Supplemental Information for:

Reproducibility of LCA models of crude oil production

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Table of contents

S1. Introduction

The volume of the reports and models' documentation examined in this comparison greatly exceeds a thousand pages of methodology, results and discussions. Many details are required to make this study completely reproducible for the reader. This Supplemental Information aims to concisely supply as much of this information as possible. In the following, we provide collected input parameters that we used in our analyses, as well as additional results which were not covered in detail in the main paper. Some of the outstanding patterns and observed discrepancies are discussed as well. OPGEE version 1.1 Draft A is used for the calculations with a few minor modifications to align the model with OPGEE 1.1 Draft B. For this study we assume standard temperature is 60°F while OPGEE 1.1 Draft A considers 32°F is standard temperature. The default value for energy demand of cryogenic nitrogen separation is taken from OPGEE 1.1 Draft B.

The emissions are reported in terms of gram CO_2 equivalent per mega joule of lower heating value of produced crude oil. The abbreviations, if not defined in this text, follow those in the body of the main paper.

S2. Engineering–based models

Four engineering-based models were examined and compared to OPGEE. The comparison of engineering-based models includes fields that use conventional production methods, nitrogen flooding, and steam flooding. From each study, we prepared a data bank consisting of the input data collected from the selected models.

We first normalized the data collected from the reports to represent WTR emissions for all the case studies of engineering-based models. For example, some studies included refinery or end-use fuel combustion emissions, which were removed from the comparable results before building any OPGEE comparison cases.

We then performed a three-step analysis:

1. OPGEE is populated with input variables through the main model interface ("User Inputs & Results" worksheet). In this step, populated data included reservoir character, oil and gas qualities, and production operation characteristics. If transport distances and modes of transportation were given, they were entered. If nitrogen flooding was the recovery method for the field being modeled, the energy requirement of the N_2 separation plant was entered on the "Production & Extraction" worksheet. In all cases where data were not available from a study, OPGEE default inputs were used.

2. Input variables related to production and surface processing efficiencies were entered in the OPGEE detailed worksheets. Examples include fluid pump, compressor, and flare combustion efficiencies. Secondly, the production and surface processing configuration was adjusted in this step. Inclusion or exclusion of processing units like demethanizer and stabilization column took place in this step, if their configuration was specified in the comparable model study. As above, where these input variables are not specified in a particular study, OPGEE defaults are always used.

3. OPGEE was adjusted to ensure as close alignment of analysis boundaries as possible. For example, miscellaneous emissions sources, emissions from exploration, drilling, and land use, if given, were adjusted. If these activities were not considered within the analysis of the comparison model, then OPGEE estimates for these emissions were deducted from WTR emissions calculated by OPGEE. As above, OPGEE default values were used for any input parameter which was not provided by the comparison model.

The initial normalization of the study to a general WTR analysis boundary should not be confused with the alignment of boundaries in Step 3. The Step 3 alignment took place within the general WTR framework. Only in few cases where the use of the default value did not give meaningful and physically acceptable results, the input parameters were modified by OPGEE automatic algorithm. The changes in these three steps are cumulative.

S2.1. Jacobs 2009[5]

The collected input data and the results of the OPGEE vs. Jacobs 2009 comparison are given in Table S1 to
Table S8 and in Figure S51 to Figure S5.

S2.1.1. Outstanding model differences

Despite the normalization between OPGEE and the Jacobs model, some differences remain. First, Jacobs 2009 assumes that electricity powers pumps, compressors, and heaters in the water re-injection, stabilizer, deaerator, dehydration, and acid gas removal units. OPGEE assumes by default that the drivers and heaters are gas-fueled but allows the user to switch to electricity. OPGEE assumes by default that the consumed electricity is provided by the grid. However, the user can change the portion of the electricity which is generated onsite. Therefore, in Step 2 of the analysis, drivers and heaters were switched to electricity. One exception is that the fuel options for the amine treater heater in OPGEE are only natural gas and NGL.

Second, OPGEE includes a demethanizer. The demethanizer unit is not depicted in process flow diagram provided by Jacobs 2009.

Third, Jacobs 2009 computes the energy requirements of thermal deaeration of water before re-injection into the reservoir. This is the major energy demand in the Jacobs modeled water treatment process. Jacobs assumes that electrical heaters supply the required thermal energy. The version of OPGEE examined here does not include deaeration of water by thermal means or any other less energy-intensive means.

Fourth, Jacobs 2009 did not consider emissions associated with land use change, and drilling. OPGEE does include emissions from land use change and drilling.

Fifth, for crudes with API less than 25, Jacobs 2009 includes the use of diluent in extraction of oil. The diluent is pumped into the reservoir, separated in the crude stabilizer, and returned again to the reservoir. OPGEE does not include such use of diluent. OPGEE includes a module for use of diluents to lower the viscosity of bitumen for pipeline transport, however, we did not use this module in our analyses of the engineering-based models

Sixth, Jacobs 2009 assumes by default the re-injection of the produced gas to the reservoir. Gas re-injection can be modeled in OPGEE, but re-injected gas volume is set to zero by default. For most of the study crudes in the Jacobs 2009 study, the rate of gas reinjection is not included, therefore the default value of OPGEE (0 scf/bbl) is applied. The exception is the Jacobs 2009 “generic” crude (see below).

Seventh, for the case of generic crude oil, Jacobs 2009 assumes the re-injection of all separated CO_2 back to the reservoir. Re-injection of CO_2 is not modeled in current version of OPGEE.

The case of generic crude

Particular attention was paid to the Jacobs 2009 "generic" crude case, especially as to how the Jacobs 2009 generic crude differs from the OPGEE default crude oil settings.

First, for the case of generic crude, the choice of electrical drivers and electrical heaters instead of natural gas engines and gas fired heaters results in higher non-VFF emissions in Jacobs, 4.78 g CO_2 eq./MJ compared with 3.39 gCO_2 eq./MJ in OPGEE.

Second, Jacobs 2009 reported 0.85 gCO_2eq./MJ from deaeration of water and 1.46 gCO_2eq./MJ from pumping re-injected water. After using Jacobs inputs, OPGEE calculated emissions from pumping of water for re-injection is 0.36 gCO_2 eq./MJ (assuming as Jacobs does that electrical drivers are used). This is a significant difference. The difference between the non-VFF emissions of the two models (in Step 3) is 1.89 gCO_2eq./MJ. This remaining difference can be explained partly by the fact that thermal deaeration is not modeled in the current version of OPGEE.

Third, OPGEE considers the effect of the hydrostatic pressure of the column of water in the water injection well. This helps to significantly reduce the required pump discharge pressure. If the static pressure of the water in oil well is not considered in a model then it should be more sensitive to the reservoir depth. Jacobs 2009 provided a sensitivity analysis of the effect of the reservoir depth and WOR on the production emissions. Table S6 and Figure S1 show the results of comparison of this study with OPGEE. The emissions related to the water re-injection activity in Jacobs 2009, is quite insensitive to the change of the reservoir depth. This raises a question of how the weight of water in the water injection well is incorporated in Jacobs 2009 model.

Various study crudes

Input variables which were collected from the Jacobs 2009 report are given in

Table S7. This table shows the WTR emissions that are taken from Jacobs 2009 report. Figure S2 compares the estimated emissions from transportation of crude oil. Jacobs 2009 systematically calculates higher transportation emissions. Figure S4 compares the predicted VFF emissions from OPGEE and Jacobs 2009. The flare efficiency for Jacobs generic crude is stated (99%) but it is not clear if Jacobs 2009 used the same value for the study crude oils. The VFF emissions comparison was made for two OPGEE flare efficiencies of 95% and 99%. Figure S4 shows that OPGEE flaring emissions estimates are quite close to Jacobs 2009, but are systematically higher for the given rate of flaring and venting by Jacobs 2009. One exception is Bonny Light crude at 99% flare efficiency.

Figure S5 compares the non-VFF emissions predicted by OPGEE using inputs from Jacobs 2009 model against Jacobs 2009 results. This figure shows that Jacobs 2009 predicts higher non-VFF emissions in most cases. In general in Step 2 the emissions predicted by OPGEE are increased compared with step 1 as we switch to electrical drivers and heaters from OPGEE defaults (natural gas engines and gas-fired heaters in step 1).

Figure S5 also shows that the significantly higher emissions from production of Mars crude, predicted by Jacobs 2009, are due to the non-VFF emissions rather than a discrepancy in VFF emissions. Therefore, the source of this inconsistency is present in production activities. The two major sources that might explain this discrepancy are:

1. The absence of the thermal deaeration unit in OPGEE model
2. The possibly different approach of Jacobs 2009 in calculating the discharge pressure of the water-reinjection pump.

For the case of Mars the oil field has a depth of 14500 ft and the highest WOR of 5.5 bbl water/bbl oil. Based on the earlier discussion, and Figure S1, we would expect for this crude that the Jacobs 2009 model would predict significantly higher emissions.

Table S1. Transportation distances from Jacobs 2009 report.[5]

	Refinery	Marine (mile)	Pipe line (mile)
Venezuela	Chicago	1840	1058
Mars Platform	Chicago	0	1506
Saudi Arabia	Chicago	9843	1824
Saudi Arabia	Chicago	12434	1824
Kirkuk	Chicago	6790	1658
Nigeria	Chicago	6194	1058
Bakersfield	Los Angeles	0	102
Maya	not given	not given	not given

Table S2. Transportation emissions (to refinery gate) g GHG /MJ.

	Bachaquero	Maya	Arab Med	Mars	Bonny Light	Kirkuk	Kern River
Jacobs 2009[a]	0.96	0.96	2.44	0.98	1.6	2.09	0.07
OPGEE[b]	0.7	0.89	2.26	0.69	1.19	1.53	0.05

a – Jacobs 2009 data from Jacobs report, section 6

b – OPGEE results are based on using input data from Jacobs 2009

Table S3. Composition of produced gas according to Jacob 2009 report.[5]

	Jacobs 2009	Jacobs 2009 (water-free basis)
H_2S	1	1.0
CH_4	75	75.2
C_2H_6	14.1	14.1
C_3H_8	4.7	4.7
CO_2	5	5.0
H_2O	0.3	—
Sum	100.1	100.0

Table S4. Inputs from Jacobs 2009 generic model - OPGEE generic crude defaults are given for comparison

	OPGEE generic	Jacobs 2009 generic
Oil production (bbl/day)	1500	not given
Field depth (ft)	7240	5000
Reservoir Pressure (psi)	1557	1500
API gravity	30	30
GOR (scf/bbl)	908	1000
WOR (bbl w/bbl oil)	4.31	10
Fraction of remaining gas re-injected	0	0.54
Flaring to oil ratio (scf/bbl)	182	10
Direct venting (scf/bbl oil)	0	5
Fraction of water re-injected	1	1
Friction factor	0.02	0.1
Pipe diameter	2.8	3
Miscellaneous emissions	0.5	0.57

Table S5. Comparison of the results of OPGEE and Jacobs 2009 generic crude models (excluding transportation emissions) - Assumptions of step 3 is used. Transportation emissions are excluded for clarity.

	OPGEE default	Jacobs 2009 generic	OPGEE w/ Jacobs input - electric drivers and heaters	OPGEE w/ Jacobs input - NG engine and NG heaters
Total recovery emissions (g CO_2/MJ)[a]	6.31	7.35	6.30	4.91
-VFF recovery emissions (g CO_2/ MJ)	3.4	0.68	1.52	1.52
-Non-VFF recovery emissions (g CO_2/MJ)[a]	2.91	6.67	4.78	3.39

a - The emissions due to transportation of crude is subtracted from OPGEE WTR and non-VFF emissions predicted by the model. Jacobs 2009 production model does not report transportation emissions.

