Supplemental Information

Methane Emissions from Natural Gas Compressor Stations in the Transmission and Storage Sector: Measurements and Comparisons with the EPA Greenhouse Gas Reporting Program Protocol

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Mini-summary: Here, we describe the 45 study sites, including compressor types, operating state, facility horsepower, and other details. This is followed by a comparison of the annual GHGRP emissions reported (or the equivalent) for the study sites with the corresponding data for the Partner fleet of compressor stations. The methodological details for the onsite emissions measurements, the EPA Greenhouse Gas Reporting Protocol (GHGRP), and tracer flux are described here. Site-level onsite and tracer data presented in this manuscript are also provided.

Study Sites and Similarity of Emissions with Overall Partner Fleet

Table S1 provides a census of facilities tested in this study; individual site details are provided in Table S2, including number of compressors in each operating state, type of facility (storage or transmission), whether required to report under GHGRP (Subpart-W), type of onsite protocol employed (described in a later section), and total site horsepower. Two storage facilities were sampled in two different modes and therefore appear twice in the site-specific data tables.

Table S1: Census of facilities tested in this study. Two storage facilities were sampled in two different operating conditions (denoted in parentheses), for a total of 47 unique configurations or sites.

			Compressor Types			
Category	Number	GHGRP reporters	Reciprocating only	Centrifugal only	Both types	Sites with at least one unit operating
Transmission	37	23	12	21	4	15
Storage	8 (10)	2	7	0	1	5
Total	45 (47)	25	19	21	5	20

The representativeness of the study site emissions to the Partner fleet was evaluated by comparing the 2012 GHGRP-reported (or GHGRP-equivalent) annual emissions for the study sites with the 2012 GHGRP-reported (or GHGRP-equivalent) emissions for Partner facilities for which such data are available. 2012 GHGRP data were available for twenty nine study sites. Twenty-five of these sites were required to report under the GHGRP. Four were non-reporter facilities, at which the company performed an onsite survey but the annual facility emissions were not above the 25,000 MT-CO_2e and so were not required to be reported under GHGRP. These data were compared against 343 Partner facilities for which 2012 GHGRP data were available (Figure S1.) Although the study sites do not have as long of a tail as the entire population, a two-sample Kolmogorov-Smirnov goodness-of-fit hypothesis test indicates that two population emissions were drawn from the same underlying distribution at 95% confidence. The study onsite surveys did not capture the emissions from the two highest emitting facilities in this study, which could have provided a long tail.

Seven facilities were not included in the tracer flux-SOE comparisons presented in the main paper. At three facilities (#1, #3, #23), the tracer flux measurements were collected in a different operating mode than the onsite measurements (even though both sets of measurement were made on the same day). Unfavorable wind/road combinations prevented the collection of tracer flux data at Sites #7, #21, #33, and so these sites are excluded from the tracer flux-SOE comparison. Tracer flux data from one site (#24) had to be discarded because the ethane/methane ratio indicated a significant non-facility source of methane, as discussed in a later section. However, the onsite emissions measurements at these seven sites (#1, #3, #7, #21, #23, #24, #33) are included in the SOE-GHGRP comparison in the main paper.

Onsite and tracer flux data were collected at a 46th site (#19), but they are not included in this paper because the primary and secondary onsite techniques used by the onsite survey to measure vent emissions differed by a factor-of-seven. At this site the compressors were vented into a common manifold to the blowdown vent stack, therefore it was suspected that there was double counting of emissions.

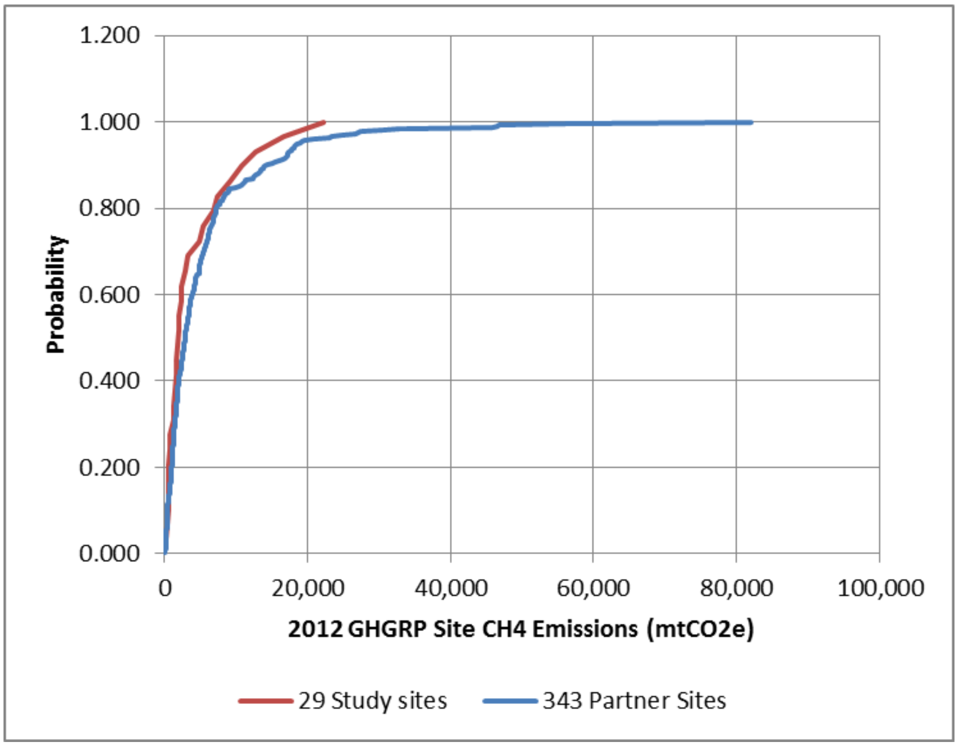

Figure S1: Comparison of total annual emissions from 29 sites tested in this study, for which 2012 GHGRP survey data are available, with the broader set of Partner sites. Both compare the data submitted by the Partners to GHGRP, or its equivalent (for non-reporter sites.)

