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Zero emission technologies for pneumatic controllers in the USA

Applicability and cost effectiveness

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Zero emission technologies for pneumatic controllers in the USA

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Carbon Limits is a consulting company with long standing experience in supporting energy efficiency measures in the petroleum industry. In particular, our team works in close collaboration with industries, government, and public bodies to identify and address inefficiencies in the use of natural gas and through this to achieve reductions in greenhouse gas emissions and other air pollutants.

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Executive Summary

Natural gas-driven pneumatic controllers are used widely in the oil and natural gas industry to control liquid level, temperature, and pressure during the production, processing, transmission, and storage of natural gas and petroleum products. However, these devices release methane into the atmosphere. Pneumatic controllers are the second-largest source of methane from the US oil and gas industry, behind only component leaks, according to US EPA's Greenhouse Gas Inventory.

US Federal rules require that new continuous-bleed controllers be *low-bleed* (defined as designed to emit less than six standard cubic feet/hour) at production sites and compressor stations and be *zero-bleed* at processing plants. Unfortunately, recent measurements have demonstrated that many controllers currently in field use are emitting more than would be expected based on design specifications.

This study was undertaken to determine whether cost-effective non-emitting technologies are available to eliminate this major emissions source. We find that these technologies have evolved considerably over the past decade and are now available and actively in use in oil and gas fields in the United States and Canada. Two technologies are mature, proven, and in relatively wide use, and as we discuss in this report, these technologies provide a cost-effective way to eliminate emissions of methane and other pollutants from pneumatic controllers.

Major findings include:

- Zero emission technologies can virtually eliminate emissions from pneumatic devices.
- A number of technologies are available. The two most promising, which this report focuses on, are electronic controllers – both solar and grid powered – and instrument air**.**

    Electronic controllers can be installed both at sites connected to the electric grid and at sites isolated from the grid.

    Instrument air technology is a well-established, mature solution to run pneumatic control systems and is widely applied globally. The technology requires a reliable power supply, either from the grid or from generators on the site.

- Currently, electronic controllers are generally used at smaller sites while instrument air is used at larger sites, due to the technical limitations of air compressors. These two technologies are on the market today, from multiple suppliers.
- Due to the market conditions, providers of electronic controllers have so far focused mainly on the development of solutions for small sites in remote locations. There thus seems to be much less field experience with using electronic controllers at medium and large sites; however, no technical barriers were identified for this type of installation.
- A number of other zero emission solutions are available today with more limited applicability (e.g. self-contained devices) or fewer documented implementations (e.g. solar-powered instrument air). Depending on the site specificities, these options can represent useful alternatives to instrument air or electronic controllers.
- Operators have successfully installed hundreds of systems. They report positive experiences on both new and retrofit sites, valuing zero emission solutions for their low maintenance costs and reliability.
- An economic analysis, assuming conservative average emission factors for pneumatic controllers, was performed for 2032 site configurations with 1 to 40 controllers (excluding emergency

shutdown devices). Both retrofit and new installations, with and without electricity on-site, were considered.

- Zero emission solutions have abatement costs below the social cost of methane used by US EPA ($1354/tCH₄ → $1354/t$CH_4$, mean value calculated for 2020 with a 3% discount rate in 2016 USD) in the vast majority of the site configurations considered (2008 out of 2032 site configurations).
- The abatement costs, calculated as described above, exceed the social cost of methane used by US EPA primarily at very small sites – those with less than three controllers (excluding emergency shutdown devices). However, if higher emission factors, as reported from recent field measurements, are used, the abatement costs at even the very small sites will fall below the social cost of methane.

Overall, we find that zero emission solutions are available today and are cost effective to implement in nearly every situation.

The following table presents a summary of both the technical applicability and economic attractiveness of the different zero emission technologies under different categories of sites. Though this analysis does not provide a detailed evaluation of the distribution of the sites in the US for each of the below categories, existing studies have suggested that the vast majority of the sites have less than 20 controllers.

			Both retrofit and new sites					
Type of of site		**Number of controllers** (excl. ESDs)	**1- 3**		**4-20**		**21-40**	
Type of of site		**Electricity on-site?**	Yes	No	Yes	No	Yes	No
Main options: Electric controller Instrument air		**Description** (of the most economic option which is technically feasible)	Grid connected **electric** controller	Solar powered **electric** controller	Grid connected **electric** controller	Solar powered **electric** controller	Instrument **air**	
Main options: Electric controller Instrument air		**Number of cases not cost effective** (i.e. abatement cost > social cost of methane) **under central assumptions**	6 / 36	11 / 36	0 / 308	2 / 308	5/ 328	
Main options: Electric controller Instrument air		**Cost effective for every site configuration** if emissions factors are:*	> 5.6 scfh for retrofit > 2.8 scfh for new sites	> 7.2 scfh for retrofit > 4.4 scfh for new sites	> 3.6 scfh for retrofit > 1.4 scfh for new sites	> 4.2 scfh for retrofit > 1.8 scfh for new sites	> 4.5 scfh for retrofit > 1.8 scfh for new sites	
Other options potentially applicable depending on the local conditions	Limited applicability	Vent gas recovery	✓	✓	✓	✓	✓	✓
Other options potentially applicable depending on the local conditions	Limited applicability	Instrument air powered by gas	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	✓
Other options potentially applicable depending on the local conditions	Limited applicability	Self contained controllers	✓	✓	✓	✓	✓	✓
Other options potentially applicable depending on the local conditions	Limited known implementations	Solar powered instrument air	Not relevant	✓	Not relevant	✓	✗	✗
Other options potentially applicable depending on the local conditions	Limited known implementations	Electric controllers powered by other power sources (TEG, fuel cell)	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	✓
Other options potentially applicable depending on the local conditions	Limited known implementations	Large solar powered electric controller (no known implementations)	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Potential solution,** but no example known.

*Emissions factors threshold listed are determined for the site configuration with the highest abatement cost within the category.
** Based on other solar applications. No fundamental barrier identified.

Abbreviations and Notes on Units

CAPEX	Capital Expenditure
CH_4	Methane
CO_2eq	Carbon dioxide equivalent
EF	Emission Factor
ESD	Emergency shut down
GHGRP	Greenhouse Gas Reporting Program – US EPA
GOR	Gas/oil ratio
Mscf	Thousands standard cubic feet
MMscf	Million standard cubic feet
MMscfd	Million standard cubic feet per day
MMT	Million tons
OPEX	Operational expenditure
SCADA	Supervisory Control and Data Acquisition
Scfh	Standard cubic feet/hour
USD	US dollars
VOC	Volatile Organic compound
VRU	Vapor Recovery Unit

Notes on units:

All the data are presented in metric tons

All monetary figures are presented in US dollars, denoted as $

Social Cost of Methane: This report uses the social cost of methane, as reported by US EPA in recent regulatory analyses, as a benchmark for the cost-effectiveness of measures to abate methane emissions. We use the mean value calculated at the 3% discount rate for emissions in year 2020. EPA calculates this as $1300 per metric ton in 2012 USD. We have converted this to $1354 per metric ton in 2016 USD, using a cumulative rate of inflation of 4.2%.

1. Introduction

1.1 What is the problem?

Natural gas-driven pneumatic controllers are used widely in the oil and natural gas industry to control liquid level, temperature, and pressure during the production, processing, transmission, and storage of natural gas and petroleum products. However, these devices vent methane into the atmosphere. Pneumatic controllers are the second-largest source of methane from the US oil and gas industry, behind only component leaks, according to US EPA's Greenhouse Gas Inventory [1].

Over the last few years, regulators have worked to reduce the emission of methane and volatile organic compounds (VOCs) from pneumatic controllers. US Federal rules require that new continuous-bleed controllers be *low-bleed* (defined as designed to emit less than 6 scfh) at production sites and compressor stations and *zero-bleed* at processing plants. Wyoming goes further to include intermittent-vent controllers in its requirement that *all* new controllers are designed to emit less than 6 scfh. It also requires the replacement of existing high-emitting controllers in some areas and caps allowable emissions in other areas. Recently Colorado required that existing high-continuous-bleed controllers be replaced with low-bleed controllers statewide, and other states are currently considering similar measures. Finally, some operators have reported voluntary replacements of high-bleed controllers with low-bleed controllers to programs such as US EPA's Natural Gas STAR.

Unfortunately, recent measurement studies [2,3,4] have reported higher emissions from low-bleed controllers than expected. Some controllers that are considered low-bleed according to manufacturer specifications actually bleed above the low-bleed threshold of 6 scfh. Indeed, a number of controllers appear to malfunction, emitting significantly more than they are designed to emit.

Moreover, as a class, intermittent-vent controllers, which are largely unregulated, far outnumber continuous-bleed controllers, and EPA estimates that emissions from intermittent-vent controllers are considerably higher than emissions from continuous-bleed controllers [1]. Recent work has demonstrated that some controllers designed to emit intermittently fail and begin leaking natural gas continually [2,5].

Given the wide range of applications of pneumatic controllers, their typical installation in remote, unmanned sites, and the limited resources of air quality regulators, it is very challenging for air quality regulators to ensure compliance to emissions standards for pneumatic controllers. Currently, new continuous-bleed controllers are in compliance with EPA rules, if they are designed to emit below the EPA threshold of six cubic feet per hour. In practice, they may emit more depending on installation parameters (such as the pressure of the supply-gas), malfunctions, or even tampering, e.g. production workers modify controllers bleed rates when they believe that it will improve reliability [9]. Finally, it is inherently difficult to quantify the emissions from intermittent-vent controllers, as their actuation frequency is variable and may change over time.

1.2 Objective of this project

Zero emission technologies have the potential to virtually eliminate this emission source. They have evolved extensively over the last few years, as operators have gained experience using them. Yet, although zero emission technologies are often mentioned in best practices documentation and reports, there is very limited information on overall applicability and costs (with the exception of instrument air).

This report documents how zero emission technologies are being used in gas and oil fields, and discusses the zero emissions technologies that are suitable for wide usage in common applications at oil and gas production facilities and compressor stations. The main objectives include:

- Presentation of zero emission technologies that are currently available on the market.
- Discussion of the applicability and the technical barriers to the implementation of these technologies.
- Estimates of implementation and methane abatement costs of these technologies for new installations and retrofits.

1.3 Approach and methodology

In addition to a comprehensive literature review, this report relies on interviews with a number of relevant stakeholders and a detailed cost-benefit analysis.

Interviews: Seventeen interviews were conducted. Nine were with technology providers, and eight with both small and large oil and gas companies. The interviews gathered information on field experience with the implementation of zero emission technologies, in particular on their applicability, technical barriers experienced, and actual costs and benefits.

Cost-benefit analysis of zero emission technology implementation: Based on the information gathered during the interviews, literature reviews, and online equipment quotes, a cost-benefit analysis was performed covering a wide range of possible site configurations.

The cost-benefit analysis is presented in section 4 of this report. Prior to that, section 2 includes an introduction to controller typologies, followed by a brief literature review of emissions from controllers. Section 3 presents the different zero emission controller technologies and includes a description of field experiences with these technologies. The report concludes with a brief overview of existing applicability and costs under a range of circumstances.

2. Gas Driven Pneumatic controllers – What are we talking about?

2.1 Definition

A process controller is a device that senses a physical state and then operates automatically to regulate that state[1], based on an established set-point in its control logic. Process controllers can regulate a variety of physical parameters – or *process variables* – including fluid pressure, liquid level, fluid temperature, and differential pressure. An example of a common type is a separator dump valve controller, which operates when it senses that liquid has reached a certain level. Process controllers can be electric, hydraulic, pneumatic or a combination of them. An example of a combination controller would be an electrohydraulic controller operating an electric valve to send liquid pressure to a hydraulic end-device.

Pneumatic controllers convert an input signal to a pneumatic pressure output using gas pressure. The end-device, i.e. the control valve, is adjusted by the actuator in response to signal from the controller.
A pneumatic controller uses gas pressure to open or close a mechanical device, such as a valve, when it senses the need to regulate a process condition such as liquid level, pressure, temperature, or flow.

