

Updates to OPGEE

OPGEE v3.0a candidate model versus OPGEE v2.0c

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California Air Resources Board
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Stanford University

Outline

- Part 1: Background and context
- Part 2: Updates to the OPGEE model
- Part 3: Comparisons of CI results between v2.0 and v3.0

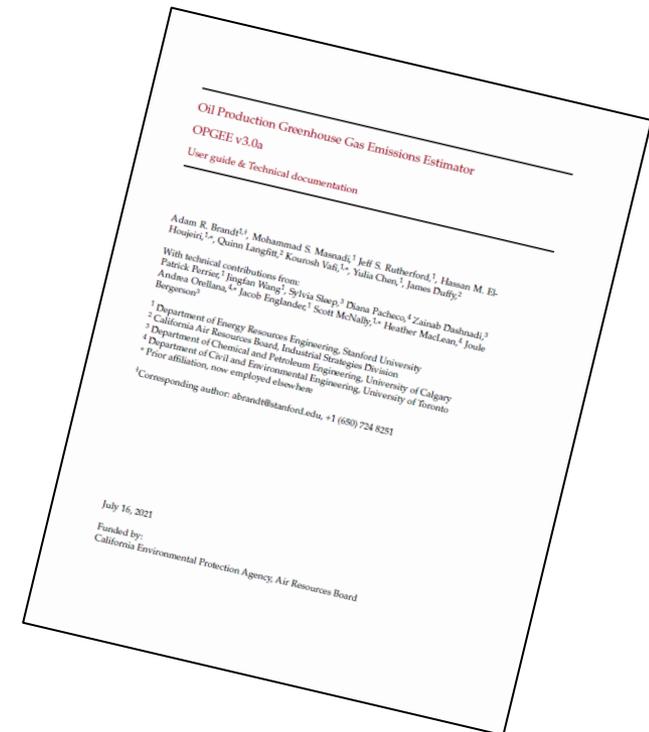
Part 1: Background and context

OPGEE model

- Model is called Oil Production Greenhouse gas Emissions **Estimator** (OPGEE)
- Estimates emissions given field parameters and technologies

The **first** open-source GHG tool for oil and gas operations

- Anyone can download, modify and use
- 36 published papers, complete documentation (~400 pp.) with all sources defined
- Funded by CARB, U.S. DOE, Carnegie Endowment, Ford Motor Co., Saudi Aramco



OPGEE model timeline

- Model development started in 2010
- First official version: OPGEE v1.0 released September 2012
- Second official version: OPGEE v2.0 released Feb 2018
- Third official version (candidate): OPGEE v3.0a - Introduced today

- Bibliography at end of slides:

Used in studies of crude oil CI for

- US (Cooney et al. 2017, Yeh et al 2017, Brandt et al. 2016)
- Canada (Cai et al. 2015, Englander et al. 2015)
- China (Masnadi et al. 2018a)
- Globe (Masnadi et al. 2018b)

Methods development

- Overall (El-Houjeri et al. 2013)
- Drilling (Vafi et al. 2016)
- Gas processing (Masnadi et al. 2020)
- Uncertainty (Vafi et al. 2014a, 2014b, Brandt et al. 2015)
- Time trends (Masnadi et al. 2018c, Tripathi et al. 2017)

Part 2: Updates to the model

Major revisions in OPGEE v3.0a

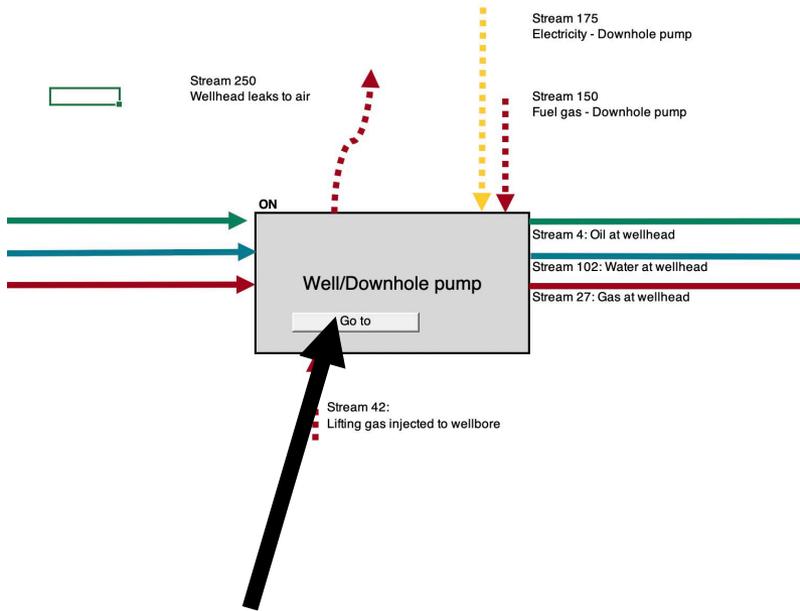
- Improved model organization and process interconnections
- Expansion of natural gas life cycle coverage and option to choose gas as the functional unit
- Improved gas processing modeling
- New methodology for venting and fugitive emissions modeling
- Updated default input values

See [slides](#) from October 2020 workshop for additional details beyond this presentation

Improvement 1: Model organization and stream tracking

- OPGEE v2.0 mostly lacked stream tracking and interconnected processes
 - Gas species tracked, but other streams were not reliably tracked
 - Process units were not on individual sheets, and unclear exactly which mass flows were entering and leaving each sheet
- OPGEE v3.0a includes a completely reworked model “skeleton”
 - All streams of oil, water, gas, etc. are tracked in mass flows
 - Conservation of mass ensured at process unit and total model level
 - Pressures, temperatures, and other properties tracked
 - Navigation aided by graphical view of process connections (PFD)

Graphical navigation



Trace flows along processing paths and click to navigate to sheets

Active field flow sheet				Field: Generic		
		Index code ↓		Stream number →		
number:		UM	1	1	2	3
5	Stream description:	STREAM_NAME	2	Crude oil in reservoir	Bitumen in mine	Crude oil at well bottom
6	Phase	Component	3	Unit	Value	Value
7	Solid	Petroleum co	M_PC	4	tonne/d	--
8	Liquid	Crude oil	M_O	5	tonne/d	204.2
	Liquid	Liquified petr	M_LPG	6	tonne/d	--
10	Liquid	Water	M_W	7	tonne/d	28.6
11	Liquid	Total liquids	M_TOTLIQ	8	tonne/d	232.8
12	Gas	N ₂	M_N2	9	tonne/d	--
13	Gas	O ₂	M_O2	10	tonne/d	--
14	Gas	CO ₂	M_CO2	11	tonne/d	--
15	Gas	H ₂ O	M_H2O	12	tonne/d	--
16	Gas	CH ₄	M_C1	13	tonne/d	--
17	Gas	C ₂ H ₆	M_C2	14	tonne/d	--
18	Gas	C ₃ H ₈	M_C3	15	tonne/d	--
19	Gas	C ₄ H ₁₀	M_C4	16	tonne/d	--
20	Gas	CO	M_CO	17	tonne/d	--
21	Gas	H ₂	M_H2	18	tonne/d	--
22	Gas	H ₂ S	M_H2S	19	tonne/d	--
23	Gas	SO ₂	M_SO2	20	tonne/d	--
24	Gas	Total gas	M_TOTGAS	21	tonne/d	--
25	Electricity	Total Elec.	E_EL	22	MWh/d	--
26	Phase	Property	23	Unit	Value	Value
27	All	Temp	T	24	°F	150.0
28	All	Temp (abs)	T_ABS	25	°R	609.7
29	All	Pressure (abs)	P	26	psia	1556.6
30	All	Contains oil	OIL_01	27	[0-1]	1
31	Liquid	Crude oil API	API_O	28	°API	30.0
32	Liquid	Crude oil spe	GAMMA_O	29	-	0.876
33	Liquid	Solution gas	GOR_OS	30	scf/bbl	297.4
34	Liquid	Saturated oil	FVF_SAT	31	bb/STB	1.170
35	Liquid	Petroleum isd	ISO_X	32	-	--
36	Liquid	Petroleum isd	ISO_CO	33	-	--
37	Liquid	Petroleum FV	FVF_UNSAT	34	bb/STB	--
38	Liquid	Petroleum vol	OVF	35	m3/std-m3	--
39	Liquid	Petroleum de	RHO_O_LB	36	lb/ft3	49.146
40	Liquid	Petroleum de	RHO_O	37	tonne/m3	0.787
41	Liquid	Petroleum flo	Q_O_bbl	38	bb/d	1632
42	Liquid	Petroleum flo	Q_O	39	m3/d	259
43	Liquid	Energy densi	LHV_O_btu	40	Btu/lb	18181
44	Liquid	Energy densi	LHV_O	41	MJ/kg	42.3
45	Liquid	Energy densi	LHV_O_bbl	42	mmBtu/bbl	5.0
46	Liquid	Energy flow r	E_LHV_O_bt	43	mmBtu/d	8184
47	Liquid	Energy flow r	E_LHV_O	44	GJ/d	8635
48	Gas	Total molar fl	TOTMOL_GAS	45	mol/d	--

