Supporting Information for:

"Evaluating environmental governance along cross-border electricity supply chains with policy-informed life cycle assessment: the California-Mexico energy exchange"

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Description of supplement

The **Life Cycle Assessment** section of this supplement provides details on the methods used to estimate life cycle GHG, water withdrawal and air quality impacts per kWh of electricity exported from Mexico to California. Reference to a parameter as a range of values indicates that the parameter in question was part of the sensitivity analysis. The **Sensitivity Analysis** section describes the parameters varied and their assumed input distribution and values. This supplement contains 26 pages (S1-S26), 10 tables (**Table S1** – **Table S10**) and 2 figures (**Figure S1** and **Figure S2**)

Life Cycle Assessment

Natural Gas Extraction

Equation (S1) is used to compute the impact of category i ($Impact_i$) associated with natural gas well preparation and extraction:

(S1) $$Impact_{extr,i} = \frac{HR*CoProd}{HC*(1-F)} * \left(\frac{\frac{Events}{well\ lifetime} * IF_{well,i}}{EUR} + IF_{prod,i} \right)$$

Equation (S1) takes the environmental impact factor of a given category ($IF_{well,i}$) applied a given number of times over the life-time of a well, normalizes it by Estimated Ultimate Recover (EUR), and adds the corresponding production stage impact factor ($IF_{prod,i}$). This impact is then adjusted to account for allocation of natural gas liquid (NGL) coproducts ($CoProd$), the expected fraction of pipeline-grade produced gas that reaches the power plant (F), the heat content of the gas (HC), and the efficiency of the power plant (HR).

Well completion events are assumed to occur once per lifetime of a well, with a recompletion frequency of 0.01/year and a 30 year well lifetime as in Heath et al 2014[1]. The EUR values used in the model are basin-specific and based on EIA and USGS assessments of existing and emerging gas resources[2–5] (shown in **Table S1**). Impact is allocated to coproducts based on prior estimates of the weight fraction of natural gas liquids (NGLs) comprising the gas in each basin[6,7] (shown in **Table S3**). A production-weighted average is computed for each basin-specific parameter using the production figures given in **Table S2** and a generation-weighted average is computed for the HR value used in our model. We assume an HC value of 1,060 Btu/Scf, taken from an emissions inventory report for the San Juan and Permian basins[6]. When they differ by natural gas extraction type (i.e. unconventional vs. conventional gas) weighted average $IF_{well,i}$ and $IF_{prod,i}$ values are used to estimate of the share of natural gas produced in each basin from unconventional wells. The value of F is obtained from estimates of pipeline transmission and storage losses, described in more detail below.

Direct emissions of CO_2 during well-site construction, produced water disposal, and well operation (including gas flaring) are calculated from the values and assumptions in Allen et al[8] and Logan et al[9] to obtain the $IF_{prod,i}$ values summed over in equation (S1).

(S2) $IF_{k,i} = EF_k * ER * MW * GC_i * GWP, i \in (CO_2, VOC), k \in (well, prod)$

CO_2-eq/VOC emissions from leaking and venting during well completion/recompletion and liquids unloading sources are computed with equation (S2), which assumes an emissions factor for the given stage (EF_k for well preparation or production), an emissions reduction efficiency (ER), and basin-specific gas composition parameters like molecular weight (MW), compound share (GC_i for compound i) and global warming potential (GWP). Allen et al's[8] range of estimates of gas venting from well completions and the EPA estimate of 36.7 MScf/2.54 MScf vented per completion/workover of conventional wells[10] are used as the value of EF_k. ER values between 0 and 76% are assumed from EPA estimates of venting from conventional wells[10] and are assumed to be 0% for fractured wells (since estimates of venting from Allen et al[8] already account for emissions reductions) . We make use of an analysis of an American Petroleum Institute and American Natural Gas Association survey of liquids unloading from 43,000 conventional and unconventional wells with and without plunger lifts[11] provided in a harmonization study and sensitivity analysis by Heath et al[12] to produce a range of plausible CO_2-eq emissions from liquids unloading. (the distribution of emissions values from liquids unloading used in the sensitivity analysis is shown in **Table S4**). Emissions from pneumatic devices and fugitive components are taken from ranges of values modeled by Allen et al[8,13].