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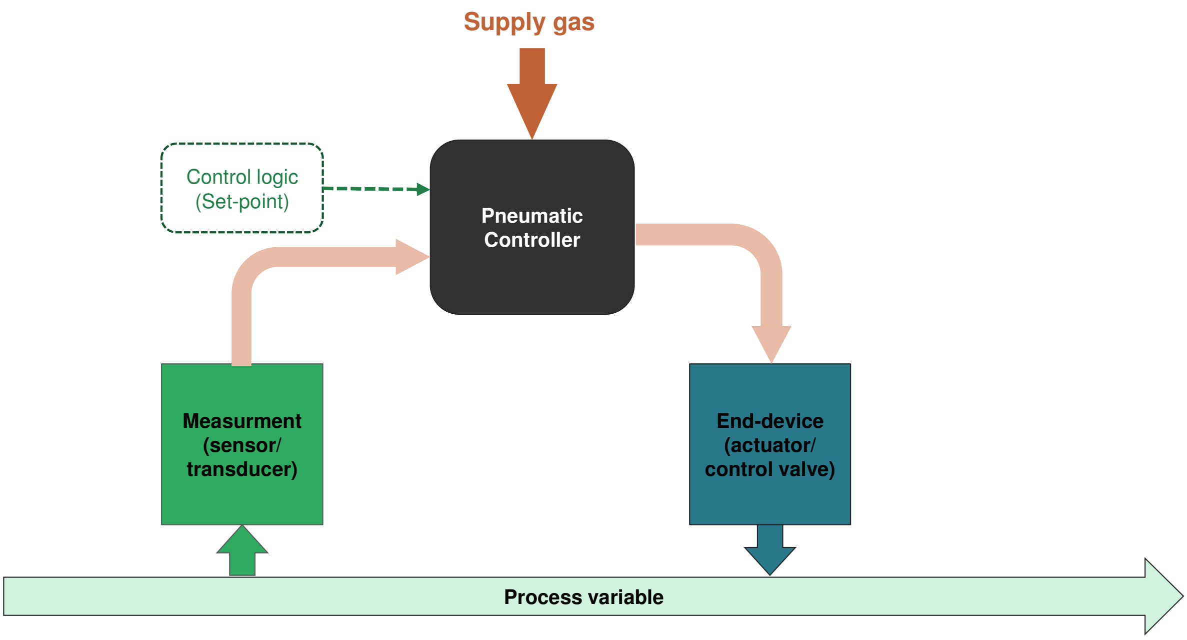
[1] In complex control systems, other process control variables might be modulated to regulate the *state* of that process variable.

Figure 1: Pneumatic Controller - concept sketch



2.2 Typology of controllers

Different typologies have been used in the literature to classify controllers, based on:

- The controller application (i.e. what the controller is used for, such as to control liquid level, pressure, or temperature)
- The emission pattern of the controller (continuous-bleed or intermittent vent)
- The end service (i.e. the way the controller regulate the parameter, such as *on/off* service or *throttle* service)

Controller application

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.

Emission pattern of the controllers

Pneumatic controllers can be designed to release supply-gas continuously or intermittently. Pneumatic controllers are thus classified as **continuous-bleed** or **intermittent-vent** (equivalent to intermittent bleed in all EPA documents), depending on whether or not they are *designed* to emit continuously.

In this study,

- emissions occurring from intermittent-vent controllers, where there is a physical barrier between the supply-gas and the end-device, are referred to as ***vent***; and
- emissions from continuous-bleed controllers, where the supply-gas provides required pressure to the end-device while the excess amount of gas is emitted, are referred to as ***bleed***.

The continuous-bleed controllers are classified into high-bleed and low-bleed in this report, depending on whether or not the controller is deemed to have a bleed rate above or below 6 scfh, in line with EPA regulations.[2]

The typology used in this report differs from the one presented in Allen et al. [2] where controllers are classified depending on their measured emissions pattern as opposed to their designed emissions pattern.

End-service typology

The end-device can be in *on/off* service or *throttle* service, depending on the process requirements. An example of on/off service is a dump-valve that controls the level of a vessel. In the "on" state, the valve is completely open to "dump" liquid. When the desired level has been achieved, the valve completely closes to its "off" state. An example of throttle service is a pressure control valve, which increases or decreases the flow of gas as needed to maintain line pressure at a fixed value. Both continuous-bleed and intermittent-vent controllers are commonly used to perform both on/off and throttling services.

A summary of pneumatic controller typology is presented in the table below. As this study focuses on eliminating emissions from these devices, only the emission pattern typology is used in the rest of the report.

Table 1: Summary of controller typology (mainly based on [6])

		Type of Service	
		On/Off	**Throttling**
Emission characteristics	**Intermittent-vent**	- Gas vented at de-actuation - Designed to emit no gas between de-actuation instances - De-actuation frequency depends on process variability	- Gas vented when end-device needs to throttle-off - Designed to emit no gas between throttle-off instances - Throttling frequency depends on process fluctuations
	High-bleed continuous controller	- Gas emitted continuously with higher bleed rates when end-device needs "off" service - Nevertheless, the average bleed amount is constant - Bleed rates are by definition deemed to be higher than 6 scfh	- Gas emitted continuously with higher bleed rates end-device needs to throttle-off - Nevertheless, the average bleed amount is constant - Bleed rates are by definition deemed to be higher than 6 scfh
	Low-bleed continuous controller	- Gas emitted continuously with higher bleed rates when end-device needs "off" service - Nevertheless, the average bleed amount is constant - Bleed rates are by definition deemed to be lower than 6 scfh	- Gas emitted continuously with higher bleed rates end-device needs to throttle-off - Nevertheless, the average bleed amount is constant - Bleed rates are by definition deemed to be lower than 6 scfh

2.3 Number of controllers and emission factors – Brief literature review.

Important work has been taking place over the last few years to measure and understand methane and VOC emissions from pneumatic controllers. This work includes measurement surveys [2,3,4,7], count of controllers per facility [1,2,8], and engineering calculations [8]. The methodology and the sampling approach vary significantly between different sources of information; thus comparisons should be made with particular care [8].

[2] It should be noted that the bleed rate is not a specification of the controller only, but also depends on the pressure and flow-rate of the supply-gas in addition to the size of the restriction orifice.

How many controllers per site?
The number of controllers per site varies depending on the number of wells and more generally the number and type of equipment used. Recent studies have demonstrated that the vast majority of sites have less than 20 controllers.

Most of the existing studies have focused only on emitting controllers [3,5,7], thus underestimating the number of controllers reported for each site, since some intermittent-bleed controllers actuate infrequently (e.g., controllers for emergency shut-down valves) and are unlikely to do so while a site is being surveyed. Two studies have performed a thorough count of the number of controllers per site [2,8]. The distribution of controller functions reported by these studies varied, perhaps due to differences in the types of sites sampled in the studies, but the overall distribution of controller counts at production sites were quite similar (Figures 2 and 3):

- Very small and medium sites (with less than 20 controllers) account for the vast majority (97%) of the sites evaluated in both studies (Figure 2)
- These sites represent 85% of the controllers (Figure 3)

Figure 2: Share of the sites depending on the total number of controllers per site

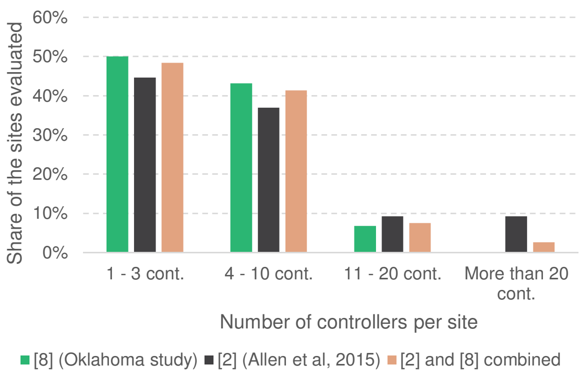
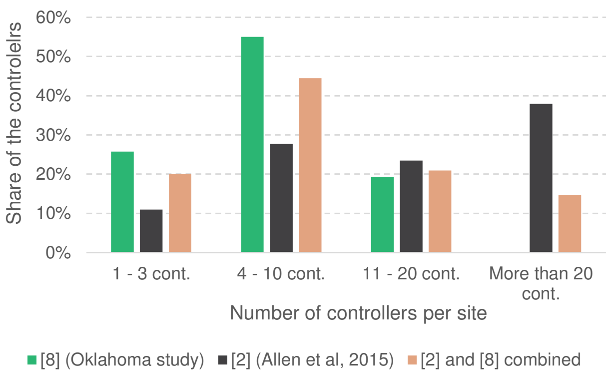


Figure 3: Share of the controllers depending on the total number of controllers per site



How much do controllers emit?
Despite the important work performed over the last few years, there is still significant uncertainty regarding emissions factors from controllers. The following figure summarizes the current emission estimates available for the different categories of controllers.

Figure 4: Emissions factors by controller category from different information sources[3]

A number of important conclusions can be drawn from the review of existing publications:

- Emissions from controllers vary between controller models and, for some models, for the same controller model between sites [2,4,7]
- A small subset of the controllers account for the vast majority of the emissions [2,7]
- Overall, recent research has demonstrated that a number of controllers behave differently than originally designed. In particular,
  - Average emission rates exceed the manufacturers' specifications [4], including some controllers designated low-bleed which emit above the threshold rate of 6 scfh [4,7]
  - Some controllers designed to emit intermittently fail and begin emitting natural gas continually [2,5]

In the analysis presented in the report, we have very conservatively adopted the lowest of the above average EFs for low-bleed in new installations and for intermittent-vent controllers. For continuous bleed controllers at existing sites, we have used the results of the recent measurement [2]. This average is consistent with a mix of low- and high-bleed in the field. The EFs are illustrated in Figure 4 and are described further in Section 4.1.

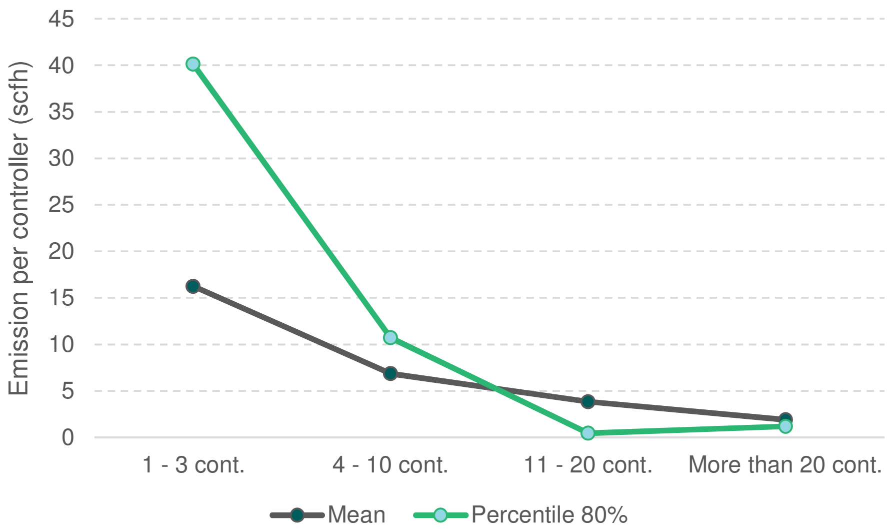
Do controllers from smaller sites emit more?

There is very little information available on how emission factors vary depending on the site's size. Analysis of recent measurements [2] suggests, however, that controllers are likely to emit much more in small than in large sites.

The following graph, plotting the mean and the eightieth percentile emission factors, shows a clear downward trend as the number of controllers per site increases. This trend could potentially be explained by the difference in terms of maintenance practices for small sites (typically unmanned and in remote area) and larger sites. In the follow-up analysis, a constant emission factor is assumed for both small and large sites.

[3] The data from [3] and [4] have been categorized and presented as described in [8]. The data from [2] have been categorized based on the "company classification into EPA category" (excluding ESD) and not based on the measured emission typology.