Mass flows

Properties

Flows and properties into and out of each process unit tracked

Gas as a primary product, different assessment points

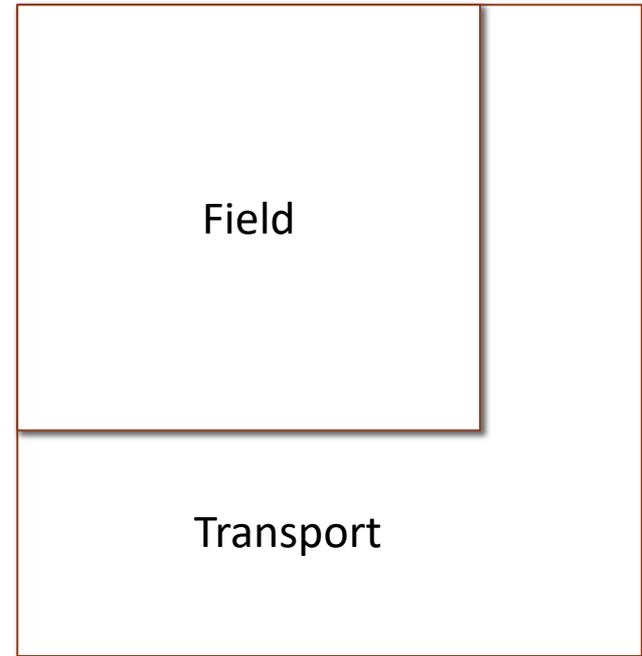
OPGEE 2.0

Always required oil to be the primary product

OPGEE 3.0

Allows for selection of oil or gas as the primary product

Expanded coverage of the gas system, including midstream and downstream processes



Oil at field boundary or refinery inlet

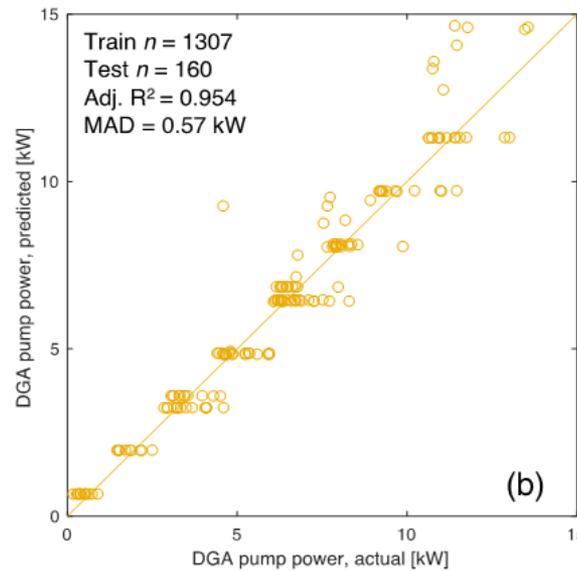
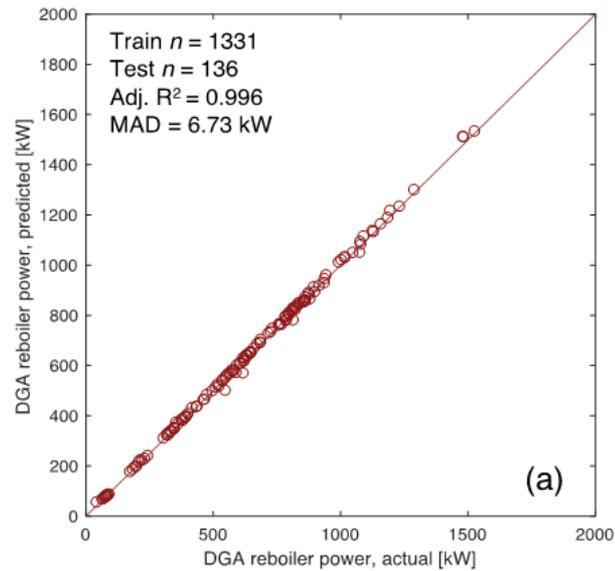
Gas at field boundary,
transportation inlet or consumer

Improvement 2: Gas processing simulation

- OPGEE v2.0 relied on "textbook" treatment of gas processing units
 - Simple models of energy use and power needs per unit of throughput
 - No way to customize process unit energy use for particular conditions
- OPGEE v3.0a includes "proxy" models generated from process simulation tools
 - Used Aspen HYSYS process simulation package
 - Simulated three key gas processing units
 - Acid Gas Removal, Dehydration, Demethanizer
 - Simulated many cases at a variety of conditions
 - Generated statistical representations to predict Aspen HYSYS results

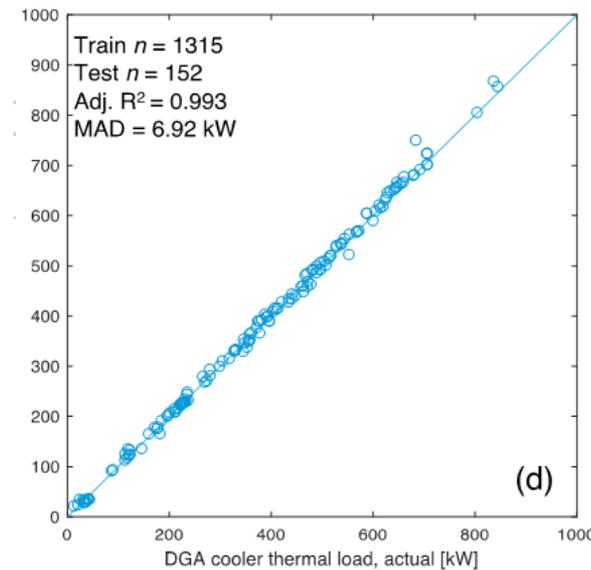
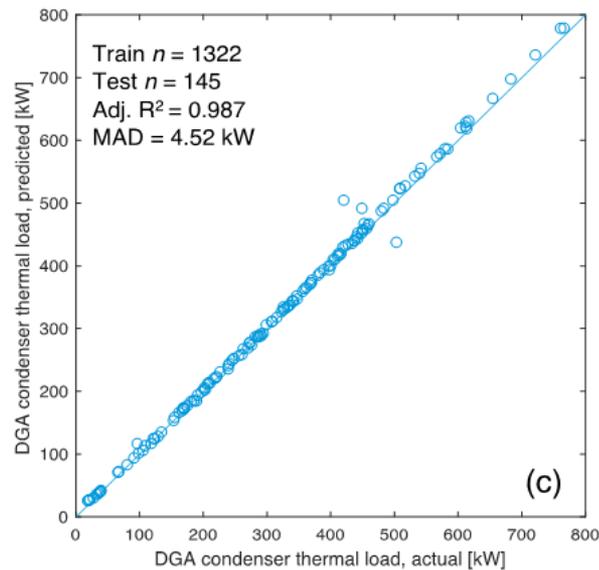
M.S. Masnadi *, P.R. Perrier , J. Wang , J. Rutherford , A.R. Brandt.
Statistical proxy modeling for life cycle assessment and energetic analysis.
Energy. DOI: 10.1016/j.energy.2019.116882

Example: Acid Gas Removal proxy model vs. AspenHYSYS output on held-out testing data



Reboiler

Pump



Condenser

Cooler

Take-aways from process simulation

- Quadratic regression able to replicate Aspen HYSYS results extremely well
- Most fits have $R^2 > 0.95$
- OPGEE now produces, for cases within our sampled input ranges, results very close to Aspen HYSYS

Improvement 3: Fugitive and vented CH₄ emissions

- OPGEE v2.0 relied on CARB survey data for fugitive and vented CH₄
 - Survey of California producers with detailed reporting on emissions
 - Emissions factors obtained from EPA GHG Inventory
 - Independent measurements lacking, with many studies done since OPGEE v2.0
- OPGEE v3.0a uses large set of measured field data for CH₄ emissions
 - Two models: “component” level as the recommended method and “site” level as a validation
 - Component data draws on multiple studies, 1000s of measured leaks
 - Recreates observed US-wide emissions (e.g., Alvarez et al. 2018)

J.S. Rutherford, E.D. Sherwin, A.P. Ravikumar, G.A. Heath, J.G. Englander, D. Cooley, D. Lyon, M. Omara, Q. Langfitt, A.R. Brandt **Closing the methane gap in US oil and natural gas production emissions inventories.** *Nature Communications*.

DOI: 10.1038/s41467-021-25017-4

Different types of methane measurement inform our understanding of emissions quantities and sources

Bottom-up

Component-level Site-level



e.g., EPA Greenhouse Gas Inventory *e.g., Alvarez et al. 2018, National estimate*

