SUPPLEMENTAL INFORMATION

Title: An Assessment of Life Cycle Greenhouse Gas Emissions Associated with the Use of Water, Sand, and Chemicals in Shale Gas Production of the Pennsylvania Marcellus Shale

NOTE: The information in this document was not peer reviewed or copy edited by the *Journal of Environmental Health*. It serves as extra reference for the reader should they want the information.

FracFocus PA Dataset

The dataset contained 36,436 entries of data pertaining to the usage of sand, water, or chemicals. After removing duplicate entries (n=1,292) and entries pertaining to the eight wells removed due to insufficient or erroneous data (n=202), 34,942 entries of data remained, of which 88% pertained to the usage of chemicals (n=30,762). Eleven percent of chemical entries did not have a chemical concentration value and were eliminated from the GHG emissions analysis for chemicals.

Quantity and frequency of use varied greatly among the 181 chemicals with CAS numbers in the dataset. Eighteen of the chemicals with CAS numbers never appeared in the dataset with a concentration value. Among the remaining 163 chemicals with CAS numbers, only 51 chemicals (31%) were used in greater than 1% of the wells and had a mean concentration of at least 100 gallons.

CAS Verification

The following online databases were used to verify CAS numbers found in the dataset. Of the 181 CAS numbers found, four could not be verified.

- The American Chemical Society’s online searchable database called Common Chemistry
- The Toxic Substances Control Act (“TSCA”) Chemical Substance Inventory

- The National Institute of Health U.S. National Library of Medicine's ChemIDplus Advanced online chemical inventory

Calculation of Concentration Values of Fluid Entries in Dataset

Concentration values were provided in the dataset as the maximum ingredient concentration in the HF fluid as a percentage by mass (which is the only concentration as a percentage of the HF fluid provided on the FracFocus forms). The total volume of HF injected fluid per well was not provided in the dataset. In order to calculate the volume for each chemical entry, the total volume of HF injected fluid per well was first calculated based on the volume of water used per well and the percentage of water in the total volume of HF fluid, both of which were provided in the dataset. For example, if the total volume of water were 4,000,000 gallons, and 85% of the mass of the HF injected fluid was reported as water, then the total volume of the HF injected fluid was calculated to be 4,705,882 gallons. In the same example, if 0.3% of the mass of the HF injected fluid were hydrochloric acid, then the total volume of the hydrochloric acid would be 14,118 gallons. All additives (except sand) were assumed to have the same density as water. Sand was computed separately as pounds per well assuming 1 gallon of HF fluid = 8.328 pounds.

The total volume of HF injected fluid was computed differently for wells where the percent of water in the HF injected fluid was not provided, even though the total volume of water used was provided (n=275). For example, if 15% of the HF fluid were sand and chemicals, then 85% was assumed to be water. In 258 of these wells, the percent of sand in the HF fluid was also not provided. For these cases, if, for example, 1% of the HF fluid were chemicals, then 99% of the HF fluid was assumed to be water.

Assessment of Greenhouse Gas Emissions

Production and Transportation of Chemicals

The EIO-LCA analysis is done at the sector level, so in order to apply EIO-LCA emissions factors to chemicals in the dataset, each chemical needed to be categorized to match a sector in the model. Table 1 displays the chemical categories (i.e., organic, inorganic, or petroleum) and the respective surrogate Producer Model sector. Chemicals that were not easily categorized were labeled as inorganic since Producer Model emissions factors for inorganic chemical manufacturing were lower than organic chemical manufacturing.

Table 1. Purchaser Model sectors used as surrogates for chemicals in dataset

Chemical Category	Purchaser Model Sector Used	Tons of CO2e Emissions for Purchasing $1M of Product
Organic	Other basic organic chemical manufacturing	2,540
Inorganic	All other basic inorganic chemical manufacturing	2,060
Petroleum	Petroleum refineries	1,260

The results of the Purchaser Model are a function of the purchase price of a product, so each chemical in the analysis needed to be assigned a purchase price. Jiang et al., (2011), who also used the EIO-LCA tool to assess GHG emissions for HF chemicals, used 2010 prices for 13 primary chemicals in the HF fluid – one for each component type of the HF fluid (Table 2). Unlike Jiang et al., (2011), our study used real-world data which included numerous chemicals for each component type in the HF fluid. Jiang et al., (2011) prices were used in our study, but in order to do so, each chemical in our dataset was first categorized based on its component type in the HF fluid. Jiang et al., (2011) prices per component type were then applied to each chemical in our dataset of the same component type. For example, according to Jiang et al., (2011), the 2010 price of isopropanol, a surfactant, was $0.95/kg (Jiang et al., 2011). Therefore, $0.95/kg was applied to all surfactants in the dataset. If a chemical appeared in the dataset with multiple component types, the dominant purpose was selected. There were several chemicals in the dataset for which each chemical entry was missing the component type in the HF fluid. The component type for these chemicals was labeled "Unknown". Unknown chemicals were eliminated from the analysis.

