CARBON LIMITS

Zero emission technologies for pneumatic controllers in the USA

Updated applicability and cost effectiveness.

November 2021

This report was prepared by Carbon Limits AS.

Project title:
Zero emission technologies for pneumatic controllers in the USA

Client:	CATF
Project leader:	Malavika Venugopal
Project members:	Stéphanie Saunier, Malavika Venugopal
Subcontracted companies:	-
Report title:	Zero emission technologies for pneumatic controllers in the USA Updated applicability and cost effectiveness
Finalized:	Final

Acknowledgements

Carbon Limits acknowledges and recognizes the support provided, among others, by the following individuals and companies (in alphabetical order). Darryl Weflen from Airworks Compressors Corp, James Martin from Advantage Energy Ltd, Sheila Stang from Airworks Compressors Corp, stakeholders from Calscan.

NOTE: This paper does not necessarily reflect the participants' views and opinions provided during their interviews, nor show the official policy or position of the organization/company they represent.

CARBON LIMITS

C J Hambros plass 2
0164 Oslo
Norway
carbonlimits.no
Registration/VAT no.: NO 988 457 930

Executive Summary

A pneumatic controller is a device that monitors certain process variables such as temperature, pressure liquid level, etc., and generates an output signal to drive a control element, such as a control valve. Natural gas driven pneumatic controllers are used widely in the oil and gas industry. These devices release methane into the atmosphere, either continuously or intermittently. In 2016, Carbon Limits was tasked to assess the applicability and cost effectiveness of zero emission controllers suitable for the oil gas industry.

Since 2016, significant progress has occurred both in zero emissions technologies and regulations promoting the transition from natural gas driven pneumatic controllers to zero-emission controllers. The provinces of Alberta and British Columbia in Canada and the state of Colorado in the United States have implemented regulations encouraging and requiring the installations of zero-emission controllers.

Owing to the increasing popularity of zero emission controllers, Carbon Limits has assessed the technological advancements in zero emission controllers and performed a cost-effectiveness study using updated costs for the presented technologies. This report is to be used as an annex to the 2016 report, ***'Zero emission technologies for pneumatic controllers in the USA[1]'.*** This report presents advancements in the zero-emission controller technologies presented in the 2016 report, and newer technologies suitable in this context. An abatement cost model is submitted as an annex to this report, which estimates the methane abatement cost and incremental capex requirements for each technology, depending on the facility requirements. Major findings from this report have been summarized below:

- The market for electric controllers and instrument air powered controllers has been developing since 2016. The new regulations have been one of the drivers for the increasing demand and development of new technological solutions.
- The barriers to implementing solar panels at well sites have been reduced, due to developments in PV technology and increasing awareness on the use of solar powered electric controllers.
- Electric controllers have some of the lowest abatement costs at most facility configurations. The market is still developing, with newer solutions being introduced into the market.
- Solar-powered instrument air is a new technology. This technology is suitable for remote sites with no access to grid electricity. The abatement cost for this technology is lower than the social cost of methane, for the sites assessed and presented in this report.[2]
- Three site configurations, ranging from 5 to 20 controllers at the facility, were assessed in this report. All of them have abatement costs much lower than the social cost of methane.

Overall, based on the cost-effectiveness model and interviews with relevant stakeholders from the oil and gas industry, zero-emission controllers are very relevant for reducing emissions from the oil and gas sector.

[1] https://www.carbonlimits.no/project/zero-emission-technologies-pneumatic-controllers-in-usa/

[2] Social Cost of Methane: The report used the social cost of methane, as reported by Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, as a benchmark for the cost-effectiveness of measures to abate methane emissions. The mean value was calculated at the 3% discount rate for emissions in year 2020. The report calculates this as $1500 per metric ton in 2020 USD. Report retrieved from: https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

Contents

Acronyms and Abbreviations

Abbreviation	Full Form
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
USA	United States of America
EPA	Environment Protection Agency
EDF	Environmental Defense Fund
USD	US Dollars
CAD	Canadian Dollars
CATF	Clean Air Task Force
AQCC	Air Quality Control Commission of Colorado
F	Fahrenheit
HP	Horsepower
ESD	Emergency Shut Down
UPS	Uninterruptible Power Supply
FSC	Fail Safe Controller
cfm	Cubic Feet per Minute
Hr	Hour
Mscf	Million Standard Cubic Feet
NPV	Net Present Value

List of figures

List of tables

1. Introduction

Summary of the 2016 report[3]

Natural gas-driven pneumatic controllers are widely used in upstream oil and gas operations, most commonly to regulate fluid level in separators and tanks, temperature of heaters and fans, pressure of vessels, and differential pressure of lines. However, these devices release methane into the atmosphere, either continuously or intermittently. In 2016, Carbon Limits was tasked to assess the applicability and cost effectiveness of zero emission controllers suitable for the oil gas industry.

The report titled ***'Zero emission technologies for pneumatic controllers in the USA[4]'*** presented several studies which demonstrate that the average emission rates for pneumatic devices far exceed the specifications provided by the manufacturers. The report provided in-depth information on the types of pneumatic devices, the average number of devices per site and assessed several literature studies focused on measuring emissions from pneumatic devices.

The report focused then on documenting five different types of zero emission controller technologies: Electric controllers, instrument air (with electric power from the grid or existing on-site generation), solar-powered instrument air, vent recovery, and self-contained pneumatic controllers. Electric controllers and instrument air pneumatic devices were found to be the most mature technologies, suitable for implementation on a large share of facilities.

The techno-economic assessment performed revealed that zero emission solutions have abatement costs below the social cost of methane used by the US EPA[5] in most of the site configurations considered (2008 out of 2032 site configurations). The abatement costs at very small sites – those with less than three controllers and no pumps (excluding emergency shutdown devices, ESD), exceeded the social cost of methane used by the US in 2016. The case studies presented in the report and the economic assessment performed assumed conservative emission factors for pneumatic controllers, often lower than the emissions factor in field measurement reports. When emissions factor from reported field measurements were used to estimate the abatement costs, even the very small sites were found to have abatement costs below the social cost of methane.

What happened since 2016?

Since 2016, zero emissions controllers have gained further interest in North America. In 2020, WZI Inc. performed a review of Oil and Gas facility controller deployment alternatives in Colorado.[6] The review, prepared for the Environmental Defense Fund (EDF) in October 2020 predominantly defines instrument air, electric controllers, and self-contained pneumatic controllers as feasible non-emitting pneumatic controller options. The technologies were deemed cost effective and technologically feasible for both retrofitting existing sites (commonly known as Brownfield sites) and for new sites (commonly known as Greenfield sites).[7]

One of the latest regulations implemented in the state of Colorado requires the implementation of zero emission pneumatic devices at new and existing oil and gas well sites. In February 2021, the Colorado

---

[3] https://www.carbonlimits.no/project/zero-emission-technologies-pneumatic-controllers-in-usa/

[4] https://www.carbonlimits.no/project/zero-emission-technologies-pneumatic-controllers-in-usa/

[5] Social Cost of Methane: The report used the social cost of methane, as reported by Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, as a benchmark for the cost-effectiveness of measures to abate methane emissions. The mean value was calculated at the 3% discount rate for emissions in year 2020. The report calculates this as $1500 per metric ton in 2020 USD. Report retrieved from: https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

[6] WZI Inc., October 2020, *Review of Oil and Gas Facility Controller Deployment Alternatives in Colorado*

[7] WZI Inc., October 2020, *Review of Oil and Gas Facility Controller Deployment Alternatives in Colorado*

Air Quality Control Commission (AQCC) revised Regulation Number 7 provisions covering pneumatic controllers at oil and gas facilities. The new revisions necessitate that all new and modified well production sites and natural gas compressor stations must use non-emitting pneumatic devices, starting from May 1st, 2021. Starting a year later, in May 2022, operators of existing well production facilities (with the exception of those with low average production per well) and gathering compressor stations must replace or retrofit a portion of their existing pneumatic controllers into non-emitting controllers, according to schedules contained in the rule.[8]

In British Columbia, Canada, the Board of the Oil and Gas Commission updated regulation 52.05 in 2018, which includes mandatory reduction of vent gas from pneumatic devices.[9] According to the update:[10]

(1) Any facility that began operating on or after January 1, 2021, must not use pneumatic devices that emit natural gas.
(2) Beginning on January 1, 2022, any large compressor station (with total installed compression power is 3 megawatts or more) or processing plant that began operating before January 1, 2021, must not use pneumatic devices that emit natural gas.[11]

The province of Alberta, Canada recently joined British Columbia in mandating the reduction of natural gas vented from pneumatic devices via the Directive 060.[12] According to the directive, any pneumatic instruments installed on or after January 1, 2022, must not emit any natural gas.[13]

Aim of this report

With the increasing popularity, and push for zero emission pneumatic devices, it is relevant to re-assess zero emissions controller technology and their cost. Are the emissions associated with gas driven controllers still very high? Are there new zero-emissions controller technologies or improvements that are relevant to the industry? How does the cost-benefit differ in 2021 compared to 2016?

