Economic Analysis of Method 21

December 2016

Prepared for
Environmental Defense Fund
257 Park Avenue South
New York, NY 10010

Prepared by
ICF International
9300 Lee Highway
Fairfax, VA 22031

Contents

Figures

Tables

Acronyms and Abbreviations

Acronym / Abbreviation	Stands For
CH_4	Methane
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
EDF	Environmental Defense Fund
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GHG	Greenhouse Gas
GHGRP	Greenhouse Gas Reporting Program
GRI	Gas Research Institute
GWP	Global Warming Potential (72)[1]
LDAR	Leak Detection and Repair
Mcf	Thousand Cubic Feet
NSPS	New Source Performance Standards promulgated under the Federal Clean Air Act
PRV	Pressure Relief Valve
scf	Standard Cubic Feet

[1] Climate Change 2007 - The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the IPCC (ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback) . Table TS.2 Retrieved from: http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4_wg1_full_report.pdf

1. Executive Summary

Leaks of natural gas, also referred to as fugitives, significantly contribute towards the total methane emissions from the oil and gas industry. Leaks occur randomly across all segments of the industry. An effective option to mitigate methane emissions from leaks is to periodically conduct surveys to identify and fix leaks. There is a tradeoff between costs for various frequencies of leak surveys and the resulting reduction in methane emissions. The analyses summarized in this report evaluate the costs and benefits of multiple scenarios in conducting leak surveys and repairs at various frequencies in five segments of the oil and gas industry – onshore production, gathering and boosting stations, gas processing plants, gas transmission compressor stations, and gas storage facilities.

Much of the discussion involving leak detection and repair is based on the average cost and emission factors at a site level. However, such static factors do not reflect the dynamics of leak surveys and associated reduction in emissions. Leak survey and repair programs when conducted on a periodic basis result in the reduction of leaks and prevent some small leaks from turning into larger leaks over time. Fewer leaks require less time to survey and reduce repair costs over time. A static average value based approach does not capture this changing leak frequency and leak magnitude over time. It also does not effectively account for the fact that a few large leaks disproportionately influence the benefits of conducting leak survey and repair programs. These large leaks, referred to as super-emitters, have been observed in real world data on methane emissions from oil and gas facilities.

ICF developed a Monte Carlo-based simulation model to analyze the dynamics of leak survey programs and to evaluate the effectiveness of such programs using multiple variables, such as the frequency of surveys. The model simulates facility characteristics, such as the types and counts of equipment, the number of leaks at a facility, and the size of each leak. These facility characteristics drive the time required to conduct the survey, which in turn influences the costs to conduct a survey. Similarly, the size of the leaks influences both the costs for repair and replacement as well as the amount of reduction achieved through each survey. The data for the model was obtained from several field studies that provide the raw data to develop statistical distributions. The model output includes a statistical distribution of various metrics, including emissions before each survey, emissions reduction after each survey, total costs, and the value of gas saved (if applicable).

In this analysis, the simulation model was run at three levels of leak survey frequency – annual, semi-annual, and quarterly. The value of gas recovered was evaluated at different levels - $0/Mcf, $3/Mcf, and $4/Mcf. For the onshore production and gathering and boosting segments only the $3/Mcf and $4/Mcf gas prices were evaluated. The onshore production segment directly accrues the benefit of reducing emissions as it owns the natural gas. The same applies to gathering systems owned or operated by producers. Natural gas processors, gas transmission pipeline operators, and gas storage operators do not own the gas and are provided a service fee. In the case of natural gas processors the service fee varies depending on the contract with the gas producers. In the case of natural gas transmission and storage the service fee is determined through rate cases. Hence, from the operator perspective the value of gas recovered is minimal (processors) to none (transmission and storage).

However, the value of gas emissions reduced is a benefit to the shipper and to the society as a whole. Therefore, to account for both of these perspectives the model was run with a scenario with no recovery of gas value ($0/Mcf gas price) and two other gas prices at $3/Mcf and $4/Mcf. The dollar per Mcf of emissions avoided for each segment and scenario is provided in Table 1 and Table 2. The emissions avoided are defined as the difference between the emissions at the beginning of the first survey and the emissions at the end of each subsequent leak survey after fixing of the leaks. Table 1 shows the cost effectiveness of implementing a Method 21 leak survey program in production, transmission, processing, storage and gathering and boosting with gas prices of $3/Mcf.

Table 1: Average Three Year Cost-Effectiveness Results from Individual Facilities ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Industry Segment	Production[2]	Transmission	Processing	Storage	Gathering and Boosting
Gas Recovery Price	$3/Mcf	$3/Mcf	$3/Mcf	$3/Mcf	$3/Mcf
Number of Contractor Employees	2	2	2	2	2
Annual Survey	$2.82 (684 Mcf)	-$0.44 (10.1 MMscf)	$8.39 (12.2 MMscf)	-$0.86 (14.9 MMscf)	$0.25 (6.1 MMscf)
Semi-annual Survey	$5.47 (1,259 Mcf)	$2.06 (20.4 MMscf)	$8.43 (23.8 MMscf)	$2.00 (34 MMscf)	$2.66 (12 MMscf)
Quarterly Survey	$8.58 (1,761 Mcf)	$3.59 (27 MMscf)	$11.13 (31 MMscf)	$3.35 (47.7 MMscf)	$4.51 (15.8 MMscf)

Table 2 shows the cost effectiveness of implementing a Method 21 leak survey program in transmission, processing, and storage with a gas prices of $0/Mcf.

Table 2: Average Three Year Cost-Effectiveness Results from Individual Facilities ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Industry Segment	Transmission	Processing	Storage
Gas Recovery Price	$0/Mcf	$0/Mcf	$0/Mcf
Number of Contractor Employees	2	2	2
Annual Survey	$4.88 (10.1 MMscf)	$13.12 (12.2 MMscf)	$6.02 (14.9 MMscf)
Semi-annual Survey	$3.60 (20.4 MMscf)	$9.82 (23.8 MMscf)	$4.00 (34 MMscf)

[2] Individual production facilities have fewer components and fewer emissions than other facilities, but there are more production facilities than processing, compressor stations, and storage facilities, making the cumulative impact of production emissions significant.

Quarterly Survey	$4.21 (27 MMscf)	$11.69 (31 MMscf)	$4.21 (47.7 MMscf)

2. Introduction

2.1. Goals and Approach of the Study

This report evaluates the costs and emission reductions that can be achieved by using Method 21 to survey oil and gas facilities for leaks and subsequently repairing and replacing equipment to address any leaks found. Currently, most studies that evaluate Leak Detection and Repair (LDAR) programs use an average value of variables, such as emissions, reductions, costs, time taken to conduct survey, and do not take into account the variation in these variables depending on the characteristics of the facilities, such as the size of facility, types of equipment at the facility, and number of leakers. They also do not directly account for larger emitters or from super-emitters. A more representative method to evaluate LDAR's performance is the use of a stochastic modeling approach. This approach allows for the analysis of multiple scenarios with varying conditions unlike the average value approach. The stochastic model gives a range of cost effectiveness for facilities of varying sizes and conditions. This approach gives a better understanding of how an LDAR program can vary across oil and gas facilities of different sizes.

2.2. Objective of the Stochastic LDAR Analysis

The stochastic modeling approach to determine the cost-effectiveness of LDAR at oil and gas facilities consists of developing facility models that replicate real world conditions and capture variations in facility size and characteristics. A Monte Carlo simulation was used to analyze facility emissions, reductions, and costs. The Monte Carlo simulation was used to compare various facilities by including inter-relationships between different factors, such as leak frequency and time required to conduct an LDAR survey.

The advantages of using the Monte Carlo simulation for this analysis is that it represents emission rates and activity data obtained from multiple real world studies using statistical distributions. The model therefore is able to replicate real world emissions and capture variations in facility size and characteristics. The model then outputs the cost effectiveness across a wide range of facility types with varying emissions and leak frequency, giving a more representative understanding of emissions.

2.3. Limitation of Analysis

While the stochastic model has many benefits, the method does present a few limitations. The model results are driven by the data inputs and therefore are only as good as the applicability of these inputs for a specific facility. The representativeness of results at the national, state, company, or facility level are limited by how well the data collected from limited geographic regions and used in this study characterizes these levels of detail. Additionally, the costs to repair or replace equipment can vary depending on location and complexity of the leak. This study uses the data on repair costs from the

Natural Gas STAR published documents and expert judgement where no data was available. Since data on costs associated with leak magnitudes per component was not available, the determination of whether a leak needs a repair or replacement is based on expert judgment. Lastly, there is limited time series data available on the impact of different LDAR frequencies on the reductions in leak frequencies from subsequent surveys. This study used limited data available from Jonah Energy LLC.[3]

3. Approach and Methodology

3.1. Overview of Methodology

Each industry segment utilizes a model that relies on segment specific information from field studies and research papers. While differences exist between the various segment specific models, each one follows the same sequence of analysis, as discussed below:

Step 1 – First, the model defines a driving factor that defines the size of the facility. The driving factor is then used to establish the number of components of each kind associated with a facility of that size. This driving factor varies by industry segment. Production uses the number of wells at a wellpad facility to drive component counts. Processing, transmission and storage each use the number of compressors per facility to drive component counts. Gathering and Boosting use the number of compressors and the number of dehydrators to drive component counts. ICF used data from published field studies to establish a standard discrete distribution for each of the driving factors.

Step 2 – Next, the model determined the count of associated components using the driving factors. The following components were evaluated as a part of the analysis: valves, connections, pressure relief valves, compressor pressure relief valves, open-ended lines, starter open-ended lines, pressure regulators, and orifice meters. Emissions from all eight sources were evaluated for the production segment, while other segment models focused on valves, connections, pressure relief valves, open-ended lines and orifice meters. Processing also included pressure regulators in the analysis.

In production, the component count was calculated using the number of wells at a wellpad defined in Step 1. The component count follows a uniform distribution between the minimum and maximum number of components identified at facilities with the same number of wells as the number of wells defined in Step 1. As an example, if a facility was defined with 1 well at the wellpad according to Step 1, then the number of valves is determined following a uniform distribution between 6 and 228 based on the data for sites with 1 well, but if facility was defined with 3 wells at a wellpad according to Step 1, then the number of valves is determined following a uniform distribution between 66 and 733 again based on the data for sites with 3 wells.

[3] Jonah Energy LLC. WCCA Spring Meeting. May 8,2015

In processing, transmission, and storage, the component counts were calculated using the following equation:

$$C_i = \frac{C_{s,i}}{D_s} D$$

Where:

C_i= Component count i (e.g. valves or connectors) for the modeled facility.

$C_{s,i}$ = Average component count i (e.g. valves or connectors) from the data source.

D_s = Average number of compressors per facility as defined in Step 1 from the data source.

D = Number of compressors at an individual facility as defined in Step 1. This value was randomly selected using the Monte Carlo simulation based on the distribution for the dataset. For instance, in processing, D was defined using the distribution of compressors at a facility in Subpart W.

In gathering and boosting the component count was calculated using the same principle as in transmission, but also included an additional driving factor. Due to the fact that there are few data sources about gathering and boosting, the number of components per compressor was assumed to be similar to transmission stations with the main difference being dehydrators. An additional factor was added to account for this variance as displayed in the following equation:

$$C_i = \frac{C_{s,i}}{D_{s,1}} D_1 + D_2 * A$$

Where:

C_i= Component count i (e.g. valves or connectors) for the modeled facility.

$C_{s,i}$ = Average component count i (e.g. valves or connectors) from the data source.

$D_{s,1}$ = Average Number of compressors per facility as defined in Step 1 from the data source.

D_1 = Number of compressors at an individual facility as defined in Step 1. This value was randomly selected using the Monte Carlo simulation based on the distribution for the dataset.

D_2 = Number of dehydrators per facility as defined in Step 1. This value was randomly selected using the Monte Carlo simulation based on the distribution for the dataset.

A = Activity factor for the number of components per dehydrators as defined in production from GRI.

Step 3 – The survey time at each facility and associated costs for surveying was based on component counts identified in Step 2. The time required to survey a facility was calculated by multiplying the average time to survey one unit of a component type by the number of components of that type at the facility. Table 3 lists the average time that was assumed to survey one component based on ICF's expert judgement and field experience.

Table 3: Time to Survey Equipment in All Segments

Component Type	Estimated Time to Survey in Seconds for Production Facilities	Estimated Time to Survey in Seconds for all Other Segments
Valve	10	10
Connection	30	30
Pressure Relief Valve	90	90
Compressor Pressure Relief Valve	90	NA
Open-Ended Line	30	30
Starter Open Ended Line	30	NA
Pressure Regulators	15	NA (15 for Processing)
Orifice Meters	120	120

The total time to survey was multiplied by the hourly wage of the contractors. In addition, a per diem and lodging cost for the portion of the day the survey took place was also added into the survey costs. The model assumes all inspections are performed by contractors rather than in-house.

Step 4 – Next, the model randomly selects the percentage of leaking components. This was done by varying the leak frequency between the minimum and maximum leak frequency as identified at a facility by the published data source. As an example, valves in the processing data source leaked between 5.2% and 10.7% of the time at the various sites in the field study. Therefore, valves in processing were assumed to leak anywhere from 5.2% to 10.7% of the time following a uniform distribution. Each industry segment used the same methodology for determining leaking components as processing, with production varying slightly.

After the first survey in the model, leaks were repaired or components replaced. In the real world new leaks develop over time. However, periodic leak detection and repair programs ensure that the number (or frequency) of leaks go down over time. Data from companies has shown that both the number of leaking components at a facility and the emissions per leak have decreased between surveys. The model tries to account for both of these declines using data presented by Jonah Energy from their survey results. Jonah Energy conducted monthly surveys from 2010 to May 2015 (partial data available for 2015).[4] In 2010 and in 2014 there were 2,959 and 1,330 leaks respectively. The results from the Jonah study are shown in Figure 1 below.

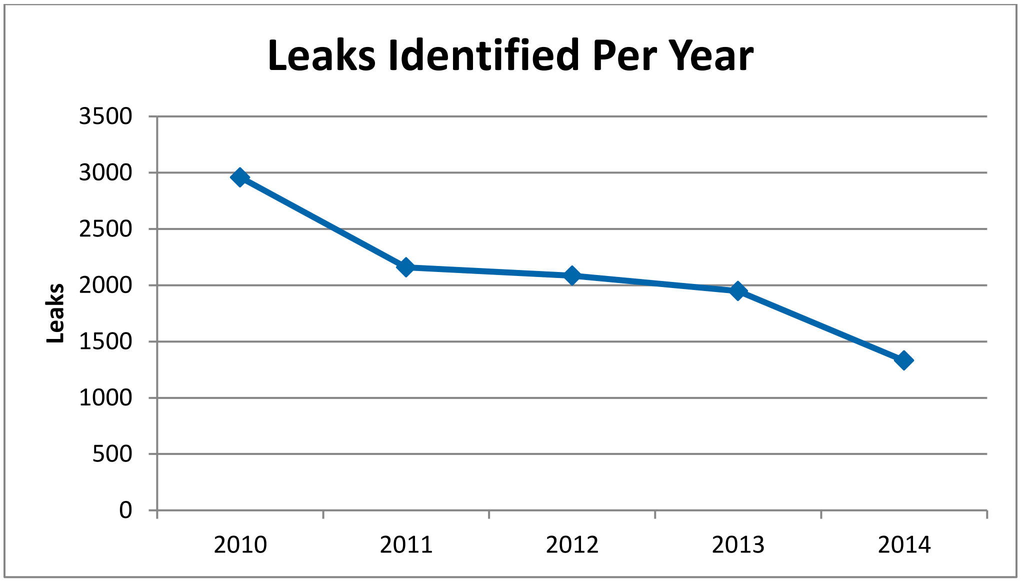

Figure 1: Number of Leaks identified by Jonah at sites[5]

The Jonah data does not provide information on whether the number of sites visited changed over the years. To overcome this data gap, ICF normalized the data and instead analyzed the number of leaks per survey. The number of leaks identified per Jonah's survey changed from 0.90 to 0.45 from 2010 to 2014 or a 50% reduction.

As Jonah data was from monthly surveys, annual, semi-annual, and quarterly surveys were assumed to follow a similar trend to Jonah's data. Annual, semi-annual and quarterly surveys were assumed to follow a similar trend between surveys with a steeper decline in leaks in the first year and slower declines in leaks after. To replicate the reduction in leak frequency, this model sequentially truncated the leak frequency distribution right tail with each successive leak survey. This analysis assumed that the leak frequency would get capped at the 60th percentile of the leak frequency distribution for a quarterly leak survey at the end of the 12th survey or year three of the analysis. Similarly, the leak frequency distribution is capped at 70th percentile for the semi-annual case and 80th percentile for the annual case.

Step 5 – The leak frequency determined in Step 4 was multiplied by the total count of components of each type at a facility as defined in Step 2 to estimate the number of components that are leaking. Each individual leaking component was then randomly assigned leak rates according to the emissions distribution for that source.

[4] Jonah Energy LLC. WCCA Spring Meeting. May 8,2015
[5] Jonah Energy LLC WCCA Spring Meeting Presentation

In addition to the reduction in leak frequency over successive leak surveys and maintenance practices, emissions per leak also decreases with increased surveying. This is because small leaks do not develop into larger leaks as frequently or because of additional awareness by operators on best practices in preventing leaks. Through Jonah's experience, the value of gas saved decreased from $117.44 per leak to $86.41 per leak from 2010 to 2014 or a decrease of 25%. Emission reductions per leak were accounted for in the model by capping the leak rate distribution on the right tail, similar to the leak frequency approach. The full cap was assumed to occur at the end of the sixth survey, regardless of the frequency of surveys. For example, in the annual survey cycle, after six surveys or six years, the leak rate was capped at the 85th percentile of the leak rate distribution, or stated differently, the right tail was truncated at the 85th percentile. Similarly, for the semi-annual case the leak rate distribution was capped at the 80th percentile, and in the quarterly case it is capped at the 75th percentile. The emission truncations were calibrated based on the overall emission reductions achieved by Jonah. This ensured that the combination of the leak frequency and the emissions per leak achieved emission reductions that aligned with Jonah's data.

Step 6 – Next, the model determined if each leak had to be repaired or replaced and then assigned costs accordingly. For valves, connections, pressure relief valves, compressor pressure relief valves, open-ended lines, starter open-ended lines, pressure regulators, and orifice meters the threshold for replacement was determined by using the average of the leak rate distribution of the leaking component type. As an example, if the randomly assigned leak rate for a particular valve in Step 5 was larger than the average valve leak rate as determined from the leak rate distribution for that component type, then the valve was replaced, otherwise it was repaired. If this randomly selected leak rate was half or less than half of the average leak rate then the cost was assumed to be half of the average repair costs. If this randomly selected leak rate was between half the average and the average leak rate, then the repair cost used was the average repair cost. Finally, if the leak rate was between the average and two times the average leak rate, then the average replacement cost was halved, otherwise it was the full replacement cost.

Step 7 – As companies address leaks through replacement and maintenance, they achieve emission reductions. In the model, replacing components were allocated 100% emission reductions, while maintenance components were allocated less than 100% emission reductions as some components still leak slightly after a repair. Valves, connections, open ended lines were allocated 95% reductions, PRVs 98%, and pressure regulators and orifice meters were allocated 100% of the reductions after maintenance. These emission reductions are outlined in the table below.