Table S6. Emissions from water re-injection . In Jacobs 2009 generic model, these emissions is the sum of emissions from energy consumption for deaeration and pumping water

Depth (ft)	**5000**			**10000**			**20000**		
WOR	**3**	**10**	**15**	**3**	**10**	**15**	**3**	**10**	**15**
OPGEE (Step 3)	0.00	0.36	1.26	0.00	0.00	0.00	0.00	0.00	0.00
Jacobs 2009 (deaerator + pump)	0.68	2.31	3.48	0.68	2.22	3.39	0.68	2.26	3.47
Dearator (Jacobs 2009)	0.26	0.85	1.28	0.26	0.85	1.28	0.26	0.85	1.28
Pump (Jacobs 2009)	0.43	1.46	2.20	0.43	1.37	2.12	0.43	1.41	2.19

Table S7. Input values from Jacobs 2009 report.[5]

	Arab Med	**Bachaquero**	**Bonny light**	**Kirkuk Blend**	**Mars**	**Maya**	**Kern River**
API	31.1	10.7	32.9	36.6	31.5	22.1	13.4
Reservoir depth- average(ft)	6100	5100	8700	7500	14500	9500	900
Reservoir depth- min (ft)	4800	1200	5000	2000	10000	6400	not given
Reservoir depth- max (ft)	6900	12000	14000	10000	19000	12000	not given
Reservoir pressure (psi)	3000	500	4300	3000	5500	1600	35
SOR (bbl/bbl)	NA	0.5	NA	NA	NA	NA	3 and 6
WOR (bbl/bbl)	2.3	0.25	2	2	5.5	3	not given
Produced Gas (scf/bbl)	650	90	840	600	1040	340	not given
Flared gas World Bank (m^3 gas/bbl)	0.8	2	27	11	0.6	0.6	not given
Flared gas World Bank (scf gas/bbl)	28.25	70.63	953.46	388.45	21.19	21.19	not given
Flared gas NOAA 2007 (m^3 gas/bbl)	0.9	2.2	19.6	9.1	0.6	1.4	not given
Falred gas NOAA 2007 (scf gas/bbl)	31.78	77.69	692.14	321.35	21.19	49.44	not given
N_2 injection (scf/bbl)	NA	NA	NA	NA	NA	1200	NA

Table S8. Jacobs 2009 results for emissions from oil production activities

	Bachaquero	Maya	Arab Med	Mars	Bonny Light	Kirkuk	California SOR = 3	California SOR = 6
Lifting	0.41	1.43	0.21	2.8	0.855	0.681		
Water Reinjection	NA	0.74	0.84	2.9	0.845	0.789		
Gas Reinjection	NA	0.89	0.25	0.6	0.49	0.3		
Water Treatment	NA	0.14	0.2	0.27	0.15	0.107		
Gas Treatment	1.43	1.49	1.43	1.59	1.33	1.48		
Venting	0.1	0.39	0.6	1.13	1	0.75		
Flaring	0.75	0.22	0.4	0.21	10.83	4.45		
Miscellaneous Energy	0.15	0.5	0.29	0.8	0.4	0.35		
Steam	1.93	NA	NA	NA	NA	NA		
Nitrogen	NA	1.3	NA	NA	NA	NA		
Transportation (g GHG /MJ)	0.96	0.96	2.44	0.98	1.6	2.09	0.07	0.07
WTR excluding Transportation	4.77	7.10	4.22	10.30	15.90	8.91	9.81	19.50
WTR emissions	**5.73**	**8.06**	**6.66**	**11.28**	**17.5**	**10.997**	**9.88**	**19.57**
- VFF emissions	0.85	0.61	1	1.34	11.83	5.2		
- Non-VFF emissions	4.88	7.45	5.66	9.94	5.67	5.797		

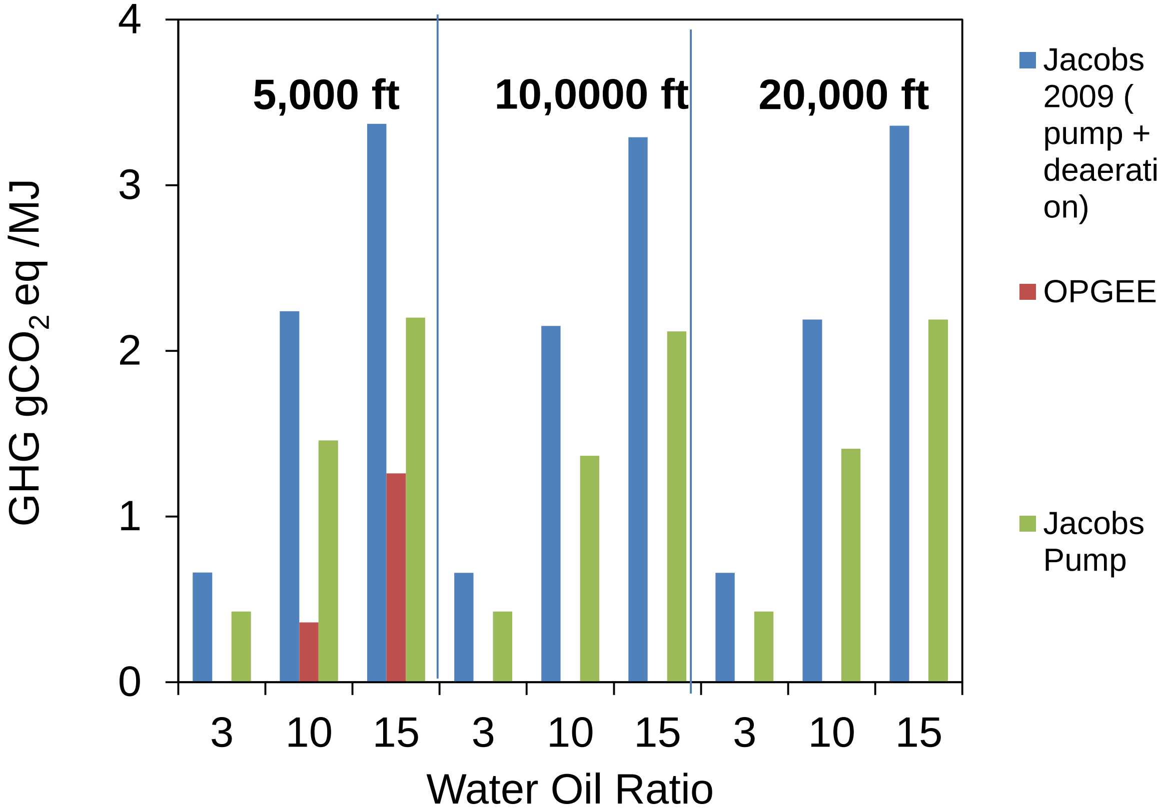

Figure S1. Comparison of the emissions from energy consumption for thermal deaeratioin and re-injection of water for the case of generic crude. The total of water deaeration and re-injection are shown for Jacobs 2009 separately .OPGEE results are based on the input data taken from Jacobs 2009 generic crude. OPGEE does not model thermal deaertation of water.

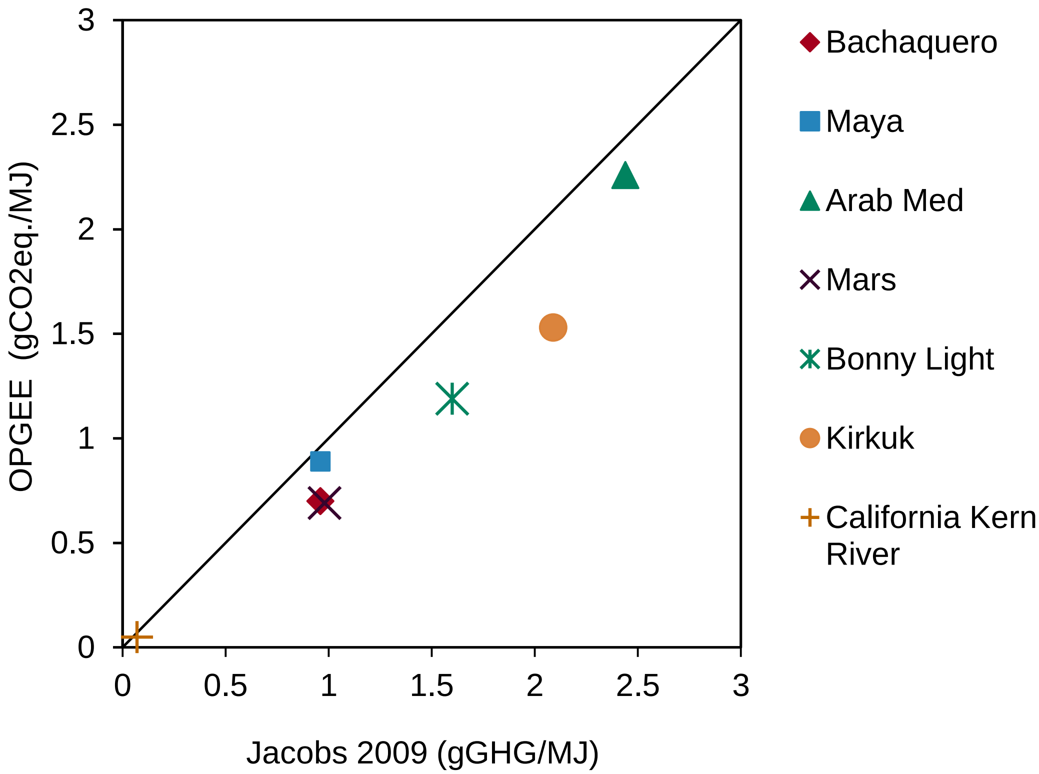

Figure S2. Comparison of the transportation emissions calculated by OPGEE with Jacobs 2009 inputs vs Jacobs 2009.For the case of Maya OPGEE defaults were used.

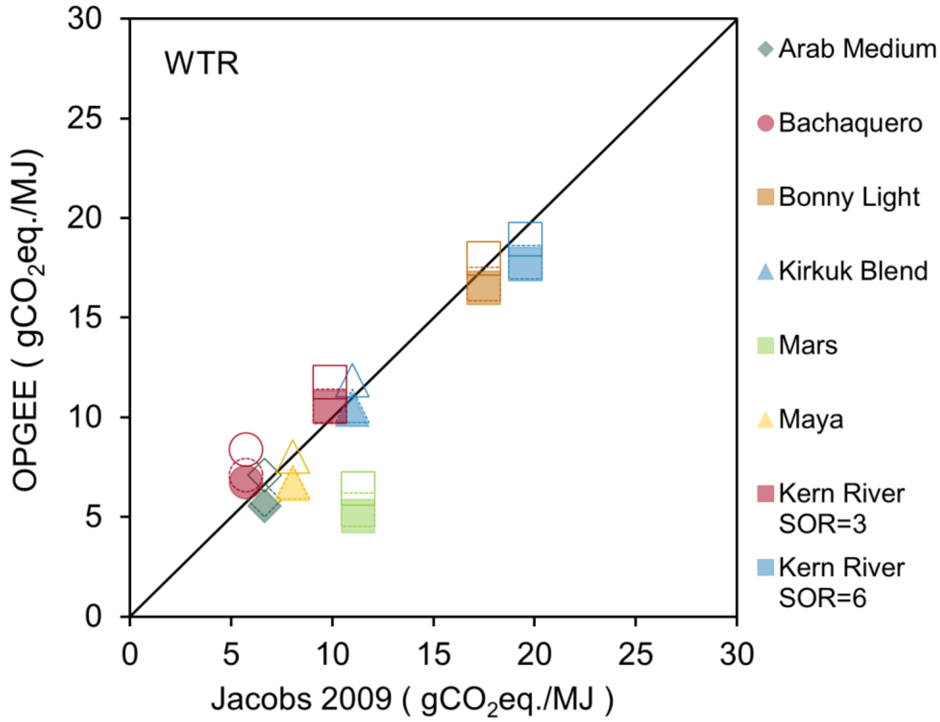

Figure S3. The OPGEE's estimates for WTR emissions using inputs from Jacobs 2009 report for the study crudes.