Table S2: Summary of Site Information: Site census, operating state, total onsite horsepower, onsite measurement protocol

	Reciprocating Compressors			Centrifugal Compressors			Subpart-W Reporter?			If Storage:	
Site #	NOP[1]	NOD[2]	OP[3]	NOP[1]	NOD[2]	OP[3]		Facility Type	Onsite Protocol	Injecting/Quiescent	Total Onsite HP
1	5	2			1		No	Storage	Study Protocol	Quiescent	18670
2		8					No	Transmission	Study Protocol		8600
3					2		Yes	Transmission	Study Protocol		24000
4					9		No	Transmission	Study Protocol		21300
5					1		No	Transmission	Study Protocol		21597
6				2			Yes	Transmission	GHGRP-equivalent		37012
7						1	Yes	Transmission	GHGRP-equivalent		37950
8					1	1	No	Transmission	Study Protocol		9150
9				3			Yes	Transmission	GHGRP-equivalent		59273
10	1	1	4		1		Yes	Transmission	Study Protocol		34600
11						1	Yes	Transmission	GHGRP-equivalent		37950
12			3				Yes	Transmission	Study Protocol		14350
13				1	2		Yes	Transmission	GHGRP-equivalent		59273
14		6					No	Storage	Study Protocol	Quiescent	6126
15			4				No	Storage	Study Protocol	Injecting	4184
16.1	2						No	Storage	Study Protocol	Quiescent	8456
16.2	1		1				No	Storage	Study Protocol	Injecting	8456
17				2			Yes	Transmission	GHGRP-equivalent		27893
18		6			1		No	Transmission	Study Protocol		11095
20			2				No	Storage	Study Protocol		8400
21			8				No	Transmission	Study Protocol		7040
22						2	Yes	Transmission	Study Protocol		7660
23	2	2	3				No	Storage	Study Protocol	Injecting	19005
24			2				No	Transmission	Study Protocol		1904
25	2				3		Yes	Transmission	Study Protocol		33704
26				1			No	Transmission	GHGRP-equivalent		16000
27		6					No	Transmission	Study Protocol		6000
28	2						No	Transmission	Study Protocol		1000
29	14				1		Yes	Transmission	Study Protocol		56975
30					4	2	Yes	Transmission	Study Protocol		20180
31						3	Yes	Transmission	Study Protocol		13500
32	5	3	5				Yes	Storage	Study Protocol	Injecting	28400
33			2				No	Transmission	Study Protocol		4740
34				2			Yes	Transmission	GHGRP-equivalent		40498
35					2		Yes	Transmission	GHGRP-equivalent		32184
36					2		No	Transmission	Study Protocol		22700
37				1	2		Yes	Transmission	GHGRP-equivalent		51763
39						1	Yes	Transmission	GHGRP-equivalent		15600
40					2		Yes	Transmission	GHGRP-equivalent		37012
41		6					No	Transmission	Study Protocol		6400
42					1		No	Transmission	Study Protocol		6280
43.1	5						Yes	Transmission	Study Protocol	Quiescent	11120
43.2	4	1					Yes	Transmission	Study Protocol	Quiescent	11120
44		1	4				Yes	Transmission	Study Protocol		26060
45		3	3				Yes	Transmission	Study Protocol		31400
46	3		1				Yes	Transmission	Study Protocol		14750
47	1	2					Yes	Transmission	GHGRP-equivalent		11600
Total ->	47	47	42	12	35	11					

Note: Two sites (16 and 43) were sampled by both onsite emissions measurements and tracer flux in 2 distinct operating modes

[1]NOP = Standby (not operating) pressurized

[2]NOD = Standby (not operating) depressurized

[3]OP = Operating

Onsite emissions measurements

As described in the text, two complementary measurement approaches were used in this study: direct onsite measurement of specific fugitive and vented emissions, and downwind tracer flux measurements of site-level methane emissions. The onsite measurements (and AP-42-based estimates of exhaust methane) are added up to the site-level Study Onsite Estimate. The onsite measurements are also used to calculate a GHGRP Estimate that calculates the emissions that would be reported under the EPA GHGRP. The three emission rates and their composition are summarized in Table S3. The onsite measurement protocol is described in this section.

Table S3: Composition of the different facility-level methane emissions estimates, broken down by EPA emissions class for the Study Onsite Estimate and GHGRP Estimate which are based on onsite measurements. Onsite measurements at storage sites are determined similarly, but storage sector tank emissions are not reported under EPA GHGRP, and are not included in the GHGRP Estimate for the storage sites. Blowdowns are excluded from all three estimates.

	Facility-Wide Emission Estimation Method		
Source Type	**GHGRP**	**Study Onsite Estimate**	**Tracer Flux**
Recip Compressor Venting (§98.233 (p))			
Rod Packing/Vent	Only if OP		
Blow Down Valve/Vent	Only if OP or NOP	As Found: OP, NOP, NOD	
Unit Isolation Valve	Only if NOD		
Centrifugal Compressor Venting (§98.233 (p))			
Wet Seal Degassing Vent	Only if OP		
Blow Down Valve/Vent	Only if OP	As Found: OP, NOP, NOD	
Unit Isolation Valve	Only if NOD		
Transmission Storage Tanks (Tanks (§98.233 (k))			Quantifies Total Site-Wide Emissions at the Time of Meaurement
Transmission Tanks	DM*	DM	
Pneumatic Device Venting (§98.233 (a))			
Pneumatics	EF	DM	
Equipment Leak Detection (§98.233 (q))			
Compressor Components	EF	DM	
Non-Compressor Components	EF	DM	
Other			
Methane in Combustion Exhaust	Reported as per Subpart C	AP-42	
Emitting but Inaccessible Sources	EF	SF	
Total			

Codes:

OP	Operating Pressurized (Direct Measurement)
NOD	Standby (Not Operating) Depressurized (Direct Measurement)
NOP	Standby (Not Operating) Pressurized (Direct Measurement)
EF	EPA Prescribed Emission Factor
SF	Study Factor, Based on study average of same source type
DM	Direct Measurement
DM*	Direct Measurement if emission is detected for a duration of 5 minutes

The comprehensive onsite survey was a two-step process. First, leak detection was performed using a FLIR GasFindIR™ or other thermal gas imaging camera. Second, methane emissions were directly measured from all detected emission points that were safely accessible within each facility. Extension poles, man-lifts, and/or scaffolding were used to quantify elevated sources. Engine and turbine exhaust emissions were not measured by the onsite survey; instead they were estimated with AP-42 emission factors (see SI section 5.)

Specific emission sources included reciprocating compressor vents, centrifugal compressor seals, compressor blowdown vents, transmission storage tanks, pneumatic devices, and fugitive leak components (valves, connectors, OELs, PRVs, regulators, meters, etc.). A Bacharach Hi-Flow® sampler was the primary measurement device, for emissions within the instrument range (0.05-10.5 SCFM). For higher flows, devices used included a rotary vane anemometer, calibrated bags, or turbine meters. Table S4 summarizes the detection limits for each device used in the onsite survey. Figure S2 shows the distribution of measurement type by each site.