Top-down



e.g., Zhang et al. 2020, Permian Basin

Policy and programs

OPGEE “component” recommended method

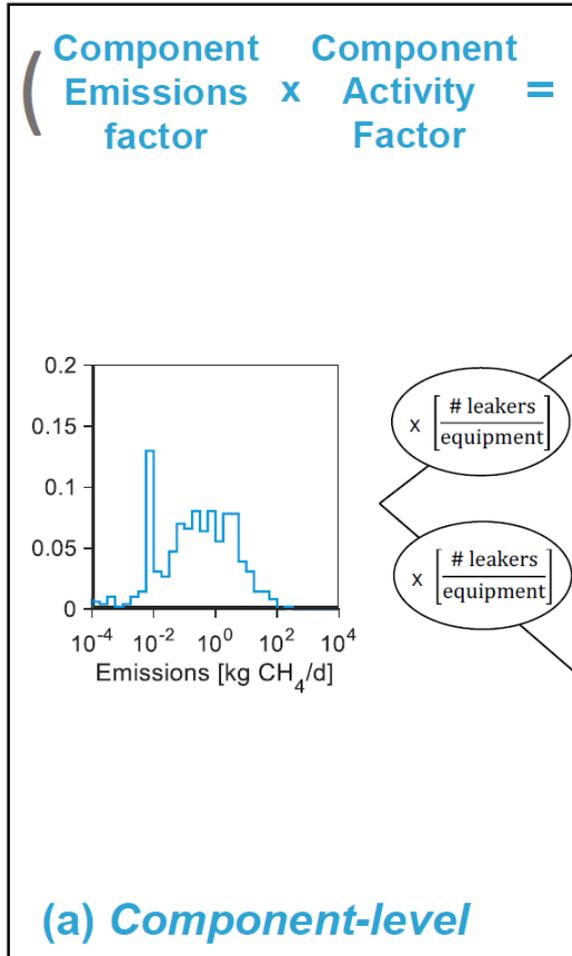
Validation and assessment

OPGEE “site” validation method

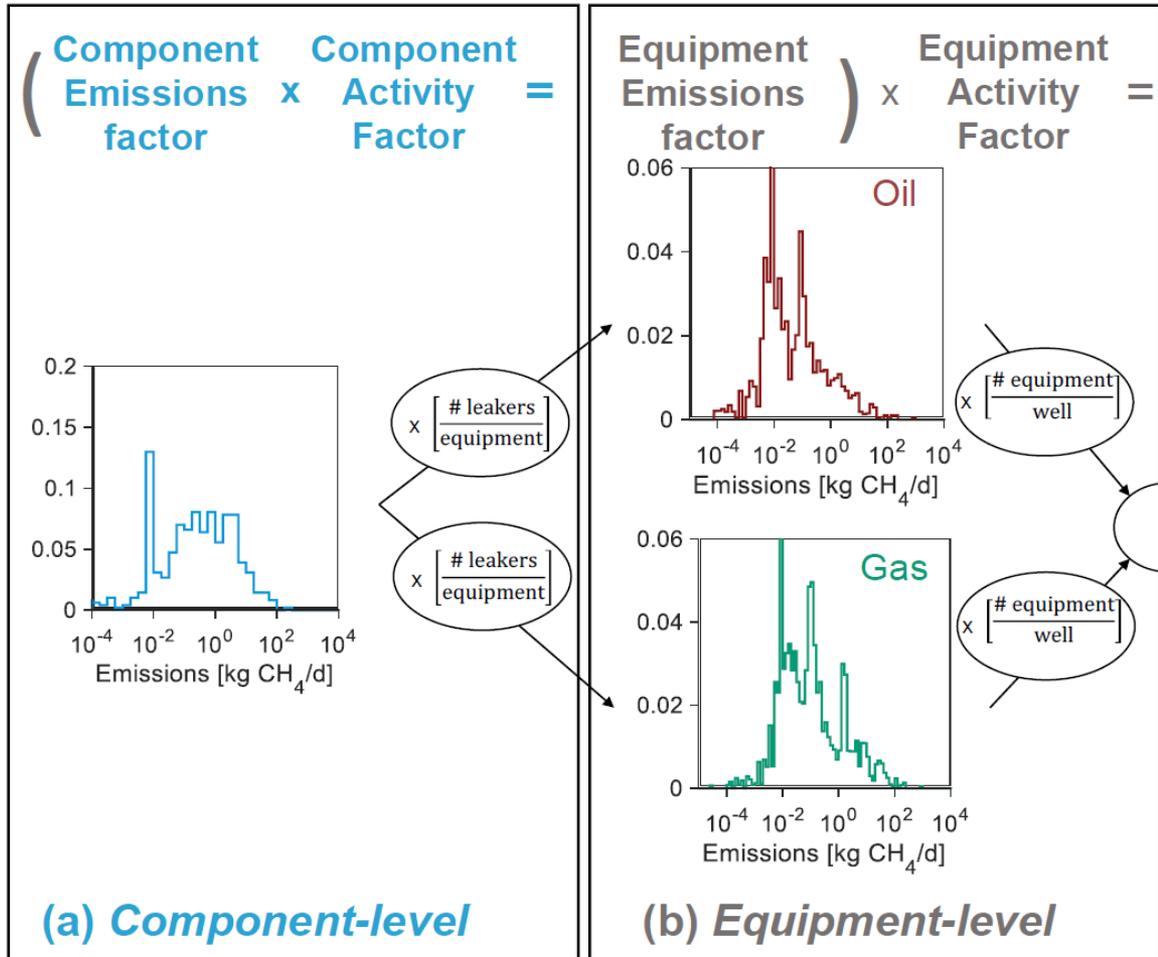
Collecting component-level data from various studies

- Comprehensive literature search of component-level surveys (6 studies, ~3200 measurements)
 - Filtered to include US studies only
 - Limited global coverage
 - Future model versions could include emissions distributions from other regions
- Data consolidated to consistent component and equipment type categories

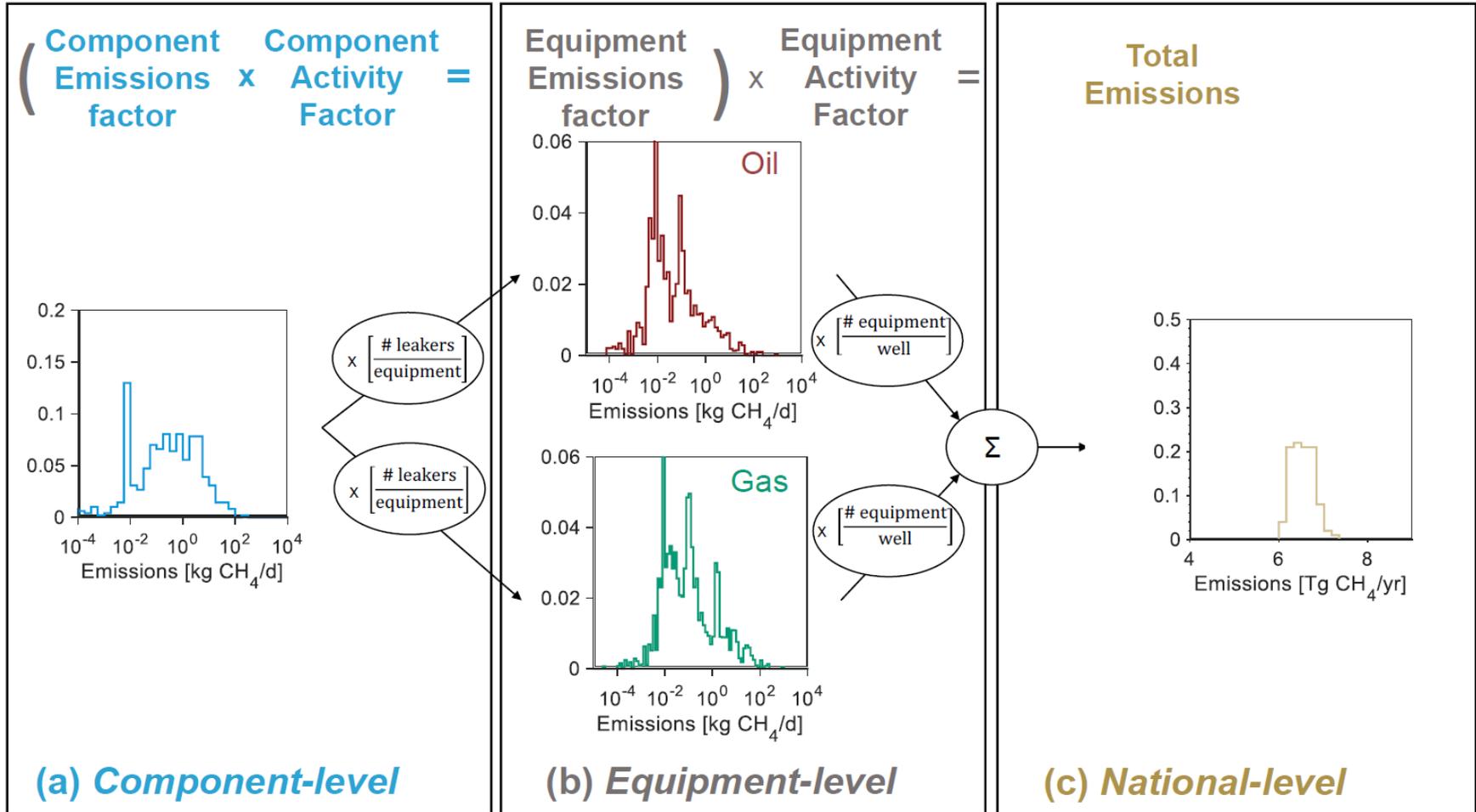
Development of a bottom-up tool



Development of a bottom-up tool



Development of a bottom-up tool



Using equipment distributions in OPGEE

- Gas productivity tranches were observed as driver of fractional loss rate
 - A stochastic leak process will tend to cause higher loss fraction in less productive wells
- A separate equipment-level loss fraction distribution was generated for each gas productivity tranche
- Loaded those average loss rates into OPGEE to apply to modeled fields based on gas production per well
 - For further details, see documentation section 8.2.2.1 on “Design of the reduced order tool”

Validating the method

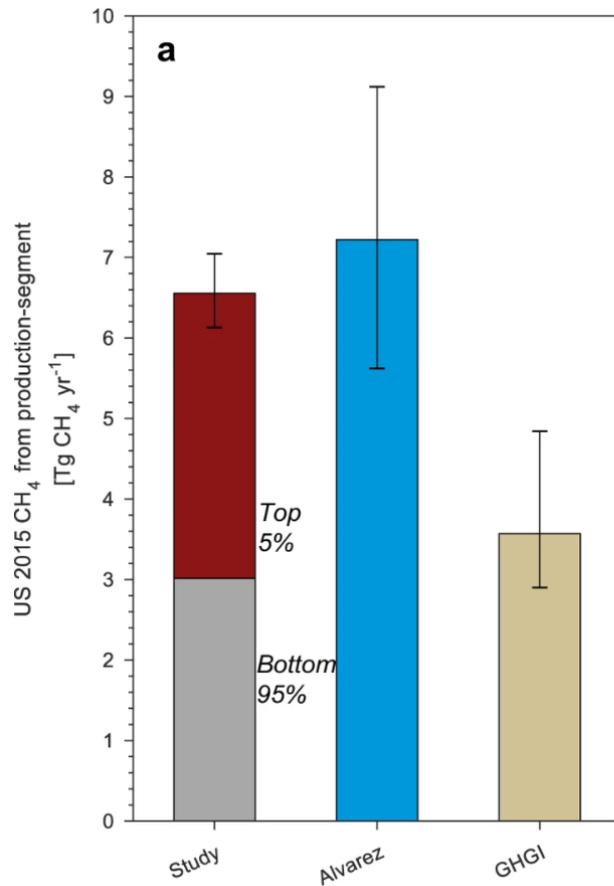
Ideally the method adopted in OPGEE would recreate the key results of literature on methane emissions from the last 5 years