This report first aims to answer these questions, by performing literature review on field measurement and estimation studies, written after 2016. Owing to the constantly changing market for zero-emission controllers, the costs associated with controllers has been re-assessed in this report. At the pace at which emission reduction technologies have been improving, this update report has an utmost importance in terms of keeping the costs and technology list updated for easier reference.

This report is intended to be an Annex-update to the 2016 report assessing zero emissions pneumatic controllers and their costs. The report intends to update the 2016 report by addressing the following:

1. Does the problem of '*leaky'* pneumatic controllers still exist?
2. What are the developments in zero emissions controllers over the past 5 years?
3. What are the changes in CAPEX, OPEX and installation of these technologies?
4. Has the applicability for these technologies changed?
5. What are the updated abatement costs for zero emission controllers?

---

[8] See further details and specification: Colorado Air Pollution Control Division, *Colorado Air Quality Control Commission's February 2021 Revisions to Regulation Number 7 Fact Sheet*, Retrieved from: https://drive.google.com/file/d/1OPRJ1nndlXjCXZx-ccdx-wO3vt8Kc4DQ/view.

[9] Does not include a pneumatic pump or a pneumatic compressor starter.

[10] Regulation of the board of the Oil and Gas Commission, *Oil and Gas Activity Act*, https://www.bclaws.gov.bc.ca/civix/document/id/regulationbulletin/regulationbulletin/r0286_2018, 2018

[11] Some exception exist for the second case, such as if the emissions of natural gas from the device do not exceed 0.17 m3 per hour, the pneumatic device need not be replaced. More details can be found here: https://www.bclaws.gov.bc.ca/civix/document/id/regulationbulletin/regulationbulletin/r0286_2018

[12] In the case of Alberta, gas-driven pneumatic devices include pneumatic instruments (e.g., controllers, switches, transducers and positioners) and pneumatic pumps.

[13] Alberta Energy Regulator, *Upstream Petroleum Industry Flaring, Incinerating, and Venting*, https://static.aer.ca/prd/documents/directives/Directive060.pdf, 2021

This report has focused on updating the costs associated with electric controllers, solar PV systems, batteries required to operate the electric controllers, and added cost-effectiveness assessment for solar powered instrument air systems.[14]

Approach & Methodology

Apart from the literature review performed, to understand the effectiveness of the previous report and relevance of the problem in 2021, stakeholder interviews[15] were performed to update the techno-economic assessment for zero emission technologies.

The interviews helped gather information on the developments in zero emission technologies, the applicability, technical barriers, and actual costs of installing electric pneumatic controllers at existing and new sites. Using this information, the cost-benefit model developed alongside the 2016 report was updated to reflect the latest developments in the technology.

The report is structured in 4 main sections:

- The first section focusses on recent studies on pneumatic controller emissions analysis, and measurement reports.
- The second section summarizes the information obtained from stakeholder consultation. It provides information on the changes in technology and improvements in zero emission pneumatic devices over the past five years.
- The third section documents changes in terms of costs of zero emission controllers
- And finally, the results of the techno-economic model are presented in the last section of this report.

[14] The instrument air technologies and baseline costs of pneumatic controllers use the same costs and assumptions as described in the 2016 report by Carbon Limits, due to these predominant reasons: (a) As compared to electric controller, using instrument air for operating controllers were a mature technology in 2016, with accurate cost estimations for components used in the technology. (b) Electric controllers have significantly increased in market share, with several new companies and technologies entering the market. Re-assessing the costs in this case is important.

[15] Representatives of five different companies were interviewed (sometimes several times) as part of this update report. Three of these companies are technology providers, and two are oil and gas companies using electric pneumatic devices at their brownfield and greenfield sites.

2. Recent studies on emissions from gas driven controllers

In 2019, Luck and colleagues at Colorado State University and other institutions published a paper on emissions from pneumatic devices at gathering and boosting stations.[16] The study consisted of multiday measurements of over 70 pneumatic devices between June 2017 and May 2018. The measurements showed abnormal emissions behavior from over 60% of the 40 intermittent pneumatic devices that were studied, and over 20% of the 24 low-bleed[17] pneumatic devices in the sample. These emissions were substantially higher than the *standard* emissions value stated by the device manufacturers. An average of 16.1 scfh was emitted from abnormally operating intermittent vent controllers, while controllers operating normally emitted only 2.8 scfh. An interesting observation made during this measurement trial was the *normal* behavior of the abnormally functioning controllers. For certain periods, the emission from most of these intermittent-vent controllers were similar to those from properly operating controllers, but the overall average emission rate for these controllers over the entire measurement period was over seven times higher than the emissions rate during the periods of normal operation. Luck et al. also note that some of the malfunctions they observed were only noted because of the very long (24+ hrs) monitoring times used in this study.[18]

A study by Littlefield et al. (2017) analyzed methane emission data reported by several studies measuring emissions from over 1,000 facilities along the gas value chain between 2013 and 2015. Littlefield et al. found that pneumatic devices at production sites are one of the top three contributors to methane emissions. Reducing emissions from these pneumatic devices were reported to be one of the most effective emission reduction strategies that could be applied in the upstream sector.[19]

A study commissioned by the Petroleum Technology Alliance of Canada used the enhanced Measurement Emission Accuracy Solution (e-MEAS^{TM}) for measuring emissions from several pneumatic systems. One of the conclusions provided in the report states that the manufacturer published steady state vent rates are not the best predictor of emissions.[20]

Finally, an interesting measurement study was performed by Stovern et. al in 2018 at facilities in Colorado's Denver-Julesburg basin. They surveyed 500 gas driven pneumatic devices servicing over 100 wells. Optical gas imaging was used to monitor emissions from pneumatic devices during regular operation and during actuation. It was observed that while 83% of the pneumatic controllers were nominally intermittent pneumatic controllers, over 10% of these devices were emitting natural gas continuously. Additionally, the study authors note that some of the controller malfunctions could not be detected in the normal-sensitivity mode of the OGI camera, but a significant number of inspections were only conducted in this normal-sensitivity mode – and it is likely that those inspections missed some malfunctions. Hence the report concludes that the reported emission frequency is an underestimation, and there could be several more controllers emitting natural gas continuously at these well pads.[21]

These studies demonstrate the persistence of the problem of over-emitting pneumatic controllers and the difficulty in measuring these emissions.

---

[16] Benjamin Luck, Daniel Zimmerle, Timothy Vaughn, Terri Lauderdale, Kindal Keen, Matthew Harrison, Anthony Marchese, Laurie Williams, and David Allen, *Multiday Measurements of Pneumatic Controller Emissions Reveal the Frequency of Abnormal Emissions Behavior at Natural Gas Gathering Stations*, 2019, Environmental Science & Technology Letters

[17] Low Bleed pneumatic devices were considered as abnormally operating if the emission rates were higher than 6 scfh.

[18] Due to problems with some of the meters used in this study, Luck et al. caution that the study results should not be used to calculate emissions factors, but the qualitative results (such as the high malfunction rate of the observed controllers) remain valid.

[19] James A. Littlefield, Joe Marriott, Greg A. Schivley, Timothy J. Skone, *Synthesis of recent ground-level methane emission measurements from the U.S. natural gas supply chain*, 2017, Journal of Cleaner Production

[20] Brian Van Vliet, *Pneumatic Vent Gas Measurement*, 2018, for Petroleum Technology Alliance of Canada

[21] Michael Stovern, Jeramy Murray, Colin Schwartz, Cindy Beeler, and Eben D. Thoma, *Understanding oil and gas pneumatic controllers in the Denver–Julesburg basin using optical gas imaging*, 2020, Journal of the air and waste management association