Figure 5: Average emission factors depending on the number of controllers per site [2]



3. Zero emission technologies – Description and technical applicability

This section provides an overview of a number of zero emission technologies available as an alternative to gas driven pneumatic controllers, based primarily on interviews and on a general literature review. A technology is considered "zero emission" if there is no methane or VOC emissions associated with its utilization.

3.1 Overview of the zero emission technology presented.

Five different technologies have been reviewed: Electronic controllers, instrument air provided by compressors (with electric power from the grid or existing on-site generation), solar-powered instrument air, vent recovery, and self-contained pneumatic controllers. Of these five different zero emission technologies, two – electronic controllers and instrument air – have reached a reliable level of maturity and are widely applicable. The remaining three technologies are either less mature (solar-powered instrument) or are applicable only in certain circumstances (self-contained pneumatic controllers and vent recovery).

The economic feasibility of the two mature and widely applicable technologies, electronic controllers and instrument air, is evaluated in detail in section 4 of this report.

The following table presents a brief summary of the different technologies evaluated.

Table 2: overview of the zero emission technologies presented

Technology	Maturity of the technology	Technical applicability limitations	Main strengths
Electronic controllers (ref section 3.2)	The technology has reached a reliable level of maturity, with hundreds of installations identified throughout this study.	Operators interviewed continue to use pneumatic ESDs. Some limitations with large numbers of controllers or high power demand chemical injection pumps.	• Can operate off grid • Reduced maintenance costs, in particular compared to wet gas driven controllers • Enables or simplifies automation of systems

Instrument air (ref section 3.3)	Extensive global experience for many years	Requires a reliable source of power Limited to installations with an air compressor > 5 HP	• Reliability • Reduced maintenance costs, in particular compared to wet gas driven controllers
Solar-powered Instrument air (ref section 3.4)	Less than 100 installations identified	Compressor up to ~20 scfh	• Operates off grid • Reduced maintenance costs, in particular compared to wet gas driven controllers
Vent Recovery (ref section 3.4)	The study identified less than 100 installations, with uncertain performance	Requires the presence of a VRU or a gas engine on site	• Reliability
Self-contained pneumatic controllers (aka "Bleed to Pressure" or integral controllers) (ref section 3.4)	Although this solution has been deployed since early 2000s and is considered a relatively well-developed technology, controllers of this type are only available for certain specific applications	Applicability is limited by a number of conditions (e.g. pressure differential, downstream pressure, etc.)	• Low-cost solution

3.2 Electronic controllers (solar powered and grid powered)

Electronic controllers adjust the position of the end-device by sending an electric signal to an electric actuator or positioner (as compared to pneumatic controllers which send a pneumatic signal to a pneumatic actuator or positioner). A motor powers the electric actuator to adjust the control valve to the desired position.

This section provides a description of the benefits, costs, and applicability of electronic controllers to both new sites and existing sites, where retrofits would be required. The description is based mainly on interviews with four oil and gas production companies that have installed these systems in their operations (from 3 to 40 installations per operator interviewed), complemented by interviews with technology providers.

Description of the technology

Electronic controllers can be installed both at sites connected to the electric grid, and at remote sites isolated from the grid. These systems typically include a control panel, electric actuators, electronic controllers, control valves, relevant switches (e.g. pressure, level or temperature switch) and a power source – connection to the grid, solar panels and batteries, or power generation on site. An electronic control system is generally designed to completely replace all pneumatically powered devices with electronic controls (with the exception of ESD, see below).

<u>Electrically powered sites</u>: Electronic controllers can be powered using 120 VAC or 220 VAC input from the grid or from on-site generation (three-phase power is not needed).

<u>Remote sites:</u> Solar control systems are driven by solar power cells that actuate mechanical devices using electric power. Systems can be customized for every application; those installed to date include up to three solar panels and eight batteries [9]. Use of solar-powered chemical injection pumps has become widespread over the past years.

Rationale for the use of electronic controllers:
For the operators interviewed, the two main drivers for project implementation were (i) to reduce methane and VOC emissions and conserve gas otherwise emitted and (ii) to reduce maintenance costs. Electronic systems have much lower maintenance costs than traditional gas-driven controller systems [10], in particular if the gas used is not perfectly dry and sweet.

Higher operating costs are also experienced for gas driven controller systems on sites where there is a need to purchase fuel gas from another source or use imported propane. These include sites with overly sour or wet gas, or with drastic drop in gas supply due to low gas/oil ratio (GOR) /low production.

Investment Costs
Each electronic control system is designed on a case-by-case basis. The investment costs depend on the number of controllers/pumps, but also on other factors such as pressure differential, pipeline diameter, and methanol volume requirement, which varies according to such factors as climate and production patterns[4]. The following table summarizes typical equipment costs for the cases evaluated:

Figure 6- Calscan pictures- Bear solar control system: Top: solar panel and control panel, bottom: Electric Actuator

Table 3: Electronic controllers – Typical investment costs for main equipment

Main items	**Approximate unit costs** USD
Level Controller & Level Control Valve	4000
Pressure Controller & Control Valve	4000
Chemical injection Pump	6000
Control panel	4000
Solar panel (140W unit)	500
Battery (100 Ah unit)	500

The operators interviewed experienced fairly smooth installations, with installation costs decreasing as they gained experience with the technology[5]. The installation costs vary by site, estimated at between $5000 and $8000 per well site. For a retrofit project, the well needs to be shut in for one or two days;

[4] Chemical injection pumps (e.g. methanol pumps) usually are the most important power consumer. Sites requiring high volumes of methanol volume injection would cause higher costs for scaled-up solar panel and batteries.
[5] After the first few sites installations.

retrofit will generally take place when other maintenance is scheduled, to take advantage of that shut-down time. Solar powered electric systems do not require back-up generators[6].

Maintenance costs

The major maintenance costs include the replacement of batteries and panels. Most batteries last three to six years, while solar panels last twenty to thirty years. The operators interviewed highlighted that they experienced minimal maintenance costs on the sites converted to electronic controllers over the last five years.

Benefits of electronic controllers

Operators highlighted a number of benefits:

- Revenue from the sale of gas: Electronic controllers eliminate methane and VOC emissions and thus increase the volume of gas available for sale.
- Automation: Electronic control systems can provide additional benefits by enabling or simplifying the installation of automation systems (SCADA, Supervisory Control and Data Acquisition), though these systems are not required in order to use electronic controllers. This can potentially reduce the need for site inspections, reducing those costs for operators. For example, an alarm can be programmed to warn the operator if the dump has been open for more than 10 min. The system can be as sophisticated or as simple as required. (Note that we have not included any estimate of these cost reductions in the calculations of cost-effectiveness discussed in Section 4.)
- Reliability: As highlighted above, operators report that the electronic system is more reliable than a gas driven pneumatic control system, as operation of the latter with even slightly wet gas can lead to condensation issues, which over time will impact the performance of the system. One operator reported corrosion issues with sour gas used for pneumatic controllers and pumps.

Technical challenges with electronic controllers

- Snow: One operator reported that snow can be a problem with solar panel and battery lifetime.
- Theft or damage: Solar panels have reportedly been stolen or used as targets for shooting.
- Chemical injection pumps: Pumps consume far more energy than controllers/actuators. Sites with a large number of pumps or with pumps with high energy or power demand may represent a challenge for 100% solar powered electric systems. In addition, shortly after completion, some wells may require high volumes of methanol injection, and powering pumps to inject this high volume can strain these systems. Some of the operators interviewed reported that this technical barrier can be solved by bringing a portable stand-alone generator to the site for a few weeks to ensure that the power requirement is met.
- Safety considerations: Due to the very low voltage of the system, the safety risks are considered acceptable by the operator who evaluated this risk.

Applicability of electronic controllers

According to interviews with operators, this solution can technically be implemented on any well site. Generally, for the sites with these systems in place, the pressure differential is up to 2000 psi and the pipe diameters are between 2- 3 inches, but the system can be designed for larger pressure drops and larger diameters as required.

[6] When properly designed (e.g. with sufficient reserve margin in the batteries), recent solar powered electric systems do not require back-up generators, due to the reduced cost of solar-panels and the availability of low-power components. These systems are routinely installed without back-up generators in North America, including in Northern Canada where in winter there is only 1 to 2 hours of full sunlight a day. [9]

The only general limitation is the incremental costs. According to the operators, given the current gas prices, implementation costs are not compensated by the value of the gas saved. The project can be economical when other factors such as lower maintenance costs improve the return on investment.

Note on Emergency Shut-Down Valves (ESD): As a rule, electric controllers/actuators will stay in position if the system fails and power is lost, wires are cut, or other failures occur. This differs from some other solutions that can be designed so that valves close (or open) if the system fails (for example if the supply gas pressure is lost). Although Calscan is developing a “fail safe” electric ESD, operators have reportedly been using pneumatic or hydraulic ESD valves, as they are “fail-safe”.

Sunlight: In northern latitudes (e.g. northern Alberta) and when the energy demand is high (e.g. several pumps), solar panels may not generate enough power, in particular for chemical injection pumps. Other power sources such as thermal electric generators or methanol fuel cells have been used in pilot implementations.

Electronic controllers at medium and large sites: Due to the market conditions, providers have so far focused mainly on the development of solutions for small sites in remote locations. There thus seems to be much less field experience with using electronic controllers at medium and large sites. No technical barriers were identified for the installation of electronic controllers in sites with available electricity. Given the recent progress in both solar panel technologies and large battery solutions, solar-powered solutions may also be appropriate for large sites without available power. However, we are not aware of any such installations. Therefore, to be conservative, we do not examine the use of electronic controllers at large sites without electricity available.
Medium or large sites may also be the result of a combination of a number of small sites (e.g. several well pads). In practice, several small independent electronic controller installations can thus be installed on one medium to large site.

Suppliers

The following table presents a non-exhaustive list of relevant providers:

Table 4: Non-exhaustive list of relevant providers:

Name of the suppliers	Website	Offer	Comments
Calscan	http://www.calscan.net/products_bearcontrol.html	Provide full customized system	Cascan's Bear Solar Electric Control System is designed mainly for well head separators, but it can also be used in other applications. It includes solar panels, batteries, electric actuators, control valves, switches, control panels and other control equipment.
Spartan	http://www.spartancontrols.com/	Provide full customized system	Spartan designs electronic control systems assembling a number of components including Emerson/Fisher electronic controllers and actuators.
Ameresco	http://www.amerescosolar.com/solar-power-solutions-oil-and-gas-industry	Provide full customized systems	Amaresco Solar designs customized off-grid solar power systems.
Emerson/ Fisher		Manufacture elec. controllers and actuators	Different brands under Emerson Process Management (including Fisher, EIM) supply electronic and electro-pneumatic control components (controllers, positioners, actuators, control valves, transducers, etc.)
Exlar	http://exlar.com/	Manufacture elec. actuators	Exlar currently offer electric actuators that can replace pneumatic actuators.

3.3 Instrument air

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. Instrument air controllers are applicable to both new sites and existing sites; however, the technology can only be implemented when a reliable power supply is available.

This section provides a description of the benefits, the costs, and the applicability of instrument air controllers and is mainly based on interviews with oil companies, reviewing their recent experience installing instrument air systems.

Description of the technology

Instrument air technology is a well-established mature solution to run pneumatic control systems and is widely applied globally. In many countries (e.g. Norway, Iran, Kazakhstan [11]), the majority of the pneumatic control systems run on instrument air.

Systems typically include:

- Heavy-duty industrial air compressors. Two compressors are generally installed for redundancy, but for cost reasons, an operator has reported using only one.
- Air dryers - part of the air compressor package.
- Wet air receiver tank - part of the air compressor package.
- Dry air receiver tank - helps provide a buffer to secure longer system autonomy in the event of a power outage or demand surge.