Key empirical features that have been found repeatedly:

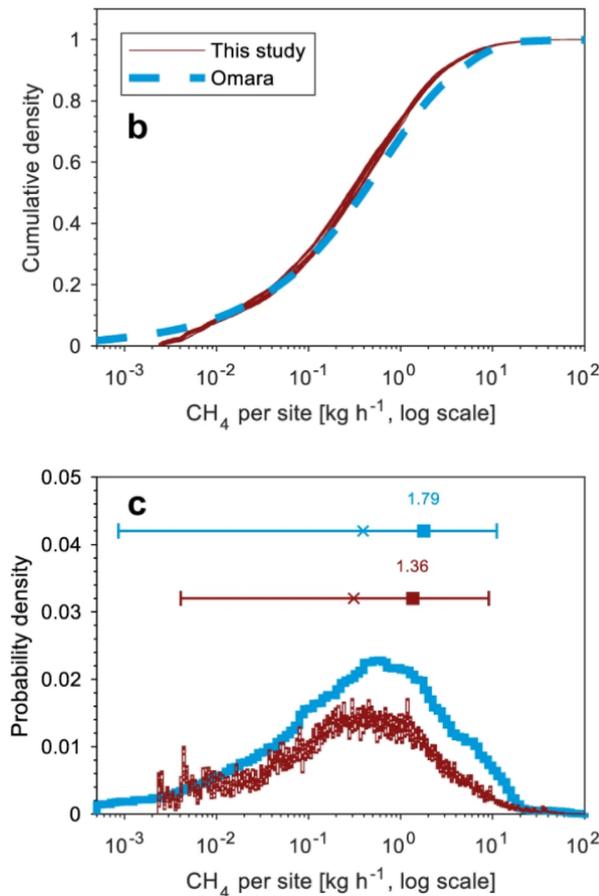
1. Larger emissions than classical EPA Greenhouse Gas Inventory methods
2. Strong dependence of loss fraction on site gas productivity
3. Strong “heavy-tailed” behavior of emissions distributions: dependence on large emitters to drive large fraction of emissions

Validating against US estimate of production-segment emissions

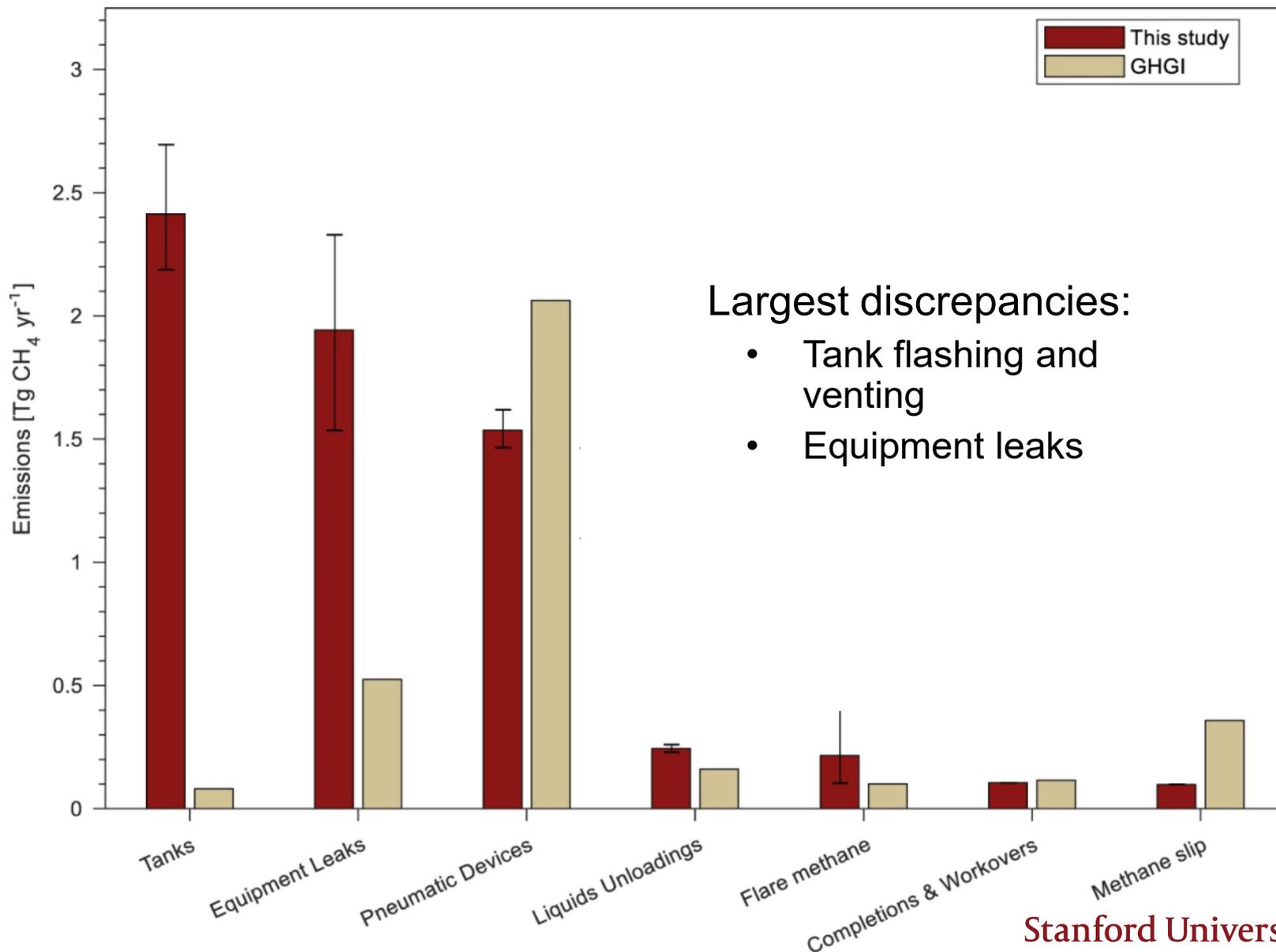
Total emissions similar to Alvarez et al. 2018 and higher than EPA GHGI



Distribution similar to Omara et al. 2018, which has the features from previous slide



Drivers of differences between this study and GHGI

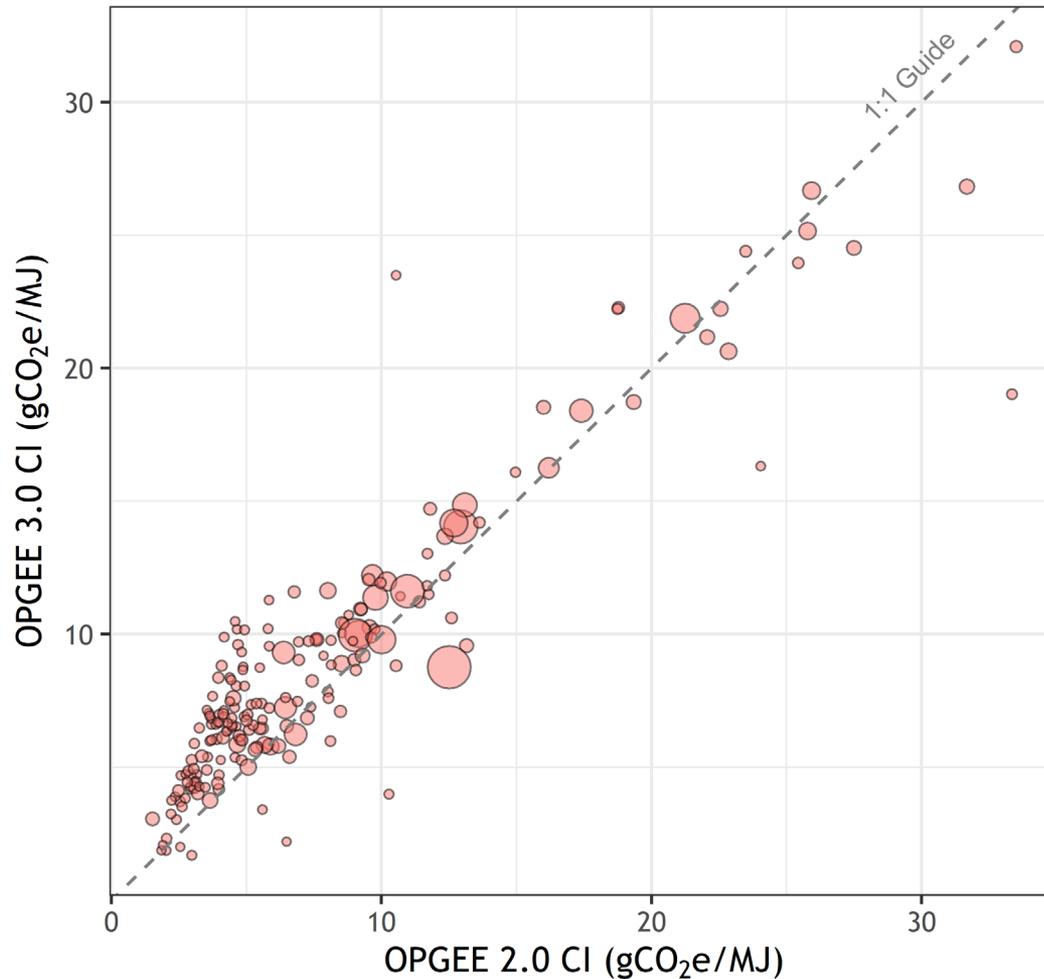


Part 3: Comparisons of CI results between v2.0c and v3.0a

Comparison of CI Values between OPGEE 2.0c and 3.0a

- 2010 LCFS baseline fields used to compare carbon intensity (CI) values between versions 2.0c and 3.0a
 - These fields represent real-world data and a range of field types
- Key definitions
 - CI: Carbon intensity
 - VF: Venting and Fugitives
 - VFF: Venting, Fugitives, and Flaring
 - Non-VFF: Combustion, land use, credit/debit, and small sources (all except venting, fugitives, and flaring)
 - GOR: Gas-to-oil ratio
 - gCO₂e/MJ: Units of carbon intensity (grams of carbon dioxide equivalent per megajoule of exported energy)