Table 4: Component Emission Reduction Percentage for Maintenance and Replacements

Component	Percentage Emission Reduction for Maintenance	Percentage Emission Replacement/Overhaul
Valve	95%	100%

Connection	95%	100%
Pressure Relief Valve	98%	100%
Compressor Pressure Relief Valve	98%	100%
Open-Ended Line	95%	100%
Starter Open Ended Line	95%	100%
Pressure Regulators	100%	100%
Orifice Meters	100%	100%

Step 8 – The simulation was run for 10,000 iterations with each iteration representing a unique and random combination of facility characteristics including the count and type of equipment and component, the number of leakers for each component type, and the leak rate of each leaking component. The model then calculated the cost effectiveness for emissions referred to in this analysis as the $/Mcf avoided. The $/Mcf avoided metric is the ratio of the total cost to conduct an LDAR survey (less any value of gas recovered) and the difference in Mcf of emissions between the emissions at the end of the survey level to the level of uncontrolled emissions during the first year that surveys begin. The total cost of conducting an LDAR survey includes the cost of surveying, travel and lodging for the survey team, repair and maintenance costs, and the gas value saved by implementing repairs.

Steps 1 through 8 can be seen in Figure 2.

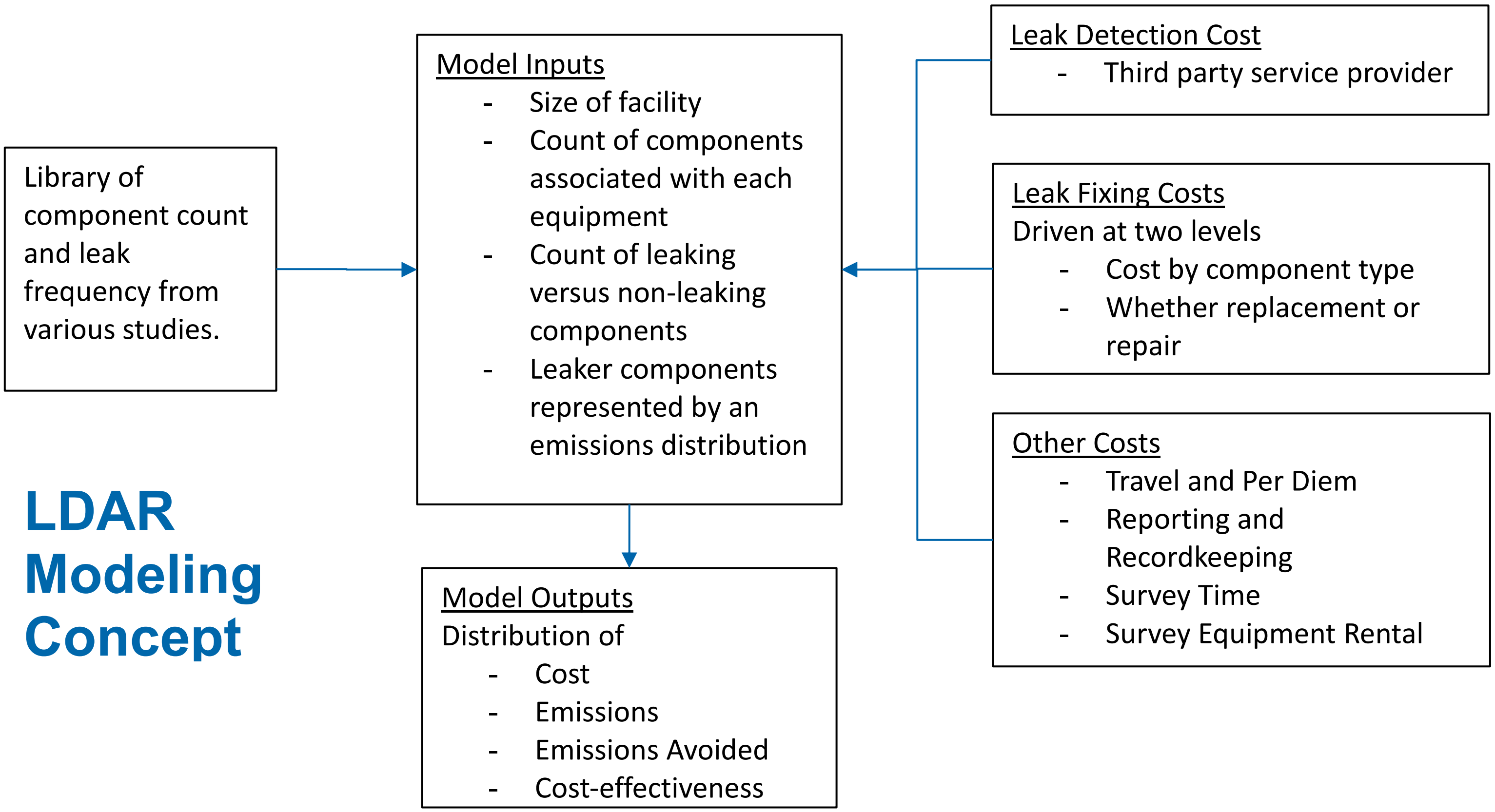

Figure 2: Schematic of LDAR Modeling Concept

3.2. All Segments Assumptions

In each of the models (Production, Processing, Transmission, Storage and Gathering and Boosting), there were constant inputs independent of the industry segment. Survey equipment costs displayed in Table 5 and the contractors billing rate ($60 per hour) were constant variables across all industry segments based on ICF expert judgement, field experience and vendor research. These assumptions drive the labor and equipment costs for surveying.

Table 5: Survey Equipment Costs in All Segments

Component	Default Costs
Toxic Vapor Analyzer (TVA)/Organic Vapor Analyzer (OVA)	$15,000
Vehicle (4x4 Truck)	$22,000

3.3. Production Data Sources

In production, eight component types were represented in the model to calculate the cost effectiveness of implementing Method 21 as an LDAR program. Each component was modeled using reports and data from site visits and measurement studies at wellpads in production. The resources used are as follows:

- *City of Fort Worth Natural Gas Air Quality Study*[6]*:* This study was utilized to determine the emission distributions for valves, connections, pressure relief valves, open-ended lines and pressure regulators. This source was also used to determine the number of components at a site for valves and connectors. Lastly, this study provided the distribution of wells at a wellpad that was used to drive the component counts at a facility.
- *Methane Emissions from the Natural Gas Industry EPA/ GRI*[7]*:* This study was utilized to determine the emission distributions on compressor pressure relief valves, starter open-ended lines and orifice meters.

3.4. Transmission, Storage, and Gathering and Boosting Data Sources

Five component types were represented in the model to calculate the cost effectiveness of implementing an LDAR program in transmission, storage and gathering and boosting. Each component was modeled using reports and data from site visits and measurement studies at compressor stations. These sources included the following:

[6] http://fortworthtexas.gov/gaswells/air-quality-study/final/

[7] Gas Research Institute. *Methane Emissions from the Natural Gas Industry*. June 1996

- Two EDF methane emission studies were utilized to determine the emissions distributions for valves, connections, and open-ended lines.
  - *Methane Emissions from Leak and Loss Audits of Natural Gas Compressor Stations and Storage Facilities*[8]
  - *Methane Emissions from the Natural Gas Transmission and Storage System in the United States*[9]
- *Clearstone Phase 1 Study:*[10] This study was utilized to determine the emissions distributions for pressure relief valves and orifice meters. Additionally, data from this study was used to determine the leak frequencies for pressure relief valves, open-ended lines, and orifice meters.
- *Methane Emissions from the Natural Gas Industry EPA/ GRI*[11]*:* This study was utilized for equipment counts per compressor, for valves, connections, pressure relief valves, and open-ended lines.
- *New Source Performance Standards*[12]*:* This regulation was utilized to provide leak frequencies for valves and connections.

3.5. Processing Data Sources

In processing, six component types were represented in the model to calculate the cost effectiveness of implementing an LDAR program. Each component was modeled using a report and data from site visits and measurement studies at processing facilities.

- *Clearstone Phase 1 Study:* [13] This study was used to model emission distributions, leak frequency and component counts at processing facilities.

[8] http://pubs.acs.org/doi/abs/10.1021/es506163m

[9] http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01669

[10] Clearstone Engineering LTD. "Identification and Evaluation of Opportunities to Reduce Methane Losses at Four Gas Processing Plants" retrieved from: https://www.epa.gov/sites/production/files/2016-08/documents/four_plants.pdf

[11] Gas Research Institute. *Methane Emissions from the Natural Gas Industry*. June 1996

[12] S40 CFR Part 60 standards of Performance for New Stationary Sources. http://www.ecfr.gov/cgi-bin/text-idx?SID=d4fff6638508368c7aca1992302d12fa&mc=true&node=pt40.7.60&rgn=div5

[13] "Identification and Evaluation of Opportunities to Reduce Methane Losses at Four Gas Processing Plants"

4. Analytical Results

4.1. Average Facility Size

Statistical distributions of facility sizes were fitted from raw data collected in production, transmission, processing, storage and gathering and boosting. This data was used to represent the range of variation within an industry segment, but the median facility size for each of these industry segments is portrayed below:

Table 6 Median Facility Size

	Production	Transmission	Processing	Storage	Gathering and Boosting
Wells	3	NA	NA	NA	NA
Compressors	NA	4	7	6	2
Dehydrators	NA	NA	NA	NA	0.5
Valve	190	663	3,293	3,411	335
Connection	1,416	3,022	16,520	10,172	1,519
Pressure Relief Valve	3	14	77	121	8
Compressor Pressure Relief Valve	>0	NA	NA	NA	NA
Open-Ended Line	33	50	324	645	25
Starter Open Ended Line	>0	NA	NA	NA	NA
Pressure Regulators	1	NA	34	NA	NA
Orifice Meters	2	9	34	12	2

4.2. All Segments Results

Model runs were conducted for five industry segments (Production, Transmission, Processing, Storage and Gathering and Boosting) as outlined in Section 2. The value of gas and the number of contractor employees necessary to complete a survey were varied during the model runs for each industry segment, yielding the results displayed in Sections 4.3 to 4.7. The three scenarios include parameter combinations of the value of gas between $3/Mcf and $4/Mcf, and the number of contractor employees necessary to complete a Method 21 survey between 1 and 2. As contractors may utilize one or two personnel to complete a survey, the labor costs were adjusted based on the number of employees conducting a survey, with all other assumptions remaining constant. Additionally, Transmission, Processing, and Storage also completed two model runs where they assumed no value for the gas saved (i.e. $0/Mcf).

Four model runs were conducted that utilized a specified gas price and a specified number of contractor employees. These model runs include annual surveying, semi-annual surveying, and quarterly surveying. The cost of annual surveying is less than semi-annual surveying which is less than quarterly surveying. The emission reductions per year are inversely correlated with costs with quarterly achieving higher emission reductions than semi-annual which are higher than annual. Surveying efficiencies (i.e. time to survey, emission volume truncation and leak frequency truncation) are achieved over multiple surveys.

The results are based on the modeled assumption that the survey and repairs were completed at the end of the survey period. Annual surveys were conducted at the end of the year, semi-annual surveys in the middle and end of a year and the quarterly surveys every three months starting three months after the starting period. The emissions avoided in the first period are zero, as no repairs were completed until after the survey. This means that annual surveying did not achieve emission reductions until after the first survey; therefore, over the three year time period the model evaluates, annual surveying conducted three surveys but only the second and third time period achieved avoided emissions. Semi-annual illustrates six surveys, but repairs were conducted after the first one allowing five surveys to achieve avoided emissions. Quarterly illustrates twelve surveys, with eleven that have avoided emissions.

4.3. Production

In production, three different scenarios were modeled to evaluate how emissions could change over time. Table 7 below displays the average cost effectiveness over a three year cycle. Each scenario is displayed yearly in Section 4.7.A.1.

Table 7: Production Scenario Average Three Year Cost-Effectiveness Results ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Case Number	1	2	3
Gas Price	$3/Mcf	$4/Mcf	$3/Mcf
Number of Contractor Employees	2	2	1
Annual Survey	$2.82 (684 Mscf)	$0.58 (684 Mscf)	$0.06 (684 Mscf)
Semi-annual Survey	$5.47 (1,259 Mscf)	$4.58 (1,259 Mscf)	$3.14 (1,259 Mscf)
Quarterly Survey	$8.58 (1,761 Mscf)	$8.15 (1,761 Mscf)	$5.73 (1,761 Mscf)

The emissions avoided due to implementing Method 21 surveying were estimated by the model. Table 8 below displays the percent of emissions avoided in the third year by implementing Method 21 surveying at a facility. The emissions avoided account for the difference in emissions in year three compared with the emissions in the base case. The emissions avoided percentages account for emissions avoided from fugitives from the following sources: valves, connections, pressure relief valves, compressor pressure relief valves, open-ended lines, starter open-ended lines, pressure regulators, and orifice meters. This percentage is not indicative of the total emission reduction opportunities at a facility.

Table 8: Year Three Emissions Avoided Compared with Baseline Emissions

Case Number	1 ,2, and 3
Annual Survey	50%
Semi-annual Survey	66%
Quarterly Survey	78%

4.4. Transmission

The Transmission segment is by law structured such that the operator does not own the gas and only collects a service fee for the volume of gas being moved through its pipelines. Therefore, any emissions avoided do not provide any direct monetary value to the operator. This suggests using no recovery for the value of gas saved (or emissions avoided). On the other hand, at an economy level it can be argued that some entity who owns the gas (typically the producer) will benefit from any recovery of gas. For example, if the transmission operator is regulated then the costs to comply with the regulation can be passed on to the entity that owns the gas. Hence, the owner of the gas pays additional fees to cover for the LDAR program and gets the value of gas saved. This suggests the use of full value of gas price in the analysis. This study did not try to resolve this issue, but rather ran the model with no recovery and recovery at full gas price as scenarios, thus providing a range of costs associated with conducting an LDAR program in this segment. In transmission, five different scenarios were modeled to evaluate how emissions could change over time. Table 9 below displays the results for the average cost effectiveness of the first three years. Each scenario is displayed yearly in Section 4.7.A.2.

Table 9: Transmission Scenario Average Three Year Cost-Effectiveness Results ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Case Number	1	2	3	4	5
Gas Recovery Price	$3/Mcf	$4/Mcf	$3/Mcf	$0/Mcf	$0/Mcf
Number of Contractor Employees	2	2	1	2	1
Annual Survey	-$0.44 (10.1 MMscf)	-$2.21 (10.1 MMscf)	-$0.93 (10.1 MMscf)	$4.88 (10.1 MMscf)	$4.38 (10.1 MMscf)
Semi-annual Survey	$2.06 (20.4 MMscf)	$1.55 (20.4 MMscf)	$1.68 (20.4 MMscf)	$3.60 (20.4 MMscf)	$3.22 (20.4 MMscf)
Quarterly Survey	$3.59 (27 MMscf)	$3.38 (27 MMscf)	$3.10 (27 MMscf)	$4.21 (27 MMscf)	$3.73 (27 MMscf)

The emissions avoided due to implementing Method 21 surveying were estimated by the model. Table 10 below displays the percent of emissions avoided in the third year by implementing Method 21 surveying at a facility. The emissions avoided account for the difference in emissions in year three compared with the emissions in the base case. The emissions avoided percentages account for emissions avoided from fugitives from the following sources: valves, connections, pressure relief valves, open-ended lines and orifice meters. This percentage is not indicative of the total emission reduction opportunities at a facility.

Table 10: Year Three Emissions Avoided Compared with Baseline Emissions

Case Number	1 ,2, and 3
Annual Survey	63%
Semi-annual Survey	85%
Quarterly Survey	90%

4.5. Processing

The gas processing segment by contractual arrangements collects a service fee on the volume of gas processed. In some instances, the processing plant may be able to increase service fee because of increased throughput due to gas saved. However, this is a fraction of the total value of gas saved. Therefore, similar to the transmission segment this study analyzed scenarios with and without value of gas saved being included. In processing, five different scenarios were modeled to evaluate how emissions could change over time. Table 11 below displays the results for the average cost effectiveness of the first three years. Each scenario is displayed yearly in 4.7.A.3.

Table 11: Processing Scenario Average Three Year Cost-Effectiveness Results ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Case Number	1	2	3	4	5
Gas Recovery Price	$3/Mcf	$4/Mcf	$3/Mcf	$0/Mcf	$0/Mcf
Number of Contractor Employees	2	2	1	2	1
Annual Survey	$8.39 (12.2 MMscf)	$6.81 (12.2 MMscf)	$6.49 (12.2 MMscf)	$13.12 (12.2 MMscf)	$11.23 (12.2 MMscf)
Semi-annual Survey	$8.43 (23.8 MMscf)	$7.97 (23.8 MMscf)	$6.93 (23.8 MMscf)	$9.82 (23.8 MMscf)	$8.31 (23.8 MMscf)
Quarterly Survey	$11.13 (31 MMscf)	$10.95 (31 MMscf)	$9.16 (31 MMscf)	$11.69 (31 MMscf)	$9.72 (31 MMscf)

The emissions avoided due to implementing Method 21 surveying were estimated by the model. Table 12 below displays the percent of emissions avoided in the third year by implementing Method 21 surveying at a facility. The emissions avoided account for the difference in emissions in year three compared with the emissions in the base case. The emissions avoided percentages account for emissions avoided from fugitives from the following sources: valves, connections, pressure relief valves, open-ended lines, orifice meters, and pressure regulators. This percentage is not indicative of the total emission reduction opportunities at a facility.

Table 12: Year Three Emissions Avoided Compared with Baseline Emissions

Case Number	1 ,2, and 3
Annual Survey	66%
Semi-annual Survey	87%
Quarterly Survey	92%

4.6. Storage

Similar to transmission, storage operators can only collect service fee. Therefore, similar to the transmission segment multiple scenarios were evaluated with and without the value gas recovered included in the analysis. In storage, five different scenarios were modeled to evaluate how emissions could change over time. Table 13 below displays the results for the average cost effectiveness of the first three years. Each scenario is displayed yearly in 4.7.A.4.

Table 13: Storage Scenario Average Three Year Cost-Effectiveness Results ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Case Number	1	2	3	4	5
Gas Recovery Price	$3/Mcf	$4/Mcf	$3/Mcf	$0/Mcf	$0/Mcf
Number of Contractor Employees	2	2	1	2	1
Annual Survey	-$0.86 (14.9 MMscf)	-$3.16 (14.9 MMscf)	-$1.83 (14.9 MMscf)	$6.02 (14.9 MMscf)	$5.06 (14.9 MMscf)
Semi-annual Survey	$2.00 (34 MMscf)	$1.34 (34 MMscf)	$1.32 (34 MMscf)	$4.00 (34 MMscf)	$3.31 (34 MMscf)
Quarterly Survey	$3.35 (47.7 MMscf)	$3.06 (47.7 MMscf)	$2.50 (47.7 MMscf)	$4.21 (47.7 MMscf)	$3.36 (47.7 MMscf)

The emissions avoided due to implementing Method 21 surveying were estimated by the model. Table 14 below displays the percent of emissions avoided in the third year by implementing Method 21 surveying at a facility. The emissions avoided account for the difference in emissions in year three compared with the emissions in the base case. The emissions avoided percentages account for emissions avoided from fugitives from the following sources: valves, connections, pressure relief valves, open-ended lines and orifice meters. This percentage is not indicative of the total emission reduction opportunities at a facility.

Table 14: Year Three Emissions Avoided Compared with Baseline Emissions

Case Number	1 ,2, and 3
Annual Survey	54%
Semi-annual Survey	77%
Quarterly Survey	84%

4.7. Gathering and Boosting

In gathering and boosting, three different scenarios were modeled to evaluate how emissions could change over time. Table 15 below displays the results for the average cost effectiveness of the first three years. Each scenario is displayed yearly in A.5.

Table 15: Gathering and Boosting Scenario Average Three Year Cost-Effectiveness Results ($/Metric Tonnes CO_2e Avoided) with Total Emissions Avoided over the First Three Years (MMcf) in Parentheses

Case Number	1	2	3
Gas Price	$3/Mcf	$4/Mcf	$3/Mcf
Number of Contractor Employees	2	2	1
Annual Survey	$0.25 (6.1 MMscf)	-$1.40 (6.1 MMscf)	-$0.18 (6.1 MMscf)
Semi-annual Survey	$2.66 (12 MMscf)	$2.17 (12 MMscf)	$2.32 (12 MMscf)
Quarterly Survey	$4.51 (15.8 MMscf)	$4.31 (15.8 MMscf)	$4.07 (15.8 MMscf)

The emissions avoided due to implementing Method 21 surveying were estimated by the model. Table 16 below displays the percent of emissions avoided in the third year by implementing Method 21 surveying at a facility. The emissions avoided account for the difference in emissions in year three compared with the emissions in the base case.