Investment costs

Interviewers highlighted that the investment costs for instrument air installation vary significantly from site to site, depending on the layout and the type of equipment already on site. Investment costs can be classified as follows:

- <u>Air compressor package</u>: This includes the purchase of the main equipment (compressors, dryers and air receiver tanks). The size of compressors, dryers, and other equipment depends on the number of pneumatic controllers to be supplied with compressed air, and on their specifications (i.e., their demand for compressed air). A small compressor station would require around 5 HP of air compression capacity, while a larger facility would require up to 20 HP. This system can be purchased as individual components or as a package, for between $20,000 and $70,000 [12].
- <u>Mechanical & installation costs</u>: Mechanical and civil work may be required, depending on the layout of the existing facility. These costs are often higher for older facilities and can include:
    - Pipe cleaning and upgrades.
    - Trenching and tubing installation, since large sites may have several independent natural gas supply systems for controllers and pumps, and air would need to be piped through the full site.
- <u>Electrical/instrumentation equipment and supplies</u>: Depending on the site and the specific project requirement, this category may include:
    - Remote terminal unit or SCADA system installation or upgrade. The control system for some plants (e.g. shutdown/start-up, safety systems etc.) may have to be upgraded to accommodate the air compressor package.
    - Upgrades and wiring needed to add the additional electrical loads from the air compressor motors.
    - Repair/replacement of a controller in case of malfunctioning controller.
- <u>Engineering/consulting:</u> The site might require additional expenditures for electrical engineering and consulting.

Although air compressors and their auxiliary equipment represent a large part of the CAPEX, the engineering, preparation and installation costs can comprise up to 70% of the total upfront investment. Installation and preparation costs may include electrical and instrumentation supplies, mechanical and civil works, additional wiring, piping, valves and fittings. These costs are higher for older facilities that are not capable of handling the extra power, or don't have a suitable layout for utilities. Overall, the total cost for a project varies between $50,000 and $250,000 [10].

Maintenance costs

Maintenance costs typically include:

- Power consumption
- Air compressor servicing, generally every 6 months.

Benefits of instrument air controllers

Operators highlight a number of benefits:

- Revenue from the sale of gas: Instrument air eliminates methane and VOC emissions and thus increases the volume of gas available for sale.
- Reliability**:** The instrument air system is a highly reliable alternative to a natural gas driven pneumatic system for grid-connected facilities.
- Reduced maintenance costs**:** Although there are some additional operating costs with the deployment of air systems, some maintenance expenses are cut as a result of stopping the use of natural gas, particularly wellhead gas (or separator gas). Due to fluctuations in the GOR, some operators reported gas shortages on-site and thus they had to use other sources, such as propane, or to purchase gas from an adjacent field. Maintenance costs due to liquids condensing in the system or sour gas damage are also avoided by replacing untreated natural gas with air.

Applicability of instrument air controllers

Two main applicability limitations were identified during the interviews:

Size of the installation:

Instrument air controllers require heavy duty industrial air compressor packages designed for continuous duty (24/7). This in effect precludes the use of air compressors smaller than 5 HP, since available 2-3 HP air compressor packages present reliability problems. One operator reported that the one-year lifetime of a smaller compressors makes them unacceptable, so a minimum of 5 HP is assumed.

Access to power

Instrument air systems may only be used in locations with access to a sufficient and consistent supply of electrical power. Operators have used instrument air at:

- Grid connected sites.
- Sites with onsite power generation. Many sites (e.g. compressor plants) have power generation for other purposes: lighting, automation and control systems, etc. The same system can also be used for instrument air if generation capacity is available. We note that a sufficient, reliable, good quality gas stream is required for power generation. Wet or sour gas may not always be used for on-site power generation, depending on the specification of generator engines, etc.

In theory, diesel powered instrument air could be installed; however, this project identified no concrete examples of this technology. One operator stated he considered, and then rejected, the use of diesel to run air compressors, due to the high costs and low perceived environmental benefits.

3.4 Other technologies

This section reviews other "zero emission" technologies at various stages of maturity. In general these technical options are either (i) not widely applicable (such as self-contained controllers and vent gas recovery) or (ii) fewer than 100 installations were identified as part of this project (such as solar powered instrument air).

Solar powered instrument air
This study identified about 40 installations of small, energy efficient motor-compressors powered by solar panels/batteries, to replace natural gas with instrument air as the pneumatic medium. TRIDO industries, the technology provider interviewed as part of this study, indicated that these systems have a maximum capacity of ~20 scfh, making them suitable for some small to medium sites which use a few low-emitting controllers. High-bleed controllers have to be retrofitted to reduce air consumption in order to reach the feasible level. Despite the lack of extensive deployment so far, an attraction of this solution lies in the fact that controllers and actuators do not need to be replaced.

Instrument air powered by other power sources
Other power sources, such as thermal electric generators or methanol fuel cells, have been used in pilot implementations to power traditional instrument air systems.

Vent Gas Recovery
Re-routing to VRU
Vapor Recovery Units (VRUs) have a long, well-established track record in the upstream oil and gas industry to recover VOCs and methane from vented sources. Typically, they consist of capturing and piping equipment, a de-liquefaction drum, and compressor(s) to inject the recovered gas into pipelines. In theory, all vent lines can be connected to the VRU, including pneumatic controllers' lines.

Nevertheless, there have been limited implementations (only one example identified in this study) of well-site vent gas recovery projects using the recovered gas from pneumatic controllers in non-engine applications. SlipStream®, as further presented below, is a technology that facilitates recovery of the gas and use of it in gas-fired engines. Another technology, Cata-Dyne™, utilizes the recovered gas as a feed to a small, flameless appliance that converts natural gas or propane into infrared radiant heat that is usable if industrial heating is required.

SlipStream®
Spartan's SlipStream® system captures vented hydrocarbons and uses them as a supplementary fuel source for natural gas-fired engines, reducing fuel consumption. This technology can thus be applied only to sites with gas-fired engines, e.g. compressor engines. Despite concerns about costs, one operator emphasized specifically the reliability of the technology, as it reportedly does not interfere with normal operations. Nevertheless, if the volume of gas emitted by the combined vents (including the controllers) exceeds the engine fuel requirements, natural gas would still be vented or otherwise controlled.

Self-contained (aka Bleed-to-Pressure or Integral Pneumatic Controllers)
Self-contained systems are designed to contain the gas typically vented from controllers and then discharge it to the control valve's downstream piping, thus resulting in zero emission.

A number of operational requirements limit the applicability of self-contained systems, the most important of which is the need for a high differential pressure across the control valve [6,13]. For instance, GE's Bleed-to-Pressure system requires more than 80 psi, and both GE and VRG Controls require a downstream pressure of maximum 300 psi [13]. Also, sour or untreated gas could cause disturbances in the operation of self-contained controllers. Nevertheless, if applicable, the technology may be cost-effective or economical in cases where the total baseline emissions are high.[7]

Due to the limited applicability or the lack of widespread field experience, the technologies described above are not further analyzed in this report. However, depending on the site specifics, these options may be applicable and cost-effective, and can represent useful alternatives to instrument air or electronic controllers; thus they are presented as potential alternative options in section 4.4.

4. Cost effectiveness of electronic controllers and instrument air

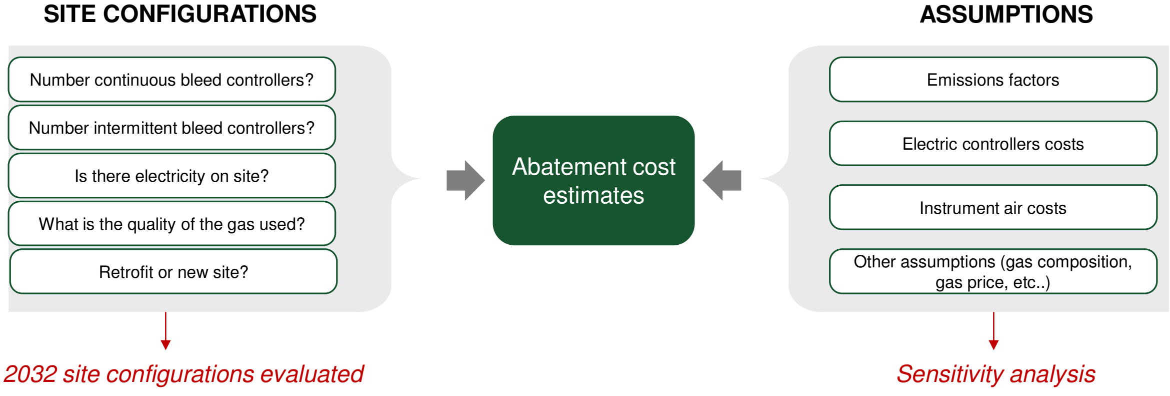
This section presents an analysis of the *cost-effectiveness* – net cost in USD per ton of avoided pollution – of employing the two main zero emission technologies, air-driven pneumatic controllers and electronic controllers, instead of natural gas-driven pneumatic controllers at new and existing sites. These results are applicable at both oil and gas production sites (well pads) and compressor stations.

4.1 Analytical approach

The cost-effectiveness of zero emission technologies will vary with the number and type of controllers at a site, in addition to many other factors, as we discuss below. Given the variety of site configurations (number and type of controllers per site, connection to the grid, type of gas handled) across the US, and the lack of information on the frequency of occurrence of these configurations, we opted to carry out cost-effectiveness assessments for both electronic and instrument air controllers for a broad spectrum of permutations of those site configuration parameters.

A number of assumptions have been made for the analysis. Key assumptions are discussed in the section below; all assumptions are detailed in the Appendix.

Figure 7: Overview of the methodology



For each permutation of the site configuration parameters, a CH_4 abatement cost (cost per metric ton of avoided pollution) was estimated.

[7] A technology provider reports an average of less than $3000 per Bleed-to-Pressure control system, leading to a payback period of less than 2 years for replacing 8 controllers.

For this analysis, a zero emission technology implementation is considered
- "economical" if the CH_4 abatement cost is negative (i.e. if the project NPV is positive)
- "cost effective" if the CH_4 abatement cost (net cost per ton of abated pollution) is lower than the social cost of methane that EPA has used in recent regulatory analyses [19] (Social cost of methane for 2020, calculated with a 3% discount rate, $1354 (2016 USD). [8]

The following sections provide more insight on:
- The abatement cost calculation
- The main assumptions
- The site configurations evaluated.

Abatement cost calculation – methodology

For each site configuration, the following were estimated:
- The CAPEX and OPEX of the zero emission technology implementation (either electronic controllers or instrument air)
- The CAPEX and OPEX of the baseline scenario (i.e. the cost incurred by the operator if the conventional pneumatic technology had been used instead of zero emission systems)
- The emissions of CH_4 and VOC under the baseline scenario

Since methane and VOC emissions will be zero if the zero emission technology is used, the abatement cost (in $/t CH_4) is then estimated as follows:

$$Abatement\ cost\ = -\frac{NPV(Cash\ flow_{zero\ emission\ project} - Cash\ flow_{baseline\ scanerio})}{NPV(Emission_{baseline\ scanerio})}$$

This approach, and its underlying assumptions, is compared to the annualized cost approach typically used by EPA in the appendix.

Main assumptions

The following table provides a list of the main assumptions applied. A full list of assumptions is available in the Appendix.

Table 5: Central assumptions

Description	Central Assumption	Comment
Gas price	2 $/Mscf	The value of recovered gas has been assumed to be similar for all emission sources, independent of the composition of the gas. Gas values from 1 to 3 $/Mcf have been assessed in sensitivity analyses.
Discount rate	7%	A 7% per year real term discount rate has been assumed. A sensitivity is presented for a 3% per year real term discount rate. This approach is consistent with EPA/BLM practice.
Remaining lifetime for a new project	15 years	The lifetime for new controller installation is assumed to be 15 years in line with EPA practice.
Remaining lifetime for retrofit project	10 years	The remaining lifetime for existing sites is assumed to be 10 years. A sensitivity is presented for a 5 years remaining lifetime.
Gas composition	0.0167 tCH_4/Mscf 0.0046 tVOC/Mscf	Gas composition assumptions for dry gas (wet gas assumptions are presented in the Appendix)

[8] EPA reports that the 2020 social cost of methane (mean value at 3% discount rate) is $1300 / metric ton of methane in 2012 USD; this is adjusted to $1354 / metric ton of methane in 2016 USD using a 4.2% cumulative inflation rate.

