the statewide stock and sales forecast presented in Section 5.4.7 as shown below.

### 5.4.7 Statewide Energy Use – Non-Standards and Standards Case

**Table 15: California Statewide Energy Use – Non-Standards Case (After Effective Date)**

| | Annual Shipments | | Stock | |
|---|---|---|---|---|
| Year | Electricity Use (GWh/yr) | Peak Demand (MW) | Electricity Use (GWh/yr) | Peak Demand (MW) |
| 2019 (standards take effect) | 520 | 81 | 6,599 | 1,032 |
| 2031 (after stock turns over) | 803 | 126 | 9,556 | 1,494 |

Source: U.S. DOE 2016b; Statewide CASE Team 2018.

**Table 16: California Statewide Energy Use – Standards Case (After Effective Date)**

| | Annual Shipments | | Stock | |
|---|---|---|---|---|
| Year | Electricity Use (GWh/yr) | Peak Demand (MW) | Electricity Use (GWh/yr) | Peak Demand (MW) |
| 2019 (standards take effect) | 492 | 77 | 6,571 | 1,028 |
| 2031 (after stock turns over) | 754 | 118 | 9,018 | 1,410 |

Source: Statewide CASE Team 2018.

**Table 17: California Statewide Energy Savings – Standards Case (After Effective Date)**

| | Annual Shipments | | Stock | |
|---|---|---|---|---|
| Year | Electricity Use (GWh/yr) | Peak Demand (MW) | Electricity Use (GWh/yr) | Peak Demand (MW) |

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[7] Shipment weighted product life of 13.0 years was used to determine stock.

|  |  |  |  |  |
|---|---|---|---|---|
| 2019 (standards take effect) | 27 | 4.3 | 27 | 4.3 |
| 2031 (after stock turns over) | 49 | 7.6 | 538 | 84.1 |

Source: Statewide CASE Team 2018.

## 5.5 Cost-Effectiveness

This section describes the methodology and approach the Statewide CASE Team used to analyze the economic impacts of the proposed standard.

### 5.5.1 Incremental Cost

Incremental cost is the calculated difference of equipment in EL 0 and EL 3. These results are represented below in Table 18. The rotary, lubricated, liquid-cooled, variable-speed product class represented the highest incremental cost.

**Table 18: Weighted Incremental Cost**

| Compressor Equipment Class | Incremental Cost Over Baseline |
|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | $2,089 |
| Rotary, lubricated, liquid-cooled, fixed-speed | $3,531 |
| Rotary, lubricated, air-cooled, variable-speed | $2,723 |
| Rotary, lubricated, liquid-cooled, variable-speed | $5,751 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

### 5.5.2 Design Life

The Statewide CASE Team referenced the numbers from the U.S. DOE's report. The U.S. DOE based the estimated average lifetime by equipment class on existing literature, and used these estimates to develop statistical distributions. The report defined two types of lifetimes: (1) mechanical lifetime, which is the total lifetime hours of operation (including routine maintenance and repairs); and (2) service lifetime, which is the number of years the consumer owns and uses the unit, and is equal to the mechanical lifetime divided by the annual hours of operation.

**Table 19: Average Service Lifetime (Years)**

| Compressor Product Class | Average Service Lifetime (years) |
|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 12.9 |
| Rotary, lubricated, liquid-cooled, fixed-speed | 13.4 |
| Rotary, lubricated, air-cooled, variable-speed | 13.2 |

| | |
|---|---|
| Rotary, lubricated, liquid-cooled, variable-speed | 13.5 |

Source: U.S. DOE 2016d.

### 5.5.3 Lifecycle Cost/Net Benefit

The per unit and total lifecycle costs and benefits of the proposed standard are presented in Table 20 below. In this case the period of analysis is the weighted average product life, 13.0 years. The cost impacts are presented in PV and NPV. The energy benefits savings per unit over the 13.0-year period are presented in Table 20 for the compressor classes evaluated, weighted by shipping. These savings validate this proposed measure's cost-effectiveness.