Results: Comparing v2.0c to v3.0a



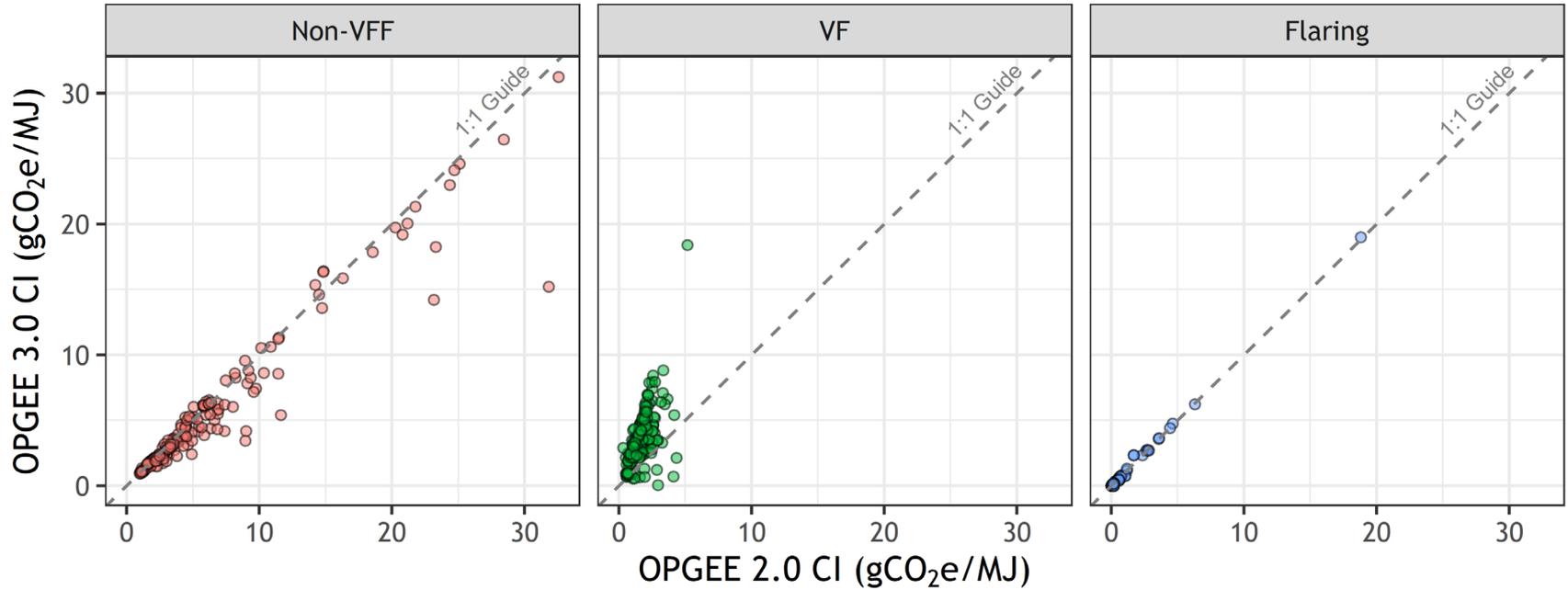
Dashed line = 1:1:
agreement

Dot size = LCFS baseline
volume

Similar CI for many fields
between v2.0 and v3.0, with
some clear differences
based on model changes