Average emissions factors assumptions
The emission factors used for this analysis are conservative averages based on the literature review (See section 2.3). The following table presents the emission factors used and the rationale for each value.

Table 6: Emission factors assumptions – central assumptions

Description	Central Assumption	Comment
Continuous-bleed controller(s) – retrofit sites only	14.4 scfh	This emission factor is applied for all the continuous bleed controllers on retrofit sites. Assumption based on [2] (Company classification into EPA categories excluding ESD)
Low bleed continuous controller (s)	1.39 scfh	This emission factor is applied for all the continuous bleed controllers on new sites. Current federal regulation (OOOO) requires that new continuous bleed controllers be low bleed. Assumption based on [16], most conservative average value between [16], [3], [4] and [2]
Intermittent-vent controller(s)	4.4 scfh	Assumption based on [2], most conservative average value between [16], [3], [4] and [2]
Chemical injection Pumps	13.3 scfh	Assumption based on [16], most conservative average value between [4], [7] and [16]
ESD	0.41 scfh	Assumption based on [2], average of the controllers classified as ESD

While measurements show that emission factors vary widely in the field, using conservative average emission factors, we are able to calculate conservative (i.e. high) abatement costs for widespread adoption of zero-emitting technologies. Sensitivity analyses are presented in the section 4.2 to reflect the field variability, which impact the site specific abatement costs.

Site configurations evaluated
As described above, we performed economic modeling on a total of 2032 permutations of site configuration parameters, covering a wide range of possible combinations of site parameters.

The following parameter inputs were used to construct the site configurations:

- Total number of controllers – from 1 to 40 controllers.
- A varying mix of continuous-bleed and intermittent-vent controllers (from 0% to 100% of intermittent-vent controllers).
- One emergency device (ESD) was added for every five controllers[9] (rounded up).
- New site (construction of new facilities) or retrofit (upgrade of existing facilities).
- Access to electricity or not.
- Whether pneumatic driven controllers currently operate on dry gas or wet gas.

To simplify the presentation of the results, the 2032 possible site configurations were then grouped into 20 larger categories depending on the total number of controllers, the presence of electricity on site, and whether the site is new or would need to be retrofit with zero emission controllers. The following table presents a matrix of the 20 different categories of site configurations evaluated, with the number of sites in each category presented in green. Each cell of this table includes a number of site configurations

[9] This number of ESDs has no impact on the final conclusion. Operators do not currently replace ESDs with electric controllers, so number and the emission factor of ESD have no effect on the cost-effectiveness of electric controllers. On the other hand, ESDs will generally be converted to instrument air, but the effect of including reasonable numbers of ESDs on the final cost-effectiveness is small due to the small air consumption of ESD. In this context, the assumption on the number of ESD did not affect the final number of sites with an abatement cost higher than the social cost of methane.

depending on the number of intermittent-vent or continuous-bleed controllers and the type of gas used to power the controllers.

Table 7: Site configurations categories (number of site configurations presented in green)

Number of Pumps	Number of controllers (excluding ESD)	New sites		Retrofit	
		No elec. on site	Elec. on site	No elec. on site	Elec. on site
0	**1 to 3 controllers**	**18**	**18**	**18**	**18**
	4 to 10 controllers	**56**	**56**	**56**	**56**
	11 to 20 controllers*	**98**	**98**	**98**	**98**
	21 to 40 controllers*		**164**		**164**
1	**1 to 20 controllers***	**172**	**172**	**172**	**172**
	21 to 40 controllers*		**164**		**164**

* Based on the analysis presented in section 3, we did not model either technology for larger sites (≥21 controller excluding ESD) without electricity on-site

- Electronic controllers were modeled at sites of all sizes with electricity available, and smaller to medium sites (up to 20 controllers) with no electricity available. Medium and large sites with electricity on-site are presented, as no technical barriers were identified for the installation of electronic controllers in such installations. However, there seems to be much less field experience for these types of installations compared to smaller sites.
- Instrument air was presented at larger sites with electricity available. For sites smaller than 20 controllers, electronic controllers were always more cost efficient than instrument air (see below).

This approach reflects the current industry experience and practice as presented by the interviewees. It is, however, important to highlight that the threshold in terms of number of controllers (20 in the analysis), depends in reality on site-specific parameters, and should only be considered as an **illustrative** threshold based on information available.

4.2 Main findings – electronic controllers

The findings of the cost-benefit analysis for electronic controllers are presented in four different sections:

- First, the full cost-benefit analysis is presented for one site configuration, to illustrate the methodology by exploring one example in detail.
- Second, a sensitivity analysis is performed for the same site configuration to show the impact of the main assumptions.
- An overview of the results for all the site configurations evaluated is then presented.
- Finally, the impact of the emission factors assumptions is described.

Example of abatement cost estimate for one example site configuration

The following table presents a full analysis for an example site configuration. The project is the retrofit of an existing site with four different controllers (one continuous-bleed, two intermittent-vent, one ESD and no pump) which represents the most common number of controllers in [8,2]. The site is not connected to the grid and currently uses dry supply gas for the controllers.

Table 8 presents the CAPEX estimate for the conversion to electronic controllers. As the project is a retrofit project, the baseline CAPEX is zero.

The detailed assumptions for the size of the electronic system (such as number of solar panels and battery requirements) are presented in the appendix. Overall, the system is oversized and always includes, for example, 10 days of energy storage.

Table 8: CAPEX estimates for electronic controller implementation (central assumptions)

Item	Assumption	#	Total USD
Controllers	$ 4000/unit	3	12 000
Control Panel	$ 4000/unit	1	4 000
140 W Solar Panel	$500 /Unit	1	500
100 Amh battery	$400 /Unit	3	1 200
Installation and engineering costs	20% of equipment costs	NA	3 540
Total CAPEX			**21 240**

Table 9: Emissions estimates (central assumptions, new sites)

Whole gas emissions in scfh	EF assumption	#	Total
Intermittent – vent controllers	4.43	2	8.9
Continuous –bleed controller	14.4	1	14.4
Total gas emissions			**23.3**

In terms of OPEX, it is assumed that batteries are replaced every 4 years and solar panels every 10 years. Given the operators' reports of minimal maintenance for electronic controllers, it has thus been assumed, conservatively, that general maintenance costs for are similar to those for continuous-bleed controllers functioning properly[10]. We do not include any estimate of savings in inspection costs due to automation (conservative assumption). Table 9 above presents emission estimates for the baseline scenario and finally Table 10 includes the abatement costs estimated.

Table 10: Final results – central assumptions

Item	Unit	Value USD
CAPEX	$	21 240
Value of the gas saved	$/year	408
NPV of the OPEX	$	1 672
NPV	$	-19 266
ABATEMENT COSTS	**$/t$CH_4$**	**751**

As presented in Table 10, for the small and remote site configuration presented, the abatement costs is well below the social cost of methane as defined above. The abatement cost for same site configuration, but at a new facility, as opposed to a retrofit, is estimated to be $847/ton CH_4. The difference is due to the difference in baseline costs and baseline emissions between new and retrofit sites (see below).

[10] Which is lower than the maintenance costs for continuous bleed controllers operating with wet supply gas.

Info Box 1: Electric conversion of pneumatic pumps

Pumps at well sites and well pads are typically used for methanol, corrosion inhibitor, de-waxing agents, or soap injection. Federal regulation (OOOOa) rules already require that emissions from new and modified chemical injection pumps be controlled in a number of circumstances.

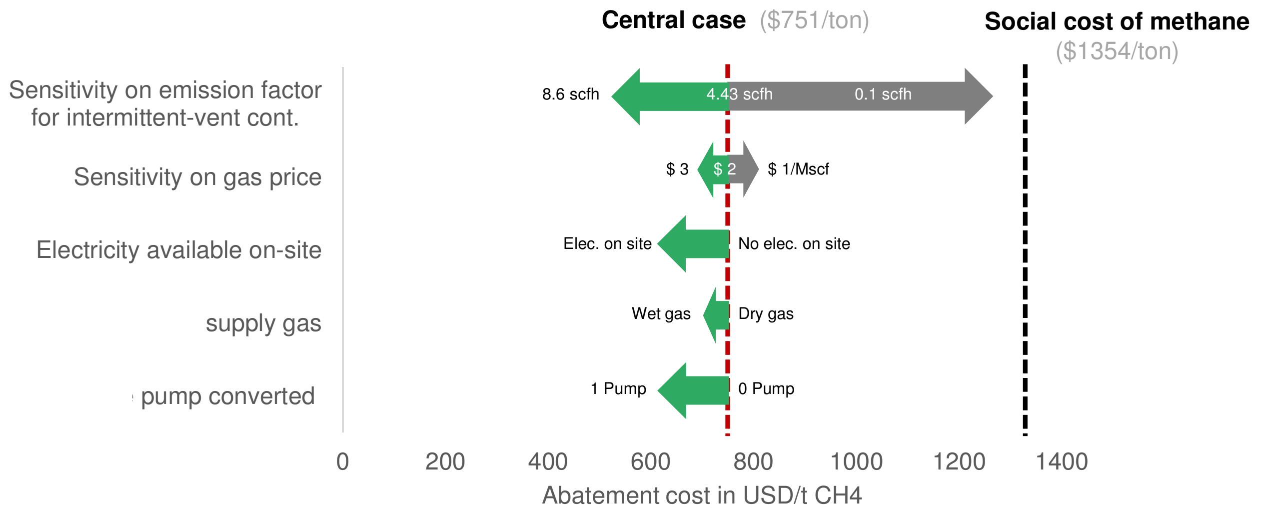
As highlighted in Section 3, conversion of chemical injection pumps to electric is both a mature and a cost effective technology.

In the analysis presented in this section, the conversion of one chemical injection pump per site is presented as a potential added benefit for the project developer. In cases with many pumps, or of major energy requirements for the pumps, the conversion of pumps to zero emission technologies could be assessed as a separate emission reduction project.

Sensitivity analysis for one example site configuration

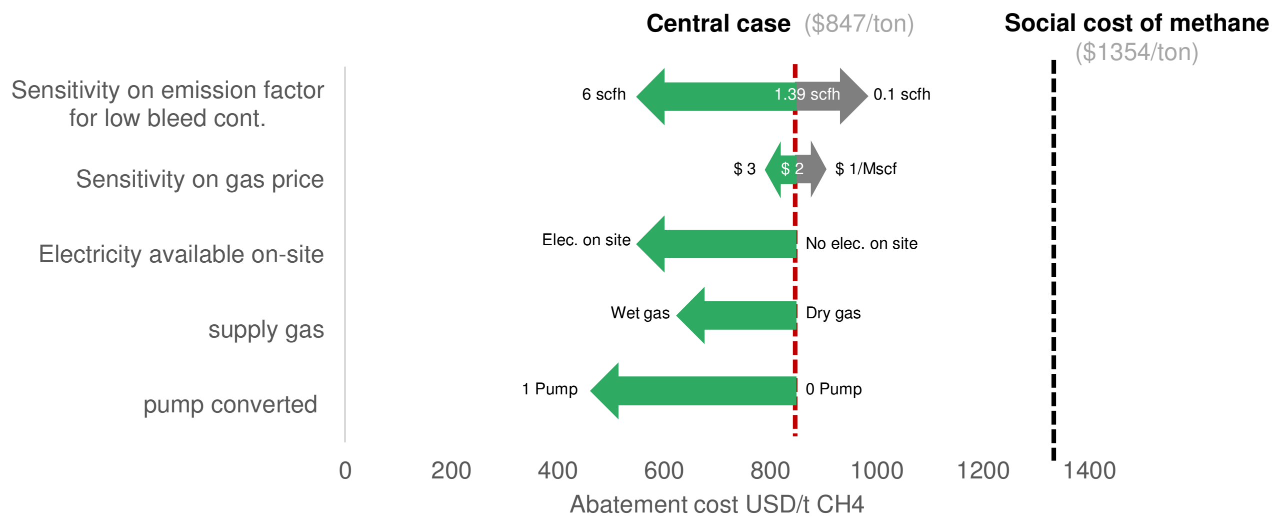
In this analysis, a number of assumptions have been made which impact the abatement cost. The following figures present sensitivity analyses for the site configuration described in the previous section, for both the retrofit case and the new site case. We examine the sensitivity of the abatement cost to changes to a few key sensitivities. A more exhaustive sensitivity analysis is presented in the appendix.