Table 2. Price per primary compound for each component type based on Jiang et al., (2011)

Component Type	Primary Compound (from Jiang et al (2011))	2010 Price ($/kg)
Proppant	Silica, quartz sand	0.065
Acid	Hydrochloric acid or muriatic acid	0.18
Friction Reducer	Petroleum distillate	0.90
Surfactant	Isopropanol	0.95
Clay Stabilizer/Controller	Potassium chloride	0.30
Gelling Agent	Guar gum or hydroxyethyl cellulose	2.00
Scale Inhibitor	Ethylene glycol	0.95
pH Adjusting Agent	Sodium bicarbonate or sodium/potassium hydroxide	0.20
Breaker	Ammonium persulfate	0.66
Crosslinker	Borate salts	0.95
Iron Control	Citric acid	0.77
Bactericide/Biocide	Glutaraldehyde	2.20
Corrosion Inhibitor	Formamide	0.95

Both chemicals with CAS numbers and proprietary chemicals without CAS numbers were included in the GHG emissions assessment of chemicals. Of the 181 chemicals with CAS numbers in the dataset, 160 chemicals were included in the analysis. The remaining 21 chemicals were eliminated due to a lack of concentration values (n=18) or an unknown component type (n=3). In addition, approximately 133 proprietary chemicals without CAS numbers were provided in the dataset with concentration values, of which 112 were included in the GHG emissions assessment of chemicals. The remaining 21 chemicals were eliminated due to an unknown component type. Please note that the three chemicals with CAS numbers eliminated from the GHG emissions assessment due to an unknown component type did have concentration values, and therefore were included in calculating chemical usage statistics detailed in Appendix A along with the 160 chemicals included in the GHG emissions assessment of chemicals (n=163).

In order to compute GHG emissions associated with the production of chemicals in the dataset, the cost of chemicals per well in each EIO-LCA category (i.e., organic, inorganic, or petroleum) were calculated (Table 3). The average chemical mass used per well was calculated by taking the total quantity from all chemical entries for each chemical and dividing by the total number of wells (1,907 wells was used instead of 1,921 due to missing information for 14 wells). Life-cycle GHG emissions factors were then applied to each EIO-LCA category of chemicals to calculate tons per CO2 equivalent (t CO2e) emissions per well (Table 4). The 2010 costs were adjusted to reflect 2002 dollars consistent with the adjustment made by Jiang et al., (2011) for each EIO-LCA category. For example, the cost per well of all inorganic friction reducers was $1,596 (Equation 1).

Equation 1. 1,773 kg/well * $0.90/kg = $1.596 per well

The cost per well of all inorganic chemicals for each component type were calculated and rolled-up together to equal $7,869 in 2002 dollars. According to the Purchaser Model, $1M of inorganic chemical manufacturing produces 2,060 t CO2e. Therefore, $7,869 of inorganic chemicals would generate 16.21 t CO2e per well (Equation 2).

Equation 2. $7,869 per well * (2,060 t CO2e)/$1,000,000 = 16.21 t CO2e per well

Table 3. Cost of HF Fluid components per well based on quantities of chemicals in dataset.