Table 16: Year Three Emissions Avoided Compared with Baseline Emissions

Case Number	1 ,2, and 3
Annual Survey	64%
Semi-annual Survey	86%
Quarterly Survey	91%

Appendix A. Detailed Results

For the Production and Gathering and Boosting segments listed below, three cases of performing Method 21 for an LDAR survey are presented. For the Transmission, Processing, and Storage segments, five cases of performing Method 21 for an LDAR survey are presented. Each case varies the gas price and the number of contractor employees utilized to perform the survey. Each case represents a different economic impact to enlist an LDAR program for a median sized facility. For each case, the figures below show the cost effectiveness of the LDAR program based on a median emissions reduction volume at the end of the third year. The results are displayed based on the frequency of testing, either annually, semiannually, or quarterly. Additionally, the price per metric tonne CO_2e avoided for each case is presented, also on a frequency of testing basis.

A.1. Production

A.1.1. Case 1 - $3/Mcf Gas Value and Two Contractors

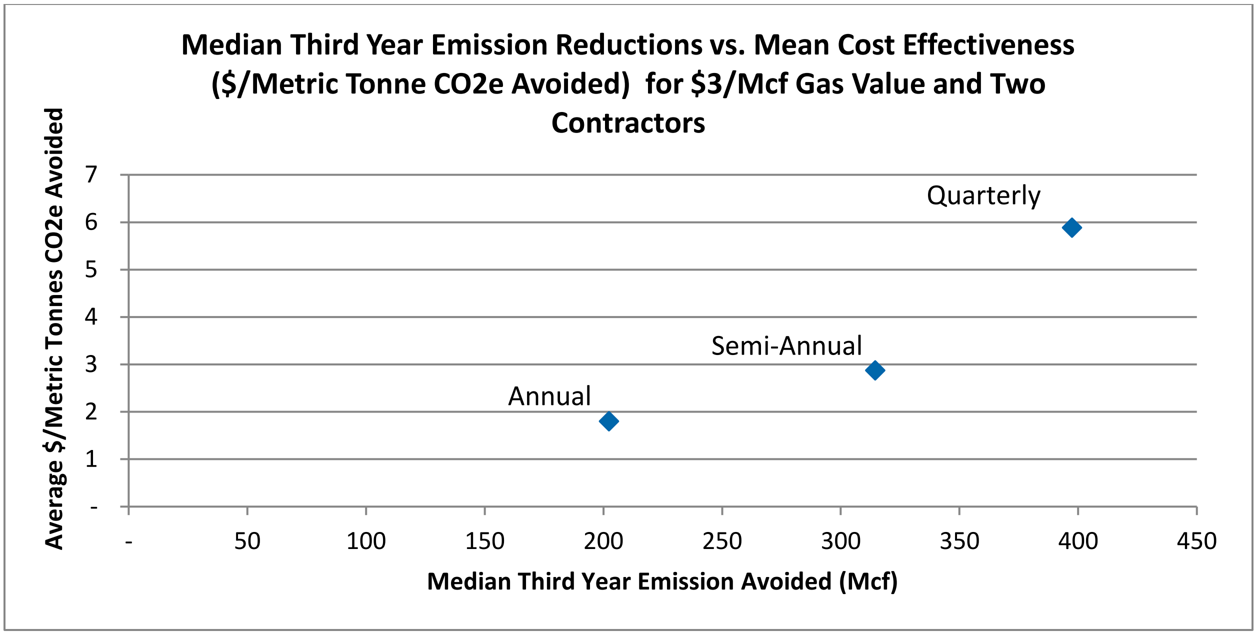

Figure 3: Production Case 1 Cost Effectiveness

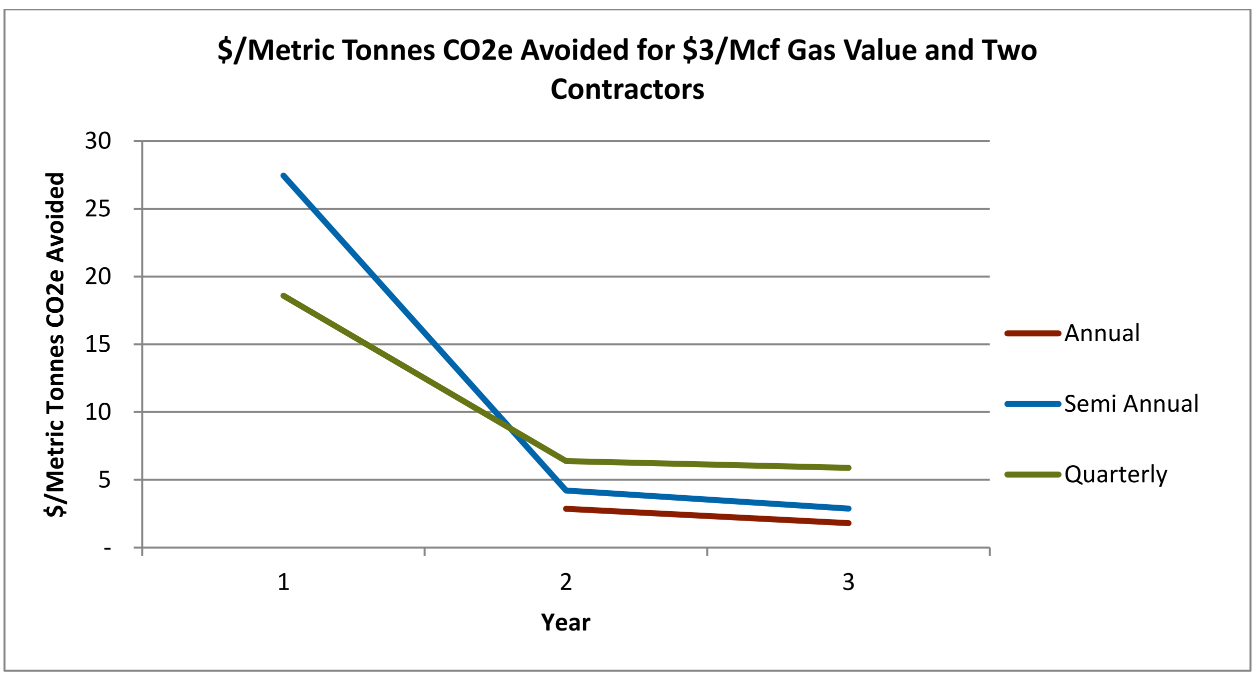

Figure 4: Production Case 1 CO_2e Avoided

A.1.2. Case 2 - $4/Mcf Gas Value and Two Contractors

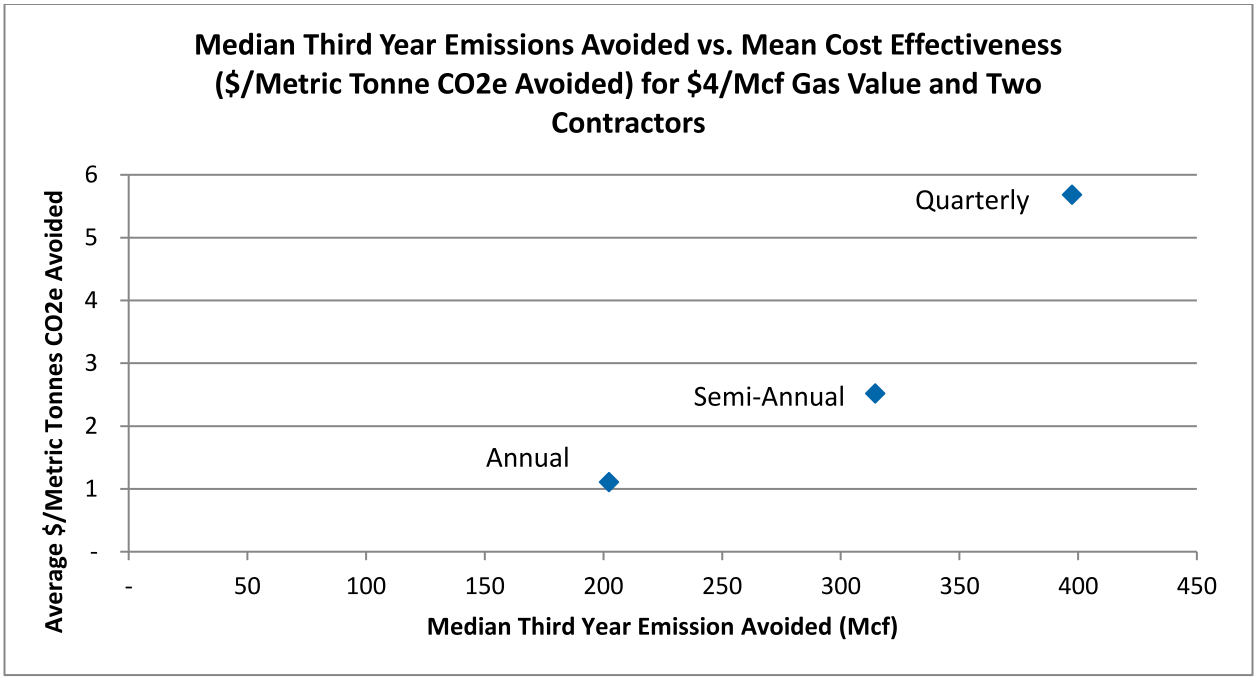

Figure 5: Production Case 2 Cost Effectiveness

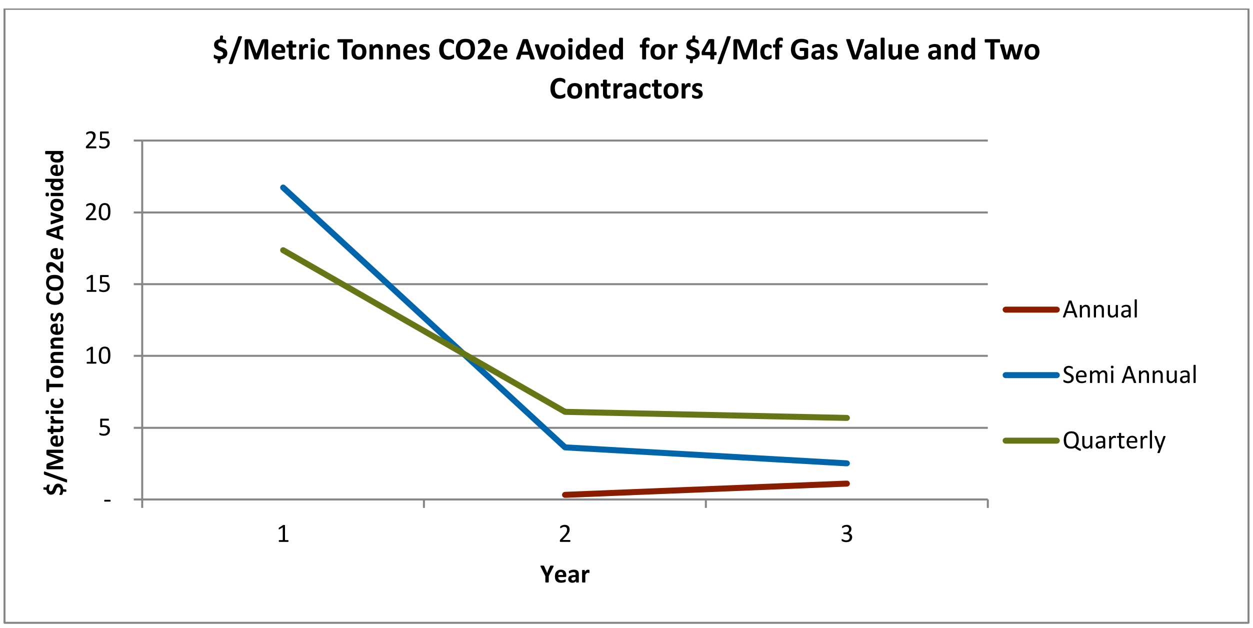

Figure 6: Production Case 2 CO_2e Avoided

A.1.3. Case 3 - $3/Mcf Gas Value and One Contractor

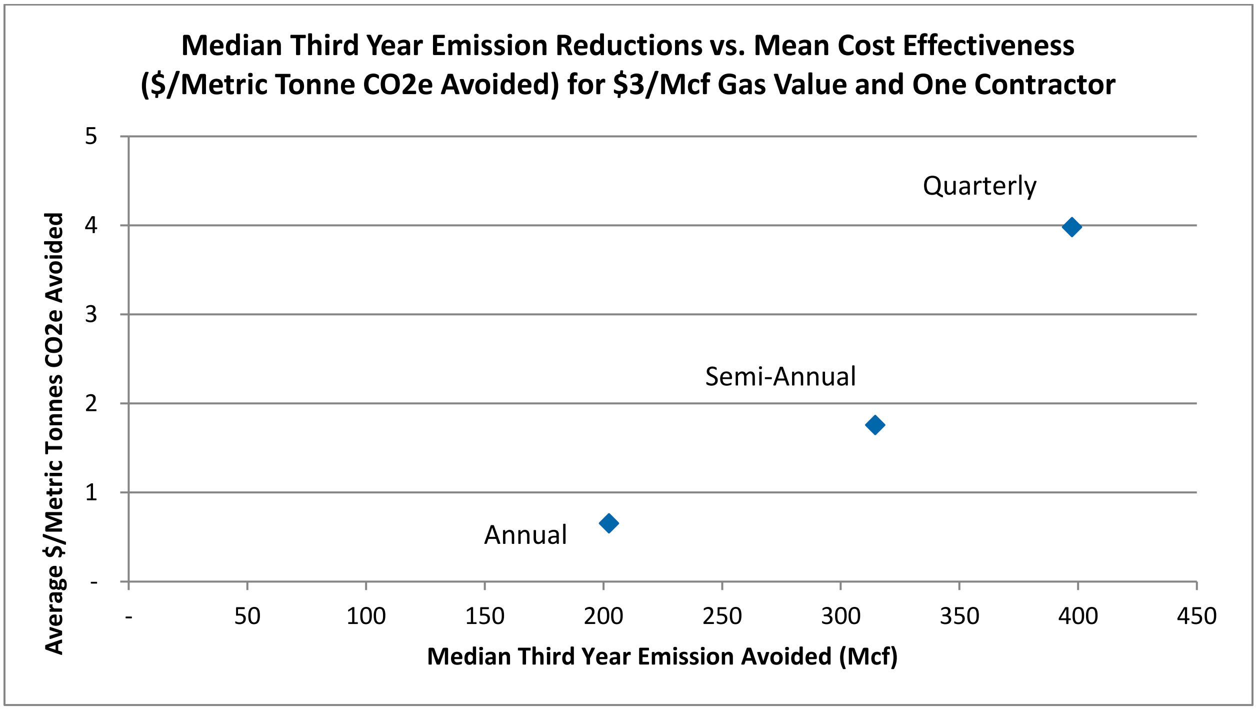

Figure 7: Production Case 3 Cost Effectiveness

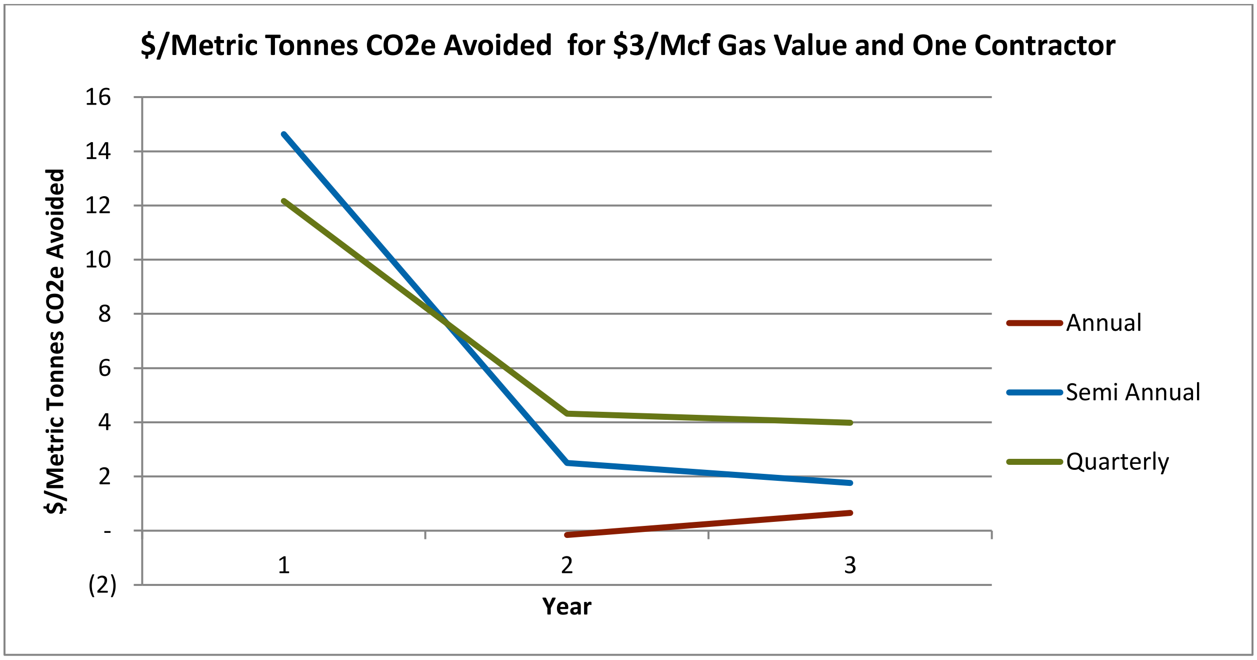

Figure 8: Production Case 3 CO_2e Avoided

A.2. Transmission

A.2.1. Case 1 - $3/Mcf Gas Value and Two Contractors

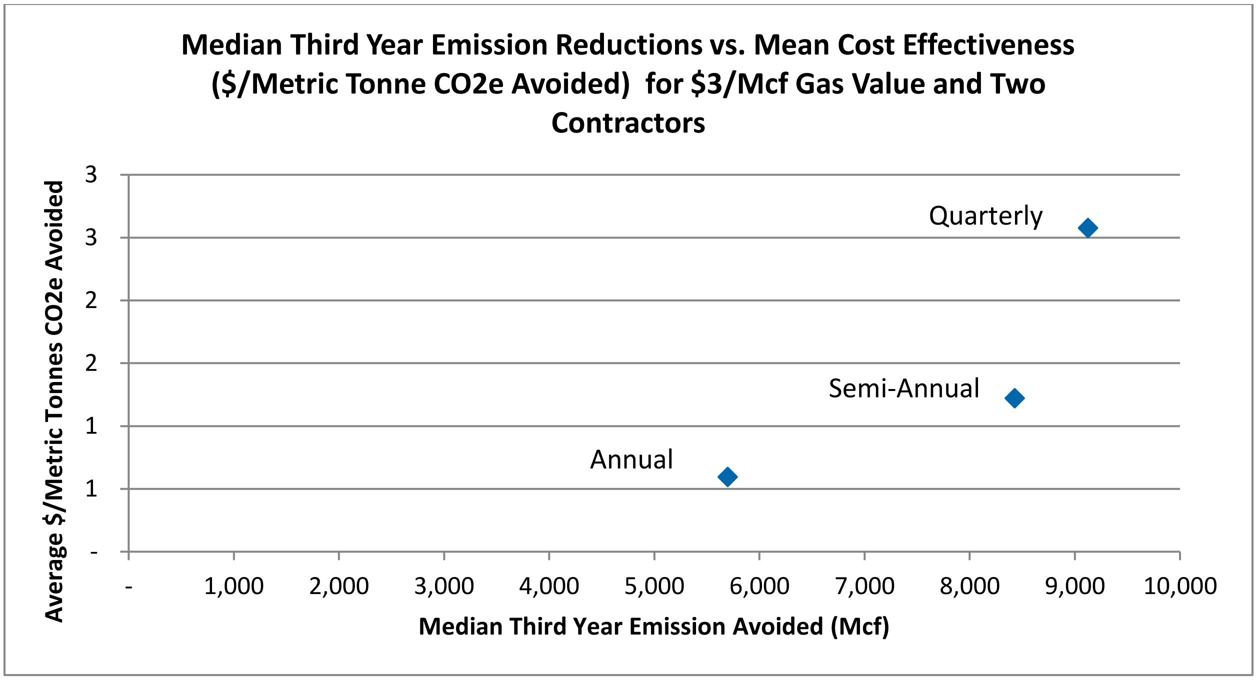

Figure 9: Transmission Case 1 Cost Effectiveness

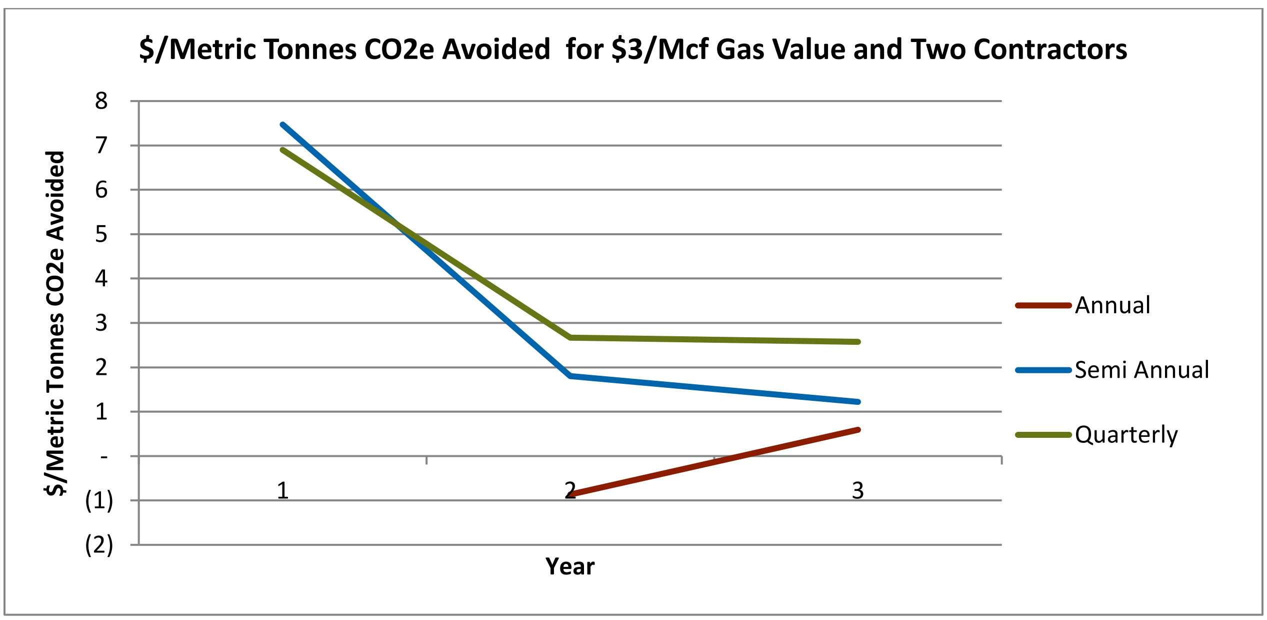

Figure 10: Transmission Case 1 CO_2e Avoided