Figure 8: sensitivity analysis – electronic controllers - retrofit



The next figure presents a similar sensitivity for the same site configuration, but at a new facility as opposed to a retrofit.

Figure 9: sensitivity analysis – electronic controllers - new



The emission factor has by far the largest impact on the abatement cost and clearly heavily impacts the cost effectiveness of the option for retrofit sites. Excluding the emission factors, the other assumptions impact up to +33% of the abatement costs and no sensitivity leads to an abatement cost higher than the social cost of methane (see appendix).

In general terms, the abatement cost is more sensitive to changes for new sites than for retrofit sites. This is due to the fact that both the incremental costs and the emissions reductions are much smaller for new sites than for retrofit sites. A small change in either of these is thus relatively larger for new sites than for retrofit sites.

The following few paragraphs describes in more detail the impact of the main assumptions:

Electricity on site

The investment costs for sites without an electricity supply are higher than for sites with electricity due to the need to install solar panels and batteries. As a result, the abatement cost for site configurations with electricity is generally ten to one hundred percent lower than for site configurations without power. In a few site configurations the abatement cost is negative (i.e. NPV>0).

Wet versus dry supply gas

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. The maintenance cost for sites with wet supply gas is estimated at $200/year/controller [10] compared to $80/year/controller for dry supply gas [18]. As a result, sites with wet gas have an abatement cost generally 5 to 100 % lower than sites with dry gas, and, in a few site configurations, the abatement cost is negative (i.e. NPV>0). Gas quality is also likely to impact the average emission rate. Due to the lack of quantitative data on this impact, however, this factor has not been taken into consideration during the analysis, but it would reduce the abatement costs of sites with wet gas even lower.

Chemical injection pumps

As pumps have high emissions factors, sites where one pump (or several) can be converted to electric power have much lower abatement costs than sites without. All the sites with one pump have an abatement cost lower than the social cost of methane. In addition, the abatement cost of converting a single chemical injection pump (without any controller) to a solar powered electric pump is lower than the social cost of methane in all the sites configurations evaluated.

New versus retrofit sites

The costs and the emissions abatement structures differ greatly for new and for retrofit sites. The main differences include:

- The incremental CAPEX (i.e. the difference between the zero emission technology CAPEX and the baseline CAPEX) for a retrofit site is usually much higher than for a new site.
- Given the current regulatory framework, it is assumed that new sites use low-bleed continuous controllers as a default, and we conservatively use the EPA emissions factor [1] for these controllers, despite measurements showing higher emissions for low-bleed controllers [3,4]. The emissions reduction for retrofit sites is higher than for new sites, as we use an emissions factor based on actual measurement [2] for continuous-bleed controllers at existing sites.

The first difference makes the abatement cost higher for retrofit sites than new sites, while the second difference has the opposite effect. Overall, in the vast majority of the site configurations evaluated, the abatement cost for new sites is higher than for the equivalent retrofit site configuration.

Overview of the results for all the site configurations

Overall, the abatement costs for electronic controller installations at 2032 site configurations were estimated during this project. Under the central assumptions, 20 of the 2032 site configurations evaluated have abatement costs higher than the social cost of methane, $1354/t. The following table shows in red the number of site configurations with abatement costs higher than that figure for each category.

Table 11: Number of site configurations with abatement costs superior to the social cost of methane – central assumptions

Number of Pumps	Number of controllers (excluding ESD)	New sites		Retrofit	
		No elec. on site	Elec. On site	No elec. on site	Elec. On site
0	**1 to 3 controllers**	**6 / 18**	**4 / 18**	**5 / 18**	**2 / 18**
	4 to 10 controllers	**2 / 56**	**0 / 56**	**0 / 56**	**0 / 56**
	11 to 20 controllers*	**0 / 98**	**0 / 98**	**0 / 98**	**0 / 98**
	21 to 40 controllers*		0 / 164		0 / 164
1	**1 to 20 controllers***	**0 / 172**	**0 / 172**	**0 / 172**	**0 / 172**
	21 to 40 controllers*		0 / 164		0 / 164

* Sites with more than 10 controllers were presented for the installation of electronic controllers. However, there seems to be much less field experience for this type of installation, compared to smaller sites. Sites with more than 20 controllers and without electricity on-site were not modelled. Though no major technical barriers were identified, we could identify no examples of installations of solar powered electronic controllers on very large sites.

A number of conclusions can be drawn from this analysis. Under the central assumptions:

- For almost all the site configurations evaluated with four or more controllers (excluding ESDs), it is cost-effective to install electronic controllers.
- For all site configurations evaluated with one chemical injection pump, it is cost effective to install electronic controllers.

A site configuration is not cost effective if the volume of gas saved does not justify the cost of implementation. In general, for a given type of site configuration (wet/dry, on or off grid, new or existing, share of intermittent controllers), the cost-effectiveness improves (fewer $/ton) with the number of controllers.

In addition, we can highlight the following patterns for the site configurations with abatement costs higher than the social cost of methane:

- For new facilities, these sites have only low-bleed continuous controllers (5 or fewer). The low bleed emission factor assumption has an important impact on the conclusion (see below).
- For retrofit facilities, these sites have only intermittent-vent controllers (3 or fewer). For retrofit sites, the emissions factor used for intermittent-vent controllers is less than that used for continuous bleed controllers (see section 4.1)

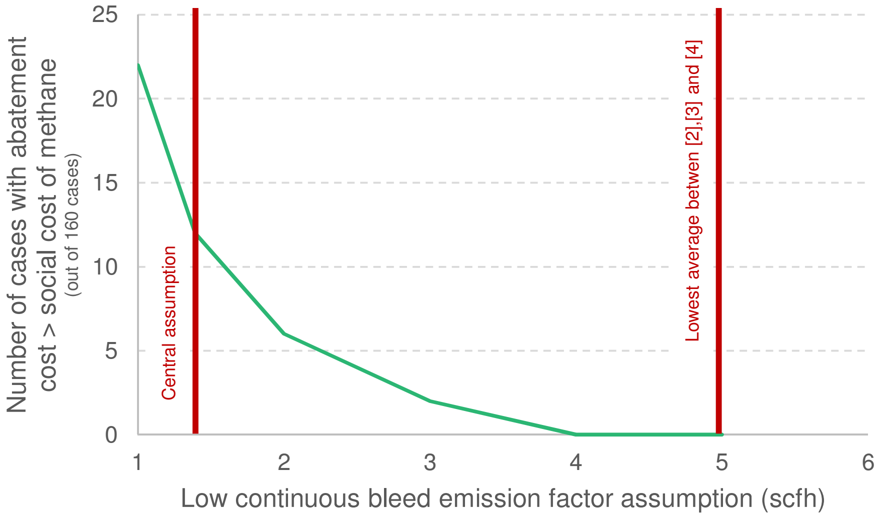
The full list of site configurations with an abatement cost higher than the social cost of methane is presented in the appendix.

Impact of the emission factors assumptions

The results of the analysis are quite dependent on the emissions factors used for the various types of pneumatic controllers.

The following graph illustrates the impact of the continuous low-bleed emission factor on the cost effectiveness of new sites with at least one continuous low-bleed device. This represents 12 of the 19 site configurations deemed not cost effective. The central assumption for the low-bleed emission factor is 1.39 scfh. But an emission factor of 4 scfh would make all sites with at least one continuous bleed controller cost effective. It is interesting to compare this figure to the results of past measurement campaigns presented in the Figure 4, which suggest that average emission factors for low-bleed devices are likely higher than 5 scfh.

Figure 10: Impact of the continuous low bleed emission factor on the cost effectiveness of new sites with at least one continuous low bleed device.



In a site without an electricity supply and with just a single controller, an electronic controller is cost-effective if the emissions from that single controller are more than 4.4 scfh for a new site and more than 7.2 scfh for a retrofit site. The point of cost-effectiveness is lower for sites with 2 or more controllers, for sites using wet supply gas, or for sites with on-site electricity. These thresholds should be compared with emissions factors observed in Figure 5 for small and very small sites.

As mentioned above, while emissions from pneumatic controllers vary widely from device to device, this analysis uses average emissions factors based on recent measurements, aiming at evaluating the cost-effectiveness of using electronic controllers on a widespread basis.

To conclude, the analysis shows that conversion to electronic controllers would be cost effective in most site configurations even using conservative average emissions assumptions. If higher emissions assumptions are considered -- as reflected in recent field measurements – virtually all site configurations evaluated would be fall below the social cost of methane

4.3 Main findings – Instrument air

As in the previous section, the finding of the analysis for instrument air is presented in three different sections:

- First, the full cost-benefit analysis is presented for one site configuration, to explain the methodology applied to one example.
- Secondly, a sensitivity analysis is performed for the same site configuration to illustrate the impact of the main assumptions.
- Finally, an overview of the results for all the site configurations evaluated is presented.

Contrary to electronic controllers, instrument air installation is only presented for site configurations with electricity available on-site.

Example of abatement cost estimate for one example site configuration

The following tables present a full analysis for an example site configuration. The project is retrofit of an existing site with 20 different controllers (5 continuous-bleed, 11 intermittent-vent, and 4 ESD). This configuration is illustrative; it is not known how representative it would be of larger sites. The site is connected to the grid or has power already generated on site, and currently uses dry gas for the controllers.

The first table presents the CAPEX estimate for the instrument air project. The detailed assumptions for the size of the instrument air system (share of the air bypassed in dryer, share of the utility air supply,[11] size of compressor, load of the compressor) are presented in the appendix. The approach in terms of system sizing proposed by Natural gas star has been applied [14], after having been quality checked against nine recently implemented projects. Overall, the system is oversized (as per the industry standard) and always includes, for example, one spare compressor. Equipment costs (including industrial grade compressors designed for 24/7 duty) have been assumed using online quotes.

As highlighted previously, installation costs for instrument air are highly site specific. Interviews have reported very low installation costs in particular when retrofitting many sites with similar designs. On the other side of the spectrum, operators have also reported high installation costs in cases where important investments, such as electric system upgrades and trenching between building or clusters of equipment, were required on the installations. The investment cost estimates presented below include some relatively conservative assumptions (i.e., high cost) in terms of equipment and installation costs. Some sensitivities are presented (appendix) to reflect the variability of the local circumstances.

[11] Because it is useful to have compressed air at a site for a variety of tasks and uses, operators typically oversize compressed air systems installed to drive pneumatic controllers. In this analysis, we assume that operators will do so, and consider the costs of the oversized system but do not make any estimate of the value of having compressed air available onsite. This approach is conservative (since operators do not strictly need oversize compression capacity for this purpose to use instrument air for pneumatic controllers), though the effect is not large.

Table 12: CAPEX estimates for instrument air controller implementation – central assumptions

Item	Assumption	Sizing /#	Value USD
Controllers and installation costs for the controllers	NA	retrofit projects (it is assumed that controller can be re-used)	0
Compressor package (Assuming 2 compressors, air drying unit and wet air receiver unit)	See list of assumption in the appendix [12]	10 HP	32 000
Other supplies costs (Instrumentation Supplies & Pipe/Valve/Fittings, electrical supplies, etc..)	1400 $/cont	20	28 000
Electrical, mechanical & civil Installation Costs, engineering	Retrofit: 100% New: 50% of equipment costs	NA	60 000
Total CAPEX			120 000

In terms of OPEX, it is assumed that compressors are replaced every 6 years. In addition, 4% of the equipment costs are accounted for normal compressor maintenance (typically every 6 months). Other OPEX costs include, for example, electricity costs.

Table 13 presents the emissions estimates while Table 14 present the final results.