**Table 20: Costs and Benefits per Unit for Qualifying Products**

| **Product Class** | **Product Life (years)** | **Lifecycle Costs per Unit (PV $)**[8] | | **Lifecycle Benefits per Unit (PV $)** | | **NPV per Unit ($)** |
|---|---|---|---|---|---|---|
| | | Incremental Cost[9] | Total PV Costs | Electricity Savings[10] | Total PV Benefits | Electricity |
| Shipment Weighted Compressor | 13.0 | 2,415 | 2,415 | 13,239 | 13,239 | 10,824 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

## 5.6 Environmental Impacts/Benefits

### 5.6.1 Greenhouse Gases

Table 21 presents the annual and stock greenhouse gas (GHG) savings for the first year the standards take effect (2019), and the year of full stock turnover (2031). The Statewide CASE Team calculated the avoided GHG emissions from the adoption of the standard, assuming an emissions rate varying by year, in accordance with California's projected emissions factors as outlined in the 2017 update to the California Air Resources Board (CARB) scoping plan to meet the 2030 greenhouse gas targets (CARB 2017).

The Statewide CASE Team used CARB data (CARB 2017) to determine an avoided carbon dioxide emission factor. CARB prepared an analysis of increasing California's Renewable Portfolio Standard (RPS) from 20 percent renewables by 2020 to 33 percent renewables by 2020 with different future electricity demand scenarios.[11] The emissions factor used in this report is intended to provide a benchmark of emissions reductions attributable to energy efficiency measures that would help achieve the low load scenario. The emissions factor is calculated by dividing the difference between California emissions in the high and low generation forecasts by the difference between total electricity generated in those two scenarios. While emission rates may change over time, 2020 is a representative year for this measure.

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[8] PV calculated using the Energy Commission's average statewide PV statewide energy rates that assume no discount rate (CEC 2017).

[9] Incremental cost is the cost difference between the baseline non-qualifying product and the qualifying product.

[10] Cost savings will be realized through lower electricity bills. Average annual electricity was used, starting in the effective year.

[11] CARB calculated GHG emissions for two scenarios: (1) a high load scenario in which load continues at the same rate and (2) a low load rate that assumes the state will successfully implement energy efficiency strategies outlined in the AB32 (Global Warming Solutions Act) scoping plan, which would reduce overall electricity load in the state (CARB 2017). The Statewide CASE Team calculated the emissions factors of the incremental electricity savings between the low and high load scenarios.

As show in Table 21 below, the estimated annual statewide GHG savings is 6,029 $MTCO_2e$ the first year the standard is in effect, and 8,033 $MTCO_2e$ after full stock turnover in 2031. The stock GHG savings is 88,341 $MTCO_2e$ in year 2031 after full stock turnover.

**Table 21: Estimated California Statewide Greenhouse Gas Savings for Standards Case**

| Product Class | Annual GHG Savings (MTCO2e/yr) | Stock GHG Savings (MTCO2e/yr) |
|---|---|---|
| 2019 (start takes effect) | 6,029 | 6,029 |
| 2031 (after stock turns over) | 8,033 | 88,341 |

Source: Statewide CASE Team 2018.

### 5.6.2 Indoor or Outdoor Air Quality

Compressors often experience compression medium leakage. For the case of standard air compressors, leakage does not pose any environmental threats. For the case of non-air compressors, leakage can have a direct environmental impact as inert gases or other process gases (which can be hazardous, toxic, or flammable) leak into the air, damaging air quality. The scope of compressors that would cause air quality damage is not covered by the proposed standard or test procedure (Van Elburg and van den Boorn 2014a).

### 5.6.3 Hazardous Materials

Certain compressors are used in hazardous environments; combustion or explosion is a possibility. Compressors are adapted to hazardous environments through modification of electrical components and enclosures that protect against sparks and high temperatures. Hazardous environment compressors are designed for their specific environments and given a rating of certification using the National Electrical Code (NEC) that matches the environment for which they are designed.

Non-air compressors use process gases that can be hazardous, toxic, or flammable. These can potentially leak into the air, which is a hazard to the surrounding community and environment. These compressors are not, however, included in the scope of the proposed standard or test procedure.

## 5.7 Impact on California's Economy

If set at a reasonable level, an appliance standard can positively impact the economy through widespread energy savings among ratepayers while also not severely impacting the manufacturing community. Several indicators suggest that the proposed standards will positively impact California's economy. Operators will benefit from lower energy bills. Manufacturers contacted by the U.S. DOE anticipated no significant financial impact with ample notice of appliance standard changes. There are no small businesses manufacturers of air compressors in this class that are based in California. Therefore, the Statewide CASE Team does not expect the proposed appliance standard to have an adverse impact on California's economy.