Estimates of $IF_{well,i}$ in (S1) above for water withdrawals in the study basins are taken from harmonized values of water withdrawn for drilling and hydraulic fracturing provided in Meldrum et al (shown in **Table S5**). $IF_{prod,i}$ for water is assumed to be negligible for both conventional and unconventional natural gas wells, a reasonable assumption since the vast majority of water withdrawn during natural gas extraction is for well completions and recompletions.

Ranges of estimates of emissions of air pollutants per well and emissions per well-year given in several prior studies[14,15] are used to produce impact factors for air quality that account for emissions of NO_x, VOCs, PM_{10}/ $PM_{2.5}$ from well preparation and production, provided in Roy et al 2014[15]. The sum of the former and the product of the latter and well lifetime is taken as the value of $IF_{well,i}$, and similar values are assumed for conventional and unconventional gas development. Basin-level VOC composition estimates are applied to estimates of venting from completions, recompletions, liquids unloading and pneumatic devices/fugitives to obtain estimates of VOC emissions from gas wells that are consistent with estimates of gas leaks and venting.

Table S1: EUR ranges for study basins

Basin	Mean EUR (MMScf)	Minimum EUR (MMScf)	Maximum EUR (MMScf)
Anadarko[a]	3,151	1,657	5,898
Permian[a]	2,054	833	3,662
San Juan[b]	685	562	846

(Sources: [a]US Energy Information Administration 2011[2]; [b]US Energy Information Administration 2015[16], using estimates of total recoverable resource from the USGS[3–5])

Table S2: Basin-level production characteristics

Basin	2013 Production (MMScf)	% Fracking*	Estimated Ultimate Recovery (MMScf/well)
Anadarko	136,085 [a]	44.43% [a]	3,150 [b]
Permian	1,792,091 [a]	12.78% [a]	2,054 [b]
San Juan	1,024,962 [a]	25.81% [a]	685 [c]

(Sources: [a] US Energy Information Administration 2017[17,18], *based on 2015 production data; [b] US Energy Information Administration 2011[2]; [c] US Energy Information Administration 2015[16])

Table S3: Basin-level gas composition

Basin	% CH4 (mass)	% CO2 (mass)	%VOC (mass)	%NGL's (mass)
Anadarko	79.70% [a]	1.57% [a]	9.93% [a]	6.56% [a]
Permian	58.39% [a]	1.84% [a]	24.00% [a]	12.64% [a]
San Juan	75.80% [b]	5.00% [b]	7.40% [b]	11.70% [b]

(Sources: [a] Texas Commission on Environmental Quality 2014[19]; [b] BLM 2016[6])

Table S4: Liquids unloading emissions distribution

Type	Percentile	Value (MMScf/well)
Hydraulic Fracturing	0%	0.01
Hydraulic Fracturing	5%	0.07
Hydraulic Fracturing	10%	0.20
Hydraulic Fracturing	25%	0.98
Hydraulic Fracturing	50%	5.10
Hydraulic Fracturing	75%	10.53
Hydraulic Fracturing	85%	29.17
Hydraulic Fracturing	90%	81.36
Hydraulic Fracturing	95%	172.47
Hydraulic Fracturing	100%	461.49
Conventional	0%	0.06
Conventional	5%	0.24
Conventional	10%	0.38
Conventional	25%	0.79
Conventional	50%	2.32
Conventional	75%	21.84
Conventional	85%	34.31
Conventional	90%	40.95
Conventional	95%	122.85
Conventional	100%	221.47

(Source: based on figures reported in Heath et al 2014[12])

Table S5: Well drilling and hydraulic fracturing water withdrawal factors collected by Meldrum et al[20] (Adapted from the original source: Meldrum et al 2013[20])