Table 13: Emission estimates – central assumptions

Emissions is scfh	EF assumption	#	total
Intermittent-vent Controllers	4.43	11	48.7
Continuous-bleed controllers	14.43	5	72.1
ESD	0.41	4	1.64
Total gas emissions			122.5

Table 14: Final results for the site configuration analyzed – central assumptions

Item	Unit	Value USD
CAPEX	$	120 000
Value of the gas saved	$/year	1073
NPV (Opex)	$	24 683
NPV	$	-121 652
ABATEMENT COSTS	$/t$CH_4$	972

The abatement cost for the same site configuration, but at a new facility, as opposed to a retrofit, is estimated to be $886/ton CH_4. The difference is because the baseline costs are higher and the baseline emissions are lower for new sites than for retrofits.

Info Box 2: Conversion of pneumatic pumps to instrument air

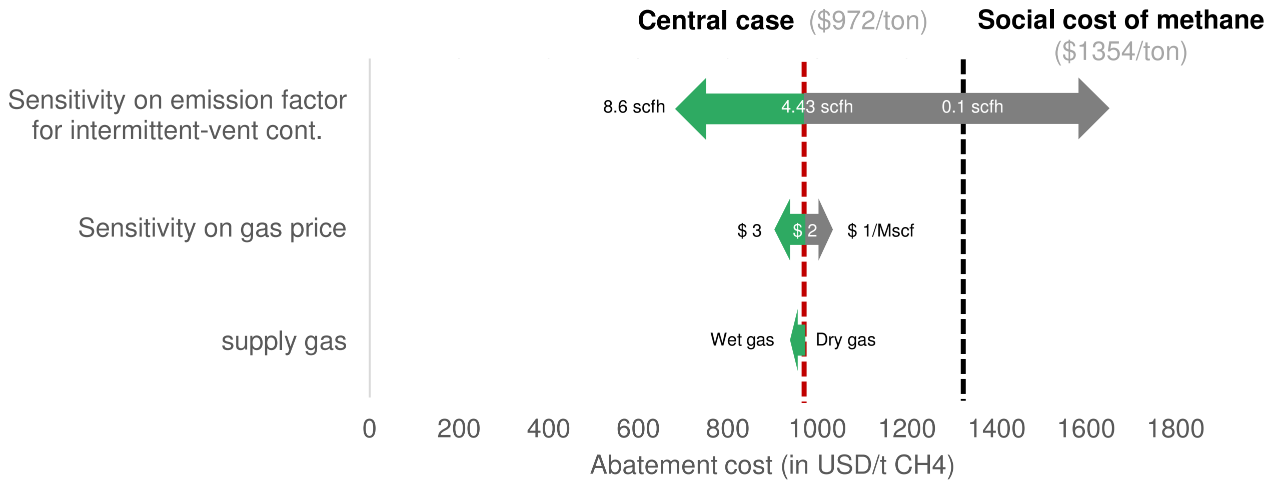
Pneumatic pumps typically emit more per device than pneumatic controllers, so converting pumps to air can represent a large emission reduction and potentially reduce significantly the abatement cost of conversion. However converting pumps to instrument air is not always technically and/or economically feasible. For sites with access to reliable source of electricity, conversion to air is applicable and cost-effective for the majority of chemical injection pumps. However, even for grid-connected sites, conversion to instrument air is not always the preferred option, as electric pumps are proven effective and low-cost.

In summary, in a number of cases, emissions reduction for pumps could be considered as a separate project from controllers. In the follow up analysis, conversion of 1 pump to instrument air is only presented as part of the sensitivity analysis.

Sensitivity analysis for one example site configuration

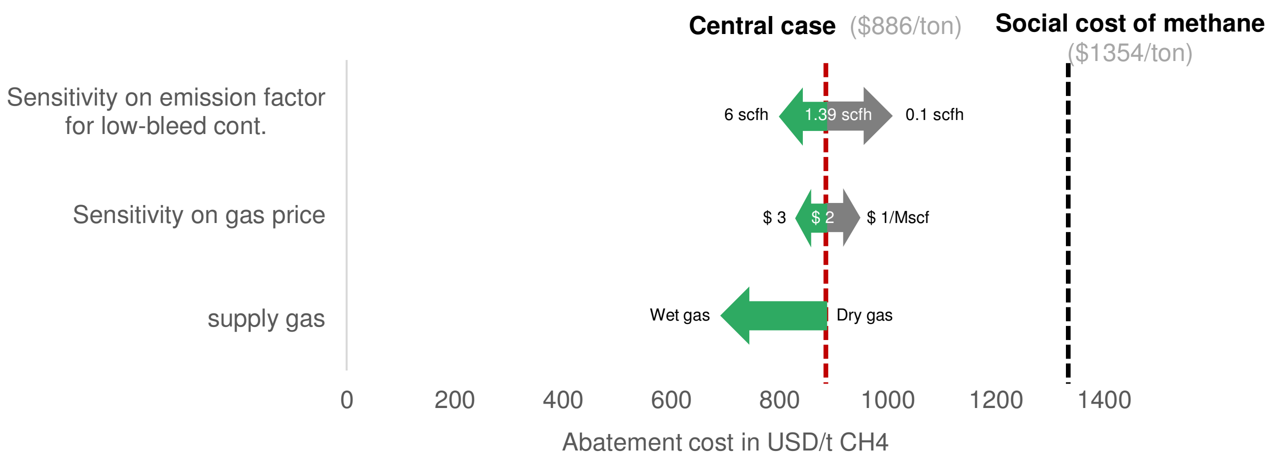
The following figures present a sensitivity analysis for the same site configuration as in the section above. The CH_4 abatement cost for a few key sensitivities is compared to the abatement cost with the central assumptions. A more detailed sensitivity assessment is presented in the appendix.

Figure 11: Sensitivity analysis – instrument air - retrofit



The next figure presents a similar sensitivity for the same site configuration but at a new facility.

Figure 12: Sensitivity analysis – instrument air - new site



As with the electronic controllers, the emission factor heavily impacts the attractiveness of the option. Excluding the emission factor, no other assumption affects the abatement cost per ton by more than 30% (see appendix).

Wet versus dry supply gas

As with electronic controllers, sites with wet gas have an abatement cost generally 5% to 50 % lower than sites with dry gas due to the difference in maintenance costs.

Overview of the results for all the site configurations

The overall abatement costs for about 328 site configurations, all with an electricity supply and no pneumatic pump conversions, were estimated, with a total number of controllers ranging from 21 to 50 (in various permutations of intermittent-vent and continuous-bleed controllers). Sites with fewer than 20 controllers are not presented, as conversion to electric is cheaper (on a per ton basis) in most of the site configurations with fewer than 20 controllers.

In terms of CAPEX, the total investment for retrofit sites varies between $90,000 and $230,000, while the investment (excluding controllers and their installation) for new sites varies between $60,000 and $120,000.

Under the central assumptions, 5 of the 328 site configurations evaluated have abatement costs higher than the social cost of methane. The following table shows in red the number of sites with abatement costs higher than $1354 /t$CH_4$ for each category of sites.

Table 15: Number of site configurations with abatement costs higher than the social cost of methane – central assumptions

Number of Pumps	Number of controllers (Excluding ESD)	New Sites	Retrofit
0	21 to 25 controllers	3 / 42	0 / 42
	26 to 30 controllers	2 / 40	0 / 40
	31 to 40 controllers	0 / 82	0 / 82

A number of conclusions can be drawn from this analysis. Under the central assumptions:

- For almost all the site configurations evaluated with more than 21 controllers (excluding ESDs), it is cost effective to install instrument air.
- For all the retrofit site configurations evaluated, it is cost effective to install instrument air.
- In a few of the new site configurations considered, it is not cost effective to install instrument air.

A site configuration is not cost effective if the volume of gas saved does not justify the cost of implementation. The new site configurations with abatement costs greater than the social cost of methane have a vast majority of low bleed continuous controllers, which we have conservatively assumed have very low emissions (1.39 scfh emission factor, see Section 4.1).

The full list of site configurations with abatement costs higher than the social cost of methane is presented in the appendix.

4.4 Summary of the analysis

As described in the section above, an economic analysis assuming conservative average emission factors was performed for 2032 permutations of site configurations with 1 to 50 controllers. Both retrofit and new installations, with or without electricity, were considered. A number of key conclusions can be drawn:

- Zero emission solutions had abatement costs below the social cost of methane (for 2020) described in the EPA 2015 Regulatory Impact Analysis in the vast majority of site configurations considered.
- The abatement costs exceeded the social cost of methane mostly for small sites – those with less than three controllers (excluding ESDs). If higher emission factors, as reflected in field measurements, are used, the abatement costs at even the very small sites fall below the social cost of methane.

The following figure presents a summary of both the technical applicability and economic attractiveness of the different zero emission technologies under different categories of sites. Though this analysis does not provide a detailed evaluation of the distribution of the sites in the US for each of the categories below, existing studies have suggested that the vast majority of the sites have less than 20 controllers.

Table 16: Summary table

Type of of site			**Both retrofit and new sites**					
		Number of controllers (excl. ESDs)	**1- 3**		**4-20**		**21-40**	
		Electricity on-site?	Yes	No	Yes	No	Yes	No
Main options: Electric controller / Instrument air		**Description** (of the most economic option which is technically feasible)	Grid connected **electric** controller	Solar powered **electric** controller	Grid connected **electric** controller	Solar powered **electric** controller	Instrument **air**	
		Number of cases not cost effective (i.e. abatement cost > social cost of methane) **under central assumptions**	6 / 36	11 / 36	0 / 308	2 / 308	5/ 328	
		Cost effective for <u>every</u> site configuration if emissions factors are:*	> 5.6 scfh for retrofit > 2.8 scfh for new sites	> 7.2 scfh for retrofit > 4.4 scfh for new sites	> 3.6 scfh for retrofit > 1.4 scfh for new sites	> 4.2 scfh for retrofit > 1.8 scfh for new sites	> 4.5 scfh for retrofit > 1.8 scfh for new sites	
Other options potentially applicable depending on the local conditions	Limited applicability	Vent gas recovery	✓	✓	✓	✓	✓	✓
		Instrument air powered by gas	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	✓
		Self contained controllers	✓	✓	✓	✓	✓	✓
	Limited known implementations	Solar powered instrument air	Not relevant	✓	Not relevant	✓	✗	✗
		Electric controllers powered by other power sources (TEG, fuel cell)	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	✓
		Large solar powered electric controller (no known implementations)	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Potential solution,** but no example known.

* Emissions factors thresholds listed are determined for the site configuration with the highest abatement cost within the category.
** Based on other solar applications.

The applicability of electronic controllers for small sites and instrument air for large sites reflects the current industry experience and practice as presented by the interviewees. It is, however, important to highlight that the threshold in terms of number of controllers (20 in the analysis), depends in reality on site-specific parameters, and should only be considered as an illustrative threshold based on information available.

Due to the market conditions, electronic controller providers have so far focused mainly on the development of solutions for small sites in remote locations. There thus seems to be much less field experience with using electronic controllers at medium and large sites; however, no technical barriers were identified for this type of installation.

These analyses indicate that the widespread adoption of zero-emitting technologies is cost effective in the vast majority of the site configurations considered. Furthermore, several factors listed should be considered:

- Conservative (low) average emissions factors have been used for low-bleed pneumatic controllers, even though recent research indicates that actual average emissions from those pneumatic controllers may be higher.
- Some of the important benefits of switching to zero-emitting technology, such as the ease of automation or remote operations associated with electrifying pneumatic controllers, are not included in our analysis of the cost-effectiveness of using zero emission technologies.
- Finally, pneumatic controllers emit natural gas, which includes (in varying amounts) other pollutants aside from methane, such as volatile organic compounds (VOCs), which are precursors to ground level smog, and toxic hazardous air pollutants (HAPs). Replacing natural-gas driven pneumatic controllers with zero-emitting technologies will eliminate emissions of these other

pollutants, in addition to emissions of methane, but we have not included the benefits of VOC or HAP abatement in our calculation of abatement costs for methane.