**Table 22: Statewide Total Lifecycle Costs and Benefits for Standards Case**

| Product Class | Lifecycle B/C Ratio[12,13] | NPV[14] | |
|---|---|---|---|
| | | For First-Year Shipments ($ million) | Stock Turnover[15] ($ million) |
| Shipment Weighted Compressor | 5.5 | 33.05 | 477.07 |

Source: Statewide CASE Team 2018.

## 5.8 Consumer Utility/Acceptance

There are currently no Federal or State standards for air compressors. Therefore, it may be necessary to educate manufacturers on the new standard requirements. CAGI already devotes resources for education and training designed to improve system-wide efficiency (CAGI 2015). Additionally, CAGI has stated that membership of their Rotary Positive Compressor Section comprises the majority of U.S. companies which participate in that market (CAGI 2015); having them as an advocate will help inform the majority of manufacturers of covered products. Thus, it may be helpful to work with CAGI in efforts to educate manufacturers.

Consumer buying behavior is dependent on the compressor size. Buying large compressors requires understanding of detailed specifications, advanced technical expertise, and coordinated sales effort. Both the seller and the consumer have a sophisticated understanding of how energy efficient products impact the overall lifecycle costs of the equipment. For medium and small compressors, buying occurs through independent distributors, air centers, and retailers, who have the technical expertise to understand the energy cost benefits of using a more efficient compressor, though the consumer is occasionally less sophisticated about the benefits of energy efficiency (Van Elburg and van den Boorn 2014a).

## 5.9 Manufacturer Structure and Supply Chain Timelines

The majority of compressors covered in this proposal are sold through manufacturers. As listed on the CAGI website, the companies that manufacture compressors which employ positive displacement and rotary motion are:

- Air Squared, Inc.[16]
- ALMiG USA Corporation
- Atlas Copco Compressors LLC
- BOGE America

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[12] The analysis does not include cost savings associated with embedded energy savings.

[13] Total PV benefits divided by total PV costs. Positive value indicates a reduced total cost of ownership over the life of the appliance.

[14] It should be noted that while the proposed standard is cost-effective, it may be more cost-effective if using alternative rate structures. For example, marginal utility rates may more accurately reflect what customers save on utility bills as result of the standard.

[15] Stock Turnover NPV is calculated by taking the sum of the NPVs for the products purchased each year following the standard's effective date through the stock turnover year (i.e., the NPV of "turning over" the whole stock of less efficient products that were in use at the effective date to more efficient products, plus any additional non-replacement units due to market growth, if applicable). For example, for a standard effective in 2015 applying to a product with a five-year design life, the NPV of the products purchased in the fifth year (2019) includes lifecycle cost and benefits through 2024, and therefore, so does the Stock Turnover NPV.

[16] Air Squared only manufactures oil-free compressors, which are not covered by the proposed standard.

- Chicago Pneumatic Compressors
- COAIRE, Inc.
- Chicago Pneumatic Tool Co.
- DV Systems Inc.
- Elgi Compressors USA, Inc.
- FS-Curtis
- Hitachi America Limited
- Gardner Denver, Inc.
- Ingersoll Rand
- Kaeser Compressors, Inc.
- Mattei Compressors
- Quincy Compressor
- Sullair, LLC
- Sullivan-Palatek, Inc.

CAGI has claimed that these members of their "Rotary Positive Compressor" section represent the majority of the companies in this market sector in the U.S. (CAGI 2016). All of the companies listed are based outside of California.

More on the typical product design cycle for compressors is explained in Section 2.8.

## 5.10 Stakeholder Positions

The key stakeholders for this rulemaking are the manufacturers listed in Section 5.9.