Table S4: Onsite measurement instrument detection limits

Instrument	Low Detection Limit	High Detection Limit
Hi-Flow™	0.05 cfm	10.5 cfm
Turbine Meter W-series	0.2 cfm	392 cfm
Turbine Meter GT-series	0.13 cfm	200 cfm
Anemometer (velocity measurement)	30 ft/min (0.15 m/s)	4000 ft/min (20 m/s)
VPAC™	0.035 cfm	Not known
Calibrated bag	Not found	240 cfm

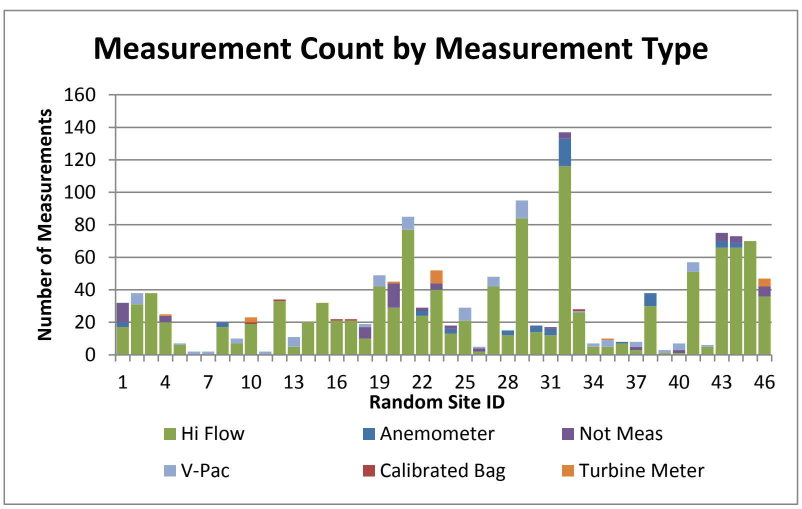

Figure S2: Measurement Count by Measurement Type, Random Site IDs

Table S5 shows the breakdown of onsite field measurements as a function of measurement method. By far the largest number of onsite emissions used the Hi-Flow™ instrument. However, the larger leaks were measured using anemometers, turbine meters, or calibrated bags.

Table S5: Count, total, and average onsite methane emissions by measurement method across 47 facilities in this study. Site 19 has been excluded for reasons explained in the text. "Estimate" refers to measurements that were detected by thermal imaging, but were below the detection limit of the Hi-Flow sampler. These were reported by the onsite team at the detection limit of the Hi-Flow sampler, and are included for completeness.

Method	Count	Total Emissions Measured Across All Sites (scfm)	Average Emissions (scfm)
Anemometer	48	558	11.6
Hi-Flow™	1154	596	0.5
Calibrated bag	5	92	18.4
Turbine meter	18	190	10.6
Rotameter	1	0.07	
VPAC™	92	60	1.6
Not measured	65		
Estimate	80	8.0	

At 13 stations (Table S2), the Partner contractor only performed a less comprehensive GHGRP-compliant survey, not the more comprehensive study onsite protocol. There are two primary differences between these two onsite measurement protocols. First, the GHGRP surveys used acoustic devices (e.g. VPAC™) to measure valve leaks. Although these devices are approved by the EPA to measure leaks across valves, they have been shown to underestimate leak rates *(1)* and therefore were excluded from the study onsite protocol. Second, the GHGRP-compliant surveys used infrared imaging for leak detection, but did not always make direct measurements of leaking components, since the GHGRP requires the use of approved emission factors for these leakers (Tables S6 and S7). In contrast, the study protocol required direct measurement of emissions from every identified leak. While the study onsite protocol required measurement of all vent emissions irrespective of the state (operating or standby), the GHGRP-compliant protocol did not report any emissions for standby/pressurized rod-packing vents since this source is excluded from the GHGRP.

The comparison between the SOE and tracer flux data indicate that the less comprehensive GHGRP survey compromised the data quality at least at Site #37, which had a leaky isolation valve (see detailed discussion in the main text.) At the other GHGRP-compliant survey sites, the impact is less clear. Excluding site #37, there was 20% discrepancy between the SOE and tracer flux of the aggregate methane emissions from the other 12 sites with GHGRP-compliant surveys (115 SCFM for aggregate SOE versus 140 SCFM for aggregate tracer flux). This bias is comparable to that associated with the use of the GHGRP emission factors discussed in the GHGRP / SOE comparison section of the main text.
Table S2 indicates that twelve of the thirteen sites with the less comprehensive GHGRP survey had

centrifugal compressors. Nine of these were centrifugal-only sites on standby, which is the majority of this class of sites (9 out of 14). However, comparisons between tracer flux and SOE for this set of sites (centrifugal standby; main text Figure 3) suggests that the trends are robust, and the use of less-comprehensive GHGRP-compliant surveys was not a significant factor at most of these lower-emitting sites (except superemitter Site #37.)

Calculation of GHGRP-equivalent estimate

The onsite measurements can be used to calculate the facility emissions that would be reported to the EPA under GHGRP. The GHGRP-equivalent estimates (not to be confused with the GHGRP-compliant onsite surveys described earlier) were derived from all the onsite data and following the procedures in 40 CFR §98 Subpart C and Subpart W, as summarized in Table S3.

For gas-driven pneumatic devices, emissions were calculated based on company-supplied device population counts (distinguished by bleed mode) and using the EPA methane emission factors listed in Table S6. For equipment leaks, emissions were calculated based on IR survey leak detection (counts of detected leaks) and the EPA methane emission factors shown in in Table S7. The data for Tables S6 and S7 are from CFR Title 40, Part 98, Subpart W, Table W-3 *(2)*. Transmission storage tank emission measurements (natural gas transmission sites only) require reporting only if the leak is detectable by the IR survey for a minimum of five minutes.