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6. Appendix

6.1 Quantitative assumptions for the model

Table 17: Quantative assumptions for the model

Description	Central Assumption	Unit	Source
GENERAL ASSUMPTIONS			
Gas price	2	$/Mscf	[15]
Interest Rate	7%	%	NA
Share methane in the gas – Dry gas	0.0167	tCH_4/Mscf	[15]
Share of VOC in the gas – Dry gas	0.0046	tVOC/Mscf	[15]
Share methane in the gas – wet gas	0.0150	tCH_4/Mscf	[15]
Share of VOC in the gas – wet gas	0.0050	tVOC/Mscf	[15]
Remaining lifetime for retrofit	10	years	[15]
Remaining lifetime for new site	15	years	[15]
EMISSION FACTORS			
Continuous Controller (s)	14.43	cf/h	[2] (Company classification into EPA categories excluding ESD)
Intermittent Controller (s)	4.43	cf/h	[2] (Company classification into EPA categories excluding ESD)
Chemical Pumps	13.3	cf/h	[16]
ESD	0.41	cf/h	[2]
Continuous Controller (s)	1.39	cf/h	[16]
Intermittent Controller (s)	4.43	cf/h	[2]
Chemical Pumps	13.3	cf/h	NA
ESD	0.41	cf/h	[2]
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	0.2026	HP/cfm	[14,10]
Sizing of compressor - constant component	4.2356	HP	[14,10]
Load of the compressor (main)	50%	%	[14,10]
Sizing of the tank	6	gallon/cfm	[10]
Lifetime of the compressors	6	years	[10,14]
ELEC CONTROLLER - COST ASSUMPTIONS			
Continuous Controller (s) + control valve	4000	$/unit	[9,10]
Intermittent Controller (s) + control valve	4000	$/unit	[9,10]
Chemical injection pump	6000	$/unit	[9,10]
Control Panel	4000	$/unit	[9,10]
Solar Panel	500	$/unit	[9,12]
Battery	400	$/unit	[9,12]
Installation Costs	20%	of Equipment costs	[9,10]
Annual check up	80	$/controller/year	[15]

ELEC CONTROLLER - ENGINEERING ASSUMPTIONS			
Battery replacement frequency	4	years	[9,10]
Solar Panel replacement frequency	10	years	[9,10]
Continuous Controller (s)	0.08	Amps/unit	[9]
Chemical injection pumps	0.17	Amps/pump	[9]
ESD	0.16	Amps/unit	[9]
Other systems	0.29	Amps/site	[9]
System Voltage	12	V	[9,12]
Battery Average Efficiency	85%	%	[9,12]
Avg. Peak Sun	4	h/days	[9,10] (Confirmed with NREL)
Battery - At Maximum Depth of Discharge	80%	%	[9]
Days of Energy Storage	10	days	[9]
Rating of the solar panel	140	W	[9,12]
Rating of the battery	100	Ah	[9,12]
Oversizing of the solar panel	50%	%	[9,10]
INSTRUMENT AIR - COST ASSUMPTION			
Compressor Package – Main -5 HP	22000	$	[12,10]
Compressor Package – Main -10 HP	32000	$	[12,10]
Compressor Package – Main -15 HP	48000	$	[12,10]
Compressor Package – Main -20 HP	70000	$	[12,10]
Compressor - Unit cost - 5 HP	7000	$	[12]
Compressor - Unit cost - 10HP	10000	$	[12]
Compressor - Unit cost - 15 HP	15000	$	[12]
Compressor - Unit cost - 20 HP	23000	$	[12]
Other supply	1400	$/controller	[10]
Other supply	1000	$/controller	[10]
Installation	100%	%	[10]
Installation	50%	%	[10]
Compressor maintenance	4%	% of Capex	[10,15]
BASELINE - COST ASSUMPTION			
Continuous Controller (s) + control valve	2698	$/cont.	[17]
Intermittent Controller (s) + control valve	2471	$/cont.	[17]
Chemical injection Pump	1500	$/unit	[12]
Labor - installation - Controller	387	$/unit	[18]
Maintenance costs - Controller- wet gas sites	200	$/cont./year	[10]
Maintenance costs - Controller- dry gas sites	80	$/cont./year	[18]

6.2 Other assumptions for the model

- General assumptions

    - 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.
- Electronic controllers:
    - In all the site configurations, it is assumed that ESDs are gas driven pneumatic controllers.
    - Electronic controllers can reduce the need for site inspections. The subsequent reduced labour costs have not, however, been taken into consideration in the analysis. (conservative assumption)
- 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 21).

6.3 Detailed sensitivity analysis

In the analysis presented, a number of assumptions have been made which affect the abatement cost. The following sections present the detailed sensitivity analysis performed.

Electronic controller – Retrofit

The following table presents a sensitivity analysis for the site configuration described in the section 4.2 (site with four controllers). The CH_4 abatement costs for a few key sensitivities should be compared to the abatement costs under the central assumption: \$751/t CH_4. The abatement cost under all the sensitivities is below the social cost of methane.

Table 18: Sensitivity analysis – retrofit site with 4 controllers– results

Name of the parameter	Central assumption	Sensitivity value	Abatement cost in \$/t CH_4
Number of pumps	0 pump	1 pump	614
Type of supply gas	Dry supply gas	Wet supply gas	702
Power on-site	No power on-site	Power on-site	611
Gas price	2 \$/Mscf	1 \$/Mscf	811
Gas price		3 \$/Mscf	692
Discount rate	7%	3%	635
Emission factors intermittent-vent cont.	4.43 scfh	8.6 scfh	522
		0.1 scfh	1267
Control Panel equipment cost	\$4000	\$6000	845
Installation Costs	20% of Equipment Costs	40% of Equipment Costs	889
Battery replacement freq.	4 years	2 years	823
Average peak sun	4 hours	2 hours	775

Electronic controller – New

The following table presents a sensitivity analysis for the site configuration described in the section 4.2 (site with four controllers). The CH_4 abatement cost for a few key sensitivities should be compared to the abatement costs under the central assumption: $847/t CH_4. The abatement costs for all the sensitivities are below the social cost of methane.

Table 19: Sensitivity analysis – New site with 4 controllers– results

Name of the parameter	Central assumption	Sensitivity value	Abatement cost in $/t CH_4
Number of pumps	0 pump	1 pump	459
Type of supply gas	Dry supply gas	Wet supply gas	624
Power on-site	No power on-site	Power on-site	548
Gas price	2 $/Mscf	1 $/Mscf	906
Gas price		3 $/Mscf	787
Discount rate	7%	3%	680
Emission factors low bleed controllers	1.39 scfh	6 scfh	547
		0.1 scfh	986
Control Panel equipment cost	$4000	$6000	1011
Installation Costs	20% of Equipment Costs	40% of Equipment Costs	1089
Battery replacement freq.	4 years	2 years	1046
Average peak sun	4 hours	2 hours	905
Low Bleed Cont. - Equipment cost	$2698 per controller	$554 per controller	993
Intermittent Cont. - Equipment cost	$2471 per controller	$387 per controller	1131

Instrument air – Retrofit

The following table presents a sensitivity analysis for the site configuration described in the section 4.3 (site with twenty controllers). The CH_4 abatement costs for a few key sensitivities should be compared to the abatement costs under the central assumption: $972/t CH_4.

Table 20: Sensitivity analysis – retrofit site with 4 controllers– results

Name of the parameter	Central assumption	Sensitivity value	Abatement cost in $/t CH_4
Type of supply gas	Dry supply gas	Wet supply gas	945
Gas price	2 $/Mscf	1 $/Mscf	1037
Gas price		3 $/Mscf	908
Discount rate	7%	3%	848
Emission factors intermittent-vent cont.	4.43 scfh	8.6 scfh	679
		0.1 scfh	1656
Other supplies costs	$1400/controller	$1800 /controller	1100
		$1000 /controller	844
Electrical, mechanical & civil installation costs	100% of equipment and supplies costs	150% of equipment and supplies costs	1212
		50% of equipment and supplies costs	732

Instrument air – New site

The following table presents a sensitivity analysis for the site configuration described in the section 4.3 (site with twenty controllers). The CH_4 abatement costs for a few key sensitivities should be compared to the abatement costs under the central assumption: $886/t CH_4.

Table 21: Sensitivity analysis – retrofit site with 4 controllers– results

Name of the parameter	Central assumption	Sensitivity value	Abatement cost in $/t CH_4
Type of supply gas	Dry supply gas	Wet supply gas	690
Gas price	2 $/Mscf	1 $/Mscf	949
Gas price		3 $/Mscf	824
Discount rate	7%	3%	734
Other supplies costs	$1000/controller	$1200 /controller	963
Electrical, mechanical & civil installation costs	50% of equipment and supplies costs	100% of equipment and supplies costs	1154
Emission factors low bleed controllers	1.39 scfh	6 scfh	800
		0.1 scfh	1011

6.4 List of site configurations with abatement cost superior to the social cost of methane

The following table presents a complete list of all the site configurations with an abatement cost higher than the social cost of methane.

Electronic controller – New sites

The abatement cost is presented for the central assumptions, but also (right column) for a low-bleed emission factor of 5 scfh (compared to 1.39 in the central assumption).

Table 22: Site configurations with abatement cost superior to $1354/ton - Electric controller – New sites

Site configuration ID	New/ retrofit	Electricity on site?	Supply gas	Pump #	Continuous Cont. #	Intermittent Cont. #	ESD #	Abatement costs – central assumptions	Abatement costs – Higher EF assumption
13	New	Electricity	Wet	0	1	0	1	1985	456
349	New	Electricity	Dry	0	1	0	1	2838	703
355	New	Electricity	Dry	0	2	0	1	1793	412
361	New	Electricity	Dry	0	3	0	1	1445	315
685	New	No electricity	Wet	0	1	0	1	3777	954
691	New	No electricity	Wet	0	2	0	1	2009	462
697	New	No electricity	Wet	0	3	0	1	1643	361
1021	New	No electricity	Dry	0	1	0	1	4446	1150
1027	New	No electricity	Dry	0	2	0	1	2595	635
1033	New	No electricity	Dry	0	3	0	1	2179	520
1039	New	No electricity	Dry	0	4	0	1	1820	420
1045	New	No electricity	Dry	0	5	0	1	1605	360

Electronic controller – Retrofit sites

The abatement cost is presented for the central assumptions, but also (right column) for an intermittent-vent controller emission factor of 7 scfh (compared to 4.43 in the central assumption).

Table 23: Site configurations with abatement cost superior to $1354/ton - Electric controller – Retrofit

Site configuration ID	New/ retrofit	Electricity on site?	Supply gas	Pump #	Continuous Cont. #	Intermittent Cont. #	ESD #	Abatement costs – central assumptions	Abatement costs – Higher EF assumption
1345	Retrofit	Electricity	Wet	0	0	1	1	1593	960
1681	Retrofit	Electricity	Dry	0	0	1	1	1750	1064
2017	Retrofit	No electricity	Dry	0	0	1	1	2282	1400
2018	Retrofit	No electricity	Dry	0	0	2	1	1573	952
2019	Retrofit	No electricity	Dry	0	0	3	1	1406	846
2353	Retrofit	No electricity	Wet	0	0	1	1	2186	1335
2354	Retrofit	No electricity	Wet	0	0	2	1	1486	891

Instrument air – Retrofit sites

The abatement cost is presented for the central assumptions, but also (right column) for a low-bleed emission factor of 5 scfh (compared to 1.39 in the central assumption).

Table 24: Site configurations with abatement cost superior to $1354/ton – Instrument air – Retrofit

Site configuration ID	New/ retrofit	Electricity on site?	Supply gas	Pump #	Continuous Cont. #	Intermittent Cont. #	ESD #	Abatement costs – central assumptions	Abatement costs – Higher EF assumption
437	New	Electricity	Dry	0	20	1	5	1651	612
438	New	Electricity	Dry	0	20	2	5	1466	589
447	New	Electricity	Dry	0	25	0	5	1595	515
448	New	Electricity	Dry	0	25	1	6	1426	501
457	New	Electricity	Dry	0	30	0	6	1392	436