During the U.S. DOE rulemaking, there were several stakeholder comments. CAGI's comments indicated that they would support TSL 2 with a revised analysis such that the standard did not impose significant hardship on the industry. They requested a defined list of equipment to be tested as part of the compressor package, suggested only inclusion of compressors with nominal horsepower of ten to 200 hp, agreed with separating the product classes based on lubricant presence, and opposed separate class designations for air-cooled and water-cooled equipment (CAGI 2016). Manufacturers associated with CAGI supported the comments submitted by CAGI. As a whole, manufacturers (both those who are associated with CAGI and those who are not) questioned the veracity of the data used in the analysis, claimed that the energy savings were overestimated, argued that the standard would put excess burden on small businesses, and asked that specialized compressors be excluded from the rulemaking (Atlas Copco 2016; Castair, Inc. 2016; CAS 2016; Ingersoll Rand 2016; Jenny Products, Inc. 2016; Kaeser Compressors, Inc. 2016; Sullair, LLC 2016; Sullivan-Palatek, Inc. 2016).

The CA IOUs advised adoption of EL 3, recommended standards for reciprocating compressors or mandating test-and-list, suggested expanding the scope to compressors over 500 hp, and otherwise supported the adoption of the standard (CA IOUs 2016). A group of trade associations led by the U.S.

Chamber of Commerce objected to the use of the Social Cost of Carbon (SCC) in the analysis (U.S. Chamber of Commerce 2016).

A group of advocacy organizations including Appliance Standards Awareness Project (ASAP), American Council for an Energy Efficient Economy (ACEEE), Northwest Energy Efficiency Alliance (NEEA), National Resources Defense Council (NRDC), Northeast Energy Efficiency Partnership (NEEP), and Alliance to Save Energy (ASE) submitted a letter advising the adoption of EL 3, recommending repeat analysis on reciprocating compressors and in constructing TSLs, advising against pre-empting state energy efficiency standards, and otherwise expressing support for the analysis (ASAP 2016). Several other advocacy organizations led by the Institute for Policy Integrity commented that the latest estimates of the SCC and the Social Cost of Methane (SCM) should not be used because they are biased downwards, and that U.S. DOE should include a qualitative assessment of all significant climate effects not currently quantified in the monetized estimate (EDF et al. 2016).

The Statewide CASE Team acknowledges these stakeholder comments and concludes that the analysis presented in this report is justified.

## 5.11 Other Regulatory Considerations

### 5.11.1 Federal Regulatory Background

In accordance with Title II of the Energy Policy and Conversation Act of 1975, the U.S. DOE has created a pre-publication Final Rule to cover a scope of compressors. The pre-publication was not published, and therefore, the compressor scope covered in this report is not preempted.

### 5.11.2 California Regulatory Background

A proposed regulation for Title 8, Section 3518 regarding Air Compressors was brought to California's Division of Occupational Safety and Health (Cal/OSHA) in 2008. The advisory committee decided not to move forward with the regulation. The proposed regulation did not address compressor efficiency.

Compressed Air Systems and related controls are covered by Title 24, Part 6 in Section 120.6(e), which applies to compressor systems with capacity greater than or equal to 25 hp. Specifically, Title 24, Part 6 requires the use of variable-speed compressors as the "trim compressor" in most situations (CEC 2016b).

### 5.11.3 Utility and Other Incentive Programs

The following U.S. organizations offer incentive programs for commercial and/or industrial compressors: MassSave,[17] ComEd,[18] PG&E,[19] Seattle City Light,[20] National Grid,[21] Energy Trust,[22] and Eversource.[23]

### 5.11.4 Model Codes and Voluntary Standards

CAGI offers a CAGI Program Verification Seal for models' specification sheets that certifies that a manufacturer's air flow capacities and efficiencies have been verified by an independent laboratory.

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[17] https://www.masssave.com/en/saving/business-rebates/compressed-air/

[18] https://www.comed.com/WaysToSave/ForYourBusiness/Documents/CompressedAirIncentivesWorksheet.pdf

[19] https://www.airbestpractices.com/energy-incentives/incentive-program-profiles/pge%E2%80%99s-third-party-energy-incentive-programs

[20] https://energy.gov/eere/femp/energy-incentive-programs-washington

[21] https://www9.nationalgridus.com/non_html/Compressed_Air_RI_Retrofit_NG-Form_03-08-2010.pdf

[22] https://www.energytrust.org/wp-content/uploads/2016/09/PE_FM0420CA.pdf

[23] https://www.eversource.com/content/docs/default-source/nh---pdfs/retrofit-compressed-air-application.pdf

The American Society of Mechanical Engineers (ASME) Standard EA-4-2008 sets requirements for conducting and reporting a compressed air system assessment. The assessment considers the entire system, from energy inputs to work performed.