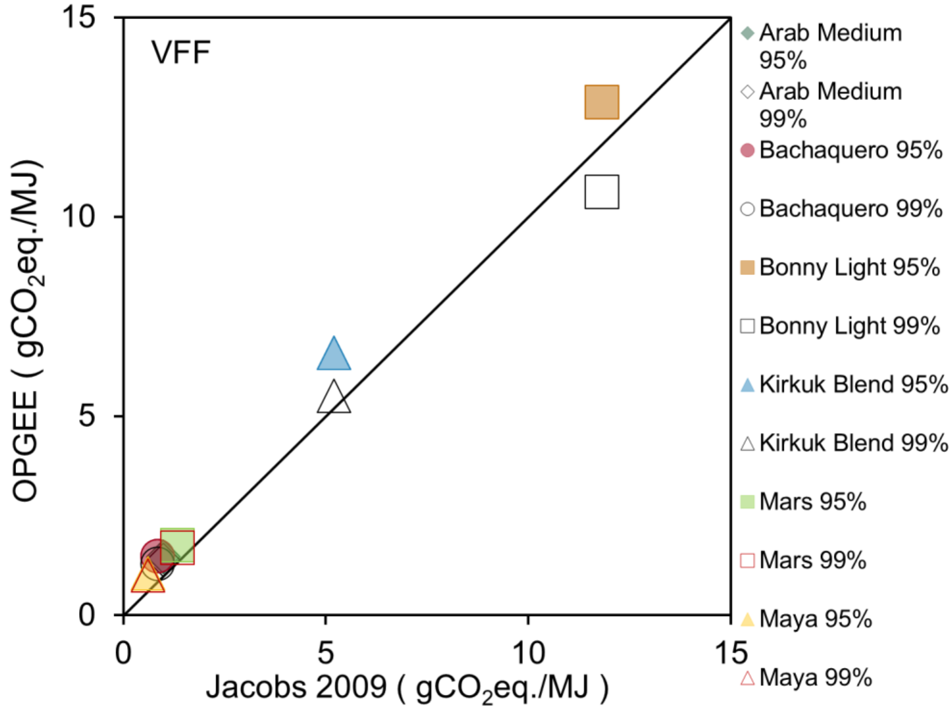

Figure S4. The OPGEE's estimates for VFF emissions using inputs from Jacobs 2009 report for the study crudes .OPGEE default for flare efficiency is 95%, Jacobs 2009 considers flare efficiency of 99 % for the generic. This value is not given for the study crudes in Jacobs 2009 report.

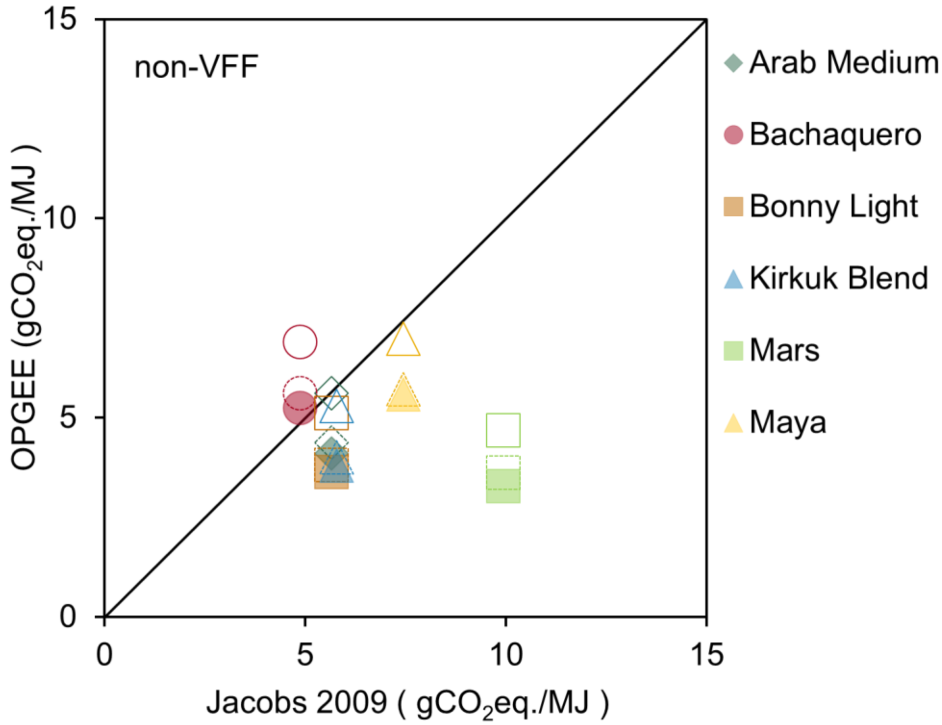

Figure S5. Comparison of non-VFF emissions: OPGEE with Jacobs 2009 inputs against Jacobs 2009 non-VFF

S2.2. TIAX[6]

Collected data from TIAX are given in Table S9 to Table S15. Additional results are shown in Figure S7 and Figure S8.

S2.2.1. General considerations

The TIAX calculations, as presented by the report, do not address energy demand of surface processing of gas and oil. For the case of conventional oil production, fugitive emissions values were not mentioned by TIAX report. Table S15 gives the fugitive emissions calculated by OPGEE and shows that neglecting the fugitive emissions can cause significant error in calculating of total emissions for the cases of Alaska – North Slope and Gulf Coast- WTI. For the other crudes the error is less significant.

S2.2.2. Results and Discussion

Figure S7 compares results from OPGEE with TIAX inputs against TIAX results. This figure shows that generally in each step of the analysis, OPGEE estimates become closer to TIAX estimates. This suggests that the aforementioned hypotheses that TIAX may not have covered surface processing activities and fugitive emissions can be true.

Figure S8 shows that a significant portion of the discrepancy between WTR emissions estimates for the case of Nigeria and Alaska come from the differences in prediction of VFF emissions. For the cases of Saudi–Medium, Venezuela–Bachaquero, California–Kern River, and Mexico–Cantarell, the VFF emissions predicted by OPGEE are close to TIAX reported values. In general OPGEE predicts higher VFF emissions than TIAX. Part of this higher estimation can be due the fact that the default flare efficiency in OPGEE is 95%. TIAX may have considered a higher flare efficiency (not specified).

Table S9. Analysis crudes, recovery methods, and data collected from TIAX report.[6]

	USA- WTI	Nigeria Escravos	Saudi Medium	Iraq Basrah Medium
Production Method	Water flooding and natural drive	Water flooding and gas lift	Water flooding, natural drive	water flooding, natural drive
Oil Production (kbbl/day)	not given	not given	not given	not given
API	40	35	30	31
SG	0.83	0.85	0.88	0.87
Sulfur content (%)	0.5	0.16	2.6	2.6
Water injected (bbl/bbl oil)	8	2.3	2.9	5
WOR (bbl water/ bbl oil)	3.00	0.15	0.43	1.50
Total produced gas = GOR (scf/bbl)	3966	1734	800	490
Produced gas Consumed (scf/bbl oil)	26	11	8	13
Produced gas exported (scf/bbl)	3940	1723	792	477
Electricity Consumed (kWh/bbl)	2.5	1.5	0.88	1.5
Water content (%)	75	13	30	60
SCGT efficiency %	33.1	33.1	33.1	33.1
Gas lift rate scf/bbl oil		416		
Portion of electricity generated on site (%)	100	74	83	83
TIAX Calculations				
Energy to inject water (kW/bbl water)	0.308	0.308	0.308	0.308
Energy to inject gas of gas lift (kW/scf gas)		0.0016		
Recovery Emissions (gCO_2/MJ)	0.2	0.1	0.1	0.2
Venting/Flaring Emissions (gCO_2/MJ)	0.8	16.7	0.2	4.9
Total recovery emissions - WTR (gCO_2/MJ)	1	16.8	0.3	5.1
Transportation Emissions - PADD 2 (gCO_2/MJ)	0.61	NA	1.6	NA
Transportation Emissions - PADD 3(gCO_2/MJ)	0.04	0.78	1.01	1.12
Transportation Emissions -California (gCO_2/MJ)	NA	NA	1.17	1.29
Average Transportation Emissions (gCO_2/MJ)	0.33	0.78	1.26	1.21
WTR emissions (gCO_2/MJ)	1.33	17.58	1.56	6.31
Electricity Credit (Btu/MMBtu) from TIAX Table 5-1	0	0	0	0

Table S10. Study crudes, recovery method, and data from TIAX report.[6]

	Alaska- North Slope
Production Method	Water alternating gas (WAG) and natural drive
Oil production (kbbl oil /day)	723.98
API	32
SG	0.87
Sulfur content (%)	0.5
Gas-reinjection (%)	92.1
Injection gas (scf/bbl)	10500
injection water (bbl/bbl)	2.6
Total produced gas = GOR (scf/bbl)	11400
Produced gas Consumed (scf/bbl)	220
Produced gas exported (scf/bbl)	680
Electricity consumed (kWh/bbl oil)	20
Water content %	—
WOR (bbl water/ bbl oil)	NA
SCGT efficiency %	33.1
Portion of Electricity generated onsite %	100
TIAX Calculations	
Energy for injection of water (kWh/bbl water inj.)	0.308
Energy for gas injection (kWh/scf gas inj.)	0.0018
Total Electricity consumption (kW/bbl oil)[a]	20
Recovery Emissions (gCO_2eq./MJ)	0.7
Venting/Flaring Emissions (gCO_2eq./MJ)	0.1
Total recovery emissions (gCO_2eq./MJ)	0.9
Emission due to transportation (gCO_2eq./MJ)	0.73
WTR emissions (gCO_2eq./MJ)	1.63
Electricity Credit (Btu/MMBtu)[b]	0

a - This is sum of energy required for both gas and water injection
b - From TIAX report, Table 5-1

Table S11. The study crudes, method of recovery, and data collected from TIAX report.[6]

	Mexico: Cantarell – Maya
Production Method	Nitrogen flooding- gas lift
Oil production (kbbl/day)	1800
API	21
SG	0.93
Sulfur content (%)	3.4
WOR (bbl/bbl)	not given
Total produced gas = GOR (scf/bbl)	372
Produced gas Consumed (scf/bbl)	4.4
Produced gas exported (scf/bbl)	367
Electricity for recovery (kWh/bbl)	0.63
Electricity for N_2 plant (kwh/bbl)	14
Electricity generated onsite (%)	66
Nitrogen (MMSCFD)	1200
Gas for gas lift (scf/bbl)	400
Nitrogen Gas (scf/bbl)	667
Natural gas consumed in N_2 plant (scf/bbl)	92
Electricity for nitrogen plant (kWh/1000 scf)	21
CCGT for nitrogen efficiency (%)	53
SCGT for other gas consumed (%)	33.1
Recovery Emissions (gCO_2eq./MJ)	1.1
Venting/Flaring Emissions (gCO_2eq./MJ)	2
Total recovery emissions (gCO_2eq./MJ)	3.1
Transportation Emissions - PADD 3 (gCO_2eq./MJ)	0.11
Transportation Emissions -California (gCO_2eq./MJ)	0.3
Average Transportation Emissions (gCO_2eq./MJ)	0.205
WTR emissions (gCO_2eq./MJ)	3.305
Electricity Credit (Btu/MMBtu)	0

a - From TIAX report, Table 5-1

Table S12. The study crude, method of recovery, and data collected from TIAX report.[6]

	Canada - Bow River Crude	**Venezuela - Bachaquero (Maracaibo)**	**California - Kern County[a]**
Production Method	Water flooding and progressive cavity pumps	Cyclic steam stimulation-sucker rod Pumps	Steam injection and sucker rod pumps
Oil production (k bbl/day)	525	2.06	236.13
API	21	17	14
SG	0.93	0.95	0.97
Sulfur content (%)	2.9	2.4	1.4
water use for steam (bbl/ day)	NA	3500	
water injected (bbl water /bbl oil)	13	NA	
Total produced gas = GOR (scf/bbl)	1860	495	1003
Produced gas Consumed (scf/bbl)	132	495	
Produced gas exported (scf/bbl)	1728	0	1003
Electricity Produced and consumed (kWh)	all consumed	2.35	
Electricity consumed for recovery (kWh/bbl)	13		
Electricity consumed (kWh)			7.4
Electricity generated onsite (%)	100	100	4310.8
Electricity produced (kWh)			319
Natural gas consumed for steam generation (scf/bbl)	not given	246	3778
Natural gas consumed for electricity (scf/bbl)	not given	not given	
Water content (%)	85	39	85
WOR (bbl water/ bbl oil)	5.67	0.64	5.67
Steam produced and consumed =SOR (bbl water/ bbl oil)	NA	1.7	4.9
Electricity generation type on site	SCGT	SCGT	cogeneration
Efficiency of SCGT (%)	33.1	33.1	not given

a- Pipeline natural gas is consumed at the cogeneration plant

Table S13. The study crudes, method of recovery, and data collected from TIAX report.[6]