Water Withdrawal (gal/well)	Process	Notes	Source
2.27E+06	Fracturing	Barnett Shale	Joint Institute for Strategic Energy Analysis (JISEA) 2012[9]
4.50E+06	Fracturing	Barnett Shale	Chesapeake Energy 2012a[21]
2.30E+06	Fracturing	Barnett Shale	Clark et al 2011[22]
3.80E+06	Fracturing	Barnett Shale	Clark et al 2011[22]
4.60E+06	Fracturing	Barnett Shale	GAO 2012[23]
2.30E+06	Fracturing	Barnett Shale	Ground Water Protection Council and ALL Consulting 2009[24]
7.66E+05	Fracturing	Barnett Shale	TWDB 2012[25]
1.19E+06	Fracturing	Barnett Shale	TWDB 2012[25]
5.47E+06	Fracturing	Barnett Shale	TWDB 2012[25]
3.75E+06	Fracturing	Eagle Ford Shale	Joint Institute for Strategic Energy Analysis (JISEA) 2012[9]
4.80E+06	Fracturing	Eagle Ford Shale	Chesapeake Energy 2012c[26]
5.00E+06	Fracturing	Eagle Ford Shale	GAO 2012[23]
1.22E+06	Fracturing	Eagle Ford Shale	TWDB 2012[25]
8.96E+06	Fracturing	Eagle Ford Shale	TWDB 2012[25]
2.50E+05	Well drilling	Barnett Shale	Chesapeake Energy 2012a[21]
2.70E+05	Well drilling	Barnett Shale	Clark et al 2011[22]
2.50E+05	Well drilling	Barnett Shale	GAO 2012[23]
4.00E+06	Well drilling	Barnett Shale	Ground Water Protection Council and ALL Consulting 2009[24]
1.25E+05	Well drilling	Eagle Ford Shale	Chesapeake Energy 2012c[26]
1.25E+05	Well drilling	Eagle Ford Shale	GAO 2012[23]
8.51E+04	Well drilling	(generic) Conventional gas	Clark et al 2011[22]
1.17E+05	Well drilling	(generic) Conventional gas	Clark et al 2011[22]
2.93E+02	Well drilling	(generic) Conventional gas	IEA 2012[27]
2.93E+02	Well drilling	(generic) Conventional gas	IEA 2012[27]
6.50E+04	Well drilling	Generic	Chesapeake Energy 2012b[28]
6.00E+05	Well drilling	Generic	Chesapeake Energy 2012b[28]
1.30E+05	Well drilling	Generic horizontal	Noble Energy Inc and CSU 2012[29]
7.70E+04	Well drilling	Generic vertical	Noble Energy Inc and CSU 2012[29]
2.97E+06	Well drilling	On-shore conventional well	DOE 1983[30]

Gathering, Processing, Transmission and Storage (GPTS)

Equation (S3) is used to compute the impact of category i ($Impact_i$) associated with natural gas well preparation and extraction. Equation (S4) is used to estimate the fraction of pipeline gas that makes it to the power plant (F), which is applied to impact estimates of natural gas extraction in (S1), and GPTS in (S5):

(S3) $Comb_{GPTS} = \frac{3.6MJ*kWh^{-1}}{1.12*10^6 MJ*MMSCF^{-1}*Eff} * \left(PI_{comp} + \frac{PI_{trans}*Miles_{epng}}{TP*CF}\right)$

(S4) $F = 1 - LR - Comb_{GPTS}$

Equation (S3) computes the fraction of processed gas entering the transmission system that is combusted to power compressor stations ($Comb_{GPTS}$), based on the power required to compress a standard cubic foot of gas (PI_{comp}), the power required to maintain 1 mile of pipeline under pressure (PI_{trans}), the miles in EPNG's transmission network ($Miles_{epng}$), the total rated throughput of the EPNG network (TP, in MMScf/year), its assumed operating capacity factor (CF), and heat conversion efficiency of the network's compressors (Eff). Gas combusted in the transmission and storage network, along with system-level leakage rate (LR) is used to compute the fraction of processed gas that arrives at the power plant (F) in equation (S4).

The analysis assumes a PI_{comp} value of 10kWh/MMBtu of gas compressed to 4,000 psi given by the American Gas Association[31], and a PI_{trans} of 0.08kWh/mile[32], and makes use of data on the size and annual throughput rating of EPNG's transmission network from Kinder Morgan[33] and the EIA[34] to produce values of $Miles_{epng}$ and TP. Compressors generally operate at a capacity factor (CF) of 40%-80%[15] and a thermal efficiency of 20%-40% depending on whether they are reciprocating or centrifugal[35] (efficiencies for each type are taken from Greenblatt 2015[36]). A weighted average CF is computed using survey data on compressor characteristics from Zimmerle et al (shown in **Table S6**). An updated methane leakage rate of 0.3%-0.5% is assumed for gas transmission and storage[37] as well as new estimates of gas leaks during gathering and processing[38].