A.2.2. Case 2 - $4/Mcf Gas Value and Two Contractors

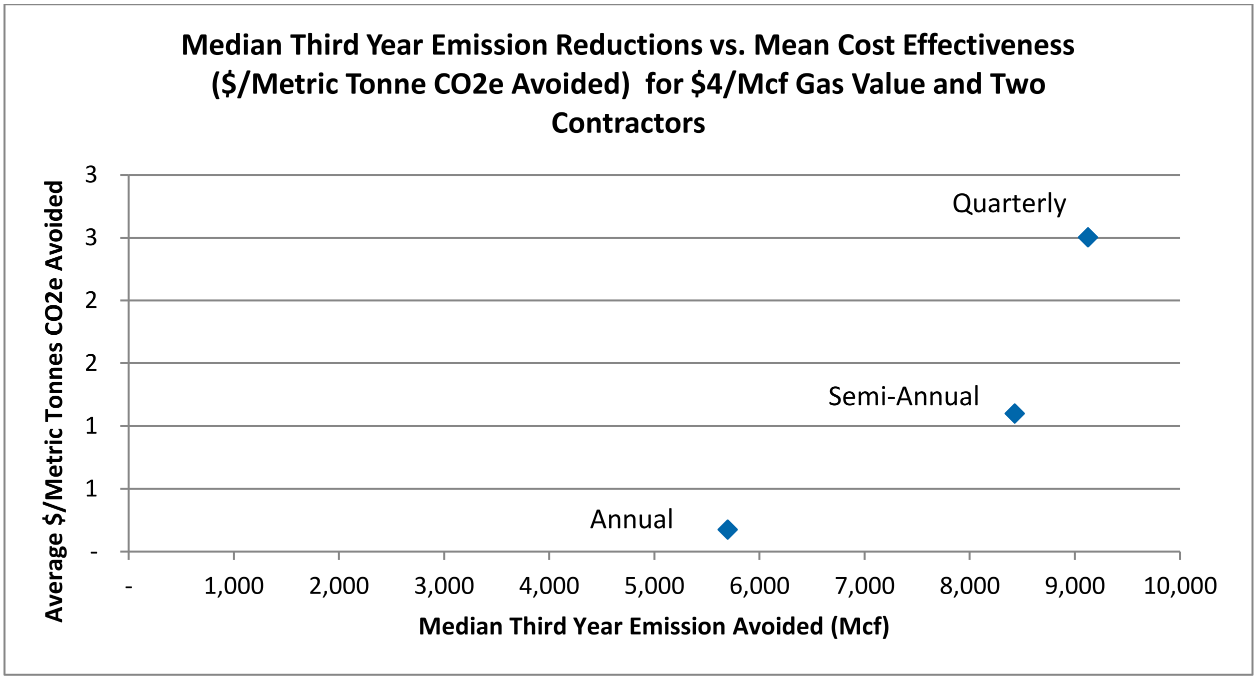

Figure 11: Transmission Case 2 Cost Effectiveness

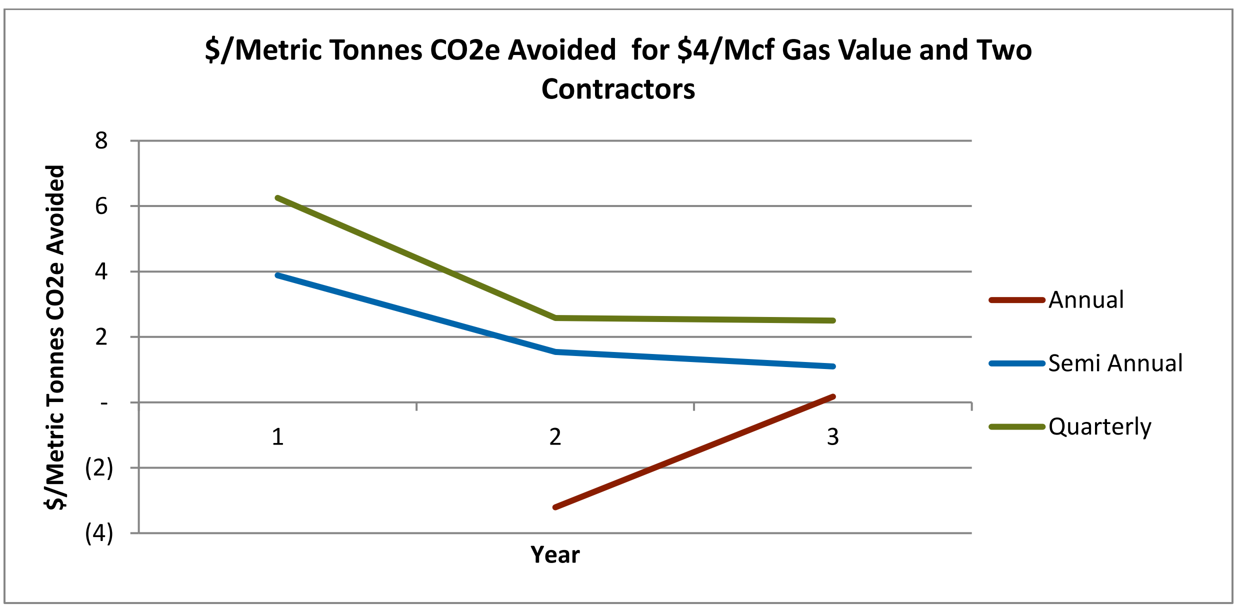

Figure 12: Transmission Case 2 CO_2e Avoided

A.2.3. Case 3 - $3/Mcf Gas Value and One Contractor

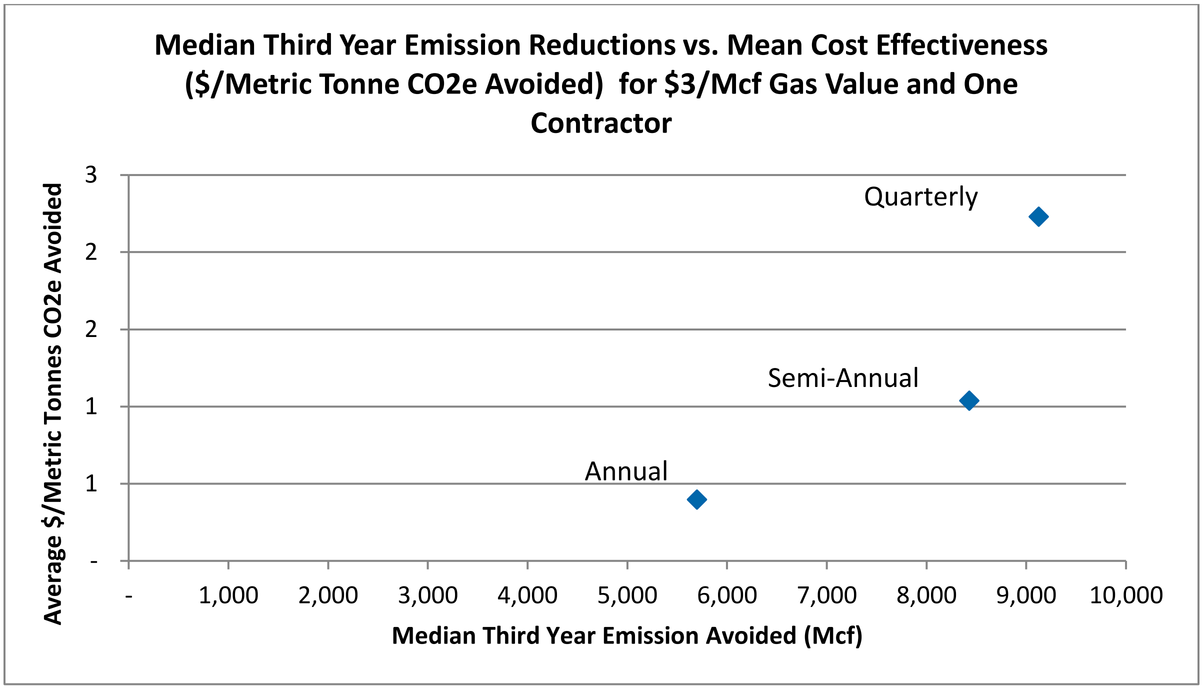

Figure 13: Transmission Case 3 Cost Effectiveness

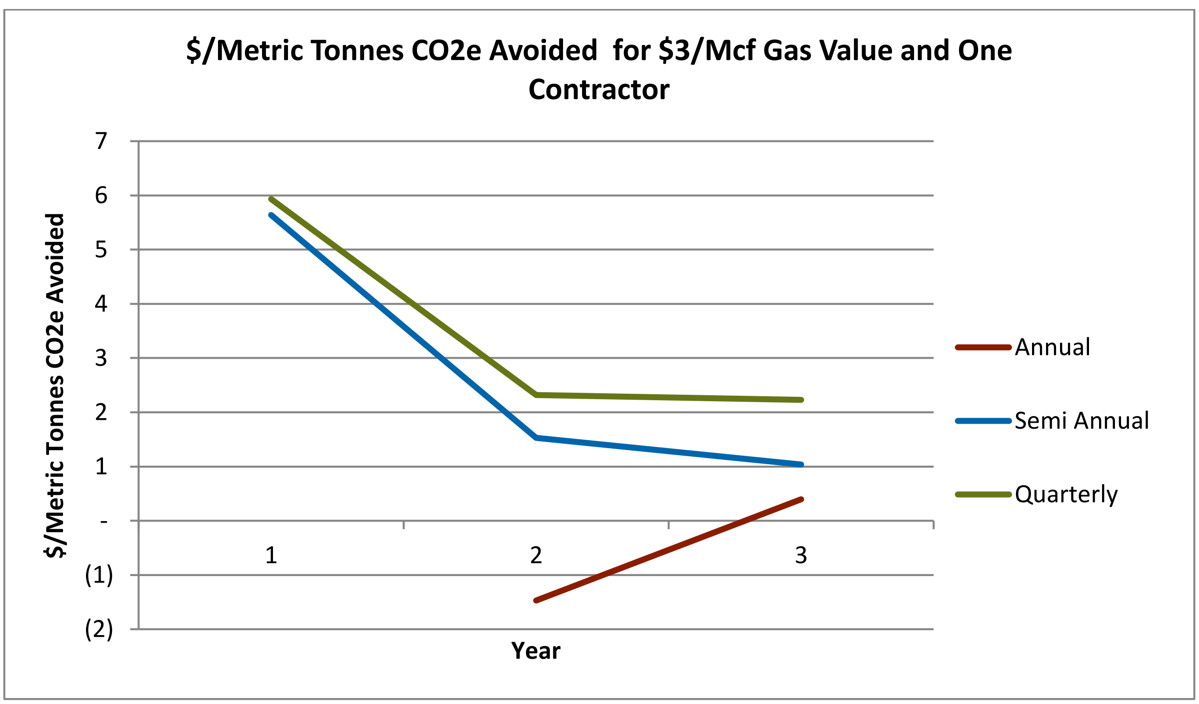

Figure 14: Transmission Case 3 CO_2e Avoided

A.2.4. Case 4 - $0/Mcf Gas Value and Two Contractors

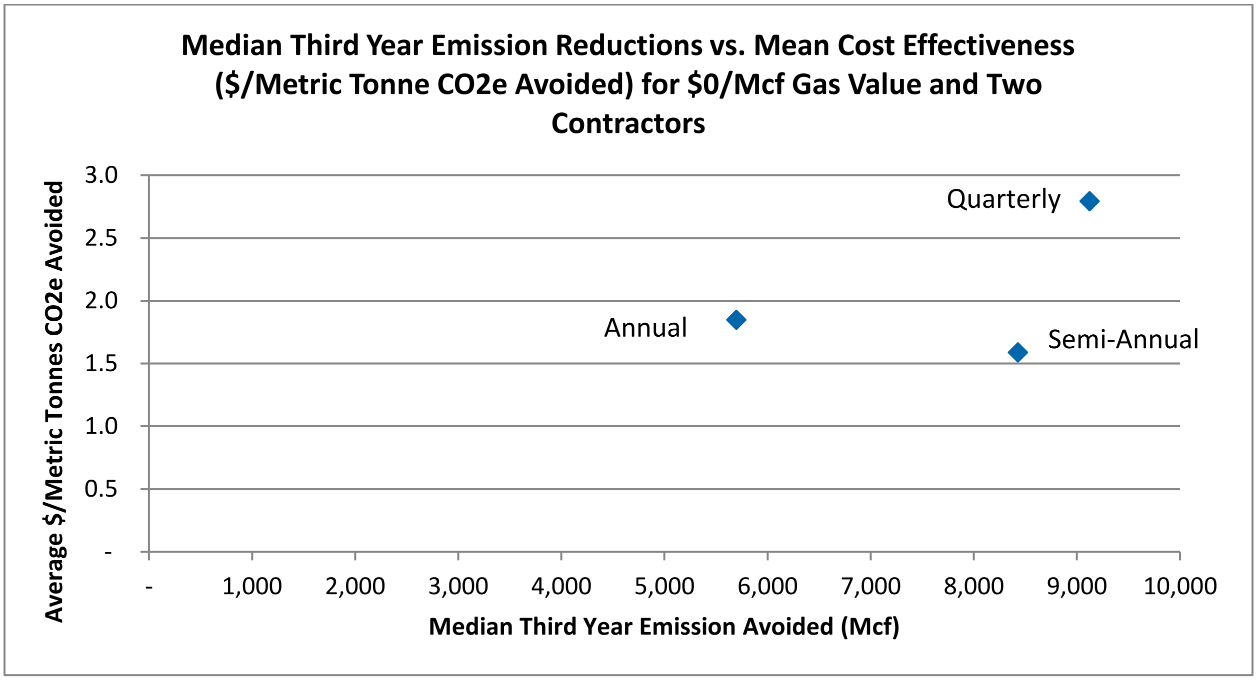

Figure 15: Transmission Case 4 Cost Effectiveness

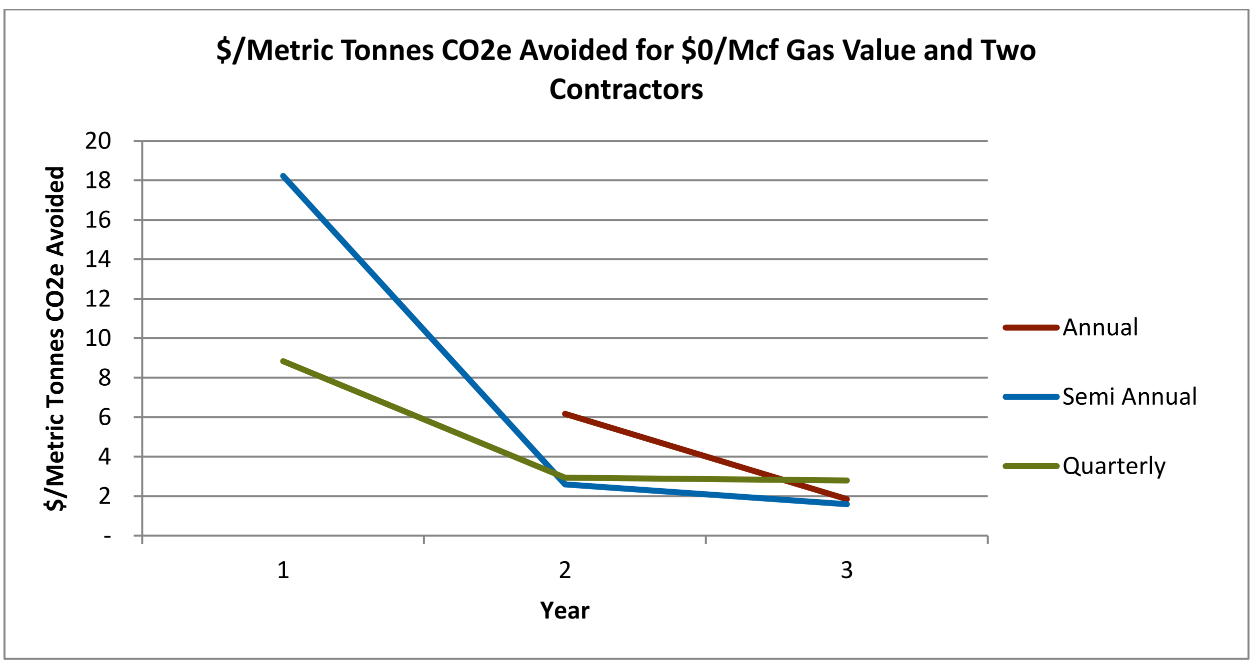

Figure 16: Transmission Case 4 CO_2e Avoided

A.2.5. Case 5 - \$0/Mcf Gas Value and One Contractor

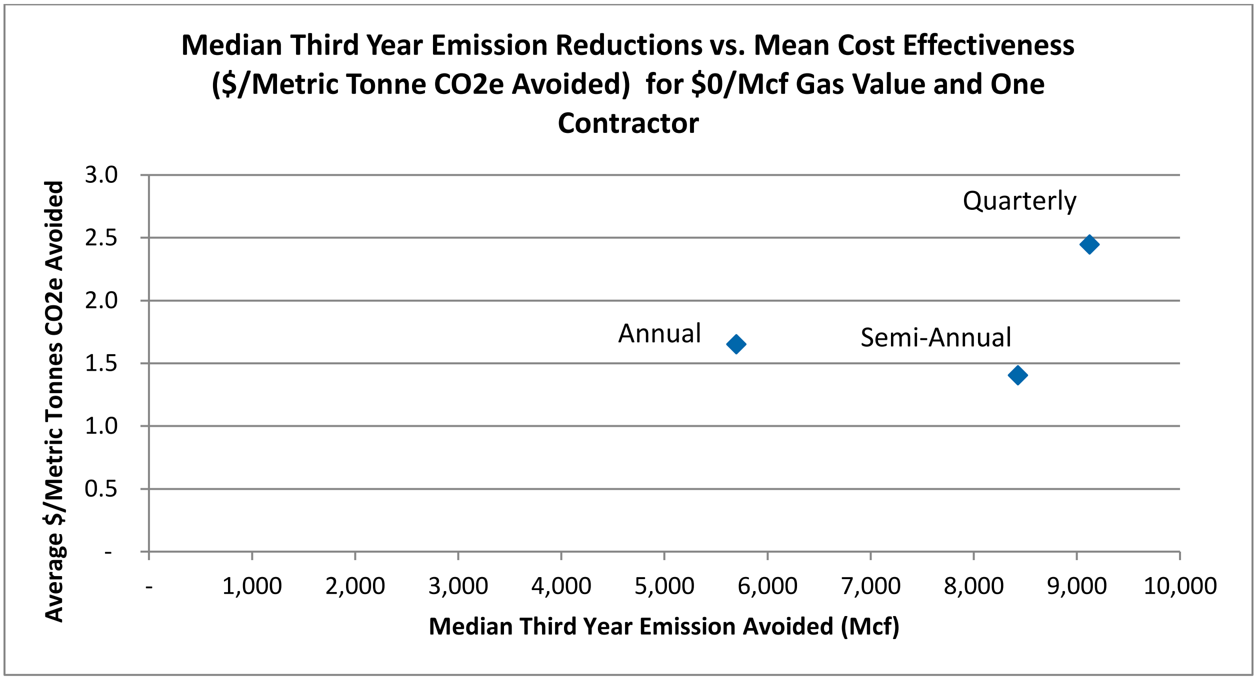

Figure 17: Transmission Case 5 Cost Effectiveness

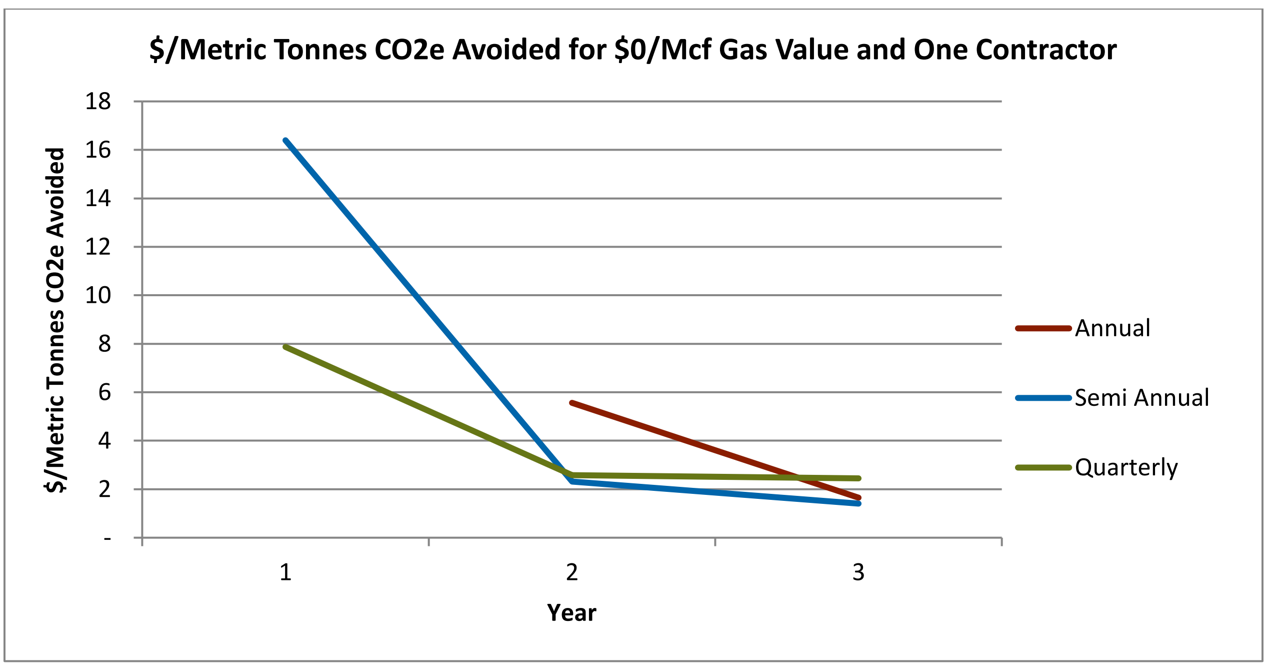

Figure 18: Transmission Case 5 CO_2e Avoided

A.3. Processing

A.3.1. Case 1 - $3/Mcf Gas Value and Two Contractors