	Canada - Bow River Crude	**Venezuela - Bachaquero (Maracaibo)**	**California - Kern County***
Production Method	Water flooding and progressive cavity pumps	Cyclic steam stimulation-sucker rod Pumps	Steam injection and sucker rod pumps
TIAX calculations			
Energy for pumping oil and water (kWh/bbl fluid)	4.1	1.109	not given
Energy for pumping oil (kWh/bbl oil)	8.5	1.82	7.39
Energy for steam generation (kWh/bbl water)		0.31	
Energy for steam generation (kWh/bbl oil)		0.53	
Recovery Emissions (g CO_2 eq./MJ)	1.1	1.1	11.6
Venting/Flaring Emissions (g CO_2 eq./MJ)	1.8	1.8	0.6
Total recovery emissions (excld. transport.)(g CO_2 eq./MJ)	2.8	10.3	12.2
Transportation Emissions – PADD 3(gCO_2 eq./MJ)		0.24	
Transportation Emissions - PADD 2(gCO_2 eq./MJ)	0.92		
Transportation Emissions -California (gCO_2 eq./MJ)			0.3
Average Transportation Emissions (gCO_2 eq./MJ)	0.92	0.24	0.3
WTR emissions (g CO_2 eq./MJ)	3.72	10.54	12.5
Electricity Credit (Btu/ MMBtu) from TIAX Table 5-1	0	0	195089

Table S14. Emissions from transportation of crude oil to the refineries according to TIAX compared with OPGEE default value

Crude Oil	Destination	Transportation Emissions g CO_2 eq. /MJ
Alaska	California	0.73
California Heavy	California	0.1
Texas	PADD 2	0.61
Texas	PADD 3	0.04
Canada Heavy	PADD 2	0.92
Iraq	PADD 3	1.12
Iraq	California	1.29
Mexico	PADD 3	0.11
Mexico	California	0.3
Nigeria	PADD 3	0.78
Saudi	PADD 2	1.6
Saudi	PADD 3	1.01
Saudi	California	1.17
Venezuela	PADD 3	0.24
	Average[a]	**0.72**
	OPGEE default	**0.89**

a – this is an arithmetic average of the transportation emissions without consideration of the volumetric portion of the imported crude oils

Table S15. Fugitive emissions calculated by OPGEE

Crude Oil	Total fugitives ($g\ CO_2$ eq./MJ)
Iraq-Basrah-Medium	0.059
Venzuela Bachaquero	0.077
Mexico- Cantarell	0.082
Nigeria-Escravos	0.140
Saudi- Medium	0.154
US-Gulf Coast-WTI	0.661
US- Alaska	1.762

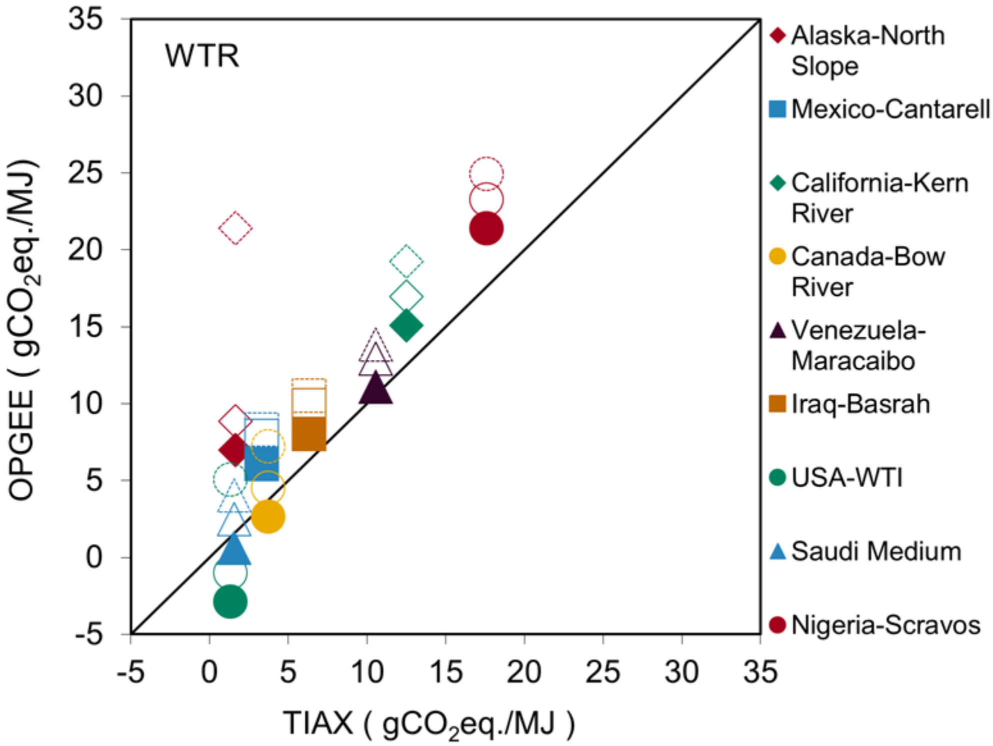

Figure S6. Comparison of WTR emissions predicted by OPGEE with inputs from TIAX against TIAX report.

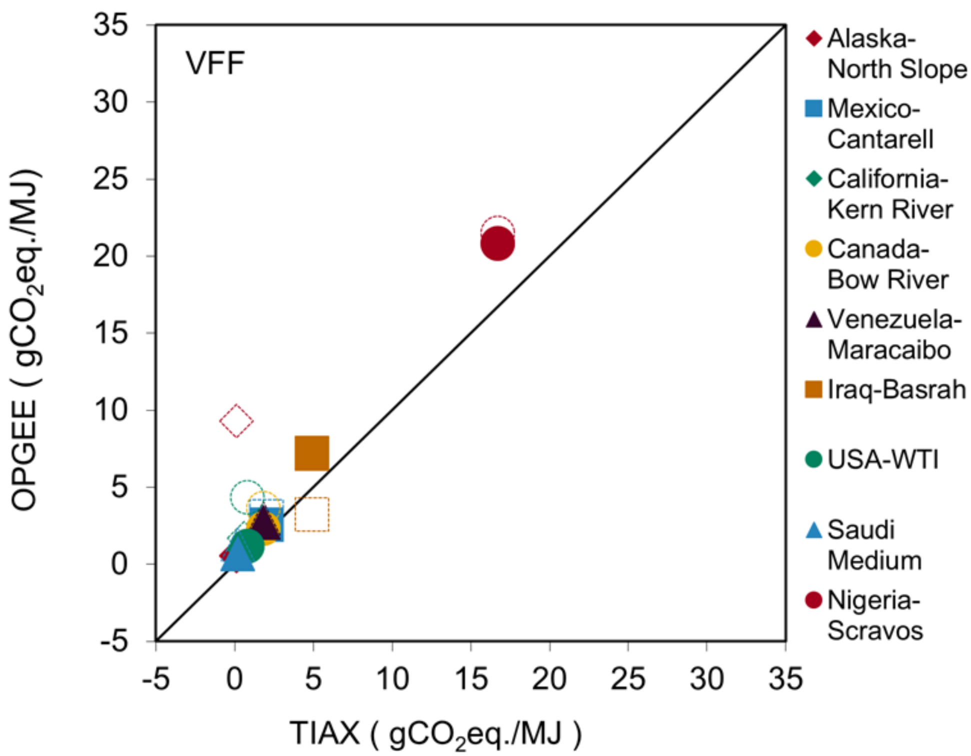

Figure S7. Comparison of VFF emissions predicted by OPGEE with inputs from TIAX and VFF emissions from TIAX report.

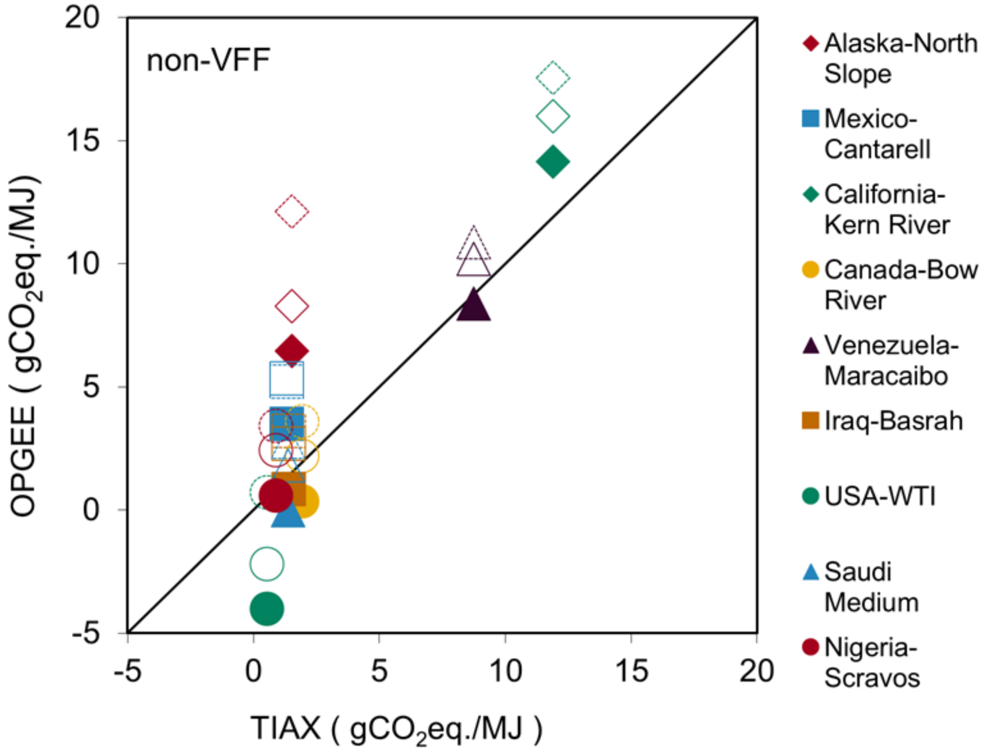

Figure S8. Non-VFF emissions calculated by OPGEE with inputs from TIAX vs. non-VFF emissions reported by TIAX

S2.3. Energy-Redefined 2010 (ER)[7]

Table S16 to Table S18 present data collected from the ER report. Figure S9 to Figure S11 show detailed results of the comparison. ER does not include, emissions from construction activity, freight or personal transportation, buildings, well workovers and testing, exploration and seismic activities, and changes in land use.

S2.3.1. Input values

A number of general considerations regarding ER input values are described below.

First, the water oil ratio (WOR) is not given by ER and OPGEE's default value is used in place of reported data. This is a key uncertainty, because WOR is a significant driver of emissions intensity.

Second, it is not clear how ER used the initial reservoir pressure in its model. We used OPGEE default average pressure which is approximated based on the reservoir depth instead.

Third, the ER model boundary is from well to refinery output gates. We used ER data on energy consumption for refining of crude oils to back-calculate WTR emissions.

Fourth, for the case of Cantarell oil field , ER did not provide with the rate of nitrogen injection and the energy required for nitrogen separation from air. OPGEE v1.1 Draft A does not have any default value for energy requirement for nitrogen separation. We used the default value from OPGEE v1.1 Draft B which is taken from Kuo et al.[8]

S2.3.2. Results and Discussion

Figure S9 compares WTR emissions reported by ER against OPGEE with inputs from ER. For the case of Dacion, it is not clear whether ER modeled a conventional or unconventional method of recovery. We used both steam flooding and default method of recovery of OPGEE to study this case (Dacion A and B respectively). This figure shows that in general at each step of comparison the results of OPGEE become closer to those of ER. The case of Iran – Kupal and Dacion B are exceptions. The estimate of WTR emissions for Iran - Kupal and Dacion B by ER are significantly higher than OPGEE estimates. For most of other oil fields the WTR emissions estimated by OPGEE are higher than the estimations of ER. For the cases of Duri, Dacion A , and Bu Attifel, WTR estimates of OPGEE are significantly higher than ER.