(S5) $Impact_{GPTS,i} = \frac{HR}{F} * \left(Comb_{pt\&s} * HC * \frac{0.0335bhp}{MMBtu} * IF_i\right)$

The impact of each category ($Impact_{t\&s,i}$ for category i) is estimated in (S5) using the values computed in (S3) and (S4), the heat content (HC) of 1,060 Btu/Scf assumed for the region[6], and the corresponding impact factor IF_i. For processing, an IF_i value of 18g CO_2-eq/kWh taken from Logan et al 2012[39] is used. Emissions factors of CO_2 and atmospheric contaminants from compressor engines (shown in **Table S7**) vary by engine type (reciprocating or centrifugal) and prime mover type (lean-burn 2-stroke, lean-burn 4-stroke, rich-burn 4-stroke or combustion turbine, or electric) and weighted average IF_i values are also calculated using survey data from Zimmerle et al[40]. Ranges of NO_x, VOC and PM emissions during gas processing are taken from Roy et al[15]. CO_2-equivalent emissions from PT&S system leakages are also computed by assuming a pipeline methane content of 95% by mass. A small amount of water is used to cool compressor engines, (0 - 1.38E-03 gal/bhp-hr for reciprocating engines and 0.11 - 0.80 gal/bhp-hr for combustion turbines)[41], and a weighted average range of values is computed to estimate water needs for gas compression

Table S6: Compressor breakdown

Prime Mover	Type	Share of Capacity
Electric	Electric	7.3%
Combustion Turbine	Centrifugal	46.1%
Lean 2-stroke	Reciprocating	33.2%
Lean 4-stroke	Reciprocating	10.1%
Lean 4-stroke	Centrifugal	1.1%
Rich 4-stroke	Reciprocating	2.2%

(Source: Zimmerle et al 2015[42], based on reported compressor counts and capacities)

Table S7: Assumed compressor emission factors

Prime Mover	Type	NOx Emission Factor (lb/bhp-hr)	VOC Emission Factor (lb/bhp-hr)	PM Emission Factor (lb/bhp-hr)
Combustion Turbine	Centrifugal	2.87E-03 [a]	2.20E-05 [a]	3.53E-04 [a]
Lean 2-stroke	Reciprocating	8.47E+00 [b]	9.50E-01 [b]	1.50E-01 [b]
Lean 4-stroke	Reciprocating	1.66E+00 [b]	5.10E-01 [b]	1.00E-02 [b]
Lean 4-stroke	Centrifugal	1.66E+00 [b]	5.10E-01 [b]	1.00E-02 [b]
Rich 4-stroke	Reciprocating	1.28E+00 [b]	5.00E-02 [b]	3.00E-02 [b]

(Sources: [a] U.S. EPA 2017[43]; [b] BLM 2016[6])

Generation

(S6) $Impact_{gen,i} = HR * IF_{gen,i}$

Equation (S6) is used to compute impact of each category accruing in the generation phase $Impact_{gen,i}$, based on the range of weighted average heat rates of the two power plants (HR, in $MMBtu/kWh$) and the estimated generation impact factor $IF_{gen,i}$. The California Energy Commission's Quarterly Fuel and Emissions Report (QFER) provides production and fuel use data for these plants from 2007 onwards, which is used to obtain HR distributions for the power exported to California. Emissions data for these facilities are not available, but the Mexican plants are required to use the same air quality control technologies as those in California[44] and thus likely have very similar emissions rates. Therefore, average emissions factors from EPA eGRID power plant-level operational data for all combined cycle facilities built after 2000 in the state of California are used to estimate emissions per MMBtu of fuel burned. VOC and PM emissions are not reported in the EPA eGRID database, so emission values for natural gas combustion turbines from Cai et al[45] are used. All assumed emissions factors are shown in **Table 1** in the article. Ranges of water consumption rates are obtained from USGS estimates of power plant water consumption in 2010[46] (shown in **Table S8**) and an estimation method based on Bolorinos et al[47] that uses water consumption factors of combined cycle facilities with recirculating cooling systems built after 2000 (described in more detail in the "Sensitivity Analysis" section).