LCFS Volume (MMbbl/yr) ● 20 ● 40 ● 60 ● 80

Different effects in different parts of the model

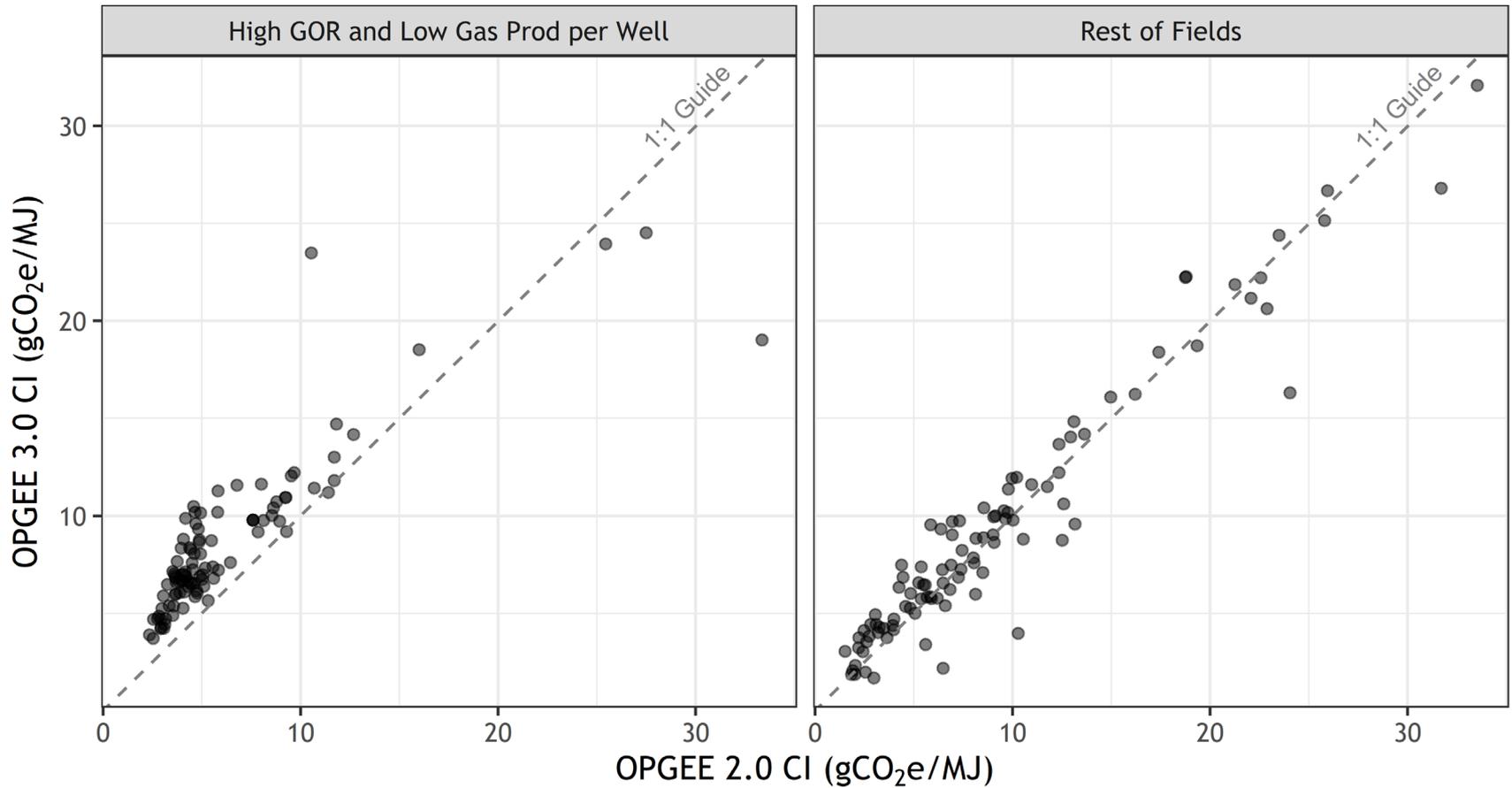


Non-VFF emissions
lower for most
fields in 3.0

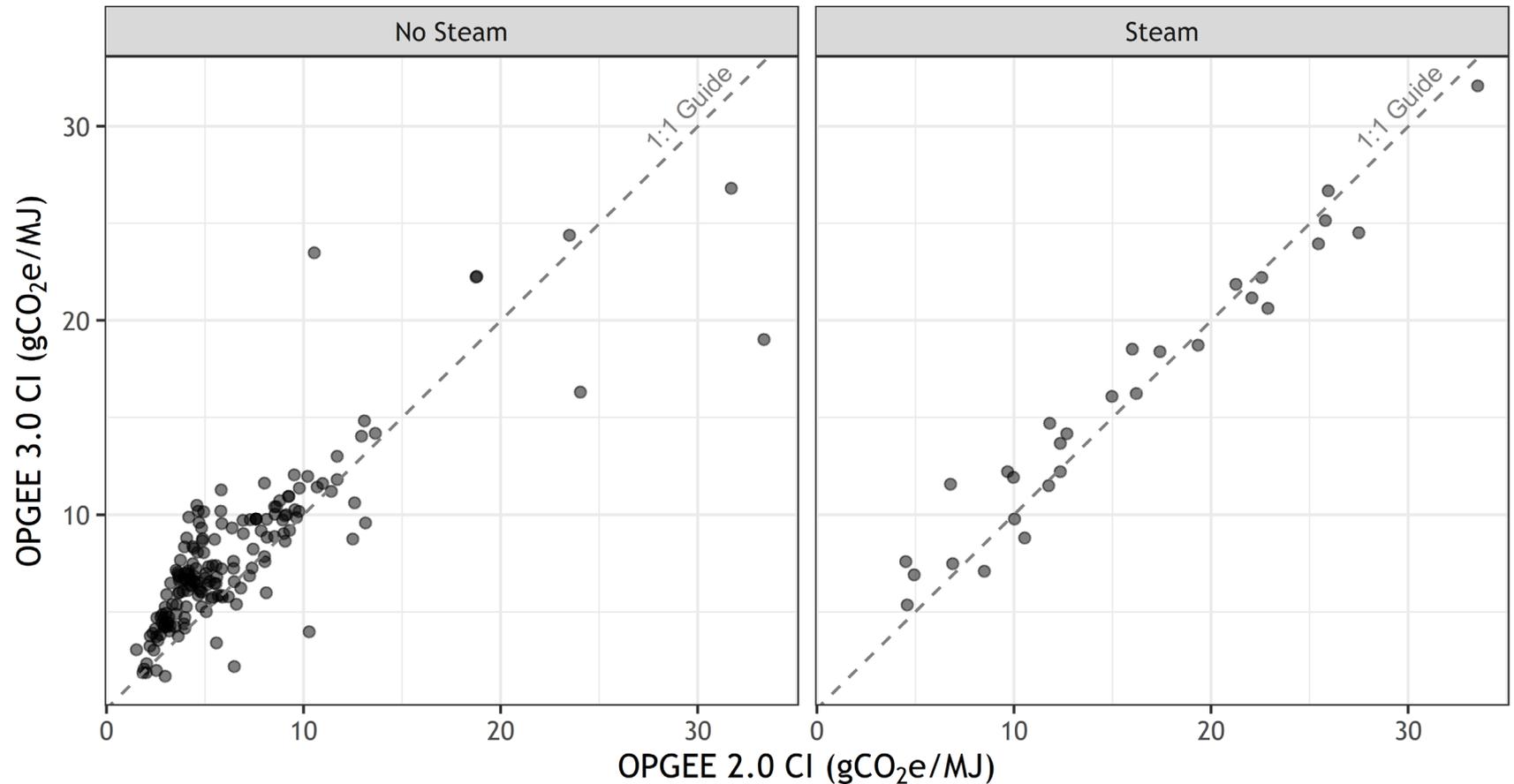
Venting and fugitive
emissions higher for
most fields in 3.0

Flaring emissions
essentially
unchanged

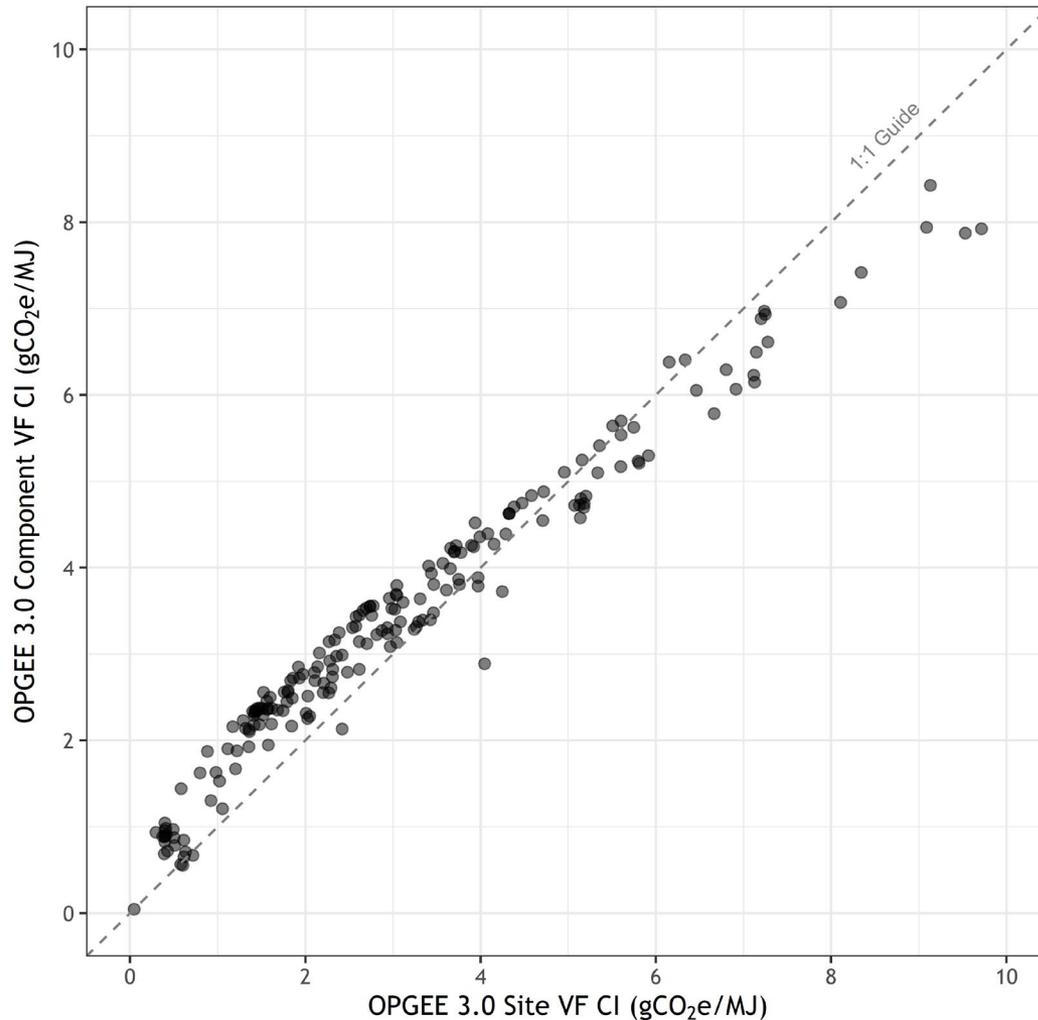
CI differences driven by changes in VF emissions for certain field types