3. Technological developments in zero-emission controller technologies

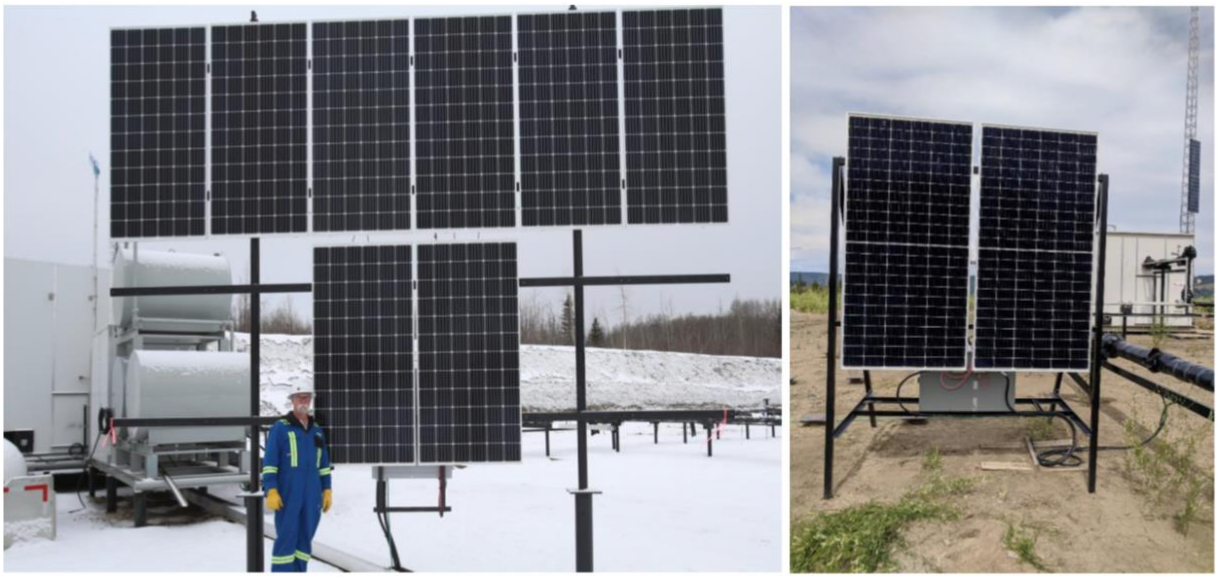
Owing to the developments in zero emission pneumatic controllers, the first topic addressed during stakeholder interviews were the changes in electric controller and instrument air technology and the market trends over the past five years. Both the technology providers and operators using electric controllers attested to the increasing knowledge and availability of electric controllers in the market. Several new controller models have been introduced in the market, suitable for a wide variety of oil and gas facilities in the USA. The increasing demand has helped technology providers to develop more advanced models, bridging some of the shortcomings that existed five years ago.

The following sub-sections target the most important developments and address some of the frequently asked questions with respect to zero-emissions controllers.

Suitability of solar panels for sites with more than 30 controllers

The 2016 report and cost-benefit model assumed that electric controller operated by an on-site solar PV system would only be suitable for sites with 30 or fewer controllers. When questioned about this validity of this assumption, the interviewed stakeholders noted that this bottleneck has been addressed by the falling prices of PV panels and battery systems, and the ease of installation of solar PV systems today. Improvements in the PV output and reduced costs of PV panels and battery systems have aided in over-sizing the system if required, for emergency purposes. Furthermore, some of the well operators interviewed mentioned vertical stacking of solar panels, which ensure a higher PV capacity installed within a smaller area.

Figure 1: Vertically stacked solar PV panels at Tourmaline Oil Corporation well site (Source: Tourmaline Oil Corporation)



Battery requirement and temperature dependence

One interesting fact mentioned by the technology providers was the capacity and durability of the battery systems depending on the location where the battery is placed. Having the batteries inside a room, where average temperature is around 70 F can reduce the battery capacity required by almost 14% compared to the capacity required at 32 F. Similarly, the capacity required at -4 F is almost 35% higher than the requirement at 32 F.[22] Having a battery box installed on site can be beneficial, especially in regions with very low temperatures. The costs and suitability of battery boxes are highly site specific. Some sites might even have a pre-existing shed or enclosure to place the battery, without an additional battery box requirement. Based on the interviews with technology providers, the addition of battery boxes could make the equipment cost of batteries 2% to 10% higher. This cost has not been incorporated in the model, due to very high variability in choices for battery placement within the sites. However, in regions with significant temperature changes within a year, the model assumes the lowest outdoor temperature, to ensure the sizing of battery can fulfill the energy requirements when the output is lowest, without the use of box or shed. Since enclosures may be less costly than increasing battery capacity to ensure sufficient sizing in ambient temperature, this simplification may overestimate cost for many configurations.

High electricity demand per actuation

One frequent feedback received for the previous report was the high electricity utilization during periods with frequent actuation and the sizing of solar PV according to the number of actuations at the site. The stakeholders who were presented with the question mentioned the improvements in the PV system sizing calculation. Due to the reduced costs and the stacking solar panel technology, PV systems and batteries can be oversized at facilities to ensure adequate power is provided during high actuation period and other emergency requirements.

According to some of the operators interviewed; a higher number of actuations occurs in the first few months of well operation. In one case, the operator reported using a gas driven pneumatic controller, to compensate for the excess energy needed. Within 3 to 4 months of the well initiation, electric pneumatic controllers were installed with an adequately sized PV system. Note however that other operators use zero emissions controllers from the beginning of well operation, independent of the required frequency of actuation, and in fact this is required for new wells in a number of jurisdictions.

Methanol Fuel Cell

Several technology providers mentioned the possibility of adding an additional methanol fuel cell, to support the solar PV system installed at the facility. The methanol fuel cell acts as an alternative power source, during low solar outputs. In some cases, battery systems installed are connected to both the solar PV system and the methanol fuel cell. This is done to ensure the battery systems retain the 10-day energy backup required to operate the controllers in the site. However, most sites use the methanol fuel cell only in case of emergencies when the solar PV output is not sufficient to satisfy the power requirements. It is not clear whether methanol fuel cells are commonly used by operators choosing to install non-emitting pneumatic devices. In the cost-effectiveness model, the user can see the change in incremental capex and abatement cost with the addition of methanol fuel cell. A 50-Watt fuel cell costs around $20,000. In addition, methanol must be purchased when consumed.

Emergency Shut Down

Emergency Shutdown (ESD) Systems are specialized highly reliable control systems designed to protect the personnel and the facility in case of unexpected event such as over pressurization. ESD valve are typically controlled by gas driven devices that push the actuators to the '*safe mode*' (typically, closed position for a valve) in case of emergencies. Most oil and gas sites will have one or more pneumatic ESD system(s) installed at their facilities. In the 2016 report, electric valve systems were generally considered to not be reliable enough for ESD systems, given the reliability required of an ESD to ensure site safety, and it was thus assumed that gas driven controllers would still be used for ESD even when the rest of the facility was converted to electric controllers.

[22] Interview with technology provider

However, there are now new zero emission ESD systems available in the market. First, a zero-emission ESD consisting of an uninterruptible power supply (UPS) device and a failsafe controller (FSC) that can push actuators to the safe position when a failure is detected. At well sites with these systems, all actuator control lines pass through a remote terminal unit (RTU).[23] When the UPS and FSC system is installed, the actuator lines are passed through the FSC along with the RTU, ensuring the failsafe system is triggered whenever a failure in power or the RTU is detected. The FSC and UPS together can provide power fail-safe operation for up to nine actuators.

A second zero-emission ESD system described by one of the stakeholders interviewed is the Emergency Shutdown Valve (ESDV) electric actuators system. In these systems, a mechanical fail-safe opens or closes the valve on loss of power, for example by using a spring, similar to the approach often used with pneumatic actuators. While this system may be preferred by some in the industry given familiarity with the approach, this choice is facility and operator specific. The 2021 report and model use the UPS and FSC system. Using a non-emitting failsafe system can further reduce the emissions from pneumatic controllers and eliminate the need for regular maintenance of otherwise gas driven ESD controllers.[24]

Instrument Air powered by solar panels

Instrument air controllers are systems where pressurized natural gas is replaced with compressed air as a source of energy and signaling medium for pneumatic controllers and pneumatic actuators. Since controllers use air, instead of natural gas, they only vent air to the atmosphere, eliminating emissions from pneumatic controllers.[25] The 2016 report and model presented compressed air pneumatic controllers as a viable option for well sites with access to grid electricity.

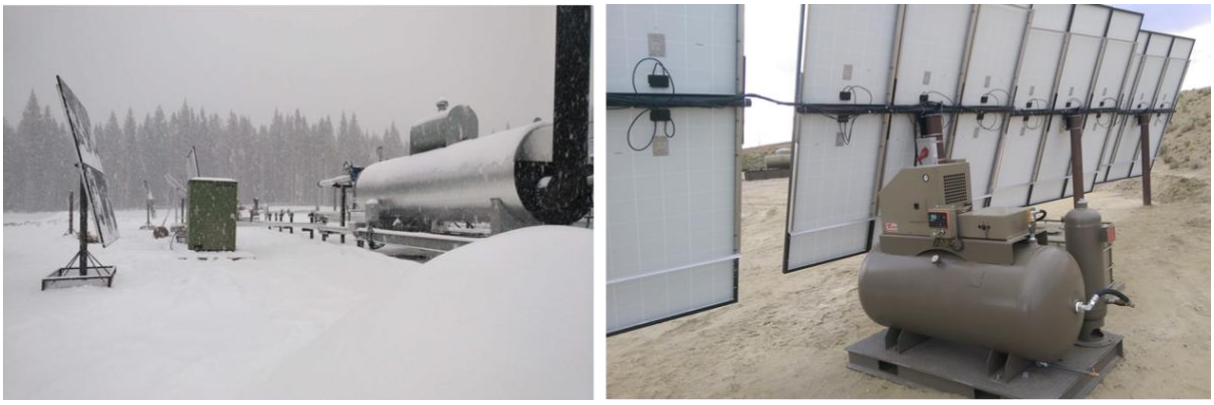
A new technology package called the Aurora Eco-System, offered by Air Works Compressors, provides an instrument air system powered by solar PV or wind power installed at the well-sites. As of mid-2021, the solar-powered Aurora Eco-System package has been installed in 22 sites in Alberta, Wyoming, Utah, and Peru.[26] The Aurora Eco-System can supply pneumatic controllers and other devices with compressed air, replacing the use of natural gas. It has been designed for off-grid locations and can be installed using existing onsite infrastructure and instrumentation circuits.