Table S6: Natural Gas Pneumatic Emission Factors *(2)*

Count	High Bleed	Low Bleed	Intermittent
# Devices	18.2 scfh/device	1.37 scfh/device	2.35 scfh/device

Table S7: Natural Gas Equipment Leak Emission Factors *(2)*

Leaker	Compressor Component	Non Compressor Component
Valve	14.84 scfh/device	6.42 scfh/device
Connector	5.59 scfh/device	5.71 scfh/device
Open-ended line	17.27 scfh/device	11.27 scfh/device
Pressure relief valve	39.66 scfh/device	2.01 scfh/device
Meter	19.33 scfh/device	2.93 scfh/device

Tracer Flux measurements: method details and uncertainty estimation

The tracer flux method used by this study is described in detail by Roscioli et al. Here we provide some additional study-specific details. The tracers were nitrous oxide (N_2O) and acetylene (C_2H_2). Nitrous oxide was typically released onsite at flow rates between 25-45 SLPM (1 atm, 298 K), while acetylene was limited to a flow rate of 15 SLPM due to safety considerations. These two tracers were chosen because they are widely-available industrial gases, and can be measured accurately at 1-Hz time resolution or faster. (The 1996 GRI/EPA study used sulfur hexafluoride, which has a GWP100 of 22,800 compared to 298 for N_2O, and hence was not used in this study.)

Key assumptions of the tracer flux method are 1) that the methane and tracers undergo equivalent dispersion; 2) that there are no unintentional sources of the tracer; and 3) that background-corrected methane concentrations are only due to emissions from the target site. These were evaluated by using two tracers; measuring upwind and downwind transects with tracer release turned off; and by comparing the plume ethane/methane ratios with Partner company-provided gas composition data. Upwind and downwind transects at the facilities, conducted when no tracers were flowing, showed no significant sources of nitrous oxide and acetylene at these sites. The ethane/methane data are discussed in the main text.

For this study, the mobile laboratory made continuous measurements of methane, ethane, and tracer concentrations at various distances downwind of the source. CMU used a dual-laser Aerodyne Quantum Cascade Tunable Infrared Laser Differential Absorption Spectroscopy (QC-TILDAS) instrument to measure ethane, nitrous oxide, and carbon monoxide at 1-Hz and a Picarro cavity ringdown spectroscopy (CRDS) instrument for methane and acetylene at 3-5 Hz. ARI used three Aerodyne TILDAS instruments for the same set of species. Minimum detection limits were: CH_4 5 ppb, C_2H_2 0.5 ppb, N_2O 0.2 ppb, C_2H_6 0.3 ppb. Sharp CO spikes indicated interference from passing vehicular traffic; these plumes were eliminated from the analysis. The sampling protocol included daily span and zero checks, with the calibration verified once each day, and a zero every fifteen minutes. All data were post-processed at a 1-Hz time resolution.

Uncertainty Estimation:

The Aerodyne (ARI) and Carnegie Mellon University (CMU) teams used two different but complementary empirical approaches to estimate the uncertainty associated with the tracer flux data. Most of the sites sampled by ARI were found in a single state (typically not operating) all through the tracer flux measurements. This meant that the methane facility-level emission rate (FLER) was stable over the measurement period and the plume-to-plume variability of the estimated emissions provides an estimate of the uncertainty of the measurements. Many of the CMU sites included operating compressors, which meant that the facility methane emissions often varied through the day. So the method precision was determined by comparing the recovery rate of the second tracer in dual tracer correlation plumes sampled by the CMU team in the field. As shown later, the method precision (uncertainty) on dual tracer correlation plumes were found to be similar for two approaches. This lends greater confidence to these empirical uncertainty estimates.

The ARI method of determining method precision consists of the following steps:

1. For all plumes of a certain type at a given facility, calculate the relative deviation (RD) from the method-specific mean emission rate for each plume as:

   $$RD_i = (FLER_i - FLER_{avg,method})/FLER_{avg,method}$$

2. Plot a histogram of the relative deviations for all plumes of a given type across all sites (Figure S3).

3. The method-specific precision is the standard deviation of the histogram.

Figure S3 illustrates the ARI data for dual correlation plumes. These are data for all the sites that were on standby (not operating.)

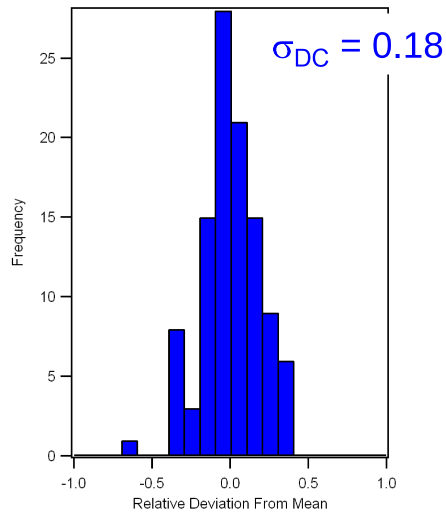

Figure S3: Distribution of relative deviation from mean for plumes measured at non-operating sites using two tracers. The standard deviation of this distribution is 18%.

For the CMU dual tracer correlation plumes, the relative error in recovery was calculated as the difference between the N_2O/C_2H_2 slope of the captured downwind plume and the onsite release ratio for all recovered plumes. A cumulative distribution of the relative errors for the 167 dual-correlation plumes is shown in **Figure S4**. For 109 plumes where the two tracers were recovered to within ±50% of the onsite release ratio (the "good ratio" of 1.5), sixty-eight percent of the plumes fall within ±24%. (For all 167 dual correlation plumes, the relative error for the recovery of the two tracers is ±40%.) For dual tracer plumes, the methane FLER is calculated using the average of the FLERs based on the CH_4/N_2O and CH_4/C_2H_2 regression slopes, and thus, each dual tracer correlation result is the product of two independent measurements of the methane FLER. Therefore, the 1 SD error in the CH_4 FLER from dual tracer correlation plumes is estimated to be 17% (24%/sqrt(2)), which is essentially the same as the uncertainty for similar plumes sampled by Aerodyne.

Similar analyses to that shown in Figure S3 and S4 were performed for the three different types of plumes. The resulting uncertainties are summarized in Table S8.

Table S8: Uncertainties (1-σ) on site-level methane emission rates calculated from individual tracer flux plumes.