Figure S10 compares the non-VFF emissions estimated by ER against OPGEE with inputs from ER. In first and second steps of the analysis, general agreement in non-VFF emissions between OPGEE and ER is poor. In particular, OPGEE non-VFF emissions estimates for Duri and Dacion A are significantly higher. ER referred to use of steam flooding as the recovery technique for the case of Duri. The OPGEE default SOR of 3 bbl water/bbl oil was used in both cases. If instead we reduce the SOR to 0.5 bbl water/bbl oil then the non-VFF emissions for Dacion A and Duri are reduced from 19.60 and 17.16 g CO_2 eq./ MJ oil in the third step to 8.11 and 5.85 g CO_2 eq/MJ oil respectively. The non-VFF emissions from ER report for Dacion and Duri are 1.0 and 1.7 g CO_2

eq./MJ oil respectively which are still significantly lower than OPGEE estimates, even with an atypically low SOR. Clearly there is divergence in how these fields are modeled. For other oil fields, especially at the third step of analysis, the non-VFF emissions estimated by OPGEE are closer to those of ER 2012.

Figure S11 shows the comparison of OPGEE VFF emissions to ER VFF emissions. Here we see also very poor alignment between the models, but in the opposite direction OPGEE emissions are much lower than those of ER. This shows that the significant discrepancy between OPGEE and ER estimates for emissions from Kupal noted above is not due to the non-VFF emissions but because of significantly different flaring rates.

Table S16. Input data taken from ER report.[7]

Oil fields	Production volume (kbpd)	API gravity	Depth (ft)	Start Year	Initial pressure (psig)	GOR
Mexico - Cantarell	772	21.5	8528	1981	941	887
US- Mad Dog	65	42	20190	2005	12141	322
Canada - Hibernia	139	35	12500	1984	7517	2200
Iran-Kupal	55	32	10500	1970	2191	3800
Saudi- Ghawar	5319	34	6920	1951	3957	570
Venezuela -Dacion	42	20	6000	1953	2600	750
Libya - Bu Attifel	340	40.7	14000	1972	7209	2400
Russia, Samotlor	600	34.2	5800	1970	2255	240
Indonesia Duri	233	22	770	1958	267	1200
UK- Forties	63	37	7000	1975	3128	400
Norway-Gulfask	79	41	5709	1987	2551	700

Table S17. Emissions (g CO_2 eq./MJ) for refining of a crude oil in European refineries vs API gravity. Data from ER.[7]

Emissions	API
3.17	60.1
4.42	50.3
5.06	45.3
5.73	40.3
6.32	35.4
6.96	30.4
7.63	25.2
8.24	20.4

Table S18. Outputs of OPGEE with inputs from ER.[7]

		Dacion A	Dacion B	Mad Dog	Hibernia	Kupal	Ghawar	Cantarell	Bu Attifel	Samotlor	Duri	Forties	Gulfask
Step1	WTR	22.39	8.92	5.26	5.81	9.78	4.32	7.36	11.68	7.37	21.45	5.21	4.34
	VFF	2.79	2.79	0.91	3.18	6.78	1.27	2.03	8.47	3.57	4.12	1.91	1.23
	non-VFF	17.97	6.13	4.35	2.63	3.00	3.05	5.33	3.21	3.80	17.33	3.30	3.11
Step 2	WTR	22.08	8.59	5.22	5.63	9.19	4.25	6.35	10.64	6.86	20.97	5.01	4.30
	VFF	2.48	1.85	0.87	3.00	6.19	1.20	1.86	7.43	3.06	3.64	1.71	1.19
	non-VFF	17.79	6.74	4.35	2.63	3.00	3.05	4.49	3.21	3.80	17.33	3.30	3.11
Step 3	WTR	20.27	6.78	1.99	3.58	7.25	2.42	4.49	8.46	5.06	19.22	3.18	2.50
	VFF	2.48	1.85	0.87	3.00	6.19	1.20	1.86	7.43	3.06	3.64	1.71	1.19
	non-VFF	17.79	4.93	1.11	0.58	1.06	1.23	2.63	1.04	1.99	15.57	1.47	1.31
Drilling & development and land use		1.33	1.31	2.73	1.55	1.44	1.33	1.36	1.68	1.31	1.26	1.33	1.31
Miscellaneous		0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Dacion A : OPGEE steam flooding

Dacion B : OPGEE default recovery method

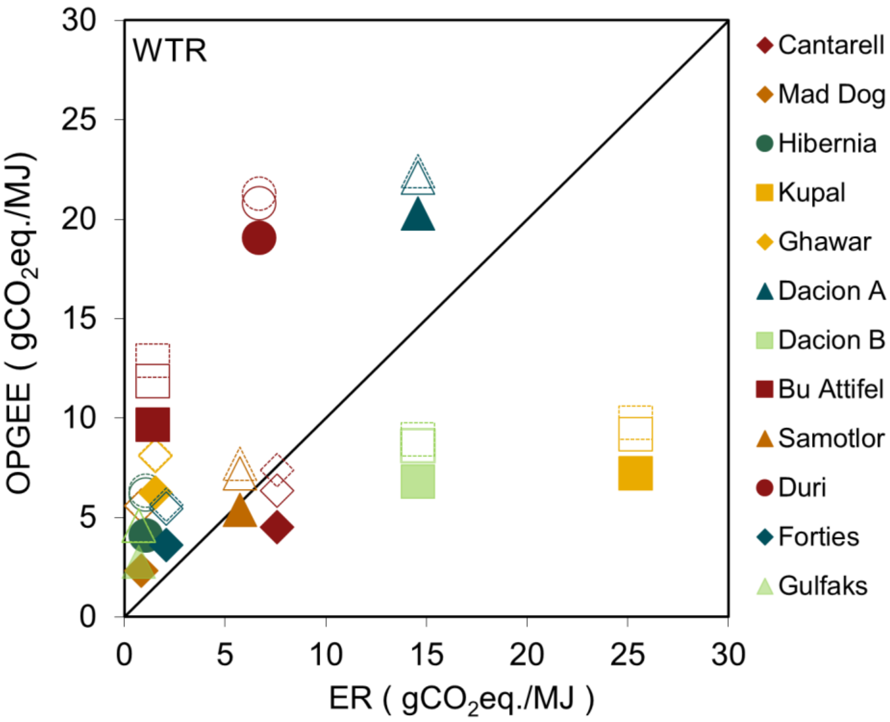

Figure S9. Comparison of WTR emissions. ER vs OPGEE with inputs from ER .

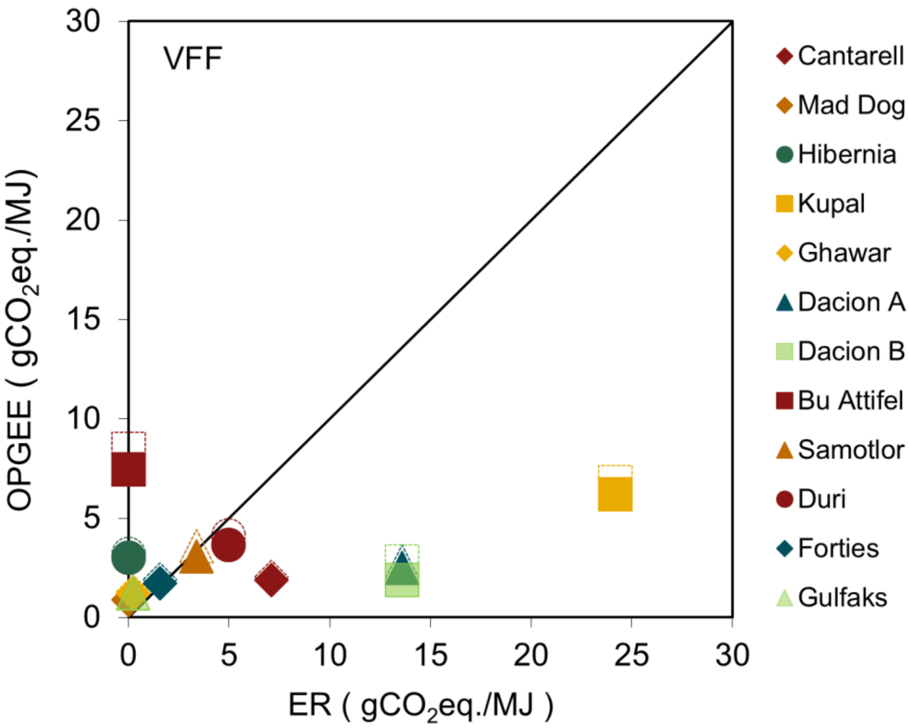

Figure S10. Comparison of VFF emissions. ER vs OPGEE with inputs from ER.

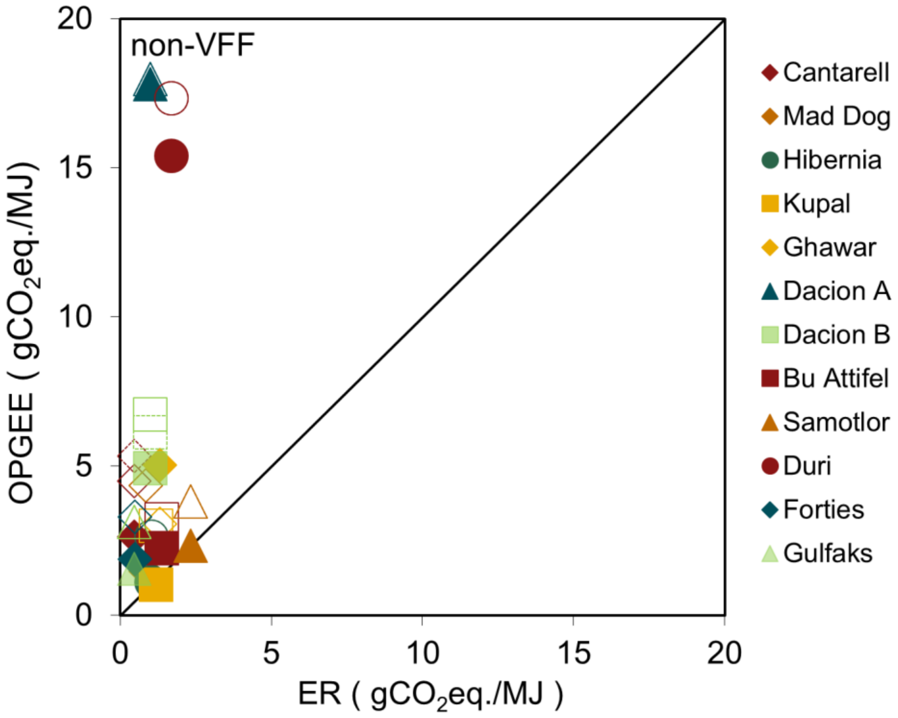

Figure S11. Comparison of non-VFF emissions. ER vs OPGEE with inputs from ER.

S2.4. Jacobs 2012[9]

The Jacobs 2012 model is similar to Jacobs 2009 model, but the focus of the study is European market. The collected data from Jacobs 2012 are documented in Table S19 to Table S27. Detailed results comparisons are given in Figure S12 to Figure S16.

S2.4.1. Transportation of crude oil

Figure S12 compares the transportation emissions calculated by OPGEE against Jacobs 2012. The overall range of the emissions from transportation of crude oils to European refineries is 0.2 to 2.1 gCO_2 eq./MJ according to Jacobs 2012. The transportation emissions for the case of Saudi Arabia is not given. We used the average value of 1.15 gCO_2 eq./MJ with error bars to represent the entire given range (0.2 to 2.1 gCO_2 eq./MJ). In order to calculate a WTR value for Jacobs 2012 to compare with OPGEE, the arithmetic average of the transportation emissions for each oil field was used. This is an arbitrary choice in absence of data and should not be given any interpretation. Figure S12 shows that OPGEE calculates lower emissions from transportation of crudes using the same pipeline and marine distances and the size of the oil tanker.