The International Organization for Standardization (ISO) 11011:2013 standard sets requirements for conducting and reporting compressed air system assessments. It considers the entire system and focuses on three subsystems: supply, transmission, and demand.

#### 5.11.5 Compliance

There is currently no required rating or labeling system for the products in the scope of this report. However, the proposed test procedure requires mandatory test-and-list for all products within the scope of the proposed standards.

# 6. Conclusion

The Statewide CASE Team proposes that the Energy Commission adopt energy conservation standards, and testing and reporting requirements for commercial and industrial air compressors. The U.S. DOE nearly completed energy conservation standards for air compressors, but did not finalize the regulatory changes in the Federal Register. Therefore, air compressors are eligible for a state level energy conservation standard. The Statewide CASE Team drew heavily from past efforts by the DOE and EU. The Statewide CASE Team proposal includes elements from both efforts. The EU regulation was ultimately more stringent and covered a wider scope of compressors than the incomplete U.S. DOE regulation. The Statewide CASE Team proposes efficiency levels at EL 3 for rotary lubricated compressors within the capacity bounds specified in Section 2.5 (equal to the EU levels). The Statewide CASE Team proposes testing and reporting requirements for reciprocating compressors, non-lubricated rotary compressors, and rotary compressors from one to ten and 200 to 500 hp within the product scope defined in Section 2.5.2. The dataset generated from these efforts will inform future energy conservation standards for those categories of compressors.

The standards proposed by the Statewide CASE Team will achieve significant, cost-effective, technically feasible energy savings. The savings are estimated at 538 GWh/yr and 84 MW of demand reduction after stock turnover in 2031. This proposal will yield savings of 8,033 MTCO2e per year, and a total 88,341 MTCO2e total after stock turnover in 2031. This proposal will lead to significant cost savings for consumers with $33 million in first-year savings, and over $477 million NPV after stock turnover in 2031. Additionally, on a shipment weighted basis there is a lifecycle B/C ratio of 5.5.

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# Appendix A: Electricity Rates

The electricity rates used in the analysis presented in this report were derived from projected future prices for residential, commercial, and industrial sectors in the Energy Commission's "Mid-case" projection of the 2017-2027 Demand Forecast (CEC 2017), which used no discount rate and provide prices in 2016 dollars. The Statewide CASE Team then applied a 3% discount rate to future years relative to 2018. The sales weighted average of the five largest utilities in California was converted to 2018 dollars using an inflation adjustment of 1.03 (U.S. DOL 2018). See the rates by year below in Table 23.

**Table 23: Statewide Sales Weighted Average Commercial and Industrial Electricity Rates 2017 – 2027 (PG&E, SCE, SDG&E, LADWP and SMUD - 5 largest Utilities) in 2018 cents/kWh**

| Year | Commercial Electricity Rate (2018 cents/kWh) | Industrial Electricity Rate (2018 cents/kWh) | Sector Weighted Average (2018 cents/kWh) |
|---|---|---|---|
| 2017 | 17.41 | 12.91 | 13.06 |
| 2018 | 17.45 | 12.99 | 13.15 |
| 2019 | 17.27 | 12.89 | 13.04 |
| 2020 | 17.05 | 12.76 | 12.90 |
| 2021 | 16.67 | 12.51 | 12.65 |
| 2022 | 16.12 | 12.07 | 12.21 |
| 2023 | 15.60 | 11.68 | 11.82 |
| 2024 | 15.23 | 11.40 | 11.53 |
| 2025 | 14.80 | 11.08 | 11.21 |
| 2026 | 14.41 | 10.83 | 10.95 |
| 2027 | 14.03 | 10.60 | 10.72 |
| 2028 | 13.65 | 10.38 | 10.49 |
| 2029 | 13.29 | 10.16 | 10.27 |
| 2030 | 12.93 | 9.95 | 10.05 |
| 2031 | 12.59 | 9.74 | 9.84 |

Source: CEC 2017, Statewide CASE Team 2018.