According to the stakeholders from Air Works Compressors, the Aurora system, using a non-continuous rotary type compressor, provides reliable operation starting at 2.5 CFM.[27] This air compressor system can be sized, and tailor-made based on the facility requirements, to deliver between 2.5 CFM and 60 CFM. As per the stakeholders at Air Works Compressors, an additional advantage of the Aurora air compressor is operating cycle. Typical well pads with the Aurora package operate with a 2.5 Minutes On/10 Minutes Off cycle, making it more efficient in terms of the electricity required to operate the compressor. This can reduce the power requirements by over 50%, compared to a typical continuously operating air compressor.[28] The Aurora package is available with an optional methanol fuel cell power generator, to add power capacity at remote locations that may need more power than provided by the solar panel in periods of particularly low sunshine. In general, the installation of the Aurora package along with the solar panels and batteries (and the optional methanol fuel cell) has been performed by

[23] A remote terminal unit (RTU) is part of a broader remote monitoring system. An RTU is programmed to monitor equipment or activity throughout a system. For example, an RTU might be checking engine temperature. If it starts to get too high (or low) that triggers an alert which it sends to a master station control center.
[24] Main reference from Calscan's Bear FSC and UPS systems. Other technology providers mentioned availability of similar systems. More information on FSCs: http://www.calscan.net/products_bearfamily.html
[25] For more information on compressed air systems and their applicability for well sites, refer to Zero emissions pneumatic controllers report by Carbon Limits at: https://www.carbonlimits.no/project/zero-emission-technologies-pneumatic-controllers-in-usa/
[26] Source: Stakeholder from Aurora Eco-System, by Airworks Compressor Corp.
[27] The 2016 report and model set pre-requisites on the site and compressor size, based on interviews with well-site operators. A minimum of 5 HP compressor size and 30 controllers were required for the site to be applicable for compressed air systems to be profitable at the location. This assumption has been removed in the new version given the technological development reported by Aurora.
[28] https://www.airworkscompressors.com/aurora-instrument-air-package/

the Aurora manufacturer. The installation costs for this system are provided as a percentage of equipment costs associated with the installation. More details on installation costs have been provided in Section 4.2.

Figure 2: Aurora package installed at well-sites. The instrument air system has been designed all environments: From +112°F to -40°F (+45°C to -40°C)[29]



The technical assumptions for solar powered air compressors have been summarized in Table 1, while the CAPEX and OPEX have been discussed in section 4.

Table 1: Engineering assumptions for solar powered instrument air systems[30]

Item Description	Value	Unit
Share of the air bypassed in dryer	5%	%
Share of the utility air supply	150%	%
Sizing of compressor - variable component	0.20	HP/cfm
Sizing of compressor - constant component	4.24	HP
Load of the compressor (main)	30%	%
Duty Cycle	30%	%
Lifetime of the compressors	10	years

[29] https://www.airworkscompressors.com/aurora-instrument-air-package/

[30] Source: Stakeholder from Aurora Eco-System, by Airworks Compressor Corp.

4. Update on the costs of zero-emission pneumatic controllers

This section aims to shed light on the changes in initial investment and operational expenditure for electric controllers and solar power operated instrument air controllers. The cost analysis for instrument air controllers when the site is connected to the grid has not been updated.[31] This section documents general information on typical costs and the assumptions for the techno economic model.

4.1. Updated information on equipment costs

Electric Controllers

The pneumatic system includes a controller, and actuator and a control valve. While transitioning from a pneumatic system to an electric system, the controller and actuator are swapped for an electric controller and electric actuator. In the 2016 model, switching to electric controllers required a switch in the control valve associated with the retrofitted controller, adding significant cost. A shortcoming that has been bridged during the developments for electric controllers over the past five years is the adaptability of controllers to existing control valves. Today, most electric controllers and actuators can be connected to the existing valves present at well sites.

To reflect this technological change, the price for controllers in the model has been split to represent the cost of controller, actuator and control valve separately. While new valves are required for new sites, retrofit sites can make-do without swapping the actuator control valve in most cases. The 2021 model has a toggle option where the user can choose to replace or continue using existing control valves.

There have not been any drastic changes in the prices of the controllers or equipment associated with installation of electric controllers. Interviewed stakeholders vouched for the prices to be within their estimates, though the actual price of the whole system varies for each facility. The central assumptions for electric controllers have been presented in Table 2 along with information of typical costs.

Table 2: Central cost assumptions for electric controllers[32]

Item	Cost Assumption	Remarks
Controller	$2,000/unit	The price ranges between $1,000 and $3,000 depending on the parameter being controlled (level, pressure etc). A value mid-way has been assumed as the average cost of a controller.
Control Valve	$2,500/unit	Applicable for new sites. Price varies between $1,000 to $3,000 depending on the size of the valve, $2,500 has been taken as a conservative estimate to represent most facilities.
Chemical Injection Pump	$6,000/unit	While some technology providers mentioned a lower price (between $4,000 and $5,000), a conservative price has been assumed, after interviews with both technology providers and well site operators.
Control Panel	$5,000/unit	The price ranges between $3,000 and $6,000 depending on the facility. A conservative price has been assumed after interview with technology providers and well site operators.

[31] For the model we have not changed the cost of compressed air technologies or the baseline costs of pneumatic controllers from the costs and assumptions described in the 2016 report by Carbon Limits, due to these (predominant) reasons: (a) As compared to electric controllers, both traditional pneumatic controllers and compressed air systems for operating controllers were mature technologies in 2016, with accurate cost estimations available for components used in the technologies and (b) electric controllers have significantly increased in market share, with several new companies and technologies entering the market.

[32] Interview with technology providers and well site operators

Solar powered instrument air

The predominant cost in the case of solar powered instrument air comes from the compressor unit. While the instrument air technology providers offer the solar panels and batteries as a part of the compressor-controller package, it has been presented separately to ensure transparency in terms of sizing and prices of the power production units. The central assumptions for solar powered instrument air systems have been summarized in Table 3.

Table 3: Central cost assumptions for solar powered instrument air system[33]

Item	Cost Assumption	Remarks
Compressor (2.5 HP – 5.0 HP) Compressor (10 HP) Compressor (15 HP) Compressor (20 HP)	\$7,000/unit \$10,000/unit \$15,00/unit \$23,000/unit	Data provided by one technology provider. Unit costs are used when compressors are replaced after their lifetime.
Compressor Package (2.5 HP – 5.0 HP) Compressor Package (10 HP) Compressor Package (15 HP) Compressor Package (20 HP)	\$30,000/package \$37,000/package \$45,000/package \$50,000/package	Data provided by one technology provider. Package costs are used in the initial CAPEX calculation.
Compressor maintenance	4% of capex	No maintenance required for the electric motor, as per the interviewed technology provider
Compressor Lifetime	10 years	Data provided by one technology provider.

Additional power units

The cost assumptions for methanol fuel cells, FSC plus UPS systems, and the solar PV and battery costs are discussed in this section. While the FSC and UPS units are relevant for electric controllers, the methanol fuel cell and solar and battery costs are relevant for both electric controllers and solar powered instrument air controllers.