Fields using steam injection mostly fall near parity line

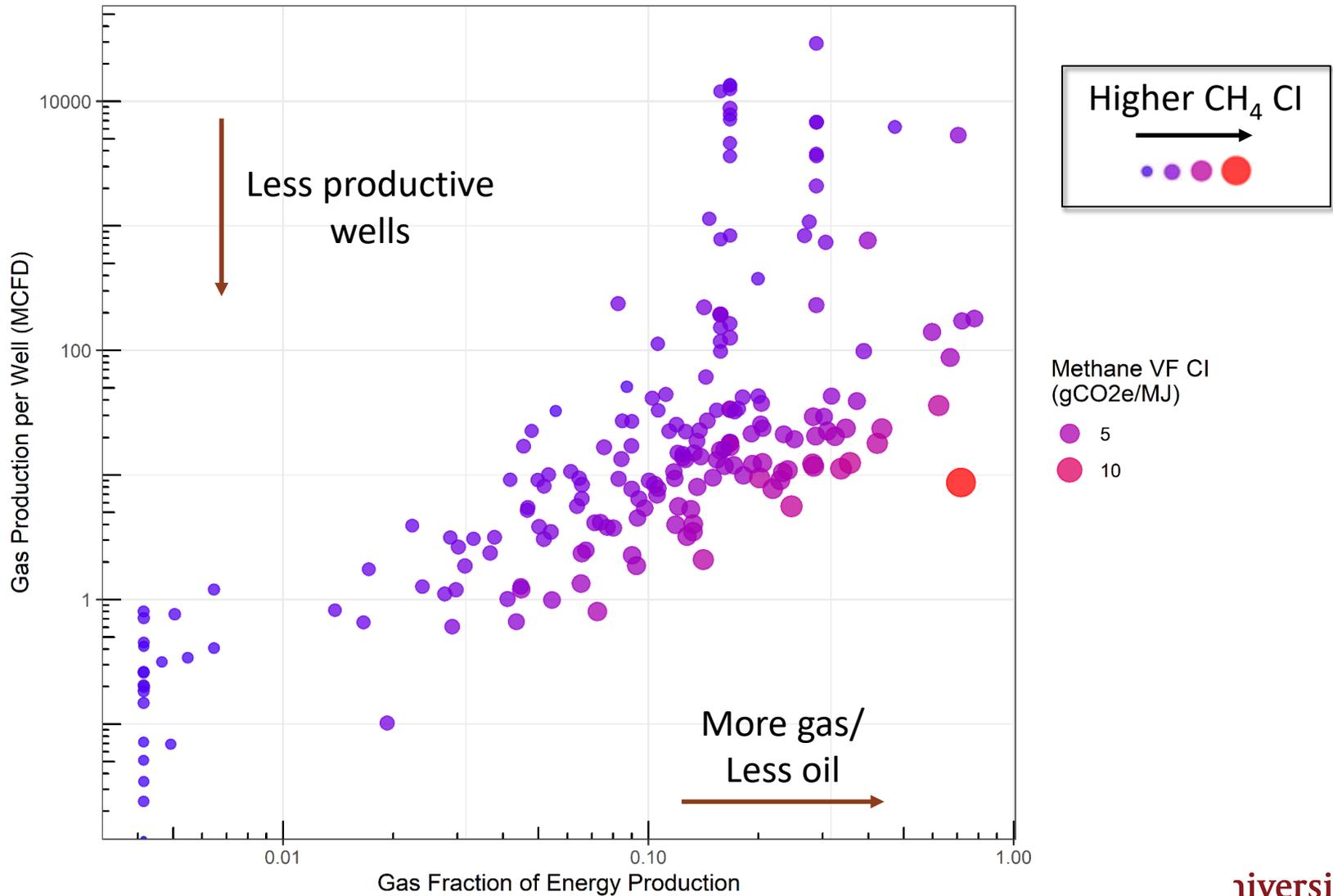


Validation of component fugitives method against alternate site method

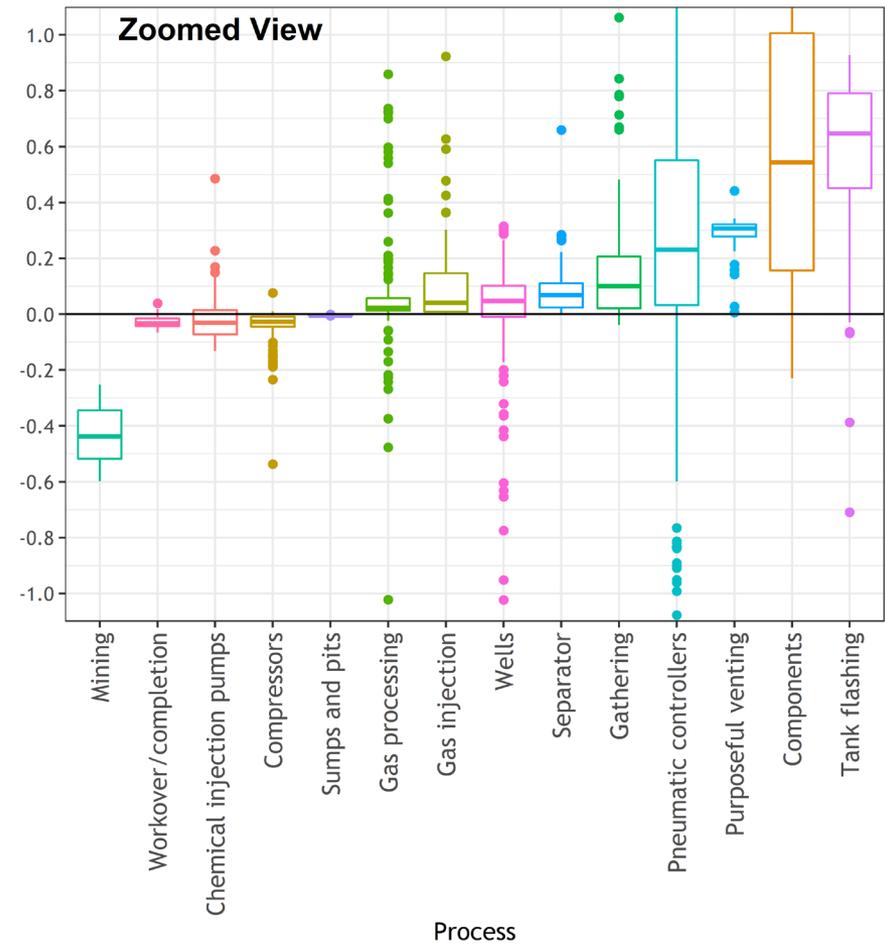
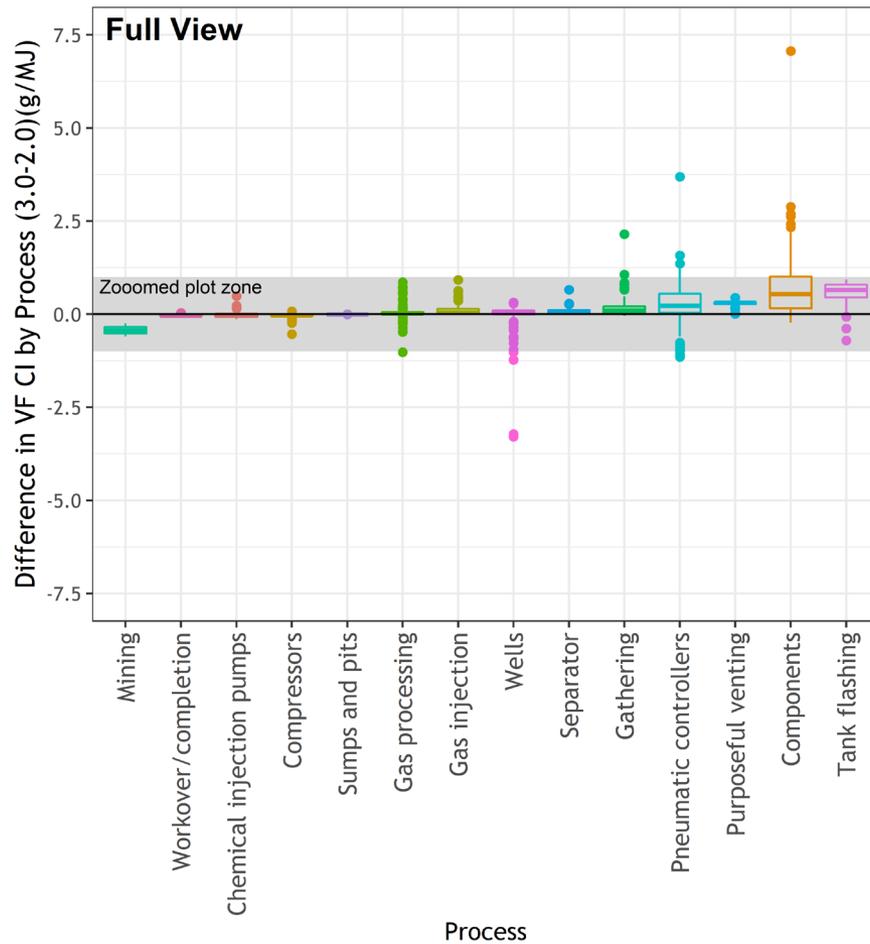


General agreement
between (recommended)
“component” approach
and (validation) “site”
approach

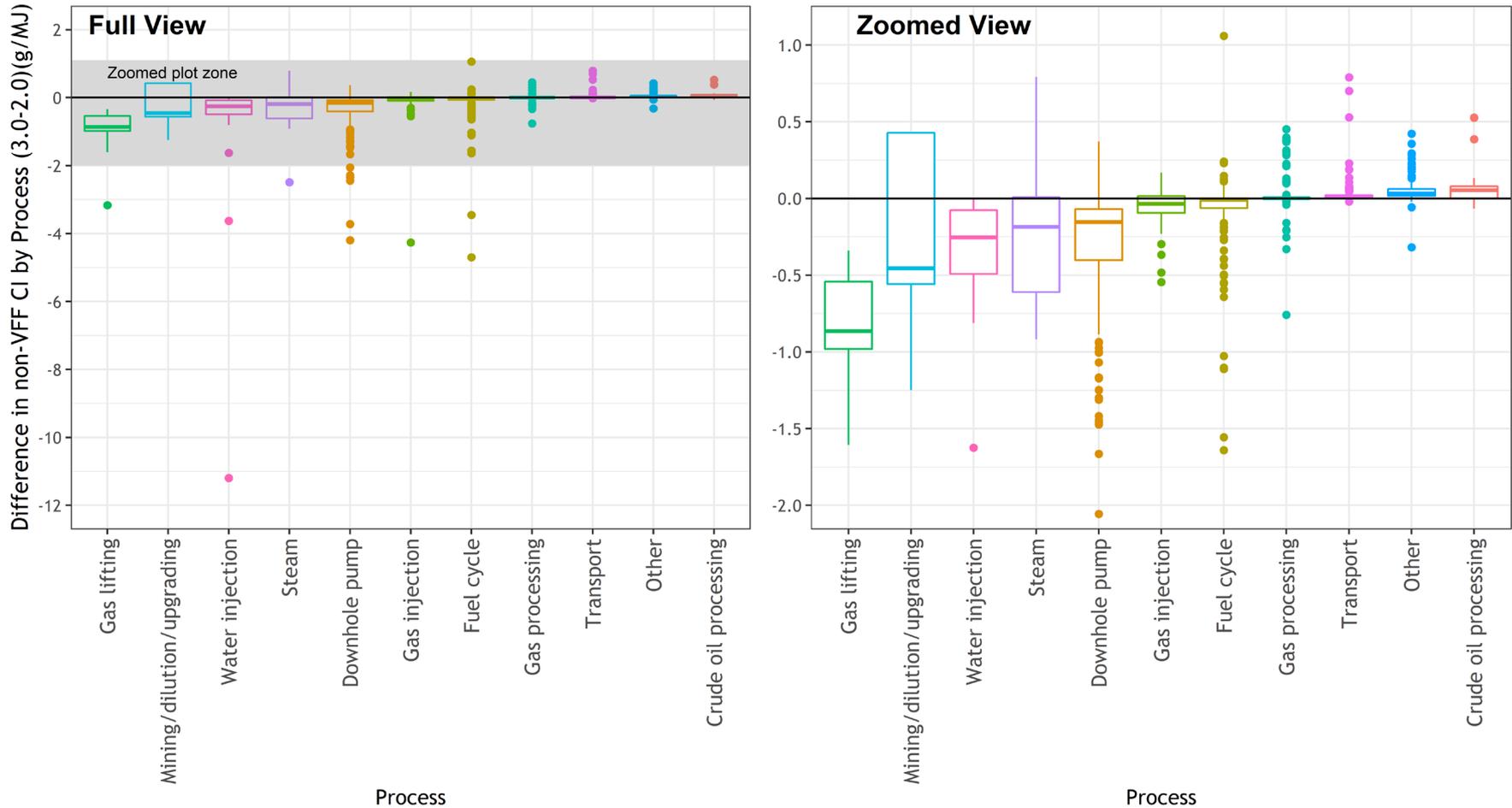
More gas, less productivity -> Higher CI



Venting and fugitive changes by equipment type



Non-VFF changes by component/source/unit



Takeaways and next steps

Takeaways:

- OPGEE v3.0 contains fundamental improvements to gas handling, process simulation, and stream tracking
- Results between v2.0 and v3.0 are generally similar, with changes due to important improvements in modeling and corrections
- Fugitives higher for low productivity fields, gas compression work lower

Next steps:

- Improved field-level flaring estimates generated using GIS dataset and satellite flaring estimates
- Improved regionally specific equipment and activity counts to incorporate federally reported data (GHGRP)

Bibliography (1)

Jing, L., H.M. El-Houjeiri, J.C. Monfort, A.R. Brandt, M.S. Masnadi, D. Gordon, J.A. Bergerson. 2020. **Carbon intensity of global crude oil refining and mitigation potential**. Nature Climate Change. 11-25. DOI: 10.1111/jiec.12954

M.S. Masnadi *, P.R. Perrier , J. Wang , J. Rutherford , A.R. Brandt. **Statistical proxy modeling for life cycle assessment and energetic analysis**. Energy DOI: 10.1016/j.energy.2019.116882

A.R. Brandt. **Accuracy of satellite-derived estimates of flaring volume for offshore oil and gas operations in nine countries**. Environmental Research Communications. DOI: 10.1088/2515- 7620/ab8e17.