# Appendix B: Load Factors

**Table 24: 2013 Electricity Consumption and Peak Demand for the Top 5 California Utilities[24]**

| Sector & End-Use | Coincident Load | | Annual Energy | | Load Factor[25] |
|---|---|---|---|---|---|
| | MW | % of Total | GWh | % of Total | |
| **Residential** | | | | | |
| Cooking | 581.4 | 1% | 2833.1 | 1% | 56% |
| Clothes Dryer | 759.4 | 1% | 4419.5 | 2% | 66% |
| Dishwasher | 211.1 | 0% | 2237 | 1% | 121% |
| Freezer | 302.4 | 1% | 2132.1 | 1% | 80% |
| Miscellaneous | 2849.3 | 5% | 23139.9 | 9% | 93% |
| Multi-Family Water Heater | 114.2 | 0% | 1189.4 | 0% | 119% |
| Pool Heater | 33.0 | 0% | 155.6 | 0% | 54% |
| Pool Pump | 769.3 | 1% | 3689.7 | 1% | 55% |
| Refrigerator | 1736.4 | 3% | 13996.2 | 5% | 92% |
| Solar Water Heat - Back-up | 0.0 | 0% | 0.2 | 0% | 63% |
| Solar Water Heat - Pump | 0.8 | 0% | 2.3 | 0% | 31% |
| Spa Heater | 64.9 | 0% | 247.6 | 0% | 44% |
| Spa Pump | 261.5 | 0% | 990.4 | 0% | 43% |
| Single Family Water Heater | 196.5 | 0% | 1709.6 | 1% | 99% |
| Television | 807.2 | 1% | 6003 | 2% | 85% |
| Waterbed Heater | 737.0 | 1% | 12003.7 | 5% | 186% |
| Clothes Washer | 122.2 | 0% | 824.6 | 0% | 77% |
| Air Conditioning | 15739.6 | 28% | 8378.51 | 3% | 6% |
| Space Heating | 0.0 | 0% | 3441.46 | 1% | 0% |
| **Commercial** | | | | | |
| Other | 3344.8 | 6% | 23762.2 | 9% | 81% |
| Domestic Hot Water | 144.5 | 0% | 675.7 | 0% | 53% |
| Cooking | 94.5 | 0% | 721.9 | 0% | 87% |
| Office Equipment | 263.3 | 0% | 1699.2 | 1% | 74% |
| Refrigeration | 888.4 | 2% | 7872.6 | 3% | 101% |
| Exterior Lighting | 40.9 | 0% | 5909.2 | 2% | 1649% |
| Interior Lighting | 4856.2 | 9% | 30686.2 | 12% | 72% |
| Ventilation | 1787.3 | 3% | 10366.1 | 4% | 66% |
| Air Conditioning | 7714.7 | 14% | 15724.95 | 6% | 23% |
| Space Heating | 0.0 | 0% | 2702.77 | 1% | 0% |
| **Subtotal** | 19134.6 | 34% | 100120.82 | 38% | 60% |

Source: CEC 2016a.

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[24] The top five California Utilities are Pacific Gas & Electric (PG&E), San Diego Gas & Electric (SDG&E), Southern California Edison Company (SCE), Sacramento Municipal Utility District (SMUD), and Los Angeles Department of Water and Power (LADWP).

[25] Load factor is the ratio of average annual load to coincident peak load. The load factors for commercial exterior lighting and residential waterbed heaters are very high because their consumption is mainly off-peak.

# Appendix C: EL 2 Results

The tables (Table 25 through Table 32) in this appendix show all the relevant results for a compressors energy conservation standard at EL 2 instead of the proposed EL 3 results in Analysis of Proposal. EL 2 was the efficiency level that U.S. DOE decided to pursue. These results are from the U.S. DOE analysis but adapted to California's population and electricity rates. The only change to the standard language between ELs would be a shift in the d-value for each equipment class, shown in Table 4.

The important takeaways from the EL 2 results are that the energy savings are lower (315 GWh/yr at EL 2 compared to 538 GWh/yr at EL 3 after stock turnover) but the lifecycle B/C ratio is higher (6.5 at EL 2 compared to 5.5 at EL 3). The Statewide CASE Team notes that the B/C ratio is still significantly above unity at EL 3, and stands by its recommendation of EL 3 for the compressors standard. These results are merely being displayed for the Energy Commission's convenience, because EL 2 was what U.S. DOE proposed in its pre-published final rule.