Table 4: Central cost assumptions for power producing units[34]

Item	Cost Assumption	Remarks
Solar Panel (140W)	\$400/unit	Almost all interviewed stakeholders mentioned very low costs for solar panels, ranging between \$75 and \$200 per panel. A cost of \$400 has been assumed to include the cost of cables and mounting boards for the solar panels.
Solar Panel (320W)	\$500/unit	Same reasoning as above. Slightly higher cost has been assumed for the higher capacity of the panels.
Battery (100Ah, 12V)	\$200/unit	Like the case of solar panels, battery costs can be lower, ranging between \$100 to \$250 per battery. A conservative cost has been assumed to factor in the battery box and cables required for the installation.
Battery (1100Ah, 24V)	\$3,500/unit	While some technology providers mentioned a lower price, ranging between \$2,000 and \$3,500, a conservative price has been assumed.
Methanol Fuel Cell	\$20,000/unit	Most interviewed technology providers and well site operators confirmed this price.
FSC + UPS System (Zero emission ESD)	\$3,500/unit	Based on interviews with two technology providers.[35]

[33] Interview with one technology provider for solar powered instrument air systems

[34] Interview with technology providers and well site operators

[35] All new sites are assumed to have the FSC+UPS system installed, for lower emissions. However, the costs will be lower if the operator chooses to use a gas drive pneumatic controller as an ESD

4.2. Updated installation and OPEX costs

In the 2016 report, installation and labor costs were taken to be a percentage of the CAPEX (equipment cost). To provide a more detailed estimate the labor costs, the interviewed stakeholders were asked about the installation time and costs for retrofit sites and new sites. According to the interviewees, the costs vary vastly between each facility and the type of contract with the installation company. A high share of these costs come from the time taken to travel to the operator facility. Hence the approximate travel time to the site has been added as a parameter to be entered by the user of the model. The hourly labor cost for the installation of said devices varies between different installers and is highly dependent on the facility's location. An average estimate has been assumed, on the conservative side, as presented in Table 5. Another point to note here is the cost of installation for solar powered air compressors. In the case of electric controllers, sometimes the installation is performed by a third-party installer, and not necessarily the technology provider.[36]

Another important aspect of the OPEX is the reduced maintenance cost for non-emitting controllers. In particular, pneumatic controllers driven with wet gas have high maintenance costs,[37] while electric controllers and instrument air driven controllers have significantly lower costs of maintenance. Although instrument air-driven controllers have some operating costs, some maintenance expenses are cut as a result of not using natural gas and by avoiding costs due to liquids condensing in the system or sour gas damage. The operators interviewed report positive experiences on both new and retrofit sites, valuing non-emitting controllers for their low maintenance costs and reliability.[38] The maintenance cost reduction for non-emitting controllers, relative to pneumatic controllers driven by wet gas, is accounted for in the cost model. Note, however, that the model reflects the fact that there is not a significant cost reduction relative to pneumatic controllers driven by dry gas.

Table 5: Central installation cost assumptions for electric controllers and solar powered instrument air systems

Item	Cost Assumption	Remarks
Installation cost for instrument air (Retrofit)	100% of equipment cost	Based on interview with one technology provider and aligned with instrument air.
Installation cost for instrument air (New sites)[39]	50% of equipment cost	
Labor Cost	$75/hour	Highly dependent on the services availed and the location of the facility. The price can be as low as $40 an hour and as high as $150 an hour.
Days of work Electric controller (Retrofit)	0.75 days/controller	Minimum of 1 day of work is required irrespective of the number of controllers at the well-site. The assumed values were validated by some of the technology providers and operators interviewed.[40]
Days of work Electric controller (New sites)	0.5 days/controller	
Travel time (to & from site)	8 hours	Average assumed for case studies. Parameter can be changed by the user in the model.

While some of the equipment and installation costs have been updated for electric controllers, there are no drastic changes in the costs, or the methodology applied for estimating the methane abatement costs.

[36] In the case of solar powered instrument air system, most often it is the technology provider offering the installation services. Hence, the installation cost for this technology has been assumed to be a percentage of the CAPEX, as suggested by the technology providers.

[37] From the 2016 report: Operators have reported that the quality of the supply gas affects maintenance costs. Even slightly wet (or sour) gas can lead to condensation (or corrosion) issues, which over time will impact the performance of the system.

[38] https://www.carbonlimits.no/project/zero-emission-technologies-pneumatic-controllers-in-usa/

[39] Note that the installation cost shown here for new sites is simply the gross cost of installation of a new instrument air system and controllers and is not a net cost for the instrument air system (the cost shown is *not* the incremental cost above that of installing gas-driven controllers).

[40] In case of new larger sites, the time required 'per controller' installation is less than retrofit sites. But there are cases that retrofit may turn out to be less labor intensive:
- Where valves don't need to be changed (only the controller requires change).
- When electronic systems (PLC system) and cable network are already in place (as compared to the new site where new PLC system needs to be developed)

For solar powered instrument air, a new estimate has been developed applying same principle as for electric controllers and instrument air calculations. The 2016 model has been used as the basis for developing the updated cost effectiveness model of 2021 and the 2021 cost effectiveness model is an update of the 2016 model that takes the new technologies and updated costs into consideration. The results obtained from the 2021 and 2016 models are discussed in the next Section.

5. Results of the techno-economic analysis

The analytical approach to update the model and obtain the abatement costs for different site configurations and technologies follow the same methodology as presented in the 2016 report. The results presented in this report are the abatement costs calculated using NPV, for easier comparison with the results presented in the 2016 report. The cost effectiveness model submitted with this report presents both the NPV abatement costs and the annualized abatement costs.

This section provides the incremental CAPEX (compared to a baseline scenario with gas-driven controllers), incremental OPEX and abatement costs for a few examples site configurations, and assesses the effect of the new assumptions on the abatement costs. Note that in this report, installation costs are included in CAPEX. While the previous report presented each example in detail, this report aims to show the differences in a more concise manner, followed by assessing the sensitivity to each newly added parameter. The central assumptions used for the case studies have been presented in Table 6 below. The assumptions for the emission factors follow the same logic as the 2016 report, where conservative (low) emission factors are used to assess the abatement cost.[41]

Table 6: General assumptions used for the case study assessment.[42]

Description	Central Assumption	Unit
Emission Factor (Continuous Controller)	14.43	Cf/h
Emission Factor (Intermittent Controller)	4.43	Cf/h
Emission Factor (Chemical Pump)	13.3	Cf/h
Emission Factor (Emergency Shut Down)	0.41	Cf/h
Interest Rate	7	%
Gas Price	2	$/Mscf
Remaining Lifetime for retrofit	15	Year
Share of CH_4 in dry gas	0.0167	tCH_4/Mscf
Share of CH_4 in wet gas	0.0150	tCH_4/Mscf
Travel time to & from site	8	hours

Three sample sites with different number of controllers, ESDs and electricity availability have been presented in this section. Apart from the assumptions provided in Table 6, all presented sample sites follow the following settings built in:

a) No methanol fuel cell is installed
b) Batteries are placed indoor, at room temperature

The results for the sample sites have been presented in Table 7 to Table 9.

Box 1: A note on grid connected air compressors

The technical and economic assumptions for grid connected instrument air systems are the same as the assumptions in the 2016 model and report. The assumptions for the new addition, solar powered compressed air systems, are based on the Aurora air compressor model, which has an optimized compressor design to reduce costs.

[41] https://www.carbonlimits.no/project/zero-emission-technologies-pneumatic-controllers-in-usa/
[42] Assumptions are the same as the assumptions in the 2016 model, to effectively compare the results between the 2016 and 2021 model

Sample site A: 3 continuous controllers, 2 intermittent vent controllers, 1 ESD

Table 7: Incremental CAPEX and methane abatement cost for sample site A

Site Configuration	Mitigation Option	Incremental CAPEX 2021[43]	CH_4 abatement cost 2021[44]	CH_4 abatement cost 2016[45]
New site, no electricity on site	Solar Powered Electric Controllers	$20,000[46]	$104	$146
	Grid Instrument Air[47]	-	-	-
	Solar Instrument Air	$63,000	$724	-
New site, with electricity on site	Electric Controllers	$18,000	$64	$95
	Grid Instrument Air	$42,000	$663	-[48]
	Solar Instrument Air[49]	-	-	-
Retrofit site, no electricity on site	Solar Powered Electric Controllers (Existing valves)	$24,000	$149	-
	Solar Powered Electric Controllers (New control valves)	$34,000	$256	$345
	Grid Instrument Air	-	-	-
	Solar Instrument Air	$73,000	$832	-
Retrofit site, with electricity on site	Electric Controllers (Existing valves)	$22,000	$121	-
	Electric Controllers (New control valves)	$33,000	$228	$294
	Grid Instrument Air	$60,000	$871	-
	Solar Instrument Air	-	-	-

Sample site B: 5 continuous controllers, 5 intermittent vent controllers, 1 ESD

Table 8: Incremental CAPEX and methane abatement cost for sample site B

Site Configuration	Mitigation Option	Incremental CAPEX 2021[50]	CH_4 abatement cost 2021[51]	CH_4 abatement cost 2016[52]
New site, no electricity on site	Solar Powered Electric Controllers	$32,000	$93	$119
	Grid Instrument Air	-	-	-
	Solar Instrument Air	$73,000	$465	-
New site, with electricity on site	Electric Controllers	$28,000	$62	$73
	Grid Instrument Air	$65,000	$540	-[53]
	Solar Instrument Air	-	-	-
Retrofit site, no electricity on site	Solar Powered Electric Controllers (Existing valves)	$37,000	$131	-
	Solar Powered Electric Controllers (New control valves)	$57,000	$261	$345
	Grid Instrument Air	-	-	-
	Solar Instrument Air	$86,000	$542	-
Retrofit site, with electricity on site	Electric Controllers (Existing valves)	$35,000	$107	-
	Electric Controllers (New control valves)	$55,000	$237	$300
	Grid Instrument Air	$95,000	$745	-
	Solar Instrument Air	-	-	-