Table S8: Water consumption factors of combined cycle facilities

EIA Facility ID	Estimated Water Consumption Factor (gal/MMBtu)	Minimum Water Consumption Factor (gal/MMBtu)	Maximum Water Consumption Factor (gal/MMBtu)
3604	70.3	59.5	86.6
7757	55.8	46.2	69.0
55047	83.6	71.9	101.6
55062	83.2	71.0	101.2
55065	60.4	51.6	75.9
55097	65.6	55.9	81.6
55098	122.2	104.6	150.5
55153	61.5	52.6	74.4
55200	65.6	52.5	78.7
55309	119.4	103.0	143.5
55545	60.1	51.3	73.0
10156	106.7	53.4	106.7
50541	94.9	71.2	94.9
55120	106.3	91.0	127.0
55129	67.5	55.7	91.1
55132	88.4	75.5	109.4
55176	44.5	38.6	55.0
EIA	**Estimated Water**	**Minimum Water**	**Maximum Water**

Facility ID	Consumption Factor (gal/MMBtu)	Consumption Factor (gal/MMBtu)	Consumption Factor (gal/MMBtu)
55182	55.6	47.1	66.9
55215	61.0	51.6	76.8
55217	43.0	36.3	52.7
55299	23.8	20.7	28.9
55457	55.7	46.6	69.2
55123	58.8	50.5	72.2
55124	69.4	56.8	98.8
55137	53.7	45.9	65.1
55146	55.4	46.6	68.3
55168	61.4	52.2	75.6
55200	65.6	52.5	78.7
55223	58.3	49.2	73.2
55225	57.9	48.6	71.5
55226	56.9	48.4	70.9
55282	66.0	54.3	92.7
55299	23.8	20.7	28.9
55327	61.8	53.1	74.4
55333	55.5	46.9	67.8
55455	66.3	55.1	88.3
56349	78.6	66.3	101.9
56350	67.6	58.3	82.0
7266	66.2	56.7	82.7
55151	26.2	22.3	31.7
55182	55.6	47.1	66.9
55225	57.9	48.6	71.5
55295	63.0	51.9	82.2
55306	65.4	54.2	86.5
55357	59.3	50.9	71.6
55358	56.7	48.5	68.7
55400	51.3	43.5	62.4
55464	2.5	2.0	3.1
55480	63.0	53.5	79.0
55481	63.1	52.7	83.0
55501	58.9	50.1	72.7
55518	55.4	47.1	66.9
55664	64.4	54.7	79.4
55952	81.4	67.1	112.6
10156	106.7	53.4	106.7
EIA	**Estimated Water**	**Minimum Water**	**Maximum Water**

Facility ID	Consumption Factor (gal/MMBtu)	Consumption Factor (gal/MMBtu)	Consumption Factor (gal/MMBtu)
55372	64.5	54.0	87.4
55464	2.5	2.0	3.1
55835	50.0	39.9	63.7
358	58.4	50.2	69.7
8068	105.6	87.4	140.6
10811	48.8	40.2	57.4
55393	49.5	41.9	59.5
55656	52.5	44.3	64.9
55977	59.1	46.0	74.5
55985	50.1	42.9	59.6
56026	47.8	41.8	57.7
56041	59.7	51.9	71.4
56046	53.5	46.0	64.7
358	58.4	50.2	69.7
8068	105.6	87.4	140.6
55230	56.3	47.6	70.5
55309	119.4	103.0	143.5
55343	59.6	50.5	75.8
55970	50.0	42.1	61.5
55985	50.1	42.9	59.6
56078	59.2	50.1	73.3
56298	58.9	49.4	72.2
56349	78.6	66.3	101.9
56350	67.6	58.3	82.0
57564	53.4	45.8	68.7
56349	78.6	66.3	101.9
56350	67.6	58.3	82.0
55853	24.6	21.2	29.2
55853	24.6	21.2	29.2

(Source: based on figures reported in Diehl et al 2013[46])

Manufacturing and construction of wind turbines:

Our examination of life-cycle impact estimates from manufacturing and construction in the case study region focuses on wind turbines. For GHG emissions, we rely on life-cycle GHG emissions values taken from a meta-analysis performed by Nugent and Sovacool[48]. Two of these values correspond to wind power from small wind turbines and were excluded from the analysis. Values of NO_x, VOC and $PM_{10/2.5}$ emissions from manufacturing are not available (Turconi et al[49] provide estimates for the entire equipment life cycle but do not break them down further into manufacturing, construction and transportation). We thus do not estimate air quality impacts from construction of wind turbines or combined cycle natural gas facilities because disaggregated values are unavailable and estimating air quality impacts would require a more precise life-cycle inventory specific to Baja California.