**Table 25: Per Unit Energy Use and Potential Savings for Qualifying Products (EL 2)**

| Compressor Equipment Classes | Size and Application Weighted Electricity Use (kWh/yr) | Peak Demand (W) |
|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 143,516 | 22,443 |
| Rotary, lubricated, liquid-cooled, fixed-speed | 275,728 | 43,118 |
| Rotary, lubricated, air-cooled, variable-speed | 128,863 | 20,151 |
| Rotary, lubricated, liquid-cooled, variable-speed | 220,200 | 34,434 |
| Shipment Weighted Average | 165,509 | 25,882 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

**Table 26: Annual Per Unit Energy Savings (EL 2)**

| Compressor Equipment Classes | Size and Application Weighted Electricity Use (kWh/yr)[a] | Peak Demand (W)[b] |
|---|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | 4,304 | 673 |
| Rotary, lubricated, liquid-cooled, fixed-speed | 7,429 | 1,162 |
| Rotary, lubricated, air-cooled, variable-speed | 2,634 | 412 |
| Rotary, lubricated, liquid-cooled, variable-speed | 6,102 | 954 |

|  |  |  |
|---|---|---|
| Shipment Weighted Average | 4,753 | 743 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

**Table 27: California Statewide Energy Use – Standards Case (After Effective Date) (EL 2)**

|  | Annual Shipments |  | Stock |  |
|---|---|---|---|---|
| Year | Electricity Use (GWh/yr) | Peak Demand (MW) | Electricity Use (GWh/yr) | Peak Demand (MW) |
| 2019 (standards take effect) | 505 | 79 | 6,584 | 1,030 |
| 2031 (after stock turns over) | 774 | 121 | 9,241 | 1,445 |

Source: Statewide CASE Team 2018.

**Table 28: California Statewide Energy Savings – Standards Case (After Effective Date) (EL 2)**

|  | Annual Shipments |  | Stock |  |
|---|---|---|---|---|
| Year | Electricity Use (GWh/yr) | Peak Demand (MW) | Electricity Use (GWh/yr) | Peak Demand (MW) |
| 2019 (standards take effect) | 15 | 2.3 | 15 | 2.3 |
| 2031 (after stock turns over) | 29 | 4.6 | 315 | 49.3 |

Source: Statewide CASE Team 2018.

**Table 29: Weighted Incremental Cost (EL 2)**

| Compressor Equipment Class | Incremental Cost Over Baseline |
|---|---|
| Rotary, lubricated, air-cooled, fixed-speed | $906 |
| Rotary, lubricated, liquid-cooled, fixed-speed | $1,714 |
| Rotary, lubricated, air-cooled, variable-speed | $1,110 |
| Rotary, lubricated, liquid-cooled, variable-speed | $2,550 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

**Table 30: Costs and Benefits per Unit for Qualifying Products (EL 2)**

|  |  | Lifecycle Costs per Unit (Present Value $) |  | Lifecycle Benefits per Unit (Present Value $) |  | Net Present Value per Unit ($) |
|---|---|---|---|---|---|---|
| Product Class | Product Life (years) | Incremental Cost | Total PV Costs | Electricity Savings | Total PV Benefits | Electricity |

| | | | | | | |
|---|---|---|---|---|---|---|
| Shipment Weighted Compressor | 13.0 | 1,074 | 1,074 | 7,018 | 7,018 | 5,944 |

Source: U.S. DOE 2016d; Statewide CASE Team 2018.

**Table 31: Estimated California Statewide Greenhouse Gas Savings for Standards Case (EL 2)**

| Product Class | Annual GHG Savings (MTCO2e/yr) | Stock GHG Savings (MTCO2e/yr) |
|---|---|---|
| 2019 (start takes effect) | 3,196 | 3,196 |
| 2031 (after stock turns over) | 4,796 | 51,834 |

Source: Statewide CASE Team 2018.

**Table 32: Statewide Total Lifecycle Costs and Benefits for Standards Case (EL 2)**

| Product Class | Lifecycle B/C Ratio | NPV | |
|---|---|---|---|
| | | For First-Year Shipments ($ million) | Stock Turnover ($ million) |
| Shipment Weighted Compressor | 6.5 | 18.15 | 263.77 |

Source: Statewide CASE Team 2018.