[43] Incremental CAPEX (includes cost of installation), without the baseline costs of controllers included in the CAPEX. All CAPEX values presented in the table have been rounded to the nearest 1,000.
[44] Calculated using NPV
[45] Calculated using NPV, the inflation rate in the United States between 2016 and today has been 10.15%. The abatement costs presented in this row are inflation adjusted. https://www.inflationtool.com/us-dollar/2016-to-present-value
[46] The CAPEX has been rounded up/down to nearest 1,000. The actual difference in CAPEX between electric controllers at a new site with and without electricity is 1,600 USD. This is the exact cost of panels + batteries, including the incremental installation costs, for Sample Site A.
[47] This solution is not assessed when there is no electricity on site.
[48] Instrument Air technology was only assessed for sites with more than 20 controllers, in the 2016 model.
[49] This solution is not assessed when there is electricity available on site.
[50] Incremental CAPEX, without the baseline costs of controllers included in the CAPEX. All values presented in the table have been rounded to the nearest 1,000.
[51] Calculated using NPV
[52] Calculated using NPV
[53] Instrument Air technology was only assessed for sites with more than 20 controllers, in the 2016 model.

Sample site C: 10 continuous controllers, 10 intermittent vent controllers, 2 ESD

Table 9: Incremental CAPEX and methane abatement cost for sample site C

Site Configuration	Mitigation Option	Incremental CAPEX 2021[54]	CH_4 abatement cost 2021[55]	CH_4 abatement cost 2016[56]
New site, no electricity on site	Solar Powered Electric Controllers	$48,000	$55	$85
	Grid Instrument Air	-	-	-
	Solar Instrument Air			
New site, with electricity on site	Electric Controllers	$43,000	$30	$47
	Grid Instrument Air	$81,000	$275	$280
	Solar Instrument Air	-	-	-
Retrofit site, no electricity on site	Solar Powered Electric Controllers (Existing valves)	$63,000	$105	-
	Solar Powered Electric Controllers (New control valves)	$103,000	$244	$319
	Grid Instrument Air	-	-	-
	Solar Instrument Air			
Retrofit site, with electricity on site	Electric Controllers (Existing valves)	$60,000	$85	-
	Electric Controllers (New control valves)	$100,000	$224	$282
	Grid Instrument Air	$126,000	$436	$447
	Solar Instrument Air	-	-	-

The following key observations can be made based on the results obtained for the 3 sample sites:

1. All the mitigation option presented for the 3 site configurations above have methane abatement costs well below the social cost of methane.[57]
2. Electric controllers have the lowest incremental CAPEX and abatement costs in all the site configurations assessed. The difference in incremental CAPEX for solar powered electric controllers and electric controllers powered by grid electricity is not drastically high. The cost of solar panels and batteries have reduced over the last five years, reducing the differential cost of being off grid.
3. When compared to the abatement costs presented in the 2016 model, the abatement cost for electric controllers is lower in 2021, due to the updated costs. For new sites the difference is about 30%, while for retrofit sites, the calculated abatement costs compared to those of 2016 are significantly lower for cases where the valves currently installed at the site are used with the electric controllers.
4. For all technology types, retrofit sites have a higher abatement cost per tonne of CH_4 compared to new sites. This difference is majorly attributed to the incremental CAPEX used in the case of new sites. The calculations use the net cost above that of installing gas-driven controllers. Furthermore, installation at new sites have costs aggregated over several equipment, reducing the cost per controller.
5. As the number of controllers increase, the abatement cost of instrument air systems falls rapidly.

The results in Table 7 to Table 9 present the NPV abatement costs for the assessed sample sites. The model submitted an Annex to this report also estimate the annualized costs for each site configuration. Box 2 presents the annualized cost ranges for the presented sample sites.

[54] Incremental CAPEX, without the baseline costs of controllers included in the CAPEX. All values presented in the table have been rounded to the nearest 1,000.

[55] Calculated using NPV

[56] Calculated using NPV

[57] Social Cost of Methane: The report used the social cost of methane, as reported by Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, as a benchmark for the cost-effectiveness of measures to abate methane emissions. The mean value was calculated at the 3% discount rate for emissions in year 2020. The report calculates this as $1500 per metric ton in 2020 USD. Report retrieved from: https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

Box 2: A note on annualized costs

Annualized costs for assessed sample sites

The annualized methane abatement cost[58] (cost per ton of avoided methane emissions) ranges for the 3 sample sites are **presented** in the Table below. The cost effectiveness tool provided as an annex to this report calculates both the NPV cost and annualized costs for the site configurations entered by the user. For the sake of simplicity, only NPV costs have been presented in Table 7 to Table 9 of this report.

Table 10: Annualized abatement costs for the cases presented above

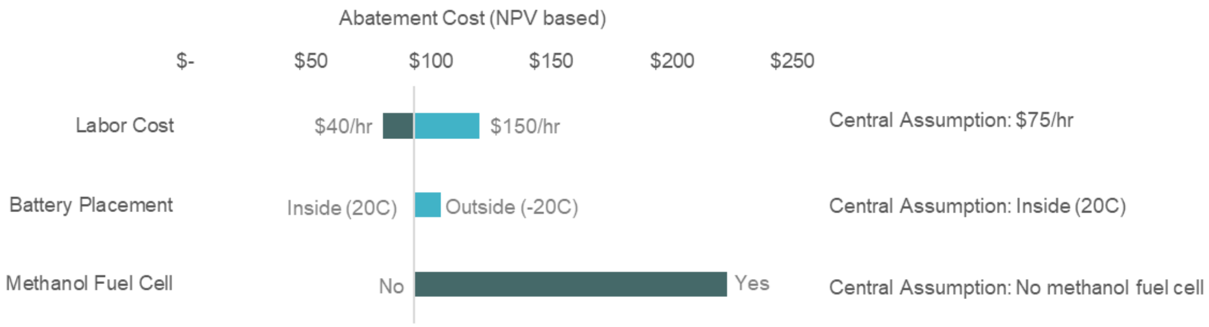
Sample sites used in Section 5	Electric Controllers	Grid Instrument Air	Solar Instrument Air
Sample site A	\$62 - \$257	\$598 - \$792	\$766 - \$875
Sample site B	\$67 - \$262	\$492 - \$683	\$496 - \$573
Sample site C	\$36 - \$245	\$251 - \$401	\$270 - \$226

To understand the effect of the newly added parameters, a sensitivity analysis has been done for electric controllers and solar powered instrument air systems in the following sub-section.

Sensitivity analysis

A sensitivity analysis was performed for a new site with 5 continuous controllers and 5 intermittent vent controllers, without access to electricity on site. The analysis for electric controllers is visualized in Figure 3 and Figure 4 shows the analysis performed for solar powered instrument air systems. (Results of the sensitivity analysis are tabulated in Appendix A).

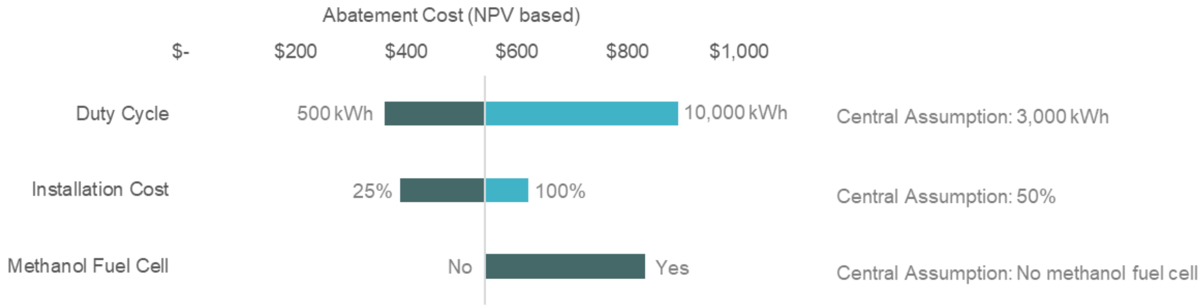
Figure 3: Sensitivity analysis for electric controllers



In this particular site configuration, the abatement cost for electric controllers changes drastically when a methanol fuel cell is added. Labor costs also have a significant effect on the abatement cost for electric controllers. This becomes more pronounced when the number of controllers increase, increasing the installation time and costs associated with the site. The placement of the battery does not have a drastic impact on the abatement cost; however, the placement of batteries can affect the performance and lifetime of the battery. Assessment of these secondary effects is beyond the scope of this report.