Component Type	EIO-LCA Category	Avg Mass per Well (kg)	2010 Price ($/kg)	Cost Per Well
Acid	Inorganic	23,649	0.18	$4,257
Antibacterial/Biocide	Inorganic	294	2.20	$648
	Organic	2,582	2.20	$5,680
Breaker	Inorganic	266	0.66	$175
	Organic	2	0.66	$1
Clay Stabilizer/Controller	Inorganic	1,258	0.30	$377
	Organic	26	0.30	$8
Corrosion Inhibitor	Inorganic	101	0.95	$96
	Organic	130	0.95	$123
	Petroleum	1	0.95	$1
Cross-linkers	Inorganic	30	0.95	$28
	Organic	1	0.95	$1
Friction Reducer	Inorganic	1,773	0.90	$1,596
	Organic	1,589	0.90	$1,430
	Petroleum	3,775	0.90	$3,398
Geling Agent	Inorganic	525	2.00	$1,051
	Organic	341	2.00	$682
	Petroleum	54	2.00	$108
Iron Control	Inorganic	4	0.77	$3
	Organic	382	0.77	$294
pH Adjusting Agent	Inorganic	11	0.20	$2
	Organic	48	0.20	$10
Proppant	Inorganic	596	0.07	$39
	Organic	287	0.07	$19
Scale Inhibitor	Inorganic	656	0.95	$623
	Organic	1,585	0.95	$1,506
Surfactant	Inorganic	256	0.95	$243
	Organic	759	0.95	$721
	Petroleum	0.27	0.95	$0
Unknown	Inorganic	2,345		
	Organic	462		
	Petroleum	215		
Total		**44,982**		**$ 23,120**

Table 4. GHG emissions from production and transportation of chemicals

EIO-LCA Category	t CO2e Emissions from Purchasing $1M of Product	Cost per Well (2010 prices)	Cost per Well (2002 prices)	t CO2e per Well
Petroleum	1,260	$ 3,507	$ 3,897	4.91
Organic chemicals	2,540	$ 10,475	$ 9,839	24.99
Inorganic chemicals	2,060	$ 9,138	$ 7,869	16.21
TOTAL		**$ 23,120**	**$ 21,606**	**46.11**

Production of Sand

Unlike the chemical analysis, EIO-LCA models were only used to assess GHG from the production of sand since an independent analysis of GHG emissions from the transportation of sand was conducted in this study. "Sand, gravel, clay, and refractory mining" was the surrogate model sector used for sand. According to Jiang et al., (2011), the 2010 price of sand was $0.065/kg. As shown on Table 1 of the main article (in pounds), the mean mass of sand from the dataset was 4.9 million lbs (2.2 million kg).

The results of the Producer Model, which excludes GHG from transportation to final consumer, are a function of the cost to produce a product. However, the purchase price of sand (i.e, the cost to the consumer) was available for this study (not the cost to the producer). By comparing the results from the Purchaser Model and Producer Model, it was determined that spending $512,820 to produce sand (under the Producer Model) and purchasing $1M of sand (under the Purchaser Model) both generate 312 t CO2e emissions from direct sand mining activities (Table 5). In addition, spending $512,820 to produce sand and purchasing $1M of sand generate 454 and 1,048 t CO2e indirect emissions, respectively, from all other sectors impacted by "sand, gravel, clay, and refractory mining" sector (e.g., power generation and supply, cement manufacturing, oil and gas extraction, etc.). The difference in these indirect GHG emissions between the Producer and Purchaser models is from activities associated with transportation to the final consumer. The Producer Model includes transportation to final consumer. The Purchaser Model does not. Therefore, since spending $512,820 to produce sand and $1M to purchase sand generate the same direct sand mining emissions (i.e., the same quantity of sand), purchasing $1M of sand generates 766 t C02e emissions in the production of sand, which excludes any GHG emissions from transportation to final consumer. The production of sand used in the HF fluid per well generates 110 t CO2e per well (Equation 3).

Equation 3. $143,610 per well * (766 t CO2e)/$1,000,000 = 110 t CO2e per well

Table 5. Emission factors from Producer and Purchaser Models for sand

Types of Activities	**t CO2e Emissions from Producing $512,820 of Sand (Producer Model)[a]**	**t CO2e Emissions from Purchasing $1M of Sand (Purchaser Model)[b]**
Direct sand mining activities	312	312
Indirect activities associated with sand mining[c]	454	1,048
Total GHG emissions	**766**	**1,360**

[a] The Producer Model incorporates GHG emissions associated with the production of a product from the extraction of raw materials to the completion of production (i.e., a cradle to gate of factory model).

[b] The Purchaser Model incorporates GHG emissions associated with the production of a product from the extraction of raw materials to the transportation of the product to the final consumer (i.e., a cradle to consumer model).

[c] Emissions from all other sectors impacted by “sand, gravel, clay, and refractory mining” sector (e.g., power generation and supply, cement manufacturing, oil and gas extraction, etc.)