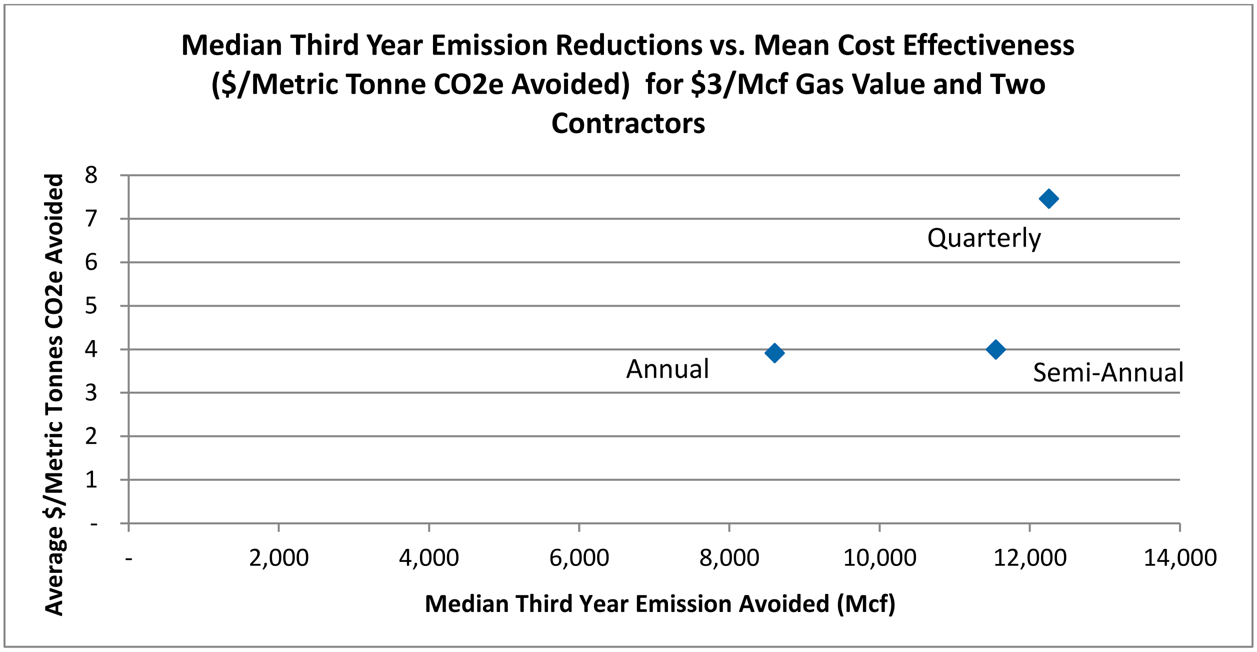

Figure 19: Processing Case 1 Cost Effectiveness

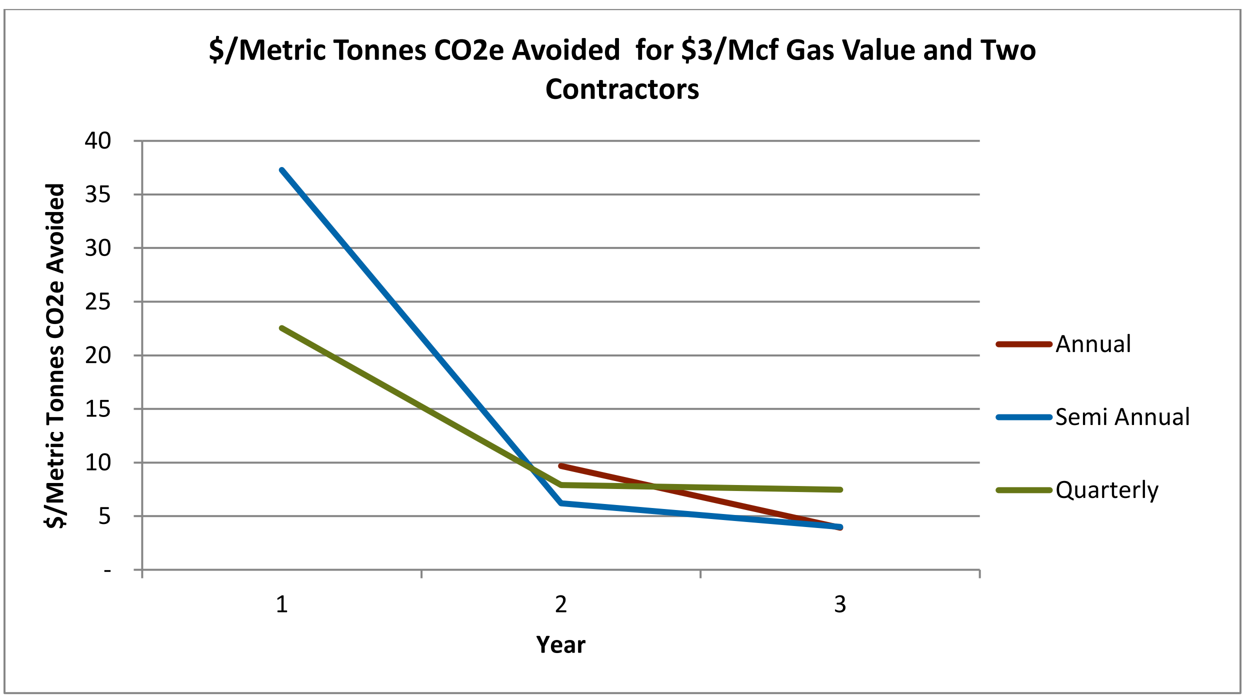

Figure 20: Processing Case 1 CO_2e Avoided

A.3.2. Case 2 - \$4/Mcf Gas Value and Two Contractors

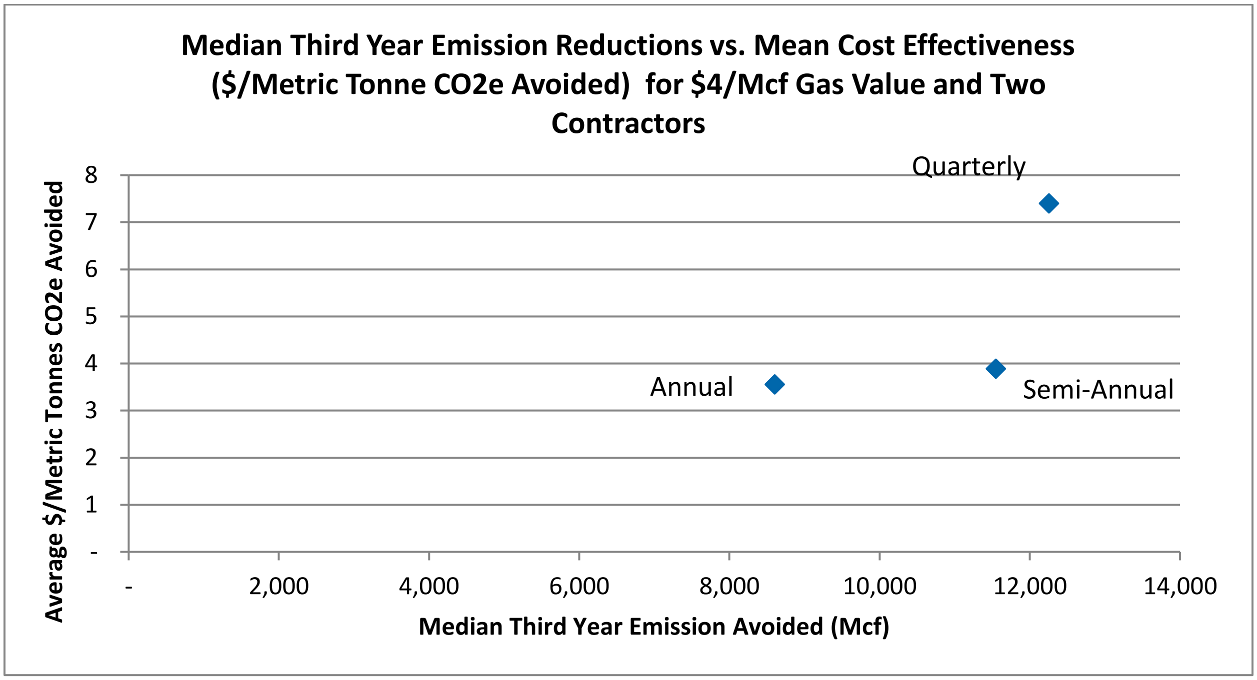

Figure 21: Processing Case 2 Cost Effectiveness

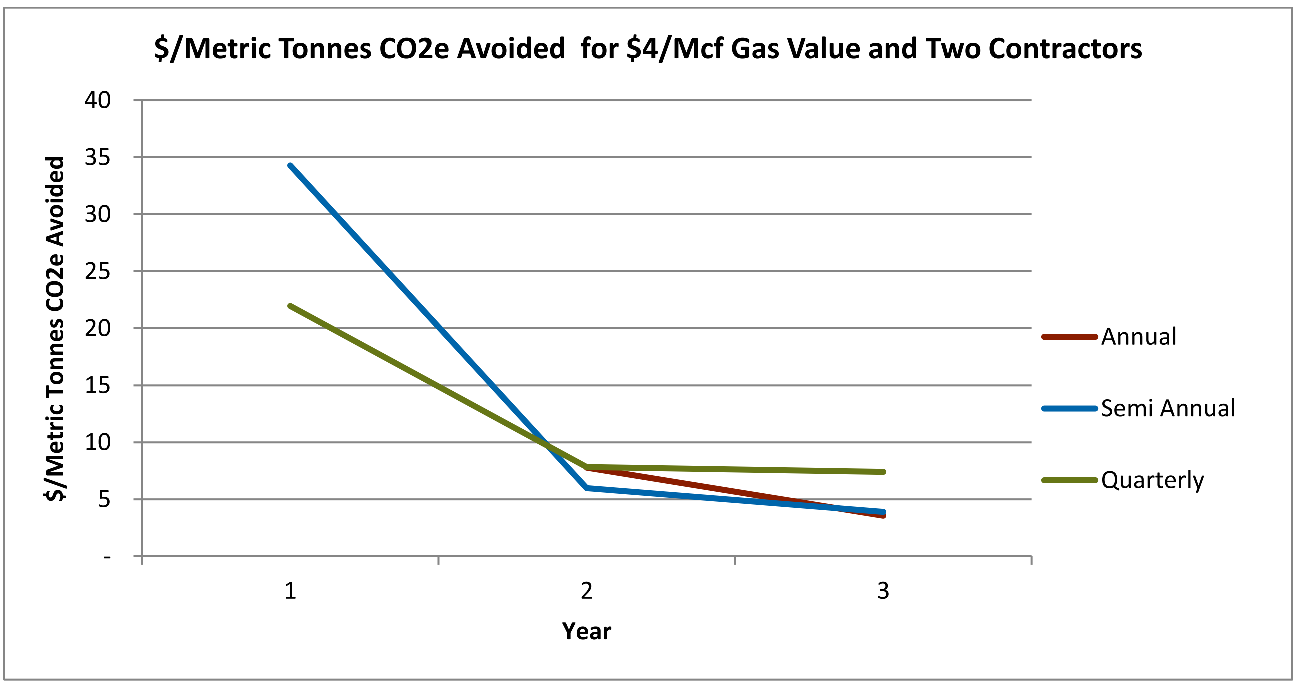

Figure 22: Processing Case 2 CO_2e Avoided

A.3.3. Case 3 - $3/Mcf Gas Value and One Contractor

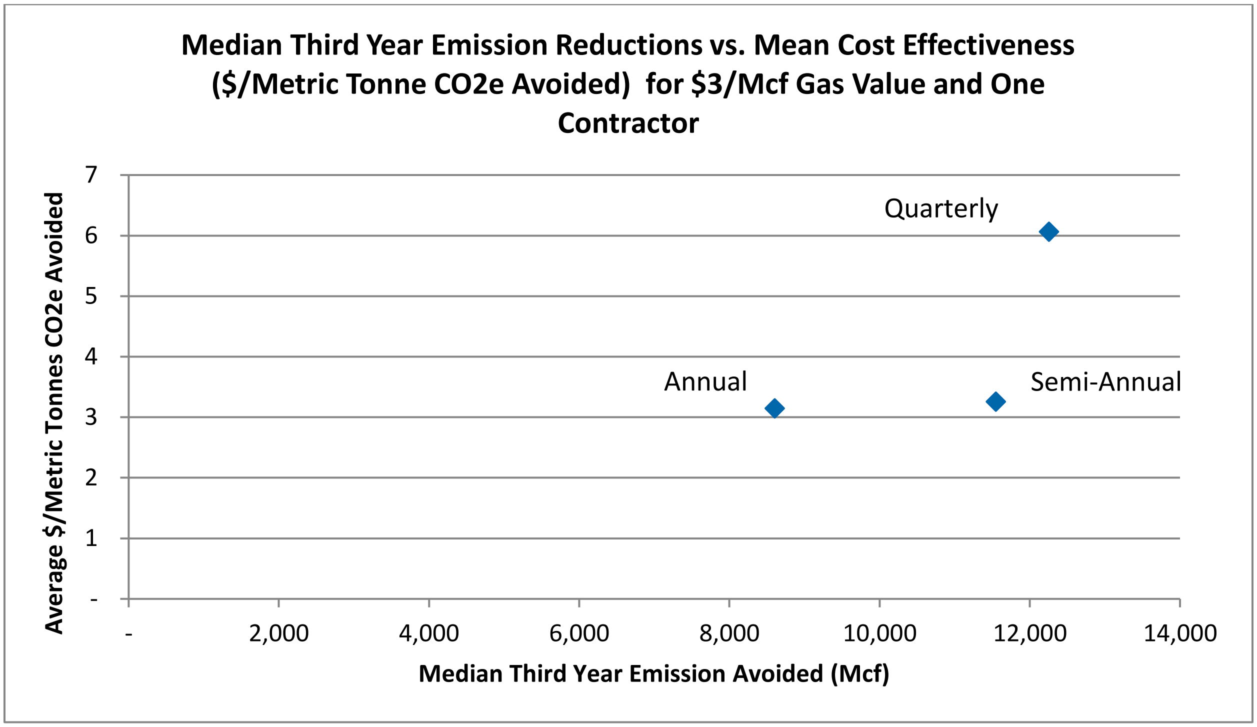

Figure 23: Processing Case 3 Cost Effectiveness

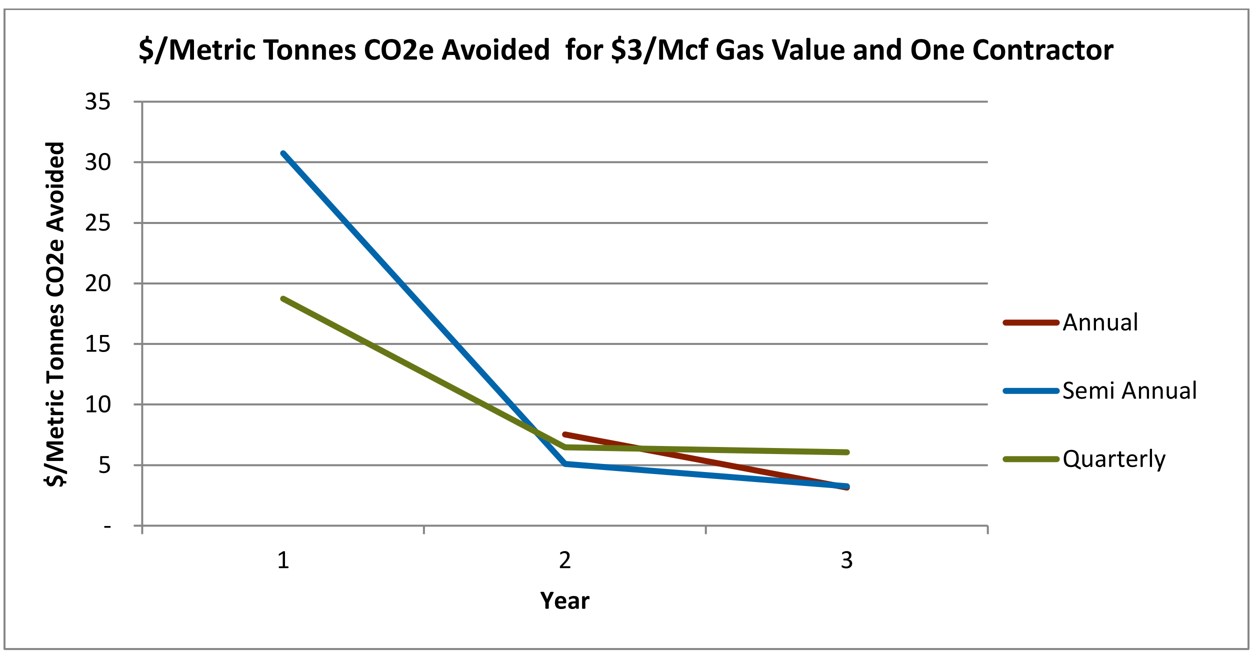

Figure 24: Processing Case 3 CO_2e Avoided

A.3.4. Case 4 - $0/Mcf Gas Value and Two Contractors

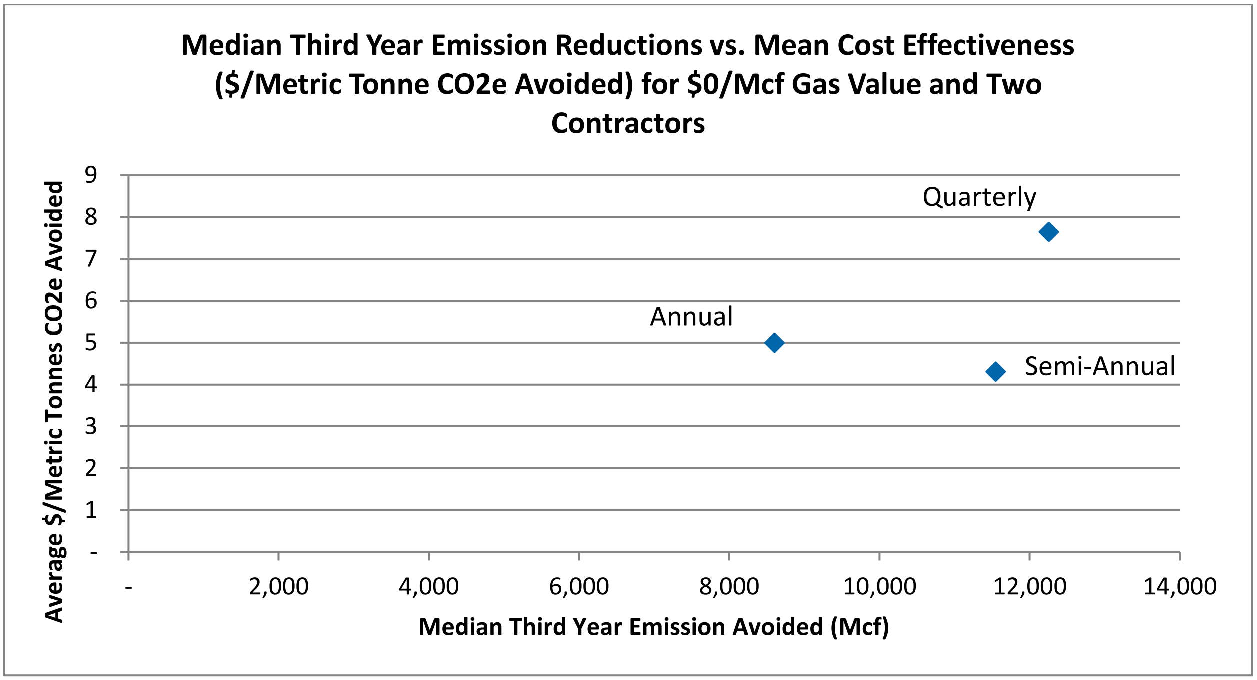

Figure 25: Processing Case 4 Cost Effectiveness

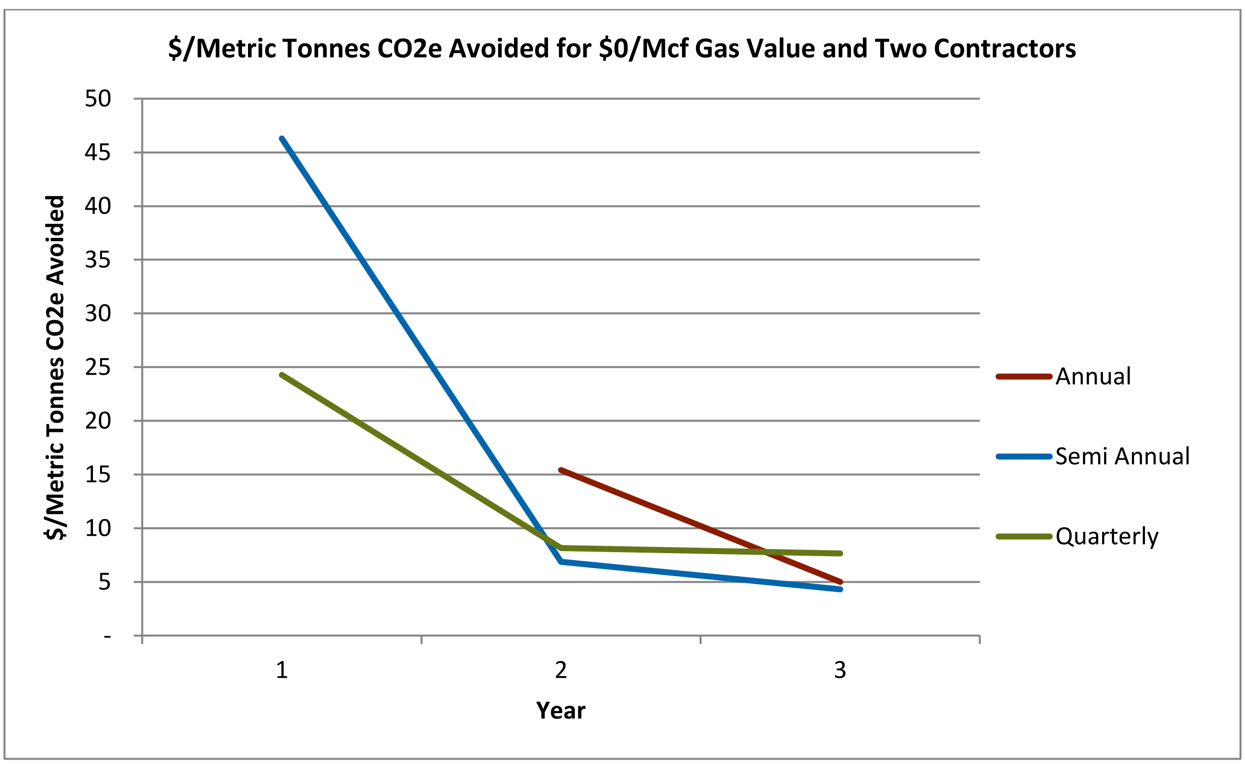

Figure 26: Processing Case 4 CO_2e Avoided

A.3.5. Case 5 - $0/Mcf Gas Value and One Contractor

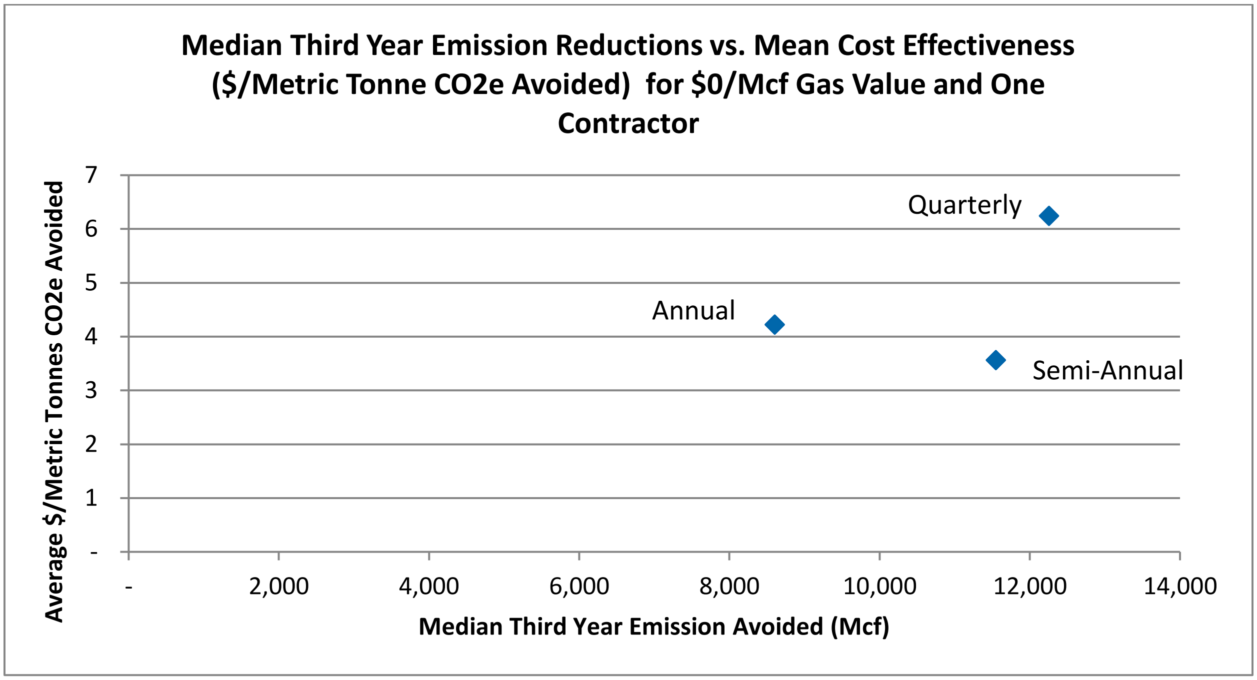

Figure 27: Processing Case 5 Cost Effectiveness