Nie, Y., S. Zhang, R.E. Liu, D.J. Roda-Stuart, A.P. Ravikumar, A. Bradley, M.S. Masnadi, A.R. Brandt, J. Bergerson, X. Bi. **Greenhouse-gas Emissions of Canadian Liquefied Natural Gas for Power Generation and District Heating in China: Three Independent Life Cycle Assessments**. Journal of Cleaner Production DOI: 10.1016/j.jclepro.2020.120701

Masnadi, M.S., H.M. El-Houjeiri, D. Schunack, Y. Li, J.G. Englander, A. Badahdah, J.E. Anderson, T.J. Wallington, J.A. Bergerson, D. Gordon, S. Przesmitzki, I.L. Azevedo, G. Cooney, J.E. Duffy, G.A. Keoleian, C. McGlade, D.N. Meehan, T.J. Skone, F. You, M.Q. Wang, A.R. Brandt. **Global carbon intensity of crude oil production**. Science. DOI: 10.1126/science.aar6859

Bibliography (2)

Brandt, A.R., M.S. Masnadi, J.G. Englander, J.G. Koomey, D. Gordon. **Climate-wise oil choices in a world of oil abundance**. Environmental Research Letters DOI: 10.1088/1748- 9326/aaae76

Masnadi, M.S., D. Schunack, Y. Li, S.O. Roberts, A.R. Brandt, H.M. El-Houjeiri, S. Przesmitzki, M.Q. Wang. **Well-to-refinery emissions and net-energy analysis of China's crude-oil supply**. Nature Energy. DOI: 10.1038/s41560-018-0090-7

Yeh, S., A. Ghandi, B.R. Scanlon, A.R. Brandt, H. Cai, M.Q. Wang, Kourosh Vafi, Robert C. Reedy. **Energy intensity and greenhouse gas emissions from oil production in the Eagle Ford shale**. Energy & Fuels DOI: 10.1021/acs.energyfuels.6b02916

Cooney, G., M. Jamieson, J. Marriott, J. Bergerson, A.R. Brandt, T.J. Skone. **Updating the US life cycle GHG petroleum baseline to 2014 with projections to 2014 using open-source engineering-based models**. Environmental Science & Technology DOI: 10.1021/acs.est.6b02819

Masnadi, M.S., A.R. Brandt. **Energetic productivity dynamics of global super-giant oilfields**. Energy & Environmental Science. DOI: 10.1039/C7EE01031A

Bibliography (3)

Masnadi, M.S., A.R. Brandt. **Climate impacts of oil extraction increase significantly with oilfield age**. Nature Climate Change. DOI: 10.1038/nclimate3347

Tripathi, V. and A.R. Brandt. **Estimating decades-long trends in petroleum field energy re- turn on investment (EROI) with an engineering-based model**. PLOS ONE. DOI: 10.1371/jour- nal.pone.0171083

Wang, J., A.R. Brandt, J. O'Donnell. **Potential for use of solar energy use in the global petroleum sector**. Energy: The International Journal. DOI: 10.1016/j.energy.2016.10.107

Brandt, A.R., T. Yeskoo, S. McNally, K. Vafi, S. Yeh, H. Cai, M.Q. Wang. **Energy intensity and greenhouse gas emissions from tight oil production in the Bakken formation**. Energy & Fuels. DOI: 10.1021/acs.energyfuels.6b01907

Wallington, T.J., Anderson, J.E., De Kleine, R.D., Kim, H.C., Maas H., Winkler, S.L., Brandt, A.R., Keoleian, G.A. (2016). **When comparing alternative fuel-vehicle systems, life cycle as- sessment studies should consider trends in oil production**. Journal of Industrial Ecology. DOI: 10.1111/jiec.12418

Brandt, A.R. (2015). **Embodied energy and GHG emissions from material use in conventional and unconventional oil and gas operations**. Environmental Science & Technology. DOI:10.1021/acs.est.5b03540

Bibliography (4)

Vafi, K. A.R. Brandt. GHGfrack: **A model for estimating greenhouse gas emissions from drilling vertical and directional wells and hydraulic fracturing.** Environmental Science & Technology. DOI: 10.1021/acs.est.6b01940

Sweeney Smith, S., A. Calbry-Muzyka, A.R. Brandt (2016). **Exergetic life cycle assessment including both inputs and pollutants.** International Journal of Life Cycle Assessment. DOI: 10.1007/s11367-016-1118-5

Kemp, C.E., A.P. Ravikumar, A.R. Brandt (2016) **Comparing natural gas leakage detection technologies using an open-source “virtual gas field” simulator.** Environmental Science & Technology. DOI: 10.1021/acs.est.5b06068

Kang, C.A., Brandt, A.R., Durlofsky, L (2015). **A new carbon capture proxy model for optimizing the design and time-varying operation of a coal-natural gas power station.** International Journal of Greenhouse Gas Control. DOI: 10.1016/j.ijggc.2015.11.023

Brandt, A.R., Y. Sun, S. Bharadwaj, D. Livingston, E. Tan, D. Gordon (2015). **Energy return on investment (EROI) for forty global oilfields using a detailed engineering-based model of oil production.** PLOSone. DOI: 10.1371/journal.pone.0144141

Bibliography (5)

Brandt, A.R., Yeskoo, T.E., K. Vafi. (2015) **Net energy analysis of Bakken crude oil production using a well-level engineering-based model**. Energy. DOI: 10.1016/j.energy.2015.10.113

Brandt, A.R., D. Millstein, L. Jin, J.G. Englander (2015). **Air quality impacts from well stimulation**. An Independent Scientific Assessment of Well Stimulation in California, Volume II: Potential Environmental Impacts of Hydraulic Fracturing and Acid Stimulations. California Council on Science and Technology, Lawrence Berkeley National Laboratory, July 2015.

Englander, J.G., A.R. Brandt, A. Elgowainy, H. Cai, J. Han, S.L. Yeh, M.Q. Wang (2015). **Oil sands energy intensity assessment using facility-level data**. Energy & Fuels. DOI:10.1021/acs.energyfuels.4b00175

Cai, H., A.R. Brandt, S.L. Yeh, J.G. Englander, J. Han, A. Elgowainy, M.Q. Wang (2015). **Well-to-wheels greenhouse gas emissions of Canadian oil sands products: Implications for U.S. petroleum fuels**. Environmental Science & Technology. DOI: 10.1021/acs.est.5b01255

Brandt, A.R., Y. Sun, K. Vafi (2015). **Uncertainty in regional-average petroleum GHG intensities: Countering information gaps with targeted data gathering**. Environmental Science & Technology. 49(1) 679-686. DOI: 10.1021/es505376t

Bibliography (6)

Vafi, K., A.R. Brandt, (2014). **Reproducibility of LCA models of crude oil production**. Environmental Science & Technology. 48(21) 12978-12985. DOI: 10.1021/es501847p

Vafi, K., A.R. Brandt, (2014). **Uncertainty of oil field GHG emissions resulting from information gaps: A Monte Carlo approach**. Environmental Science & Technology. 48(17) 10511-10581. DOI: 10.1021/es502107s

Englander, J., A.R. Brandt, S. Bharadwaj. **Historical trends in life-cycle greenhouse gas emissions of the Alberta oil sands (1970 to 2010)**. Environmental Research Letters. 8 (2013) 044036. DOI:10.1088/1748-9326/8/4/044036

Brandt, A.R., J. Englander, S. Bharadwaj (2012). **The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010**. Energy: The International Journal 55(June 15): 693- 702. DOI: 10.1016/j.energy.2013.03.080

Brandt, A.R. (2011) **Variability and uncertainty in life cycle assessment models for greenhouse gas emissions from Canadian oil sands production**. Environmental Science & Technology 46(2): 1253-1261. DOI: 10.1021/es202312p

Bibliography (7)

Brandt, A.R. (2011). **Oil depletion and the energy efficiency of oil production: The case of California**. *Sustainabilities* 3(10): 1833-1844. DOI: 10.3390/su3101833

Yeh, S., S.M. Jordaan, A.R. Brandt, M. Turetsky, S. Spatari, D. Keith (2010). **Land use greenhouse gas emissions from conventional and unconventional oil production** *Environmental Science & Technology* 44(22): 8766-8772. DOI:10.1021/es1013278

Brandt, A.R., S. Unnasch (2010). **Energy intensity and greenhouse gas emissions from thermal enhanced oil recovery**. *Energy & Fuels* 24(8): 4581-4589. DOI:10.1021/ef100410f

El-Houjeiri, H. M. A.R. Brandt, J.E. Duffy (2013). **Open-source LCA tool for estimating greenhouse gas emissions from crude oil production using field characteristics**. *Environmental Science & Technology* 47(11): 5998-6006. DOI: 10.1021/es304570m