Plume Type	**Plumes sampled by CMU lab**	**Plumes sampled by ARI lab**
Dual tracer correlation	17%	21%
Dual tracer area	34%	34%
Single tracer correlation	34%	19%

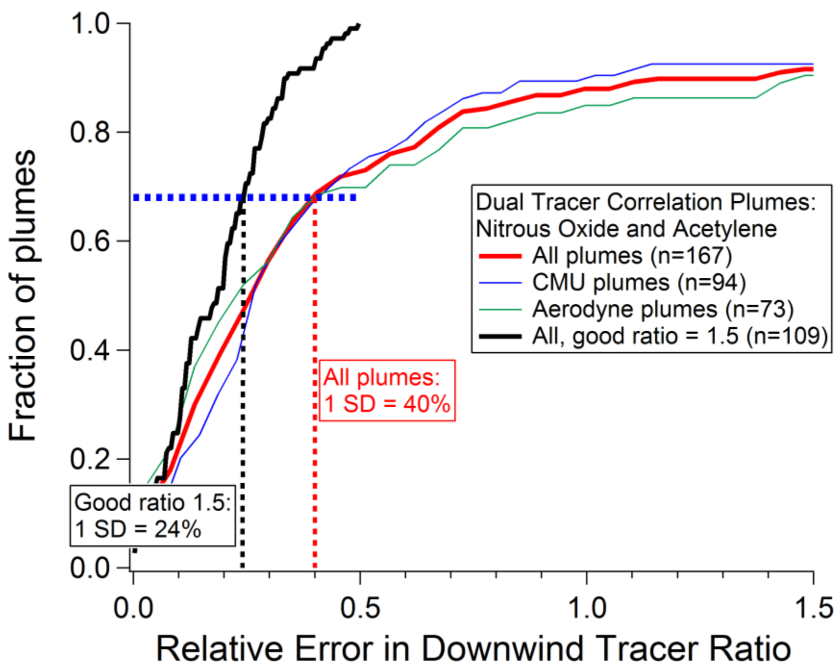

Figure S4: Cumulative distribution of the relative error in recovery of the secondary tracer for 167 dual tracer correlation plumes.

Estimation of AP42-based exhaust methane emissions

"Combustion" methane emissions refer to un-burned methane in the engine or turbine exhaust. These emissions are distinct and separate from compressor emissions such as rod packing vents in reciprocating compressors or seal vents in centrifugal compressors. These emissions were not characterized as part of the study onsite emissions measurements, but would be captured by the downwind tracer flux technique, which characterizes emissions from the entire facility. Therefore, we estimated the combustion methane emissions using US EPA AP-42 emission factors.

The EPA AP42 emissions factors differentiate different types of prime movers, including 2-stroke lean-burn, 4-stroke lean-burn, 4-stroke rich-burn, and industrial gas turbines, which have very different emissions rates for a similar fuel input due to fundamental design differences. In contrast, Subpart-C of the EPA's Greenhouse Gas Reporting Program lists one emission factor for all stationary combustion sources.

Combustion methane emissions in the Study Onsite Estimate are estimated as the product of the EPA AP42 emissions factor for the appropriate prime mover type (2-stroke lean-burn, 4-stroke lean-burn, 4-stroke rich-burn, and industrial gas turbines) and fuel flow rate. Fuel consumption data were not available so it was estimated based on the full rated horsepower of the unit divided by a representative thermal efficiency to determine heat input. Representative thermal efficiencies were obtained from a survey of manufacturer data for each prime mover type. The assumption that the units were operating at full rated load based results in an upper bound estimate (assuming the AP42 emission factors are accurate). This calculation was performed for each operating unit and then results were combined with the other data to determine the study onsite estimate for each site.

AP42 emission factors represent emissions from uncontrolled combustion sources, meaning that they do not account for exhaust after-treatment such as catalysts. This was true for 17 of the 22 study sites with operating engines. However, five sites had catalysts on one or more engines, including three sites with oxidation catalysts, and one with a non-selective catalytic reduction (NSCR) catalyst. Only one of these sites (#10) had dual-paired tracer flux and study onsite emissions measurements with the facility in the same operating state, and with significant exhaust emissions (75 SCFM from 4 2-cycle lean-burn engines, of which three have oxidation catalysts) based on AP42. However, oxidation catalysts are used largely for the removal of CO in lean-burn engines, and are expected to have little effect on methane emissions at the low exhaust temperatures found in lean burn engines. Methane conversion in Platinum and Platinum/Palladium based oxidation catalysts has been shown to decrease substantially in the first 10 hours of use in a natural gas fueled engine.*(3)* Palladium based oxidation catalysts tend to exhibit better initial methane conversion than platinum based catalysts, but lose activity towards methane rapidly in the presence of water vapor, H_2S, and SO_2. *(4)*

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Data Tables

Table S9 shows the site-level summary measurements for the onsite and downwind tracer flux measurements. The Study Onsite Estimate consists of direct onsite measurements and AP-42-based exhaust emission estimates. The GHGRP Estimate is the sum of emissions reported as per Subpart W (fugitive and vented emissions) and Subpart C (exhaust emissions.) Tables S10 and S11 show the detailed calculation of the Study Onsite Estimate (less AP-42) and the GHGRP Estimate based on the onsite measurements, study factors (when detected leaks could not be measured because they were not safely accessible), and for the GHGRP Estimate, EPA emission factors from Tables S6 and S7 for pneumatic devices and component leakers.

Table S9: Site-level methane emissions data: Study Onsite Estimate (SOE), GHGRP-equivalent estimate, and Tracer Flux.

Site #	Subpart-W (SCFM)	Subpart-C (SCFM)	GHGRP Estimate (SCFM)	Study Onsite Estimate (No AP42) (SCFM)	AP-42-based exhaust emissions (SCFM)	Study Onsite Estimate (SCFM)	Tracer Flux (SCFM)	Tracer Flux Uncertainty (1 standard error) (SCFM)	Tracer Flux Relative Standard Error	Total number of valid plumes	TF/ onsite in same mode? (1=yes)
1	53.10	0.00	53.10	85.75	0.00	85.75	100.01	9.13	9%	4	0
2	9.89	0.00	9.89	10.63	0.00	10.63	56.63	2.57	5%	10	1
3	16.31	0.00	16.31	15.98	0.00	15.98	14.20	12.18	86%	2	0
4	15.20	0.00	15.20	20.98	0.00	20.98	15.84	1.40	9%	16	1
5	1.04	0.00	1.04	0.72	0.00	0.72	2.44	0.15	6%	2	1
6	0.00	0.00	0.00	0.00	0.00	0.00	3.00	0.38	13%	6	1
7	2.55	0.25	2.80	2.55	0.97	3.52					0
8	18.16	0.04	18.20	25.63	0.14	25.77	71.62	4.94	7%	5	1
9	0.50	0.00	0.50	1.62	0.00	1.62	16.30	2.77	17%	5	1
10	63.22	0.12	63.34	106.47	59.63	166.10	114.58	13.36	12%	6	1
11	0.02	0.25	0.27	0.02	0.97	0.99	4.84	1.43	30%	2	1
12	18.97	0.05	19.02	48.44	35.32	83.76	74.60	2.35	3%	16	1
13	0.48	0.00	0.48	1.07	0.00	1.07	1.70	0.53	31%	2	1
14	3.87	0.00	3.87	3.98	0.00	3.98	318.12	156.39	49%	19	1
15	40.47	0.03	40.50	40.52	14.56	55.08	61.56	22.78	37%	7	1