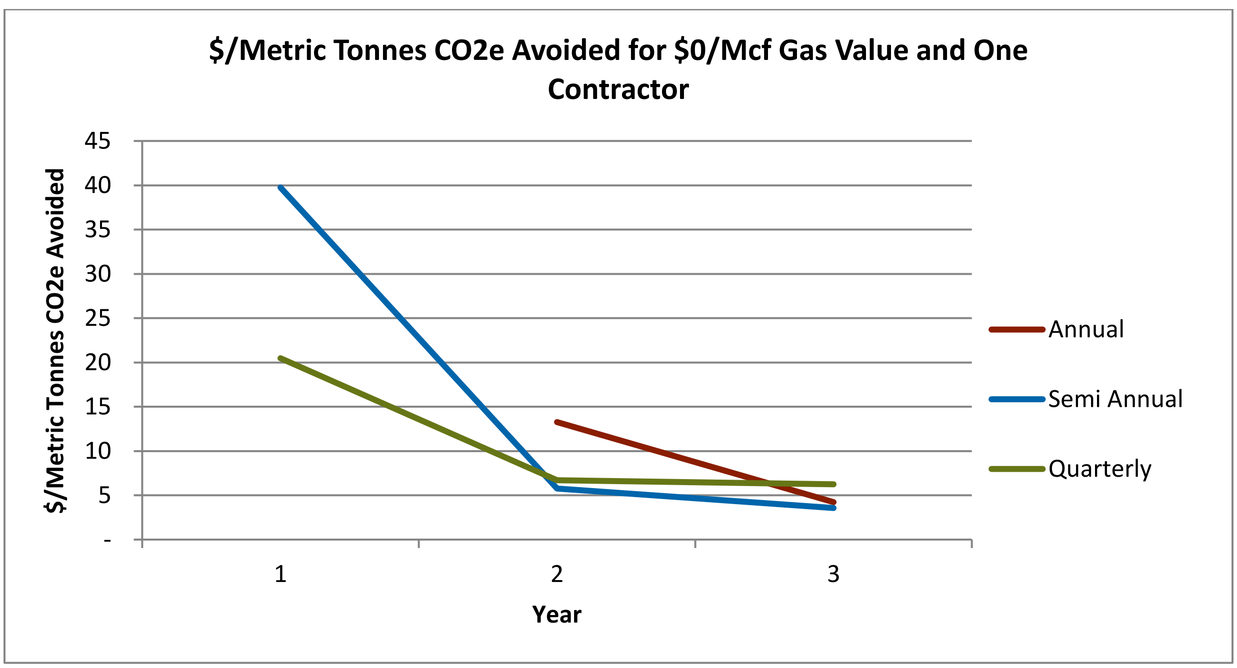

Figure 28: Processing Case 5 CO_2e Avoided

A.4. Storage

A.4.1. Case 1 - $3/Mcf Gas Value and Two Contractors

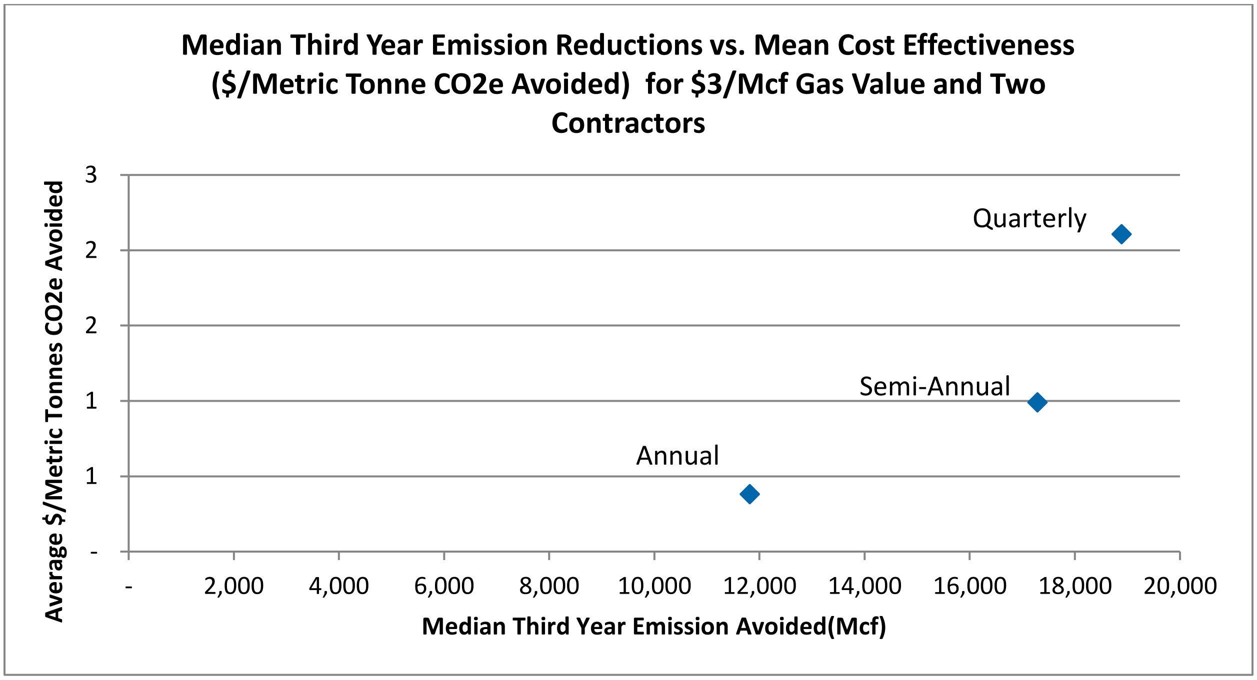

Figure 29: Storage Case 1 Cost Effectiveness

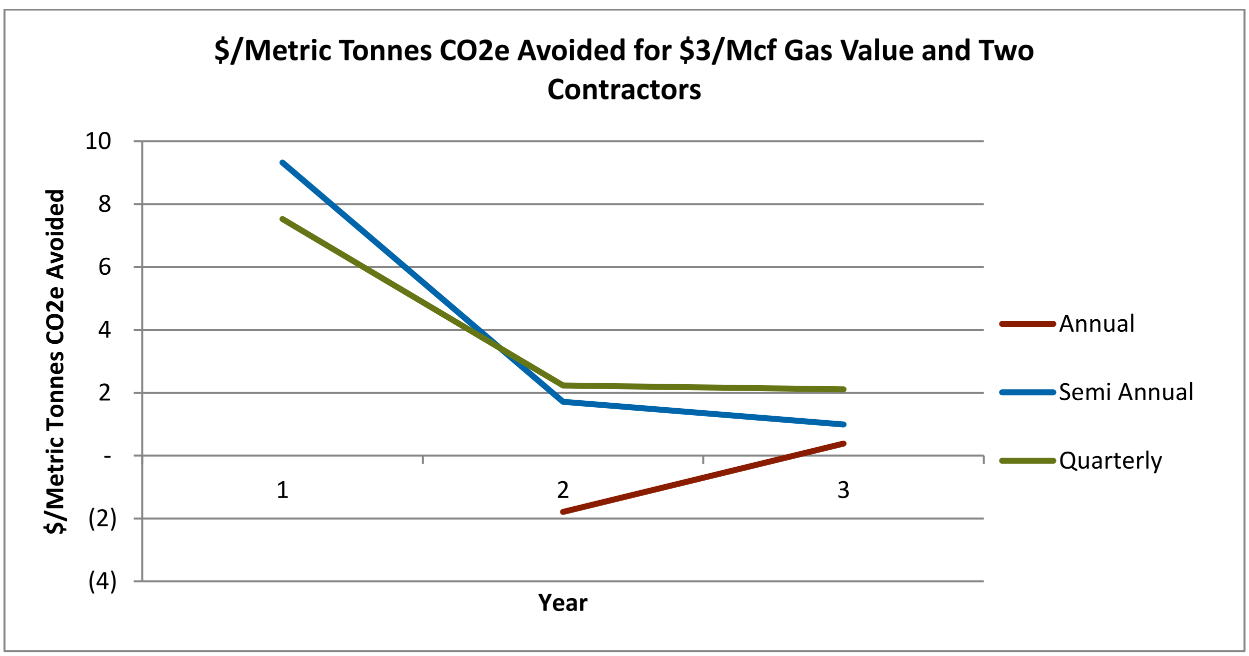

Figure 30: Storage Case 1 CO_2e Avoided

A.4.2. Case 2 - $4/Mcf Gas Value and Two Contractors

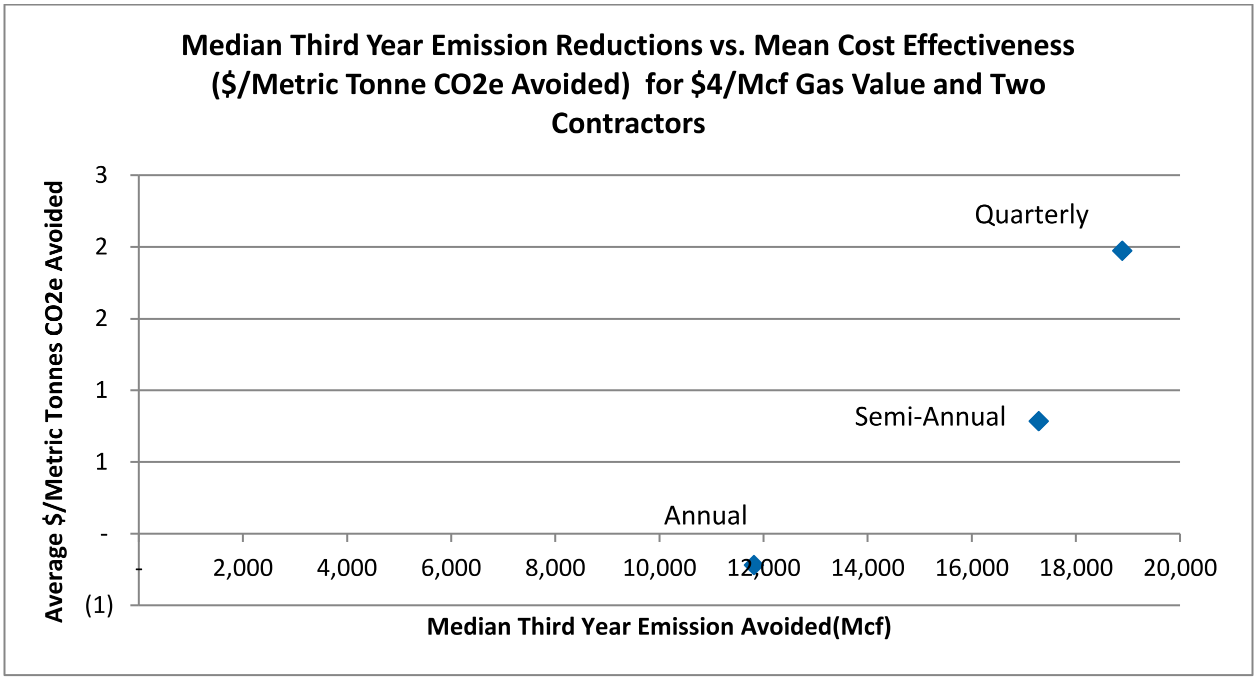

Figure 31: Storage Case 2 Cost Effectiveness

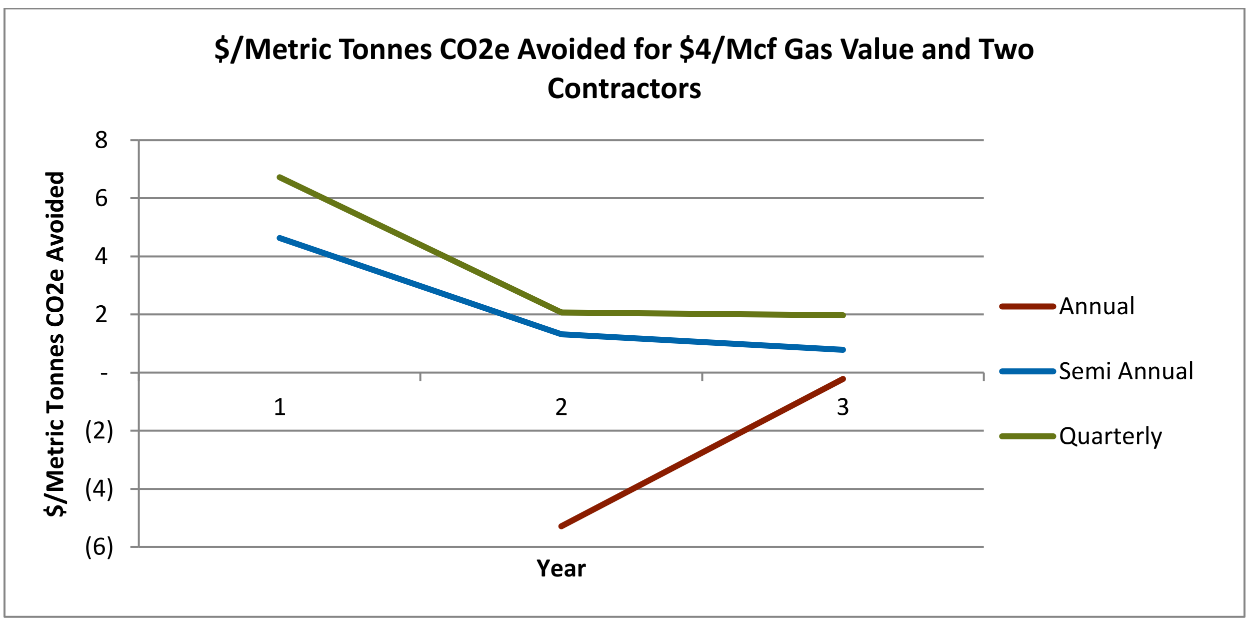

Figure 32: Storage Case 2 CO_2e Avoided

A.4.3. Case 3 - $3/Mcf Gas Value and One Contractor

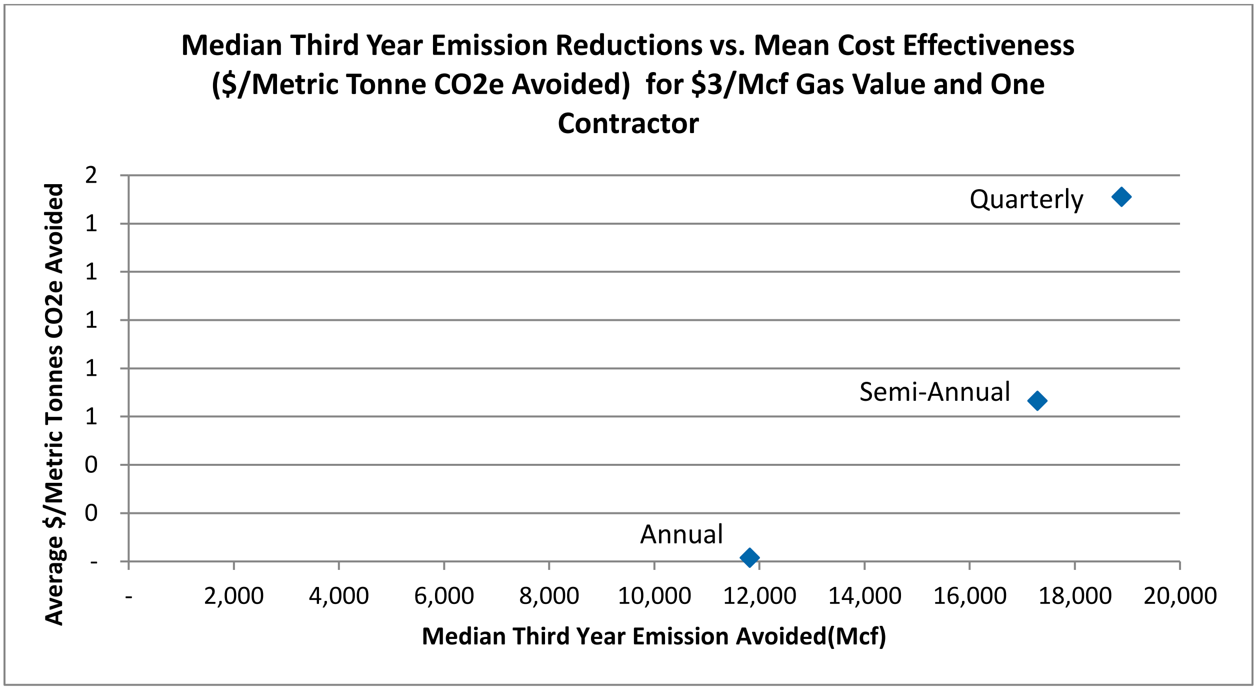

Figure 33: Storage Case 3 Cost Effectiveness

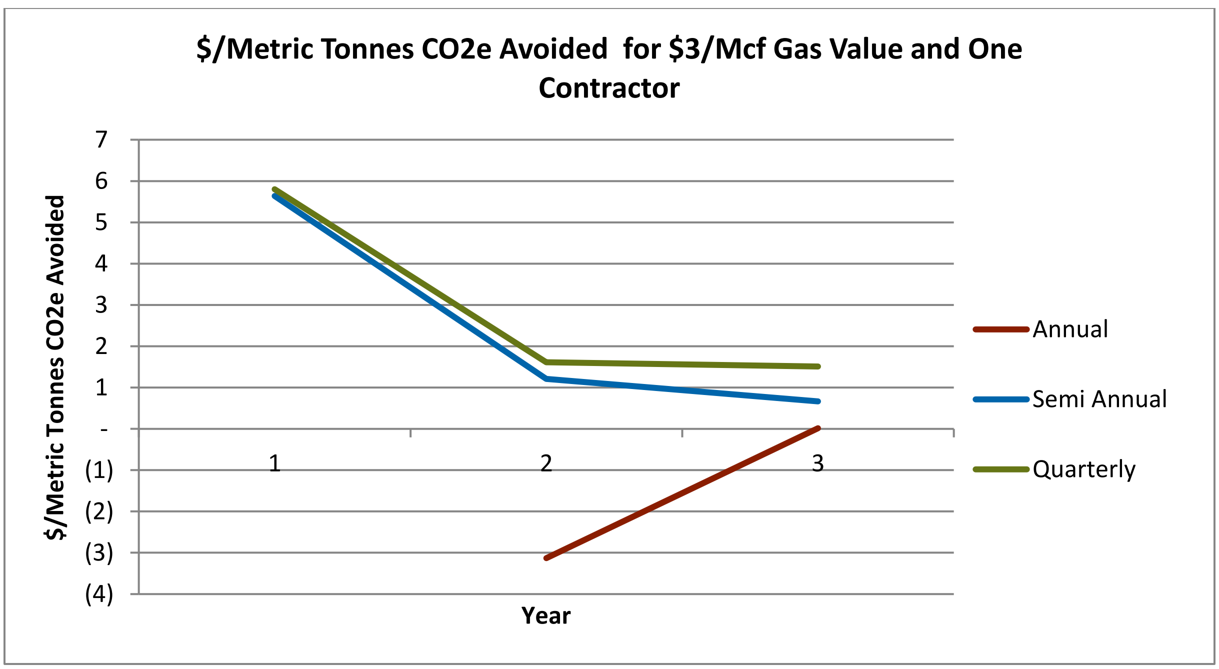

Figure 34: Storage Case 3 CO_2e Avoided

A.4.4. Case 4 - $0/Mcf Gas Value and Two Contractors

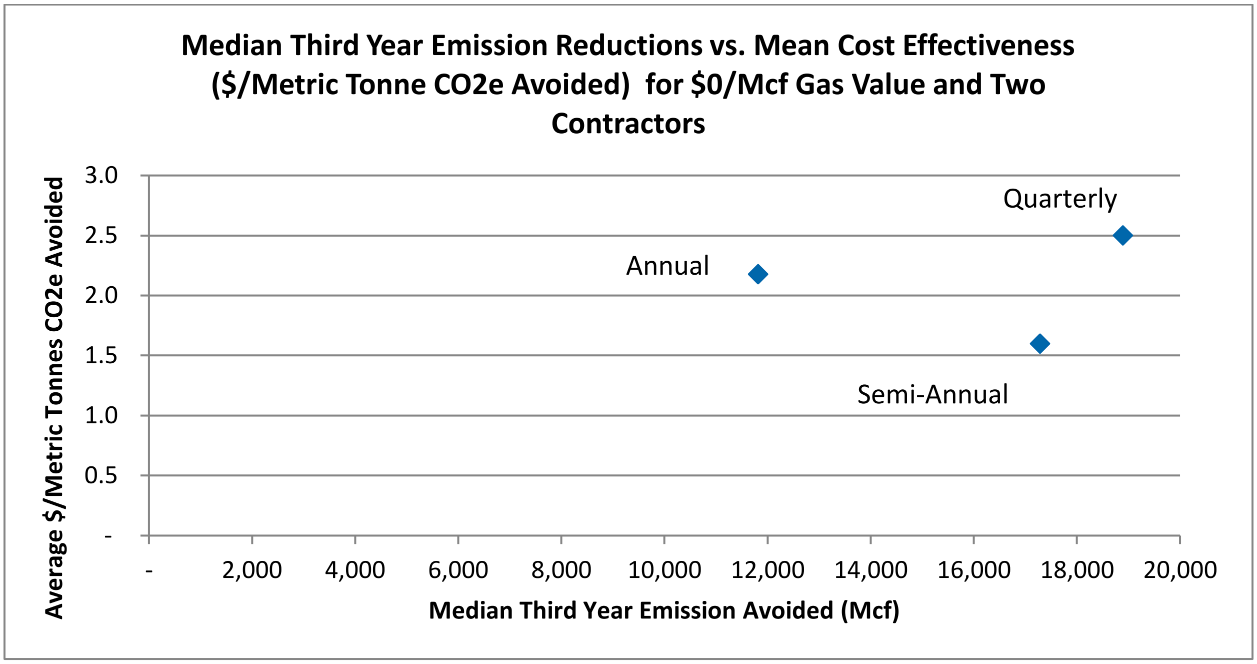

Figure 35: Storage Case 4 Cost Effectiveness

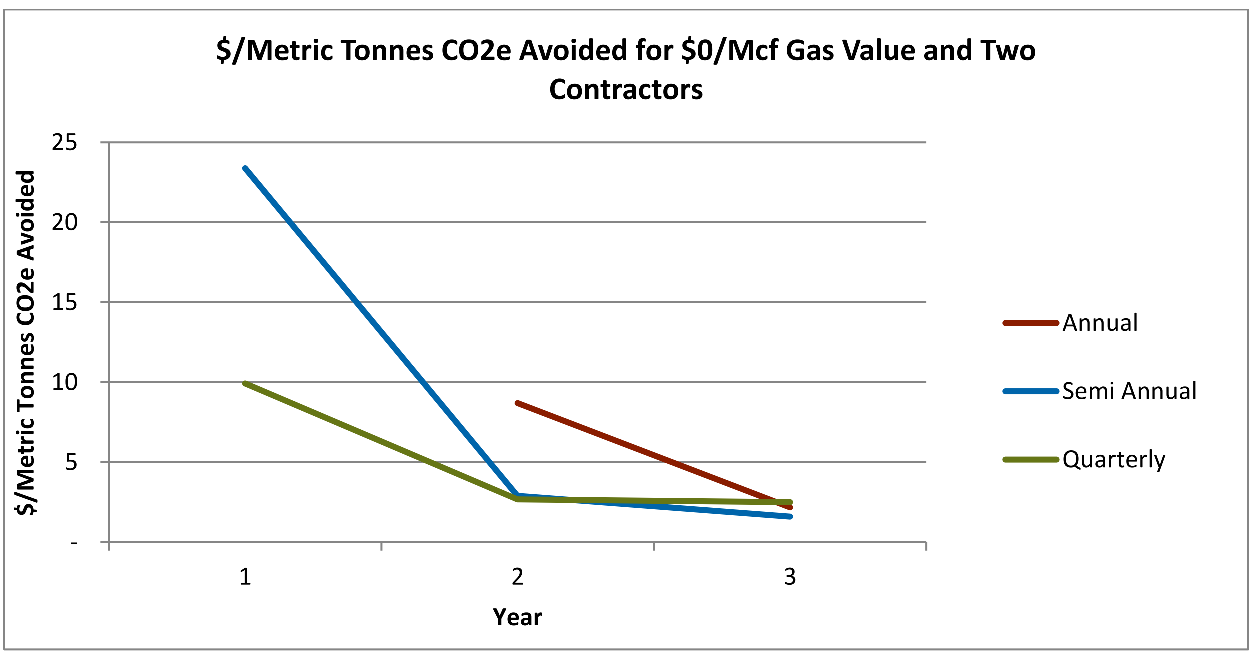

Figure 36: Storage Case 4 CO_2e Avoided