S2.4.2. Jacobs 2012 sensitivity analysis

Jacobs 2012 carried out a sensitivity analysis, using their "generic" crude oil model. Because of the noted possible differences in water re-injection energy noted above in Jacobs 2009, we wanted to examine the Jacobs 2012 treatment of water re-injection. Table S25 shows the calculated emissions for water re-injection based on the Jacobs 2012 data versus the emissions from re-injection pump in OPGEE. Figure S13 compares the emissions from energy consumption of water re-injection pumps for the case of Jacobs 2012. We compare this to OPGEE results with inputs from Jacobs 2012. Similar results were seen as above in the Jacobs 2009 comparison.

S2.4.3. Various study crudes

Table S22 shows the results of OPGEE with inputs from Jacobs 2012. Figure S13, in the main paper, compares the two models for WTR emissions. Overall, the parity chart results are concentrated around the 45° line. The error bars demonstrate the overall range of emissions that includes emissions from transportation of Canadian crude to Europe therefore it exaggerates the extent of the uncertainty as marked on the plot. The vertical error bar demonstrates the range of transportation emissions calculated by OPGEE to transport crude oil to the refineries in Europe, using input variables from Jacobs 2012 report.

Figure S15 compares the non-VFF emissions predicted by the two models. In Step 3 of the comparison, Tupi, Arab-Medium, and Ekofisk show the most level of discrepancy in predicted emissions. For all these three cases the non-VFF emissions calculated by OPGEE are less than Jacobs 2012 estimates. Comparing with other oil fields of the study crudes, Tupi is the deepest reservoir with a maximum depth of 16404 ft. This oil field has the highest reservoir pressure as well. If we assume that Jacobs 2012 did not consider the reservoir depth in calculation of the water re-injection pump, then OPGEE should calculate lesser energy demand for water re-injection. Similarly Ekofisk reservoir depth is the second highest.

For the case of Arab-Medium, OPGEE does neither model the pumping of sea water for water flooding, nor does it include thermal deaeration of water. While desalination through reverse osmosis can be modeled in OPGEE, it was not used in the analysis as Jacobs 2012 did not clearly state for which crudes they used desalination using reverse osmosis or vacuum evaporation. For the case of Jacobs 2009, we used desalination through reverse osmosis for Arab-Medium since Jacobs 2009 explicitly addressed this usage in the report. All of these factors lead us to expect lower emissions from OPGEE for Arab-Medium.

Based on the provided tables and context of the report we cannot say by certainty what portion of the produced gas is re-injected for the each of the study crudes. We know that there is gas re-injection and the portion value that Jacobs 2012 mentioned (50% or 100%) is based on the remaining gas after on-site electricity usage. OPGEE input variable for gas re-injection is the ratio of the remaining gas after vent, fugitives, and separation of C_3 and C_4 and before process usage, gas lift, and export. Due to lack of clear information and differences in gas-reinjection modeling we apply OPGEE default assumption (gas re-injection = 0 SCF/bbl). Emissions from production of crude from four oil fields are become closer to what Jacobs predicts in Step 3: Bachaquero, Mariner, Urals, and Es Sider. Jacobs 2012 reported GOR of 90 to 250 scf/bbl oil for these oil fields. These oil field have lower GOR compared with others with GOR ranging from 330 to 1000 scf/bbl oil .

Figure S16 compares the VFF emissions predictions of the two models. In Step 1 of the comparison the flaring efficiency is 95% which is OPGEE's default. In Step 2 and Step 3 the efficiency of 99% stated in the Jacobs report is applied. Both models get flaring rates from NOAA data.[10] In general, OPGEE predicts higher values for VFF emissions. The only case which does not follow the pattern is the case of Urals. The OPGEE suggested value for flaring based on NOAA for Russia is 370 scf/bbl oil. However, the GOR which is given by Jacobs 2012 for this oil field is 200 scf/bbl oil. The flaring rate therefore had to be reduced to 196 scf/bbl oil to avoid gas imbalance errors in OPGEE. This is an important subtlety: GOR can change with time, and it is important that the FOR and GOR are consistent with each other.

Table S19. GHG emissions from transportation of crude oil. Data from Jacobs 2012 report.[9]

Oil Field	Refinery	Emissions from transportation of crude oil (gCO_2 eq./MJ crude oil)
Venezuela	Italy	0.98
Venezuela	France	0.87
Venezuela	Germany	1.06
Russia	Italy	1.25
Russia	France	1.32
Russia	Germany	1.37
North Sea-Forties	Italy	0.61
North Sea- Forties and Ekofisk	France	0.22
North Sea- Forties and Ekofisk	Germany	0.33
Nigeria	Italy	0.84
Nigeria	France	0.575
Nigeria	Germany	0.735
Libya	Italy	0.345
Libya	France	0.61
Libya	Germany	0.795
Iraq	Italy	0.515
Iraq	France	0.9
Iraq	Germany	1.08
Iran	Italy	0.71
Iran	France	1.12
Iran	Germany	1.33
Brazil	Italy	0.8
Brazil	France	0.775
Brazil	Germany	0.94

Table S20: Carbon intensity of production of diesel fuel from crude oil. Data from Jacobs 2012.[9]

	Transport and delivery (gCO_2 eq./MJ diesel)	Delivery (gCO_2 eq./ MJ fuel)	Transport to refinery (gCO_2 eq./ MJ diesel)	Conversion factor (MJ crude / MJ fuel)	Transport to refinery (gCO_2 eq./ MJ oil)	Refinery Location
Saudi Arabia	2.30	0.42	1.88	1.05	-	France
Saudi Arabia (>=)	2.00	0.42	1.58	1.05	1.50	Germany
Saudi (>=)	2.00	0.42	1.58	1.05	1.50	US Gulf Coast
Iran	2.00	0.42	1.58	1.05	1.50	France
Iran	2.00	0.42	1.58	1.05	1.50	Germany
Iraq	1.60	0.42	1.18	1.05	1.12	France
North Sea 3 (Mariner)	2.30	0.42	1.88	1.05	-	US Gulf Coast

The sign, >=, indicates that the data value can be larger. These data were read from the related figure in Jacobs 2012 and the quality of the diagram is a cause of this uncertainty.

Table S21. Carbon intensity of producing diesel fuel from crude oils. Data from Jacobs 2012.[9]

	Transport and delivery (gCO_2eq./MJ gasoline)	Delivery (g CO_2eq./ MJ fuel)	Transport to refinery (g CO_2 eq./ MJ gasoline)	conversion factor MJ crude / MJ fuel)	Transport to refinery (g CO_2 eq./ MJ oil)	Location
Saudi Arabia	2.30	0.42	1.88	1.05	1.79	France
Saudi Arabia	1.70	0.42	1.28	1.05	1.22	Germany
North Sea 3 (Mariner) (<=)	1.40	0.42	0.98	1.05	0.93	Germany
Iran	2.00	0.42	1.58	1.05	1.50	France
Iran	2.00	0.42	1.58	1.05	1.50	Germany
Iraq	2.00	0.42	1.58	1.05	1.50	France

The sign, <=, indicates that the data value can be lower. These data were read from the related figure in Jacobs 2012 and the quality of the diagram is a cause of this uncertainty.

Table S22. Inputs for OPGEE default, OPGEE with Jacobs 2009 generic crude inputs, and OPGEE with Jacobs 2012 generic inputs.[9]

	OPGEE default	OPGEE with Jacobs 2009 generic input	OPGEE with Jacobs 2012 generic inputs
Field depth (ft)	7240	5000	5000
Reservoir Pressure (psi)	1557	1500	1500
API gravity	30	30	30
GOR (scf/bbl)	908	1000	1000
WOR (bbl water/bbl oil)	4.31	10	10
Fraction of remaining gas re-injected	0	0.536	0.538
Flaring to oil ratio (scf/bbl)	182	10	10
Venting - to oil ratio (scf/bbl oil)	0	5	1
Fraction of water re-injected	1	1	1
Friction factor	0.02	0.1	0.02
Pipe diameter	2.8	3	3
Flaring Efficiency (%)	95	99	99
Miscellaneous emissions (g CO_2 eq./MJ oil)	0.5	0.57	0.54

Table S23. Emissions from recovery of crude oil (transportation emissions excluded). Step 3 assumption used .

	OPGEE default	Jacobs 2009 generic	Jacobs 2012 generic	OPGEE with Jacobs 2009 generic inputs	OPGEE with Jacobs 2012 generic inputs
Total recovery emissions (g CO_2 eq./MJ)	6.31	7.35	6.57	6.30	5.82
VFF (g CO_2 eq./ MJ)	3.40	0.68	0.64	1.52	1.26
non-VFF recovery emissions (g CO_2 eq./MJ)	2.91	6.67	5.93	4.78	4.56

Table S24.Jacobs 2012 sensitivity analysis using the generic crude production model . Emissions in gCO_2 eq./MJ. Data from Jacobs 2012.[9]

Reservoir Depth (ft)		5000	
WOR	3	10	15
Lifting	0.26	1.30	1.91
Water re-injection	0.66	2.29	3.43
Gas-reinjection	0.39	0.44	0.39
water treatment	0.22	0.61	0.88
Gas treatment	1.50	1.54	1.50
Venting	0.66	0.62	0.61
Flaring	0.04	0.09	0.05
Miscellaneous Energy	0.40	0.52	0.79

Reservoir Depth (ft)		10000	
WOR	3	10	15
Lifting	1.42	3.87	5.44
Water re-injection	0.66	2.20	3.30
Gas-reinjection	0.39	0.35	0.35
water treatment	0.22	0.61	0.88
Gas treatment	1.50	1.54	1.53
Venting	0.65	0.57	0.60
Flaring	0.05	0.05	0.10
Miscellaneous Energy	0.39	0.81	1.10

Reservoir Depth (ft)		20000	
WOR	3	10	15
Lifting	2.31	6.21	8.88
Water re-injection	0.70	2.16	3.22
Gas-reinjection	0.40	0.39	0.40
water treatment	0.13	0.57	0.90
Gas treatment	1.58	1.47	1.10
Venting	0.58	0.60	0.90
Flaring	0.08	0.10	0.10
Miscellaneous Energy	0.49	1.00	1.50

Table S25. Comparing emissions from energy consumption of water re-injection pump for the Jacobs generic crude model against OPGEE with inputs from Jacobs 2012 generic crude model (gCO_2 eq./MJ crude oil)

Reservoir Depth (ft)		**5000**			**10000**			**20000**	
WOR	3	10	15	3	10	15	3	10	15
Water re-injection-Jacobs 2012	0.66	2.31	3.46	0.67	2.22	3.33	0.71	2.18	3.25
Deaeration - Jacobs 2012	0.26	0.85	1.28	0.26	0.85	1.28	0.26	0.85	1.28
Water re-injection pump Jacobs 2012	0.41	1.46	2.18	0.41	1.37	2.05	0.45	1.33	1.97
Water re-injection pump-OPGEE with Jacobs input	0.00	0.37	1.27	0.00	0.00	0.00	0.00	0.00	0.00

Table S26. Inputs from Jacobs 2012 report for study crudes (gCO_2 eq/MJ).[9]

	Venezuela Bachaquero	**Saudi Arab Medium**	**Nigeria Bonnty Light**	**Iraq Kirkuk**	**Norway Ekofisk**	**Libya Es Sider**	**UK Forties**	**Iran Sirri**	**Russia Urals**	**Brazil Tupi**	**UK Mariner**
Crude API	10.72	31.1	32.88	36.49	37.53	36.70	40.30	32.20	31.78	28.50	11.86
Sulfur (wt%)	2.78	2.56	0.16	0.13	0.22	0.37	0.56	1.81	1.32	0.38	1.29
Crude LHV (GJ/bbl)	6.34	5.76	5.82	5.72	5.69	5.71	5.6	5.77	5.8	5.93	6.38
Reservoier depth -min (ft)	1200	4800	4900	2000	8200	6050	7000	7050	5294	13123	5140
Reservoier depth -average (ft)	5100	6100	8700	7500	10000	7100	9000	7525	5864	14764	5728
Reservoier depth -max (ft)	11500	6900	14200	10300	13800	8200	11000	8000	6435	16404	6317
Reservoir temperature (°F)	200	200	200	200	200	200	200	207	200	200	115
Reservoir pressure (psi)	500	3000	4300	3000	5000	1000	2814	4200	1375	8232	2151
GOR (scf/bbl)	90	650	840	600	500	250	450	330	200	1000	185
WOR (bbl/bbl)	0.25	2.3	2.0	2.0	2.00	2.00	2.00	2.00	3	2.00	5.00