Site #	Subpart-W (SCFM)	Subpart-C (SCFM)	GHGRP Estimate (SCFM)	Study Onsite Estimate (No AP42) (SCFM)	AP-42-based exhaust emissions (SCFM)	Study Onsite Estimate (SCFM)	Tracer Flux (SCFM)	Tracer Flux Uncertainty (1 standard error) (SCFM)	Tracer Flux Relative Standard Error	Total number of valid plumes	TF/ onsite in same mode? (1=yes)
16.1	3.19	0.00	3.19	38.44	0.00	38.44	35.03	2.64	8%	19	1
16.2	4.63	0.02	4.65	39.32	13.76	53.09	48.78	8.21	17%	8	1
17	1.45	0.00	1.45	3.97	0.00	3.97	13.57	0.26	2%	6	1
18	9.98	0.00	9.98	8.29	0.00	8.29	8.72	1.30	15%	7	1
20	22.81	0.05	22.86	37.45	32.30	69.75	95.68	5.22	5%	6	1
21	14.53	0.05	14.58	8.44	5.22	13.66					0
22	83.11	0.07	83.18	83.56	0.27	83.83	8.61	0.89	10%	4	1
23	35.64	0.02	35.66	54.31	14.35	68.66	53.23	3.61	7%	8	0
24	18.48	0.01	18.49	23.04	6.69	29.73					0
25	12.26	0.00	12.26	10.87	0.00	10.87	45.61	3.70	8%	3	1
26	0.59	0.00	0.59	1.18	0.00	1.18	2.03	0.22	11%	5	1
27	6.94	0.00	6.94	10.58	0.00	10.58	23.03	3.87	17%	3	1
28	4.91	0.00	4.91	15.39	0.00	15.39	2.88	0.14	5%	14	1
29	24.59	0.00	24.59	55.65	0.00	55.65	61.78	3.92	6%	9	1
30	67.74	0.02	67.76	68.66	0.07	68.73	54.79	7.28	13%	4	1
31	116.84	0.10	116.95	117.63	0.40	118.04	75.34	1.88	2%	3	1
32	95.61	0.07	95.68	129.89	45.69	175.58	121.62	12.77	10%	14	1
33	63.27	0.03	63.30	61.82	16.59	78.41					0
34	0.70	0.00	0.70	1.01	0.00	1.01	9.58	0.16	2%	15	1
35	36.15	0.00	36.15	39.28	0.00	39.28	16.88	2.69	16%	3	1
36	14.80	0.00	14.80	14.79	0.00	14.79	1.66	0.21	13%	6	1
37	14.18	0.00	14.18	14.61	0.00	14.61	875.93	119.35	14%	9	1
39	0.07	0.21	0.28	0.11	0.81	0.93	3.76	1.17	31%	1	1
40	50.33	0.00	50.33	50.41	0.00	50.41	26.84	3.71	14%	10	1
41	7.61	0.00	7.61	6.22	0.00	6.22	13.58	1.31	10%	10	1
42	9.14	0.00	9.14	7.83	0.00	7.83	6.70	0.46	7%	14	1

Site #	Subpart-W (SCFM)	Subpart-C (SCFM)	GHGRP Estimate (SCFM)	Study Onsite Estimate (No AP42) (SCFM)	AP-42-based exhaust emissions (SCFM)	Study Onsite Estimate (SCFM)	Tracer Flux (SCFM)	Tracer Flux Uncertainty (1 standard error) (SCFM)	Tracer Flux Relative Standard Error	Total number of valid plumes	TF/ onsite in same mode? (1=yes)
43.1	28.70	0.00	28.70	91.17	0.00	91.17	59.77	5.46	9%	18	1
43.2	26.72	0.00	26.72	63.44	0.00	63.44	74.87	8.14	11%	9	1
44	98.24	0.11	98.35	104.17	73.44	177.61	126.48	16.80	13%	9	1
45	7.75	0.16	7.90	79.62	102.65	182.27	145.84	12.45	9%	11	1
46	21.49	0.05	21.54	36.73	30.60	67.33	78.20	7.77	10%	7	1
47	0.27	0.00	0.27	0.00	0.00	0.00	41.04	4.66	11%	7	1

Table S10: Onsite Emissions Data at Each Compressor Facility used to calculate Study Onsite Estimate (excluding exhaust methane emissions)

		Reciprocating Rod Packing				Centrigugal/ Wet Seal				Reciprocating Unit Blowdown Valve/Vent				Centrifugal Unit Blowdown Valve/Vent				Reciprocating Isolation Valve		Centrifugal Isolation Valve		Storage Tanks	
		Operating		Standby Pressurized		Operating		Standby Pressurized		Operating		Standby Pressurized		Operating		Standby Pressurized		Standby Depressured		Standby Depressured			
Site #	Sector	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)
1	Storage			5	Study Factor							5	28.0					2	5.6	1	13.8		
2	Transmission																	8	2.8				
3	Transmission																			2	0.0	2	11.9
4	Transmission																			9	12.9		
5	Transmission																			1	0.0	1	0.0
6	Transmission															2	0.00						
7	Transmission													1	2.6								
8	Transmission					1	0.9							1	7.7					1	7.7	1	0.0
9	Transmission															3	0.02						
10	Transmission	4	8.3	1	1.4					4	51.3	1	0.0					1	0.0	1	2.0		
11	Transmission													1	0.0								
12	Transmission	3	14.8																				
13	Transmission															1	0.01			2	0.0		
14	Storage																	6	0.0				
15	Storage	4	10.9							4	23.3												
16.1	Storage			2	27.2					2	0.0												
16.2	Storage	1	1.4	1	26.6					1	0.0	1	0.0										
17	Transmission															2	0.00						
18	Transmission																	6	0.0	1	0.0		
20	Storage	2	Study Factor							2	Study Factor												
21	Transmission	8	0.7							8	0.0												
22	Transmission					2	79.8							2	0.0							1	0.7
23	Storage	3	6.3	2	11.5					3	16.4	2	8.6					2	1.8				
24	Transmission	2	16.3																			1	0.2
25	Transmission			2	4.2							2	0.1							3	0.9	1	4.3
26	Transmission															1	0.00						
27	Transmission																	6	0.0				
28	Transmission			2	11.5							2	3.3										
29	Transmission			14	33.3							14	2.6							1	0.0	3	3.8
30	Transmission					2	63.3							2	0.0					4	2.2		
31	Transmission					3	66.8							3	48.6								
32	Storage	5	27.5	5	18.2					5	7.7	5	28.4					3	3.1			3	7.2
33	Transmission	2	57.0							2	1.9												
34	Transmission															2	0.02						
35	Transmission																			2	36.0		
36	Transmission																			2	14.2		
37	Transmission															1	0.00			2	6.0		
39	Transmission													1	0.1								
40	Transmission																			2	42.8		
41	Transmission																	6	0.0				
42	Transmission																			1	0.0	1	7.5
43.1	Storage			5	60.2							5	Study Factor									1	2.9
43.2	Storage			4	34.4							4	Study Factor					1	0.0			1	2.9
44	Transmission	4	14.2							4	75.7							1	0.3				
45	Transmission	3	0.1															3	0.0				
46	Transmission	1	6.5	3	18.7					1	0.0	3	0.0										
47	Transmission											1	0.0					2	0.0				
Study Total		40	164.0	41	247.2	8	210.8	0	0	34	176.3	36	71.1	11	58.9	12	0.05	47	13.5	35	138.4	16	41.4
Study Factor			4.1		6.0		26.4				5.2		2.0		5.4		0.00		0.3		3.7		2.6