Estimates of water withdrawals are taken from studies presented in Meldrum et al's harmonization study of life cycle water withdrawn for electricity (shown in **Table S9**). We take water withdrawal values for construction and manufacturing of 1.5MW-4.5MW turbines and assume the harmonized average capacity factor of 30% and plant lifetime of 20 years.

Table S9: Assumed water withdrawal factors collected by Meldrum et al[20] (Adapted from the original source: Meldrum et al 2013[20])

Generation Type	Stage	Source	Life cycle water withdrawal equivalent (Gal/kWh)
Combined Cycle Natural Gas	raw materials	Inhaber 2004[50]	2.60E-04
			1.30E-04
	construction	NETL 2010[51]	6.10E-04
Wind	raw materials	Fthenakis and Kim[52] 2010	3.20E-02
		Inhaber 2004[50]	3.50E-03
			5.30E-04
	manufacturing	Elsam Engineering A/S 2004[53]	2.00E-02
		NETL 2012[54]	6.30E-05
			2.50E-02
			2.40E-02
			3.00E-02
			2.10E-02
			2.70E-02
	construction	Chataignere and Le Boulch 2003[55]	4.30E-03
			5.30E-03
			2.00E-03
			1.50E-02
			2.10E-02
			2.10E-02
			1.90E-02
			2.60E-02

Sensitivity Analysis:

Parameter Ranges

A sensitivity analysis is performed on all impact factors and stages to account for uncertainty in crucial input parameters at each phase. Following Heath et al [12], we take well EUR and liquids unloading as the most critical parameters for GHG emissions during the extraction stage. EUR is especially significant as a way of normalizing impact per well for air contaminant emissions and water withdrawals. Ranges used for the study basins are shown in **Table S1** above. To further account for uncertainty in air contaminant emissions during well construction, the range of values calculated in Roy et al[15] in their work on the air quality effects of gas development in the Marcellus shale is applied to the study's LCA.

We also account for uncertainty in water withdrawn for drilling and hydraulic fracturing by considering the estimates collected and harmonized in Meldrum et al in their review of life cycle water withdrawals associated with the power sector[20]. These values are shown in **Table S5**. For the GPTS stage, we consider a range of estimates of compressor load factor, efficiency, water withdrawal factors, gathering/processing, and transmission/storage leakage rates, which we deemed the most important sources of uncertainty in estimating environmental impact. A large source of uncertainty in estimating water withdrawals from electricity generation is the water withdrawal factor of combined cycle electricity generation units. Values used for input distributions of water withdrawal factors are shown in **Table S8**, and are adapted from an appendix to a USGS study by Diehl et al[46].

Parameter Input Distributions

Table S10 shows the method used to generate each type of input parameter varied in the sensitivity analysis. All parameters were varied independently according to their input distributions, (except Manufacturing and Construction GHG emissions, which are sampled from the same studies examined in Nugent and Sovacool[48]), each of which made as few assumptions as possible. Where studies give a simple range of values without a mid-point (or median) a uniform probability distribution function (PDF) is used, otherwise a triangular PDF is used. For liquids unloading, a simple PDF of emissions from liquids unloading from conventional and unconventional wells is constructed based on data provided in the supporting information of a study by Heath et al[12]. The pdf consists of a series of discrete block probabilities with breakpoints at the percentiles shown in **Table S4** above. For well drilling and hydraulic fracturing, values shown in **Table S3** are randomly sampled with equal weights (other input distributions of this type are referred to a "Sampling" in **Table S10**). A log-normal distribution is fit to the range of heat rates observed at the Mexican power plants (from California Quarterly Fuel and Emissions Report (QFER) data) and is sampled to generate a distribution of heat rate values.