Table S27. OPGEE results with inputs from Jacobs 2012 for study crudes .Jacobs 2012 results are also given for comparison (gCO_2 eq/MJ)

	Venezuela Bachaquero	Saudi Arab Medium	Nigeria Bonny Light	Iraq Kirkuk	Norway Ekofisk	Libya Es Sider	UK Forties	Iran Sirri	Russia Urals	Brazil Tupi	UK Mariner
Jacobs 2012											
VFF Emissions	1.42	0.82	7.66	4.77	0.47	2.58	0.43	3.28	4.11	1.02	0.23
WTR emissions	6.59	4.92	11.82	8.53	4.03	5.76	3.83	6.90	8.03	5.63	4.23
non-VFF emissions (incl. transport)	5.17	4.10	4.16	3.76	3.56	3.18	3.40	3.62	3.92	4.61	4.00
OPGEE with inputs from Jacobs 2012											
VFF inputs from Jacobs 2012-step 1	1.54	1.35	10.32	5.79	1.06	4.11	2.06	4.44	3.28	1.78	1.64
WTR inputs from Jacobs 2012- step 1	7.46	4.26	14.02	9.24	3.97	7.69	5.22	7.74	7.54	4.91	5.51
non-VFF inputs from Jacobs 2012 - step 1	5.92	2.91	3.70	3.45	2.91	3.58	3.16	3.30	4.26	3.13	3.87
VFF inputs from Jacobs 2012-step 2	1.33	1.26	8.53	4.84	1.01	3.44	1.82	3.71	2.76	1.66	1.42
WTR inputs from Jacobs 2012- step 2	8.44	5.45	13.52	9.58	5.17	8.38	6.27	8.30	8.35	6.02	7.07
non-VFF inputs from Jacobs 2012 - step 2	7.11	4.19	4.99	4.74	4.16	4.94	4.45	4.59	5.59	4.36	5.65
VFF inputs from Jacobs 2012-step 3	1.33	1.26	8.53	4.84	1.01	3.44	1.82	3.71	2.76	1.66	1.42
WTR inputs from Jacobs 2012- step 3	6.97	4.12	11.84	8.11	3.52	7.02	4.80	6.95	7.03	4.11	5.76
non-VFF inputs from Jacobs 2012 - step 3	5.64	2.86	3.31	3.27	2.51	3.58	2.98	3.24	4.27	2.45	4.34

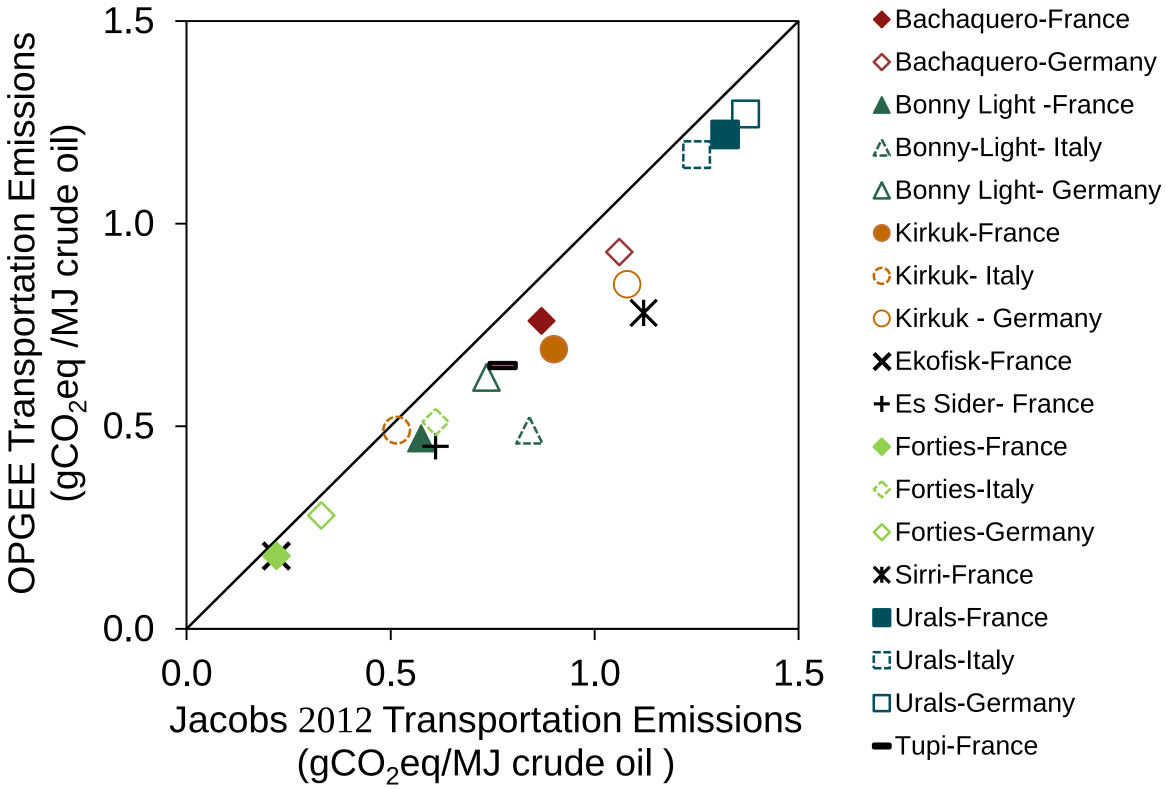

Figure S12.Emissions from transportation of study crudes

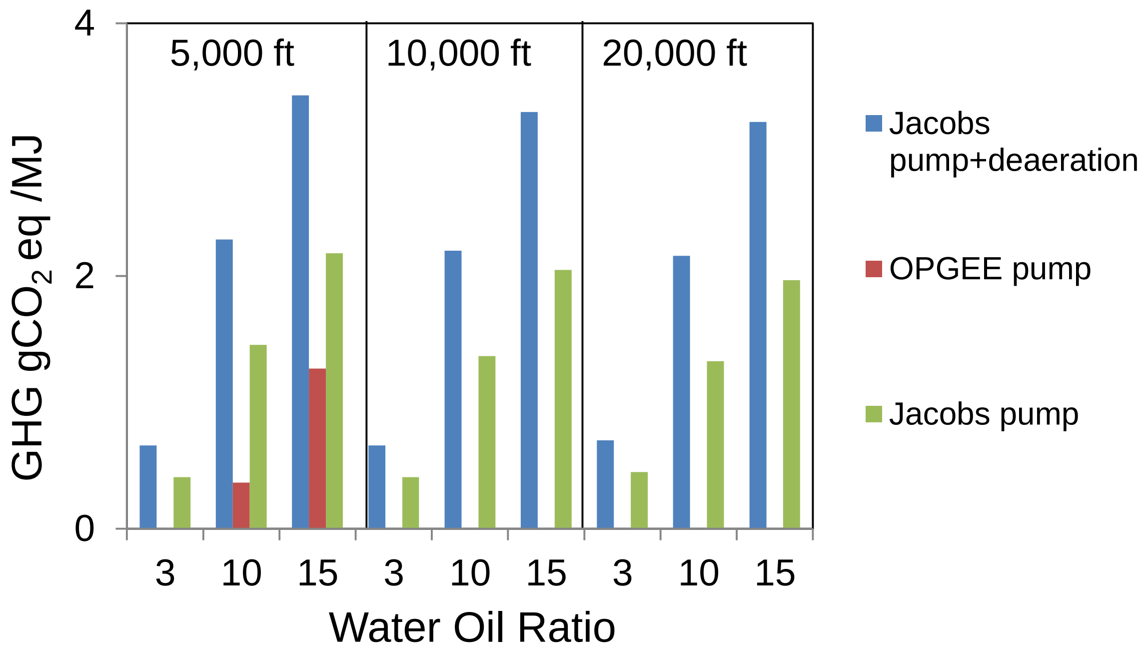

Figure S13.Comparison of the Jacobs 2012 generic crude model against OPGEE with Jacobs 2012 generic crude model inputs for sensitivity to reservoir depth and WOR. Emissions from energy consumption of water re-injection pumps are compared.

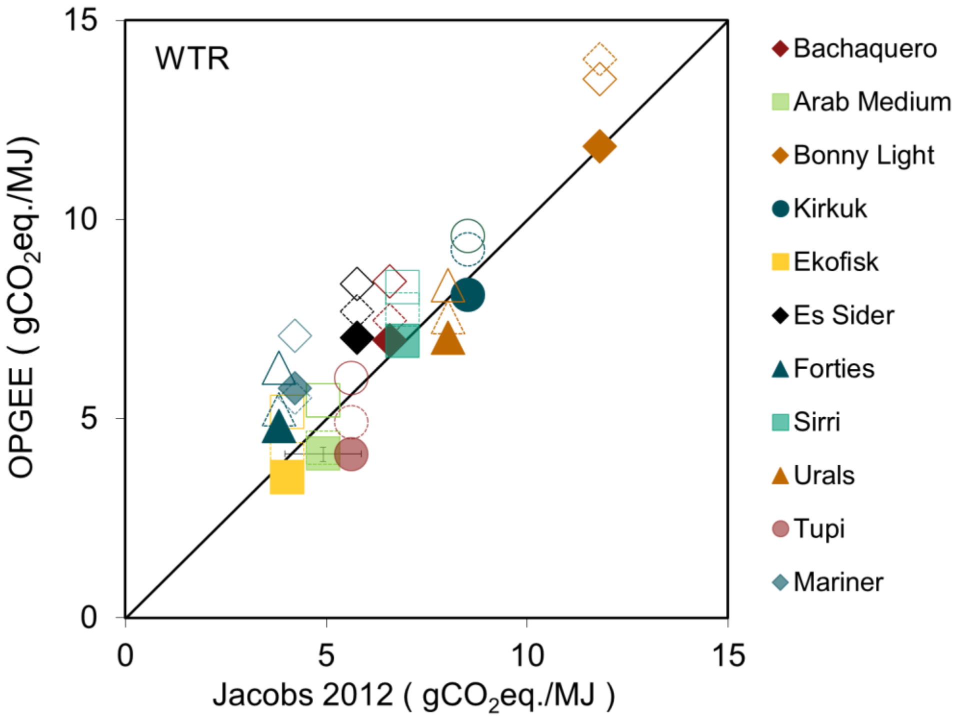

Figure S14. Comparison of WTR emissions estimated by Jacobs 2012 against OPGEE with inputs from Jacobs 2012 (includes transportation emissions)

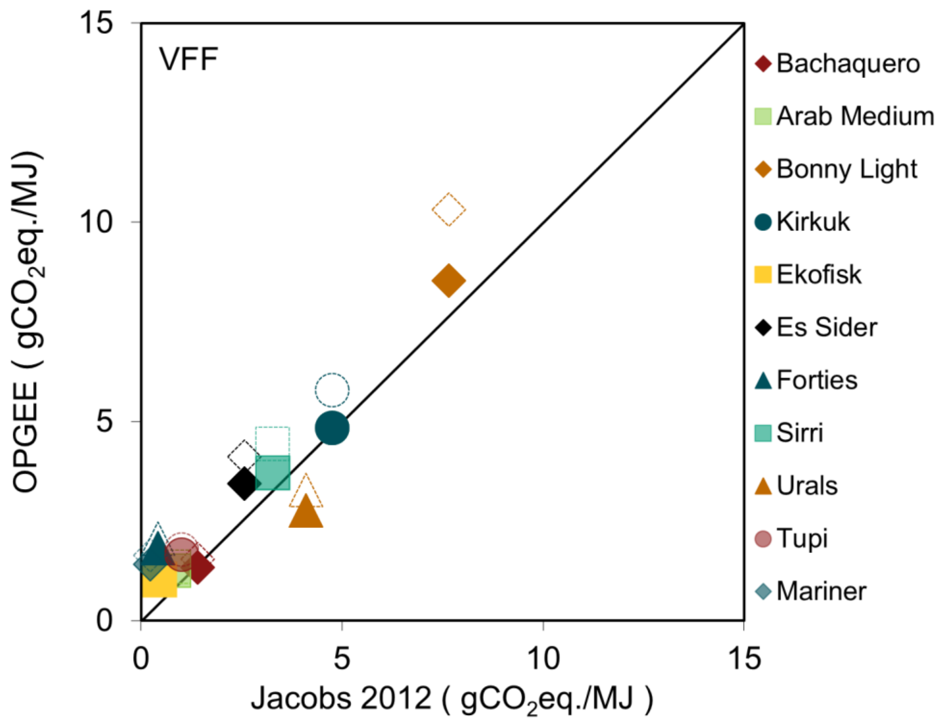

Figure S15. Comparison of non-VFF emissions estimated by Jacobs 2012 with OPGEE with inputs from Jacobs 2012 (includes transportation emissions)