[58] Environmental Protection Agency, Cost Estimation: Concepts and Methodology, Retrieved from: https://www.epa.gov/sites/default/files/2020-07/documents/cs1ch2.pdf

Figure 4: Sensitivity analysis for solar powered instrument air controllers



Compared to electric controllers, the relative effect of methanol fuel cell on the abatement cost of solar powered instrument air system is lower. The most drastic effect comes from the electricity consumed by the compressor(s). The higher the required power for the compressor, the higher the number of solar panels and batteries required to power the system. This drastically increases the abatement cost. The electricity consumed is a function of the compressor size, the duty cycle, the compressor load, and the compressor efficiency. Aurora compressors generally run at 30% duty cycle and 30% compressor load.[59] Similarly, the installation cost, presented as a percentage of the CAPEX, has a significant impact on the overall abatement cost. Both installation cost and labor costs are highly site specific, with significant impact on the initial investment and methane abatement cost of the technology deployed.

6. Conclusion

The techno-economic assessment performed for different site configurations with conservative average emission factors shows that the methane abatement costs for electric controllers and instrument air technologies are lower than the social cost of methane.[60] The extreme high-cost assumptions, as presented in the sensitivity assessment, also have abatement costs lower than the social cost of methane. A major take-away from all the interviews was the increasing awareness about zero emission controllers among operators of well sites. With more options available in the market, operators can choose the technology best suited for their facility's requirements.

[59] According to Airworks compressors, the compressor is sized to have a low power consumption, depending on the facility. On an average, this value is 30% duty cycle and 30% compressor load. However, the sizing is a function of the required cfm and pneumatic air pressure required at the facility, and might change from one facility to another.

[60] Social Cost of Methane: The report used the social cost of methane, as reported by Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, as a benchmark for the cost-effectiveness of measures to abate methane emissions. The mean value was calculated at the 3% discount rate for emissions in year 2020. The report calculates this as $1500 per metric ton in 2020 USD. Report retrieved from: https://www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostofCarbonMethaneNitrousOxide.pdf

7. References

[1]	Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014, EPA, 2016 https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html
[2]	Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers Allen et al., 2015 http://pubs.acs.org/doi/abs/10.1021/es5040156
[3]	Measurements of methane emissions at natural gas production sites in the United States. Allen, David, T., et al. 2013. www.pnas.org/content/early/2013/09/10/1304880110.full.pdf+html
[4]	Determining Bleed Rates for Pneumatic Devices in British Columbia; Final Report. The Prasino Group. 2013. http://www2.gov.bc.ca/assets/gov/environment/climate-change/stakeholder-support/reporting-regulation/pneumaticdevices/ prasino_pneumatic_ghg_ef_final_report.pdf
[5]	Fort Worth Natural Gas Air Quality Study ERG2012 https://www3.epa.gov/ttnchie1/conference/ei20/session6/mpring.pdf
[6]	API Comments on Oil & Natural Gas Sector Pneumatic Devices by EPA Office of Air Quality Planning and Standards, June 2014
[7]	Quantifying cost-effectiveness of systematic Leak Detection (LDAR) using infrared cameras, Carbon limits, 2014 (including the database used for the analysis) http://www.carbonlimits.no/project/quantifying-cost-effectiveness-of-systematic-leak-detection-ldar-using-infrared-cameras/
[8]	Pneumatic Controller Emissions from a Sample of 172 Production Facilities Prepared by Oklahoma Independent Petroleum Association, 2014 http://www.oipa.com/page_images/1418911081.pdf
[9]	Information provided by technology providers.
[10]	Information provided by operators.
[11]	Methane abatement potential from oil and gas systems in Kazakhstan Carbon Limits, 2016 http ://www.carbonlimits.no/project/methane-abatement-potential-from-oil-and-gas-systems-in-kazakhstan/
[12]	Online quotes for equipment purchase March – April 2016
[13]	Reducing Emissions Through Retrofitting of High Bleed Devices – GE 2012 https://www.epa.gov/gasstar/documents/workshops/2012-annual-conf/giernoth.pdf
[14]	Convert Gas Pneumatic Controls To Instrument Air Natural Gas Star Program 2006 https://www3.epa.gov/gasstar/documents/ll_instrument_air.pdf
[15]	Carbon Limits – expert opinion
[16]	Subpart W rulemaking and summary results https://www.law.cornell.edu/cfr/text/40/part-98/subpart-W/appendix-TableW-1A
[17]	Oil and Natural Gas Sector: Standards for Crude Oil and Natural Gas Facilities – Background Technical Support Document for the Proposed New Source Performance Standards EPA, 2015 https://www.regulations.gov/#!documentDetail;D=EPA-HQ-OAR-2015-0216-0101
[18]	INITIAL ECONOMIC IMPACT ANALYSIS For proposed revisions to Colorado Air Quality Control Commission Regulation Number 7
[19]	Regulatory Impact Analysis of the Proposed Emission Standards for New and Modified Sources in the Oil and Natural Gas Sector, EPA 2015 https://www3.epa.gov/airquality/oilandgas/pdfs/og_prop_ria_081815.pdf
[20]	Online quotes for equipment purchase March – June 2021

8. Appendix A: List of assumptions

Table A. 1: Quantitative assumptions for the model

Description	Assumption	Unit	Source	Changes compared to 2016 model
GENERAL ASSUMPTIONS				
Number of minutes per hours	60	#	NA	-
Number of hours in a day	24	#	NA	-
Number of Days in a year	365	#	NA	-
Number of work hours in a day	8	hours/day	NA	New! To calculate labor costs
HP->MW	0.00075	MW/HP	NA	-
Methane density	0.66	kg/m3	NA	-
Methane density	0.0186	kg/cf	NA	-
cf->cm	0.0283	cm/cf	NA	-
Share methane in the Gas – Dry Gas	0.0167	tCH4/Mscf	[15]	-
Share of VOC in the gas – Dry Gas	0.0046	tVOC/Mscf	[15]	-
Share methane in the Gas – Wet Gas	0.0150	tCH4/Mscf	[15]	-
Share of VOC in the gas – Wet Gas	0.0050	tVOC/Mscf	[15]	-
Lifetime new sites	15	years	NA	-
ESD emission factors	0.41	cf/h	[2]	-
GRID INSTRUMENT AIR - ENGINEERING ASSUMPTIONS				
Share of the air bypassed in dryer	17%	%	[14,10]	-
Share of the utility air supply	200%	%	[14,10]	-
Sizing of compressor - variable component	0.20	HP/cfm	[14,10]	-
Sizing of compressor - constant component	4.24	HP	[14,10]	-
Load of the compressor (main)	50%	%	[14,10]	-
Lifetime of the compressors	6	years	[14,10]	-
SOLAR INSTRUMENT AIR - ENGINEERING ASSUMPTIONS				
Share of the air bypassed in dryer	5%	%	[14,10]	New! Refer to Table 1 in Section 3
Share of the utility air supply	150%	%	[14,10]	New! Refer to Table 1 in Section 3
Sizing of compressor - variable component	0.20	HP/cfm	[14,10]	New! Refer to Table 1 in Section 3
Sizing of compressor - constant component	4.24	HP	[14,10]	New! Refer to Table 1 in Section 3
Load of the compressor (main)	30%	%	[14,10]	New! Refer to Table 1 in Section 3
Duty Cycle	30%	%	[14,10]	New! Refer to Table 1 in Section 3
Lifetime of the compressors	10	years	[14,10]	New! Refer to Table 1 in Section 3
ELECTRIC CONTROLLERS - ENGINEERING ASSUMPTIONS				
Continuous Controller (s)	0.08	Amps/unit	[9]	-
Intermittent Controller (s)	0.08	Amps/unit	[9]	-
Other controller (s)	0.08	Amps/unit	[9]	-
Chemical Pumps	0.40	Amps/pump	[9]	Updated! Based on stakeholder consultation
ESD	0.16	Amps/unit	[9]	-
Other systems	0.29	Amps/site	[9]	-
POWER PRODUCING UNITS - ENGINEERING ASSUMPTIONS				
Battery replacement frequency (100 Ah)	4	years	[9,10]	-
Battery replacement frequency (1100 Ah)	7	years	[9,10]	New! Based on stakeholder consultation
Solar Panel replacement frequency	10	years	[9,10]	-
System Voltage (Electric Controllers)	12	V	[9,12]	-
System Voltage (Solar powered instrument air)	24	V	[9,12]	New! Based on stakeholder consultation
Battery Average Efficiency	85%	%	[9,12]	-