Table S10 (continued): Onsite Emissions Data at Each Compressor Facility used to calculate SOE (excluding exhaust methane emissions)

		Pneumatic		Compressor Components										Non-compressor components											
				Connector		Valves		Open Ended Lines		Pressure Relief Valves		Meter		Connector		Valves		Open Ended Lines		Pressure Relief Valves		Meter		Inaccessible Leaks	
Site #	Sector	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Estimated Total Emissions (SCFM)
1	Storage			9	1.9	7	0.3	3	Study Factor	1	Study Factor													12	36.1
2	Transmission	5	1.7			11	3.4							4	0.5	9	2.3	1	0.0	1	0.0				
3	Transmission													27	2.9	4	0.8	1	0.4						
4	Transmission	4	0.7											6	4.7	9	1.0	3	1.0					3	0.8
5	Transmission													1	0.0	5	0.7								
6	Transmission																								
7	Transmission																								
8	Transmission			1	0.0									13	5.3	2	0.4	3	3.6						
9	Transmission													3	0.1	2	0.6								
10	Transmission	2	1.6	4	30.9	2	0.5	1	6.8					3	0.2	2	0.3	2	3.1						
11	Transmission																								
12	Transmission			14	4.8			3	27.8					11	0.4			2	0.5						
13	Transmission													5	1.1			1	0.0						
14	Storage			8	2.2	1	0.0	10	1.0									1	Study Factor					1	0.5
15	Storage			14	2.0			10	4.4																
16.1	Storage			13	1.0	1	0.0	6	10.2																
16.2	Storage			13	1.0	1	0.0	6	10.2																
17	Transmission													2	0.3	6	2.2	1	Study Factor					5	1.2
18	Transmission	8	2.2	9	0.4	12	0.1							14	1.0	11	1.4	2	3.0	1	0.0				
20	Storage			13	1.3	6	10.5	3	2.0															8	19.5
21	Transmission	13	2.3	28	1.1	11	1.1							5	0.5	9	2.4								
22	Transmission			2	0.0									12	2.1	3	0.3	5	0.5						
23	Storage	23	6.0	7	1.2	3	0.3	4	2.2																
24	Transmission					1	0.0	2	5.7					6	0.3	1	0.0							2	0.4
25	Transmission					15	0.5	1	0.1					6	0.1	4	0.1	1	0.0	1	0.1			1	0.5
26	Transmission															2	0.2	2	Study Factor					2	0.9
27	Transmission	5	1.1	2	0.4	5	0.1							17	1.8	13	6.8	1	0.3	1	0.0				
28	Transmission					2	0.0							5	0.3	4	0.2	1	0.0						
29	Transmission			26	0.5	28	10.5			2	0.2			9	0.3	16	2.1	1	0.1	3	2.2				
30	Transmission			4	0.5	5	1.8							4	0.6	2	0.3								
31	Transmission			2	0.4									8	1.5	2	0.1							1	0.2
32	Storage	36	16.1	30	2.9	30	3.8	13	2.2	3	0.2	2	0.3											10	12.3
33	Transmission	7	1.2	4	1.3	1	0.0							1	0.0	3	0.1					1	0.03		
34	Transmission															3	0.6	2	0.4					1	0.0
35	Transmission													2	3.2										
36	Transmission	2	0.2											2	0.1	2	0.3	1	0.0						
37	Transmission													1	0.3	2	0.9							2	7.5
39	Transmission																								
40	Transmission													1	0.2									2	7.5
41	Transmission	25	4.4			1	0.0							13	0.6	13	0.8	1	0.0	1	0.3				
42	Transmission	2	0.2											2	0.1	1	0.0								
43.1	Storage	2	0.1	19	4.7	32	6.1	12	10.8															5	6.4
43.2	Storage	2	0.1	19	4.7	32	6.1	12	10.8															4	4.4
44	Transmission			37	7.3			7	2.3					13	0.9			7	3.5						
45	Transmission			5	0.4	11	4.0	5	66.0					10	3.7	3	0.7	3	1.2					6	3.5
46	Transmission	6	1.4	7	0.7	34	4.8	2	2.9					13	0.9	2	0.1								
47	Transmission																								
Study Total		142	39.2	290	71.8	252	54.0	97	165.4	5	0.4	2	0.3	219	34.2	135	25.7	38	17.9	8	2.7	1	0.03	65	101.8
Study Factor			0.3		0.2		0.2		1.7		0.1		0.1		0.2		0.2		0.5		0.3		0.03		

Table S11: Data used to calculate EPA Greenhouse Gas Reporting Program (GHGRP) equivalent onsite emissions