A two-stage sampling process based on a method used by Bolorinos et al[47] is employed to produce a range of generation cooling water withdrawal factors. First, a plausible range of water consumption factors is sampled from the values in **Table S8,** which are normalized USGS estimates of water consumed per unit of fuel used for combined cycle facilities with recirculating cooling tower systems in the US Southwest (i.e. in California, Nevada, Arizona, New Mexico, Texas, and Oklahoma) that came online on or after 2000. A coefficient of variation is obtained from this range of water consumption factors (relative to the median estimate in the range). In the second stage, a value is sampled from a log-normal distribution with 2.5^{th} and 97.5^{th} quantiles corresponding to this coefficient of variation, and a median equal to the generation-weighted average point-estimate of water withdrawn per fuel used at the Mexican power plants obtained from data from the QFER (which is assumed to be a roughly accurate measure of the real water withdrawal factor).

Water consumption factors directly determine water withdrawal factors through the cycles of concentration of the cooling system, which refers to the ratio of blowdown (discharged) and makeup water flowing through the system[56]. The cooling system used at Termoelectrica de Mexicali is known to achieve 6-7 cycles of concentration[44], and a similar performance is assumed for La Rosita. Thus, variation in estimates of consumption factors is assumed to determine variation in estimates of withdrawal factors. Ranges of water withdrawal factors from the report by Diehl et al for the USGS[56] are not used because they are produced using a wider simulated range of cycles of concentration ranging (2 to 10) that are not reflective of the efficiency of the cooling systems used at the Mexican power plants.

Figure S1 shows the distributions of environmental impact estimates resulting from the sensitivity analysis as a whole and broken down by stage and impact category. As the figure shows, some sources of uncertainty result in much larger variations in the magnitude of estimates and are the main determinants of uncertainty in overall life cycle impact.

Figure S1 Sensitivity analysis distributions of environmental impact by stage and category