Avg. Peak Sun	4	h/days	[9,10]	-
At Maximum Depth of Discharge	80%	%	[9]	-
Days of Energy Storage (Electric Controllers)	10	days	[9]	-
Days of Energy Storage (Solar powered instrument air)	4	days	[9]	New! Based on stakeholder consultation
Rating of the solar panel (Electric Controllers)	140	W	[9,12]	-
Rating of the solar panel (Solar powered instrument air)	320	W	[9,12]	New! Based on stakeholder consultation
% difference in required battery capacity (at -20C or -4F)	35%	%	[9]	New! Refer to Section 3
% difference in required battery capacity (at 0C or 32F)	0%	%	[9]	New! Refer to Section 3
% difference in required battery capacity (at 20C or 68F)	-14%	%	[9]	New! Refer to Section 3
Rating of the battery (Electric Controllers)	100	Ah	[9,12]	-
Rating of the battery (Solar powered instrument air)	1100	Ah	[9,12]	New! Based on stakeholder consultation
Maximum Number of solar panel on a site	20	#	[9]	Updated! Based on stakeholder consultation
Oversizing of the solar panel (Electric Controllers)	50%	%	[9,10]	-
Oversizing of the solar panel (Solar powered instrument air)	30%	%	[9,10]	New! Based on stakeholder consultation
Maximum Number of batteries on a site	20	#		Updated! Based on stakeholder consultation
GRID INSTRUMENT AIR - COST ASSUMPTIONS				
Compressor Package – Main (5 HP)	$22,000	USD	[12,10]	-
Compressor Package – Main (10 HP)	$32,000	USD	[12,10]	-
Compressor Package – Main (15 HP)	$48,000	USD	[12,10]	-
Compressor Package – Main (20 HP)	$70,000	USD	[12,10]	-
Compressor - Unit cost (5 HP)	$7,000	USD	[12]	-
Compressor - Unit cost (10 HP)	$10,000	USD	[12]	-
Compressor - Unit cost (15 HP)	$15,000	USD	[12]	-
Compressor - Unit cost (20 HP)	$23,000	USD	[12]	-
Other supply (Retrofit sites)	$1,400	USD/controller	[10]	-
Other supply (New Sites)	$1,000	USD/controller	[10]	-
Installation (Retrofit Sites)	100%	%	[10]	-
Installation (New Sites)	50%	%	[10]	-
Compressor maintenance	4%	% of Capex	[10,15]	-
Engine Maintenance	4%	% of Capex	[10,15]	-
SOLAR INSTRUMENT AIR - COST ASSUMPTIONS				
Compressor Package – Main (5 HP)	$30,000	USD	[12,10]	New! Refer to **Table 3** in Section 4
Compressor Package – Main (10 HP)	$37,000	USD	[12,10]	New! Refer to **Table 3** in Section 4
Compressor Package – Main (15 HP)	$45,000	USD	[12,10]	New! Refer to **Table 3** in Section 4
Compressor Package – Main (20 HP)	$50,000	USD	[12,10]	New! Refer to **Table 3** in Section 4
Compressor - Unit cost (5 HP)	$7,000	USD	[12]	New! Refer to **Table 3** in Section 4
Compressor - Unit cost (10 HP)	$10,000	USD	[12]	New! Refer to **Table 3** in Section 4
Compressor - Unit cost (15 HP)	$15,000	USD	[12]	New! Refer to **Table 3** in Section 4
Compressor - Unit cost (20 HP)	$23,000	USD	[12]	New! Refer to **Table 3** in Section 4
Installation (Retrofit Sites)	75%	%	[10]	New! Refer to **Table 5** in Section 4
Installation (New Sites)	50%	%	[10]	New! Refer to **Table 5** in Section 4
Compressor maintenance	4%	% of Capex	[10,15]	New! Refer to **Table 3** in Section 4
ELECTRIC CONTROLLERS - COST ASSUMPTIONS				
Continuous Controller (s) + control valve	$4,000	USD/unit	[9,10]	Updated! Refer to **Table 2** in Section 4
Intermittent Controller (s) + control valve	$4,000	USD/unit	[9,10]	Updated! Refer to **Table 2** in Section 4
Continuous Controller	$1,500	USD/unit	[9,10]	Updated! Refer to **Table 2** in Section 4
Intermittent Controller	$1,500	USD/unit	[9,10]	Updated! Refer to **Table 2** in Section 4
Control Valve	$2,500	USD/unit	[9,10]	Updated! Refer to **Table 2** in Section 4

Chemical Pump	$6,000	USD/unit	[9,10]	Updated! Refer to Table 2 in Section 4
Control Panel	$4,000	USD/unit	[9,10]	Updated! Refer to Table 2 in Section 4
Labor Costs	$75	USD/hour	[9,10]	New! Refer to Table 5 in Section 4
Days of Work - Retrofit	0.75	days/controller	[9, 10]	New! Refer to Table 5 in Section 4
Days of Work - New Site	0.50	days/controller	[9, 10]	New! Refer to Table 5 in Section 4
Annual maintenance	$80	$/controller/year	[15]	New! Refer to Table 5 in Section 4
POWER PRODUCING UNITS - COST ASSUMPTIONS				
Solar Panel (140 W)	$400	USD/unit	[9,12]	Updated! Refer to Table 4 in Section 4
Battery (100 Ah)	$200	USD/unit	[9,12]	Updated! Refer to Table 4 in Section 4
Solar Panel (320 W)	$500	USD/unit	[9, 12]	Updated! Refer to Table 4 in Section 4
Battery (1100 Ah)	$3,500	USD/unit	[9, 20]	Updated! Refer to Table 4 in Section 4
Methanol Fuel Cell	$20,000	USD/unit	[9,20]	Updated! Refer to Table 4 in Section 4
Fail Safe System & UPS (ESD)	$3,500	USD/unit	[9,20]	Updated! Refer to Table 4 in Section 4
Electricity price US	$0.12	USD/kwh	[15]	Updated! After stakeholder consultation
BASELINE - COST ASSUMPTIONS				
Continuous Controller (s) + control valve	$2,698	USD/cont.	[17]	-
Intermittent Controller (s) + control valve	$2,471	USD/cont.	[17]	-
Chemical Pump	$1,500	USD/unit	[12,10]	-
ESD	$1,000	USD/unit	[12,10]	-
Labor - installation - Controller	$387	USD/unit	[18]	-
Labor - installation - Pump	$387	USD/unit	[15]	-
Maintenance costs - Controller- wet gas sites	$200	USD/cont./year	[10]	-
Maintenance costs - Controller- dry gas sites	$80	USD/unit	[18]	-

Other Assumptions

General assumption:

- Retrofitting is assumed to be performed during a planned maintenance, hence retrofit activities do not cause production losses; thus, no potential revenue losses are accounted for in the estimates presented.

Electric controllers:

- In retrofit configuration, it is assumed that ESDs are gas driven pneumatic controllers (that is, ESDs are not retrofit). In the case of new sites, ESD is assumed to be zero emission option with UPS and FSC.
- In retrofit configuration, it is assumed that new control valves are not required. In the case of new sites, the cost of both controller and control valves have been considered (but note that CAPEX costs for new sites are incremental costs, above that for traditional pneumatic controllers and control valves).
- Electric controllers can reduce the need for site inspections, or the cost of those inspections[61]. The subsequent reduced labor costs have not, however, been taken into consideration in the analysis.

Instrument air:

CO_2 emissions from power consumption (for non-solar powered options) have been neglected; this represents a very small volume of emissions compared to the CH_4 emissions (typically a few per cent, assuming a GWP of methane of 36 (20-year GWP) or 87 (100-year GWP)).

[61] Gas-driven pneumatic controllers must be inspected during site leak inspections under regulations in Colorado and under proposed regulations in other US jurisdictions.

Detailed sensitivity analysis

Site configuration:

- New Site
- No electricity access
- 5 continuous controllers
- 5 intermittent vent controllers
- Travel Time: 8 hours
- Dry gas supply
- 1 ESD

Table A. 2: Sensitivity analysis for some of the newly added parameters.[62]

Electric Controllers		Solar powered IA System	
Labor Cost ($/hour)	**Abatement Cost**	**Duty cycle**	**Abatement Cost**
$40	$80	10%	$373
$60	$87	30%	$465
$75	$93	50%	$619
$80	$95	60%	$638
$100	$102	70%	$718
$120	$109	80%	$737
$140	$116	90%	$811
$150	$120	100%	$891
Battery Placement	Abatement Cost	**Installation Cost (%CAPEX)**	**Abatement Cost**
Outside (-40C)	$104	25%	$360
Outside (0 C)	$96	50%	$465
Inside (20 C)	$93	75%	$541
Methanol Fuel Cell	Abatement Cost	80%	$557
Yes	$223	90%	$588
No	$93	100%	$619

[62] All abatement costs have been calculated using NPV.