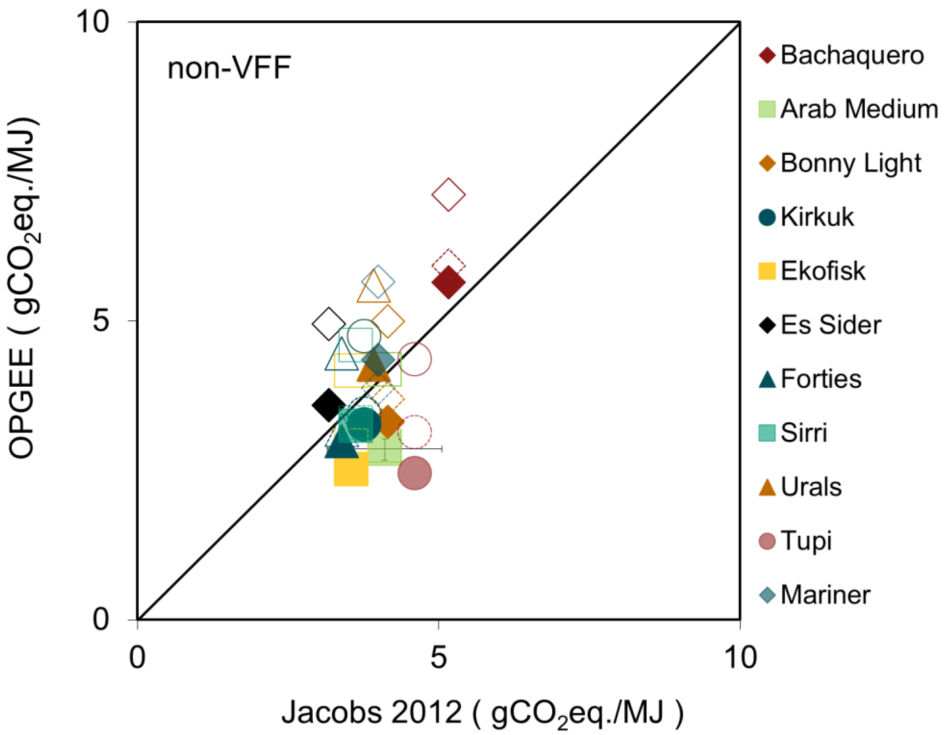

Figure S16. Comparison of VFF emissions predicted by Jacobs 2012 compared with OPGEE.

S3. Well-to-wheel transport LCA models

S3.1. GREET[11]

Results from GREET 1_2012_rev2 were gathered from sheet "Petroleum" cells B98:C109. Emissions from both crude oil recovery and transport were gathered. These were converted to $gCO_2eq.$ using GREET GWPs (identical to OPGEE GWPs).

While the emissions reported for "CH_4: Non-combustion" in row 109 of the "Petroleum" worksheet appear to be associated with the transport columns (e.g., columns C and D), these are in fact emissions associated with methane leakage from production (confirmed by personal communication A. Burnham, Argonne National Laboratory).

S3.2. GHGenius[12]

GHGenius v.4.03a was compared to OPGEE for United States conventional crude oil production. In order to model crude oil production in the United States, the following changes to the model defaults were made:

- Location was changed to "USA" on the model front sheet.
- The fraction of tonnage of US crude production was changed to 100% onshore conventional production (sheet "Crude Production" B27-G27)
- The petroleum flows were changed to be 100% US crude. On the "Petroleum Flow" worksheet, the sources of Western US crude oil, Central US crude oil and Eastern US crude oil were changed to "User input" and then set to 100% US crude.
- The heavy and light refined products were changed on the "Petroleum Flow" sheet to "User Input" and then to 99.9% US crude, 0.01% Mexico crude. This change was suggested in personal communication with Don O'Connor (developer of GHGenius) to prevent a divide by zero error in the model.

The model is then run and emissions from "Feedstock recovery", "Gas leaks and flares", and "Feedstock transmission" were gathered from the "LHV results" sheet. The results in volumetric or energy basis reported in the main paper were gathered by following formulas to appropriate energy or fugitive emissions sheets.

The comparison case in OPGEE was run by setting OPGEE to default settings for US crude oil production.

S4. NETL[13]

Only limited data are available from the NETL report. The input data collected from the NETL report production well diameter, rate of flaring, and venting emissions. Flaring and venting are reported as mass of gas per mass of total HC produced. The portion of natural gas, NGL, and crude oil produced as well as the heating values of the products for each country of the study are provided in the report. We used these data to convert the rate of flaring and vents from mass of gas per mass of hydrocarbon produced to mass of gas per mass of crude oil produced. NETL does not give the emissions from transportation of crude oil to refineries on the basis of produced crude oil. Therefore the transportation emissions are excluded in OPGEE-NETL comparison. The emissions in this section are based on the barrel of crude oil produced and processed ready for transport. Figure S17 compares the emissions estimated by two models. This figure shows that OPGEE estimates for Algeria are significantly higher than NETL.

To examine possible causes of this discrepancy, we construct another case where we assume that the rate of flaring and vents could actually be based on the mass of the crude oil produced only. In this case, the OPGEE estimates improve in alignment, especially for the case of Algeria becomes very close to the value that NETL reports (see Figure S18). Except for Algeria and US, the mass of crude oil produced is 80 to 99 percent of total hydrocarbon mass. For Algeria, NETL reports that crude oil production contributes 32.8 percent of the total hydrocarbon. After this adjustment, OPGEE estimates are close to NETL yet in all cases OPGEE estimates are slightly higher than NETL.

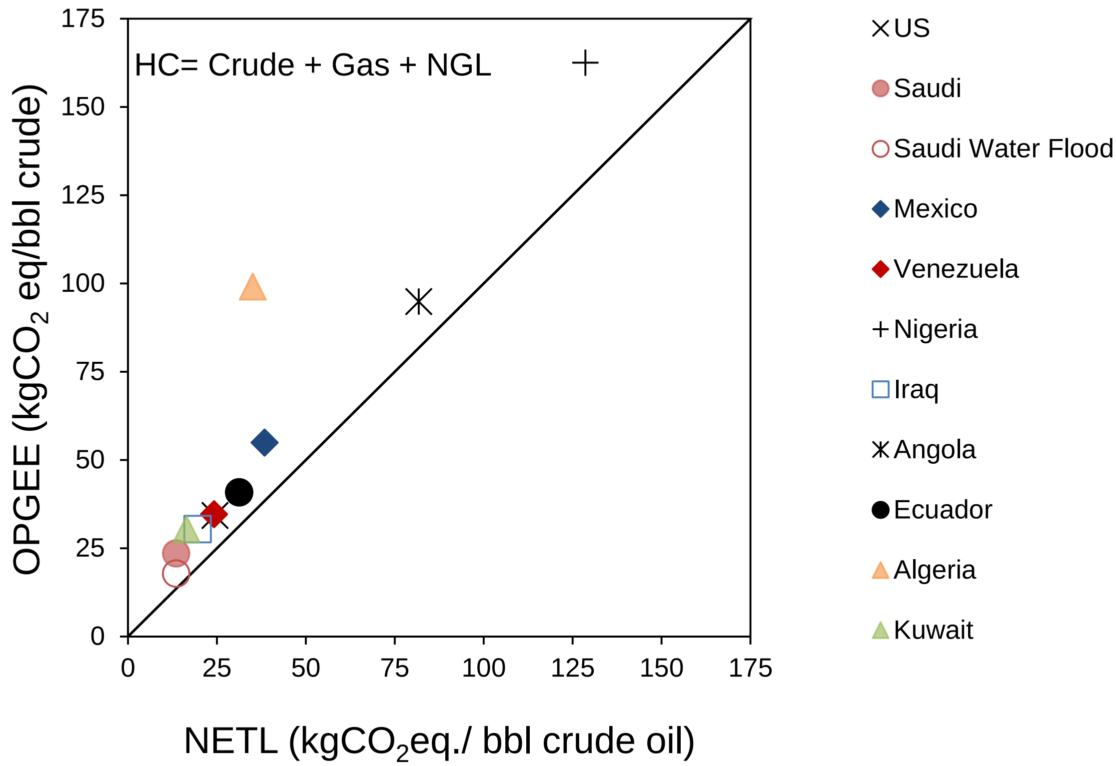

Figure S17. Comparison of emissions NETL against OPGEE with inputs from NETL. Saudi water flooding case is assumed to be natural drive.

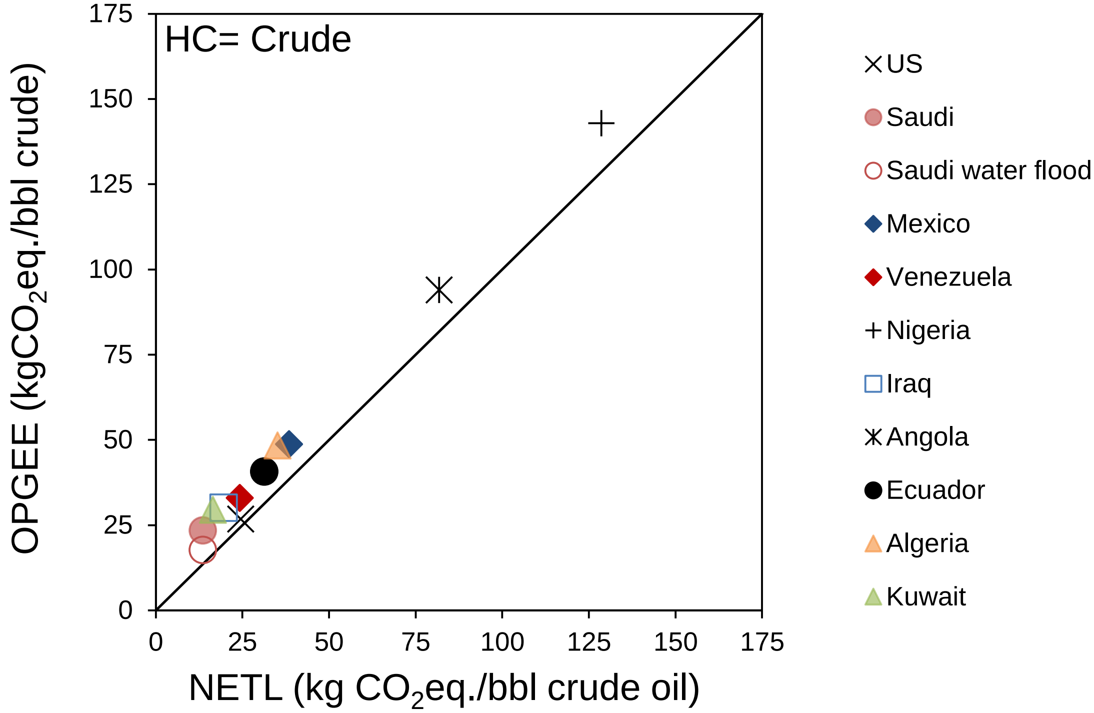

Figure S18. Comparison of emissions NETL against OPGEE with inputs from NETL. It is assumed that total hydrocarbons produced consists of only crude oil. Saudi water flooding case is assumed to be natural drive.

S5. References

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