		Reciprocating Rod Packing		Centrigugal/ Wet Seal		Reciprocating Unit Blowdown Valve/Vent				Centrifugal Unit Blowdown Valve/Vent		Reciprocating Isolation Valve		Centrifugal Isolation Valve		Storage Tanks	
		Operating		Operating		Operating		Standby Pressurized		Operating		Standby Depressurized		Standby Depressurized			
Site #	Sector	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)
1	Storage							5	33.6					1	13.8		
2	Transmission											8	2.8				
3	Transmission													2	0.0	2	11.9
4	Transmission													9	12.9		
5	Transmission															1	0.0
6	Transmission																
7	Transmission									1	2.6						
8	Transmission			1	0.9					1	7.7			1	7.7	1	0.0
9	Transmission																
10	Transmission	3	8.3			1	51.3	1	0.0					1	2.0		
11	Transmission									1	0.0						
12	Transmission	3	14.8														
13	Transmission													2	0.0		
14	Storage											6	0.0				
15	Storage	4	10.9			4	23.3										
16.1	Storage																
16.2	Storage	1	1.4														
17	Transmission																
18	Transmission											6	0.0	1	0.0		
20	Storage	2	8.2			2	10.4										
21	Transmission	8	0.7			8	0.0										
22	Transmission			2	79.8					2	0.0					1	0.7
23	Storage	3	6.3			3	16.4	1	8.6			2	1.8				
24	Transmission	2	16.3													1	0.2
25	Transmission							2	0.1					3	0.9	1	4.3
26	Transmission																
27	Transmission											6	0.0				
28	Transmission							2	3.3								
29	Transmission							14	2.6					1	0.0	3	3.8
30	Transmission			2	63.3					1	0.0			4	2.2		
31	Transmission			3	66.8					3	48.6						
32	Storage	5	27.5			3	12.9	2	28.4			3	3.1				
33	Transmission	2	57.0			2	1.9										
34	Transmission																
35	Transmission													2	36.0		
36	Transmission													2	14.2		
37	Transmission													2	13.9		
39	Transmission									1	0.1						
40	Transmission													2	50.7		
41	Transmission											6	0.0				
42	Transmission													1	0.0	1	7.5
43.1	Storage							3	5.9								
43.2	Storage							2	3.9			1	0.0				
44	Transmission	2	14.2			3	75.7					1	0.3				
45	Transmission	3	0.1									2	0.0				
46	Transmission	1	6.5														
47	Transmission							1	0.0			2	0.0				
Study Total		39	172.2	8	210.8	26	191.9	33	86.5	10	58.9	43	7.9	34	154.3	11	28.4

Table S11 (continued): Data used to calculate EPA Greenhouse Gas Reporting Program (GHGRP) equivalent onsite emissions

		Pneumatic						Compressor Components												Non-compressor components									
		High Bleed		Low Bleed		Intermittent		Connector		Valves		Open Ended Line		Pressure Relief Valve		Meter		Connector		Valves		Open Ended Line		Pressure Relief Valve		Meter	
Site #	Sector	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)	Number	Total Emissions (SCFM)
1	Storage					30	1.2	11	1.0	8	2.0	3	0.9	1	0.7												
2	Transmission	5	1.5			34	1.3			11	2.7							4	0.4	9	1.0	1	0.2	1	0.03		
3	Transmission	4	1.2	1	0.02													27	2.6	4	0.4	1	0.2				
4	Transmission																	6	0.6	9	1.0	4	0.8				
5	Transmission					10	0.4											1	0.1	5	0.5						
6	Transmission																										
7	Transmission																										
8	Transmission							1	0.1									13	1.2			3	0.6				
9	Transmission																	3	0.3	2	0.2						
10	Transmission							4	0.4	2	0.5	1	0.3					3	0.3	2	0.2						
11	Transmission																										
12	Transmission	1	0.3	3	0.07	5	0.2	14	1.3			3	0.9					11	1.0			2	0.4				
13	Transmission																	5	0.5								
14	Storage							8	0.7	1	0.2	10	2.9														
15	Storage	7	2.1					14	1.3			10	2.9														
16.1	Storage							13	1.2	1	0.2	6	1.7														
16.2	Storage							13	1.2	1	0.2	6	1.7														
17	Transmission																	2	0.2	10	1.1	1	0.2				
18	Transmission	6	1.8	3	0.07	35	1.4	9	0.8	12	3.0							14	1.3	11	1.2	2	0.4	1	0.03		
20	Storage					4	0.2	16	1.5	7	1.7	3	0.9														
21	Transmission	15	4.5	4	0.09	63	2.5	28	2.6	11	2.7							5	0.5	9	1.0						
22	Transmission							2	0.2									12	1.1	3	0.3	5	0.9				
23	Storage							7	0.7	3	0.7	4	1.2														
24	Transmission									3	0.7	2	0.6					6	0.6	1	0.1						
25	Transmission					37	1.4			15	3.7	1	0.3					6	0.6	4	0.4	2	0.4	1	0.03		
26	Transmission																			2	0.2	2	0.4				
27	Transmission	3	0.9	2	0.05	34	1.3	2	0.2	5	1.2							17	1.6	13	1.4	1	0.2	1	0.03		
28	Transmission									2	0.5							5	0.5	4	0.4	1	0.2				
29	Transmission	3	0.9	2	0.05	95	3.7	26	2.4	28	6.9			2	1.3			9	0.9	16	1.7	1	0.2	3	0.1		
30	Transmission							4	0.4	5	1.2							4	0.4	2	0.2						
31	Transmission							2	0.2	1	0.2							8	0.8	2	0.2						
32	Storage	18	5.5			42	1.6	31	2.9	30	7.4	13	3.7	3	2.0	2	0.6										
33	Transmission	7	2.1	1	0.02	29	1.1	4	0.4	1	0.2							1	0.1	3	0.3					1	0.05
34	Transmission																			3	0.3	2	0.4				
35	Transmission																	2	0.2								
36	Transmission																	2	0.2	2	0.2	1	0.2				
37	Transmission																	1	0.1	2	0.2						
39	Transmission																										
40	Transmission																	1	0.1								
41	Transmission	7	2.1	12	0.27	54	2.1			1	0.2							13	1.2	13	1.4	1	0.2	1	0.03		
42	Transmission	1	0.3	2	0.05	25	1.0											2	0.2	1	0.1						
43.1	Storage	31	9.4	2	0.05			21	2.0	32	7.9	12	3.5														
43.2	Storage	31	9.4	2	0.05			21	2.0	32	7.9	12	3.5														
44	Transmission							37	3.4			7	2.0					13	1.2			7	1.3				
45	Transmission							5	0.5	12	3.0	6	1.7					10	1.0	4	0.4	6	1.1				
46	Transmission	6	1.8	4	0.09	50	2.0	7	0.7	34	8.4	2	0.6					13	1.2	2	0.2						
47	Transmission					7	0.3		0.0																0.0		
Study Total		145	44.0	38	0.87	554	21.7	300	28.0	258	63.8	101	29.1	6	4.0	2	0.6	219	20.8	138	14.8	43	8.1	8	0.3	1	0.05