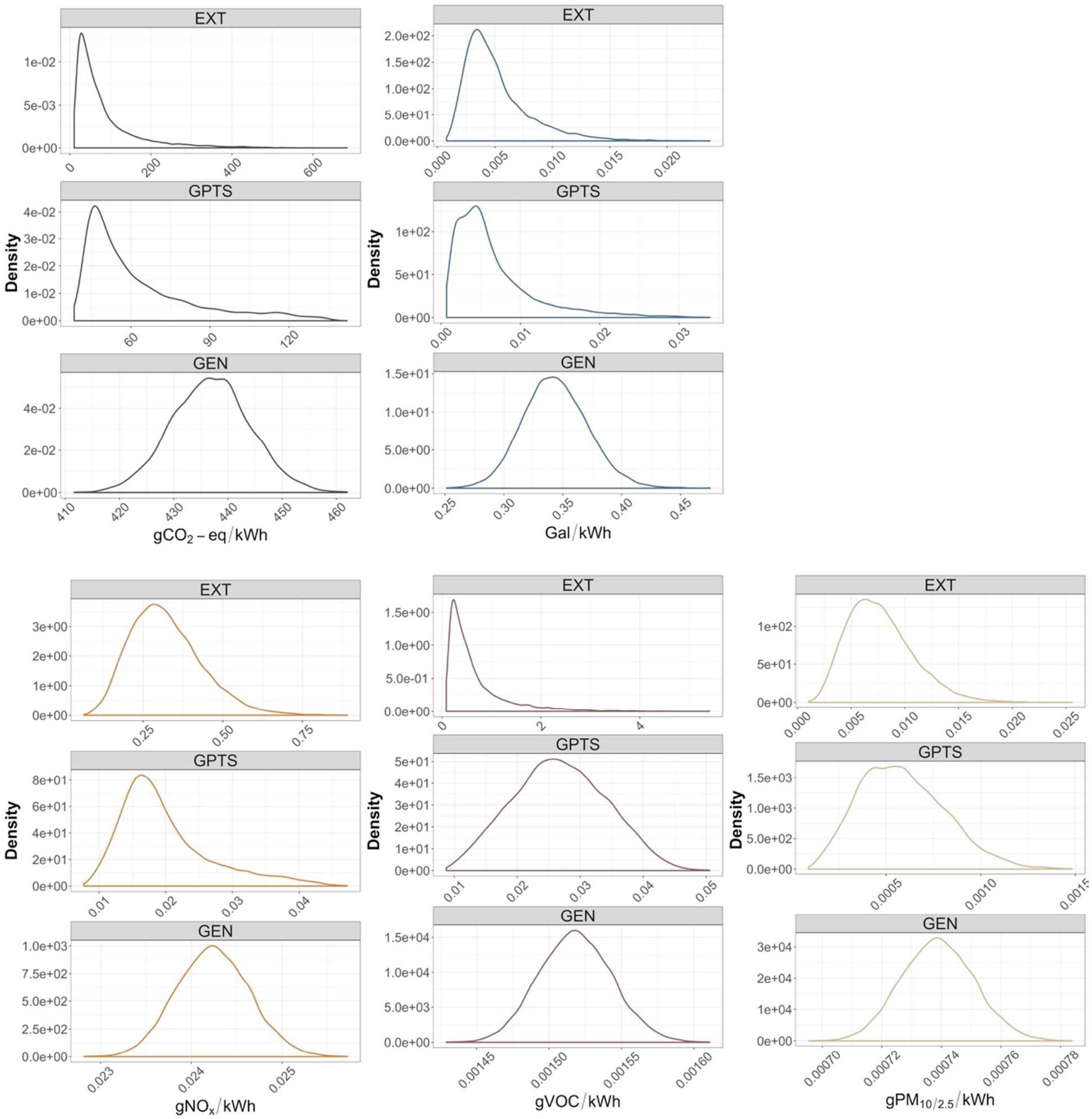

Figure S2: Sensitivity analysis distributions of GHG and Water Withdrawal impacts by stage (9.1% wind energy):

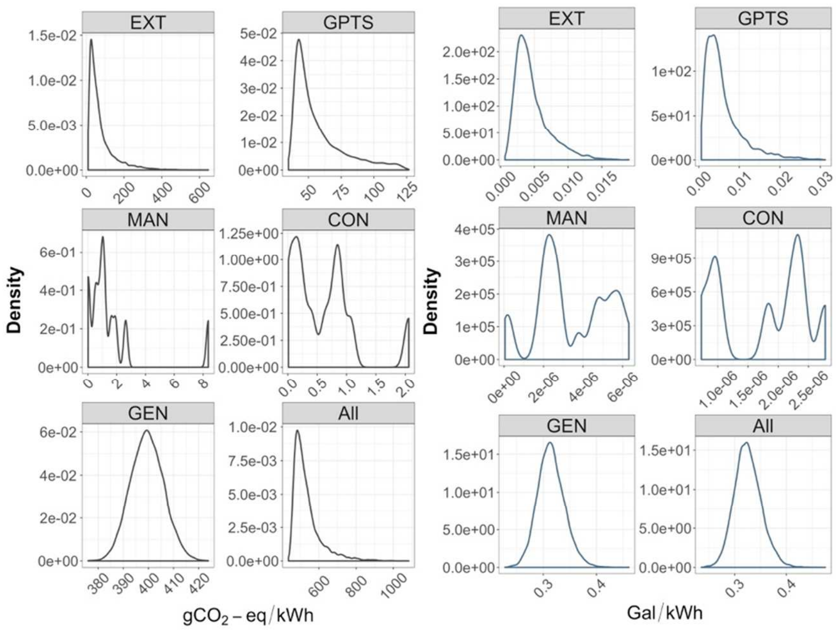

Table S10: *Sensitivity analysis parameters and estimation (EXT: Extraction, GPTS: Gathering, Processing, Transmission & Storage, GEN: Generation)*

Stage	Parameter	Method
EXT	EUR	PDF: triangular
	Completion Emissions	PDF: triangular
	Liquids Unloading Emissions	PDF: block
	Fugitive emissions	PDF: triangular
	Pneumatic component emissions	PFF: triangular
	Drilling Water Withdrawal	Sampling
	Hydraulic Fracturing Water Withdrawal	Sampling
	Air Quality Parameters	PDF: triangular
GPTS	Transmission & Storage Leakage Rate	PDF: triangular
	Gathering & Processing Leakage Rate	PDF: triangular
	Compressor Efficiency	PDF: uniform
	Compressor Load Factor	PDF: uniform
	Compressor Water Withdrawal Factor	PDF: uniform
GEN	Heat Rate	PDF: log-normal
	Cooling Water Withdrawal Factor	Sampling + PDF: log-normal
MAN	Water Withdrawal Factor	Sampling
	GHG Emissions Factor	Sampling
CONST	Water Withdrawal Factor	Sampling
	GHG Emissions Factor	Sampling

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