A.4.5. Case 5 - $0/Mcf Gas Value and One Contractor

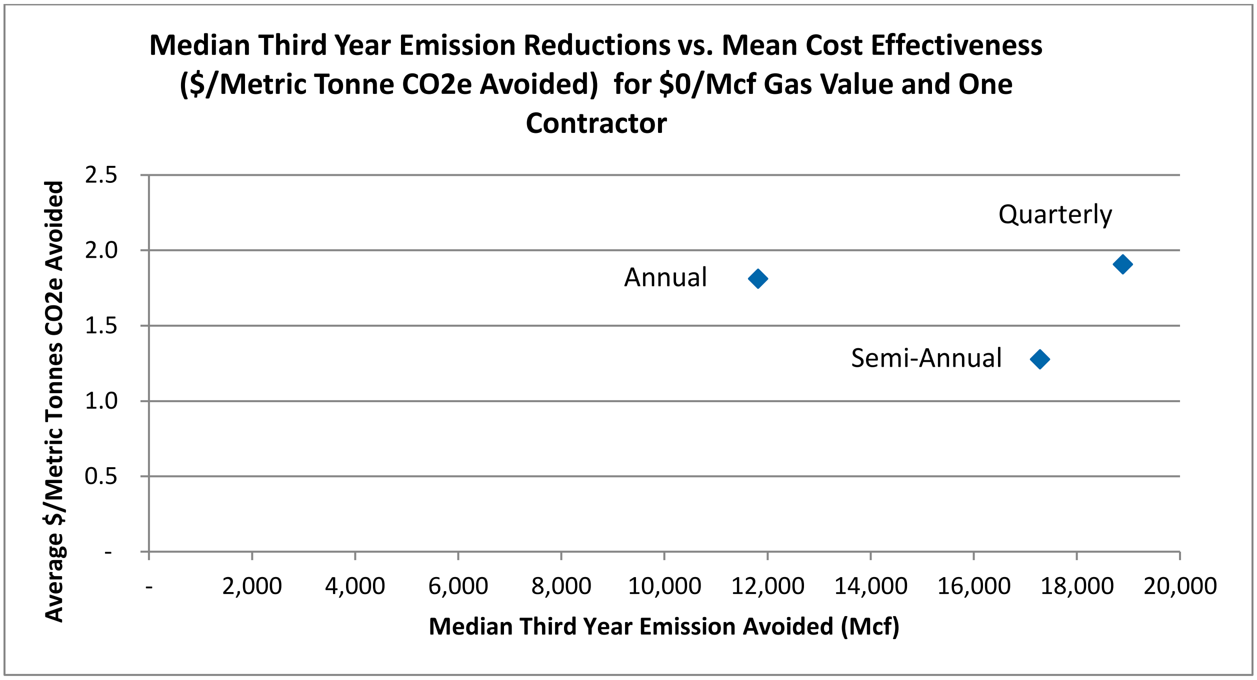

Figure 37: Storage Case 5 Cost Effectiveness

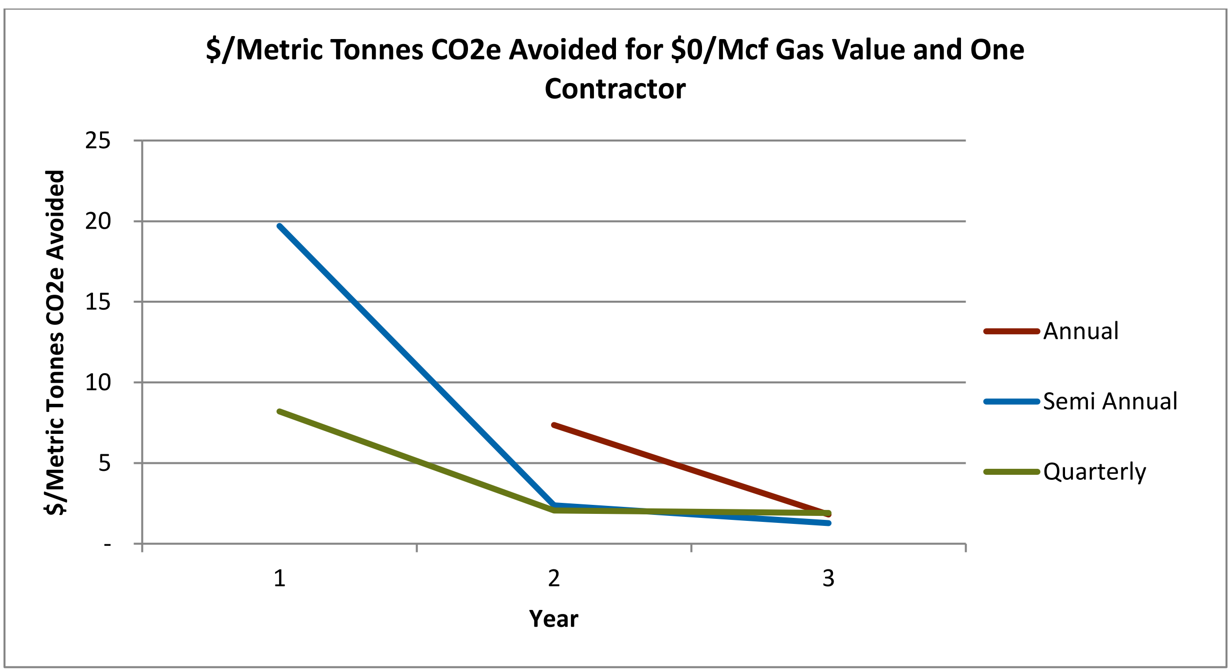

Figure 38: Storage Case 5 CO_2e Avoided

A.5. Gathering and Boosting

A.5.1. Case 1 - $3/Mcf Gas Value and Two Contractors

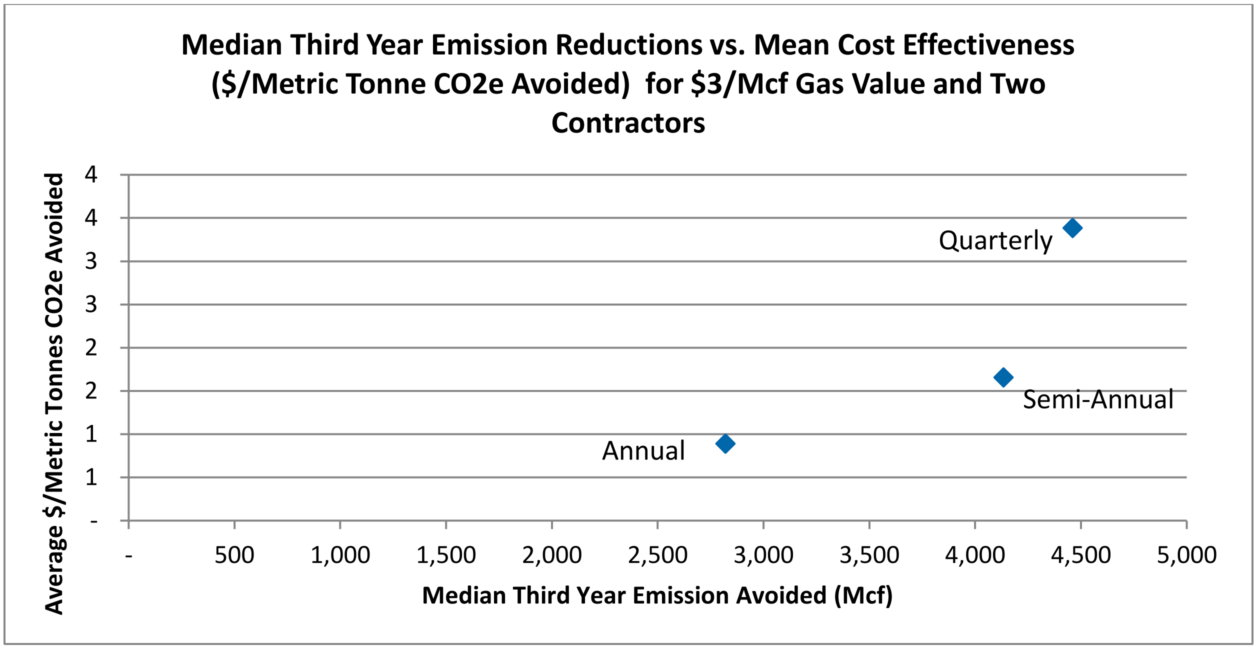

Figure 39: Gathering and Boosting Case 1 Cost Effectiveness

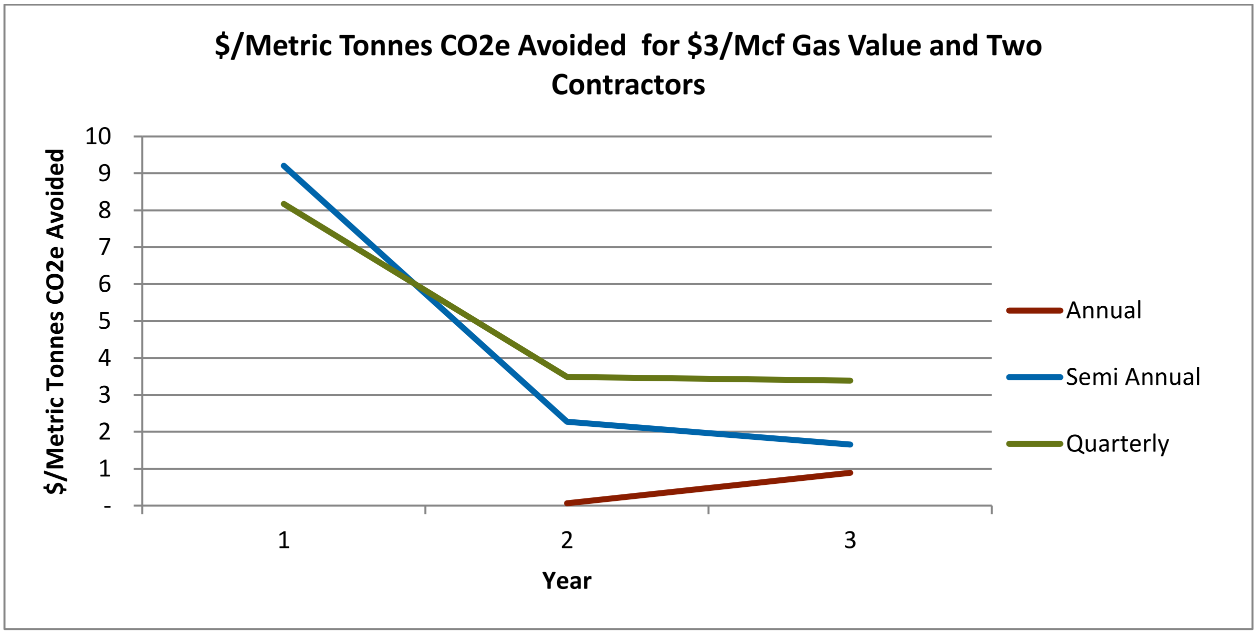

Figure 40: Gathering and Boosting Case 1 CO_2e Avoided

A.5.2. Case 2 - $4/Mcf Gas Value and Two Contractors

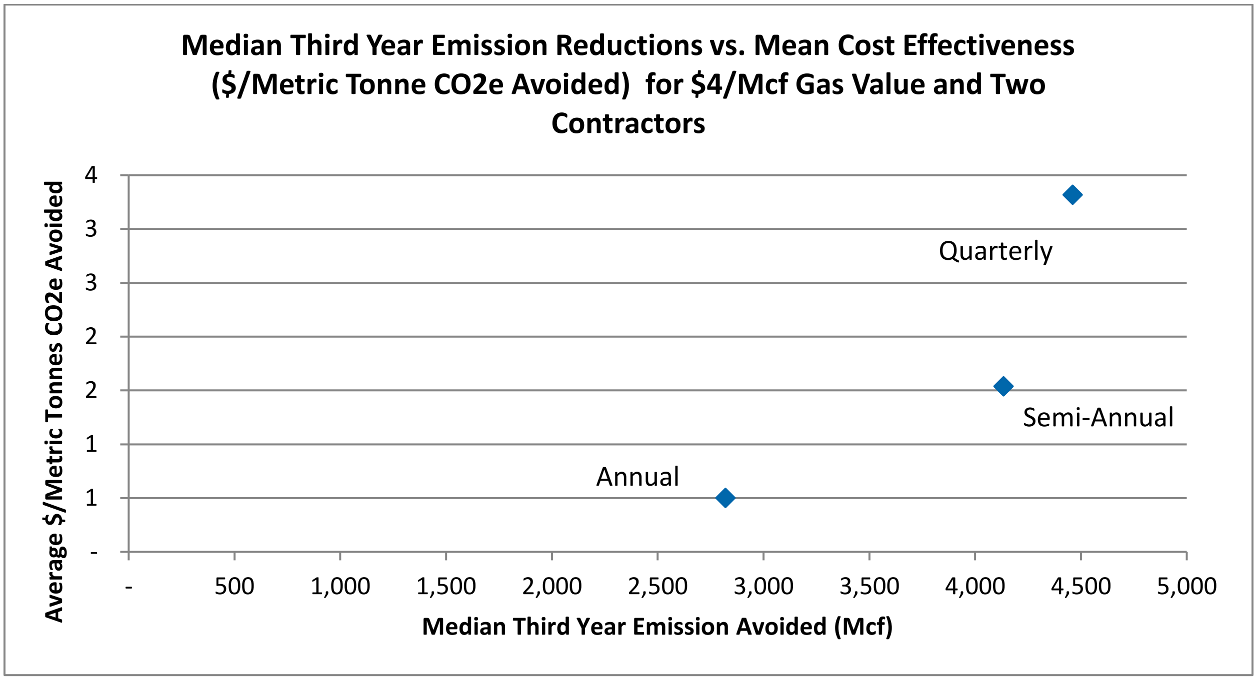

Figure 41: Gathering and Boosting Case 2 Cost Effectiveness

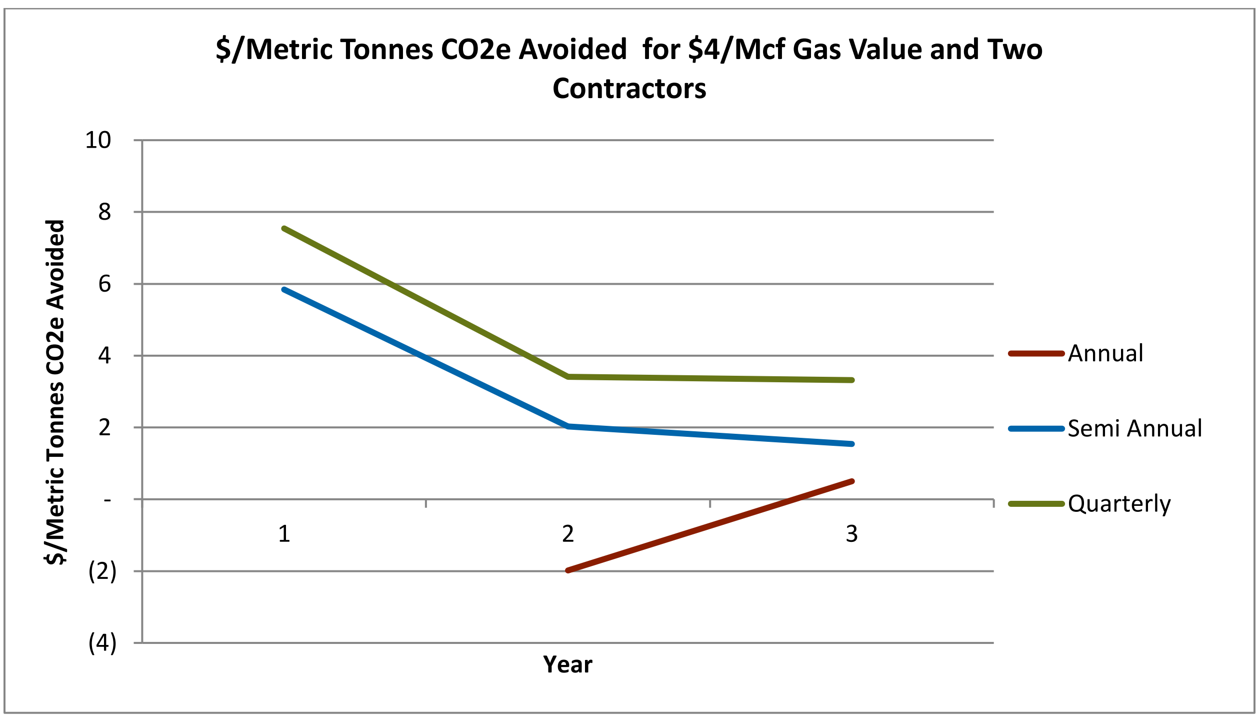

Figure 42: Gathering and Boosting Case 2 CO_2e Avoided

A.5.3. Case 3 - $3/Mcf Gas Value and One Contractor

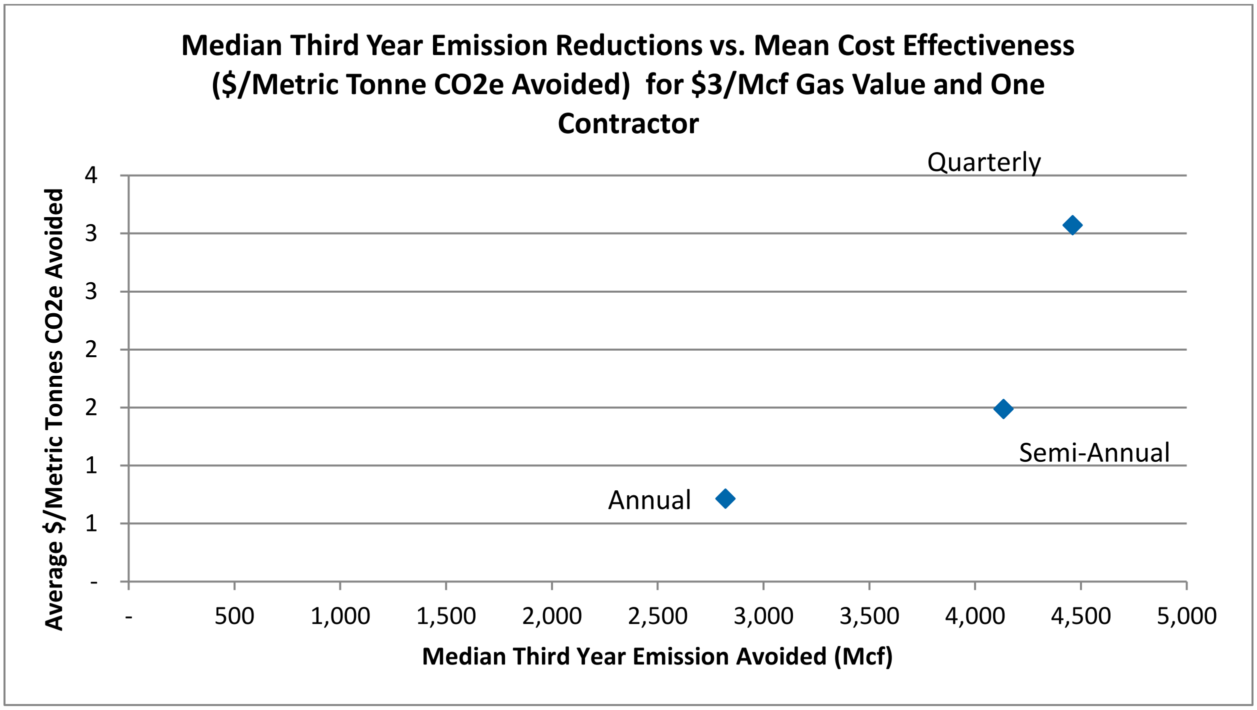

Figure 43: Gathering and Boosting Case 3 Cost Effectiveness

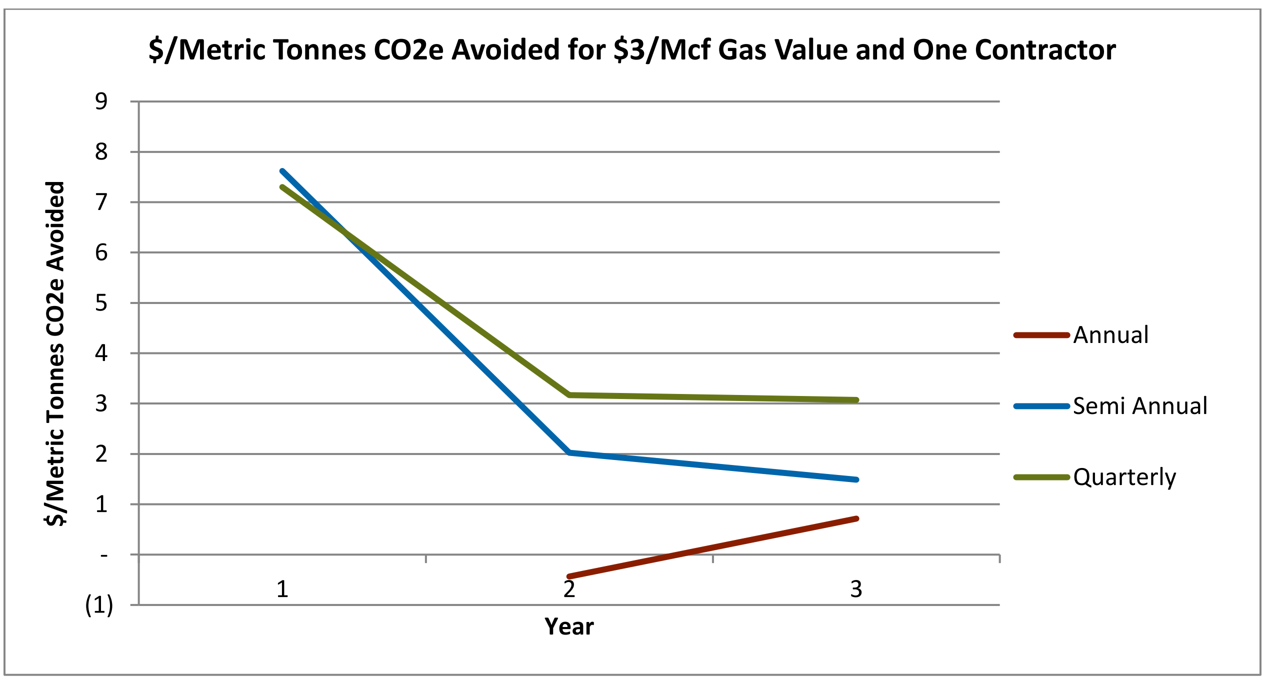

Figure 44: Gathering and Boosting Case 3 CO2e Avoided