Transportation of Sand and Water

Background – Transportation of Sand

Wisconsin was used as the starting point for the base case transportation of sand. Wisconsin has an abundance of high-quality sand resources desirable for use in HF. As a result, Wisconsin has been experiencing a substantial increase in permit requests to mine for sand. As of 2012, Wisconsin had approximately 60 mining operations involved in extracted high-quality silica sand with an additional 20 mining operations being proposed. (Wisconsin DNR, 2012) Sand for Marcellus Shale gas production is almost exclusively delivered from the Midwest via rail, where it is loaded onto trucks at transload stations in New York and PA and transported to the well sites (Gannett Fleming GFX Freight Solutions, 2011). Most commonly sand is transported by truck from sand mines to processing plants with access to rail (Wisconsin DNR, 2012).

Transportation of Sand – Stage 1: Mine to Processing Plant

The average distance sand travels from mine to processing plant was estimated based on results of a 2013 case study of the transportation impacts of frac sand mining in Chippewa County, WI, conducted by the National Center for Freight & Infrastructure Research & Education from the University of Wisconsin-Madison. The study mapped out the actual haul routes from five operational sand mines and three proposed sand mines to their respective processing plants and calculated the mileage for each route. The truck mileage used in our assessment was 18.8 miles, which was the mean distance traveled from sand mine to processing plant. (Hart, Adams, & Schwartz, 2013)

Transportation of Sand – Stage 2: Processing Plant to Transload Station

Through visual inspection of the silica sand formation in Wisconsin, the center of Eau Claire County, WI was selected as the center of WI mining activity and the starting point for the rail trip from WI to PA. Figure 1 shows the areas of WI where sandstones for mining are found, the locations of sand minds (active, proposed, and in development), as well as the starting point for the rail trip from WI to PA. Through visual inspection of the Marcellus Shale formation, the connecting point of Clearfield, Elk, and Jefferson Counties was selected as the center of the Marcellus shale formation and the end point for the rail trip from WI to PA (Figure 2). According to US Silica Holdings, Inc., Canadian Pacific Railway is the only North American Railroad to serve the Marcellus Shale (US Silica, 2012). As shown in Figure 4, Canadian Pacific lines extend southward from Canada (through Buffalo) to the Marcellus Shale. However, due to a lack of evidence confirming that the Canadian route using Canadian Pacific lines was the exclusive route used to transport sand to the PA Marcellus shale, an entirely U.S. route was also considered (Figure 3). The average of the two routes was used in the base case scenario, and the entirely U.S. route and the Canadian route were used in the low-end and high-end scenarios, respectively.

Figure 1. Sand mines in Wisconsin as of July 2011 (Golden, 2011)

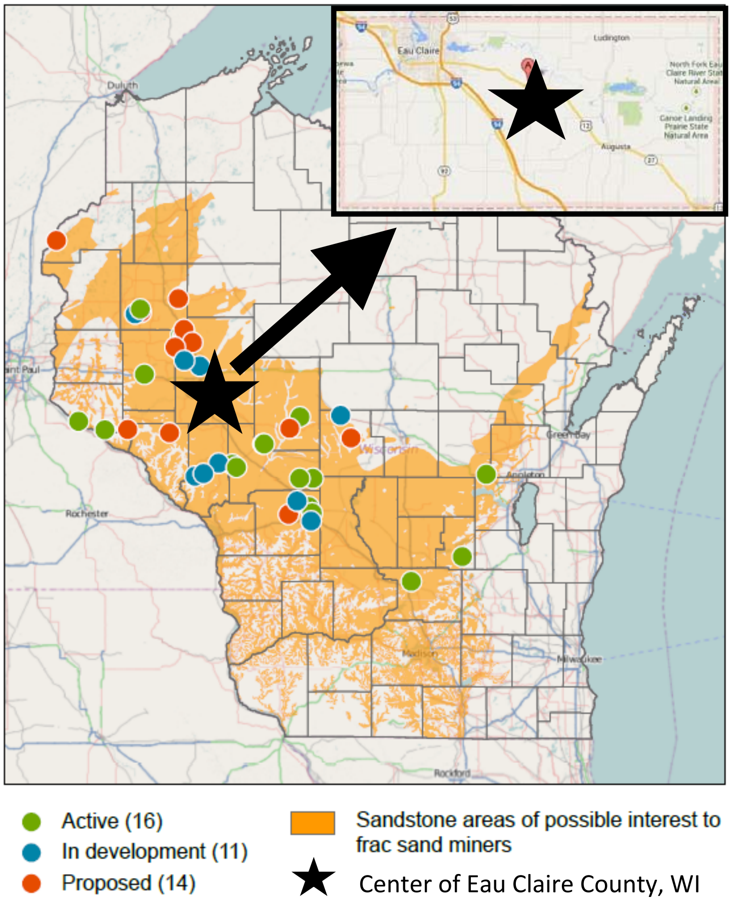


Figure 2. End-point for WI to PA rail route of sand (PA DEP, 2011)

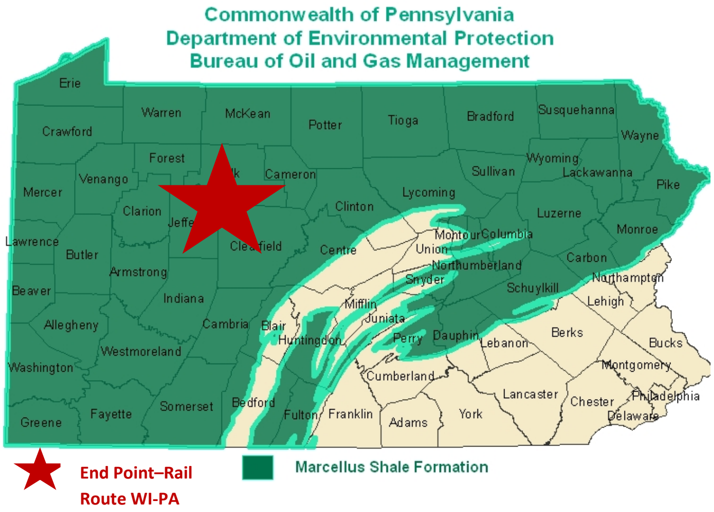
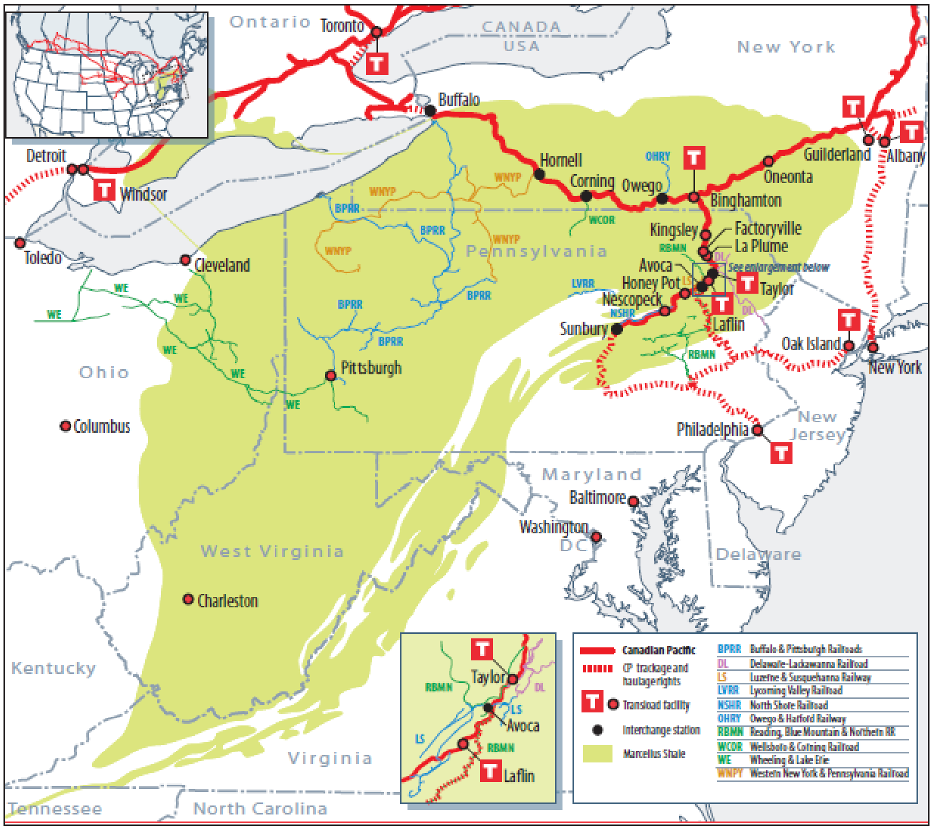


Figure 3. WI to PA rail routes used in sand transportation assessment

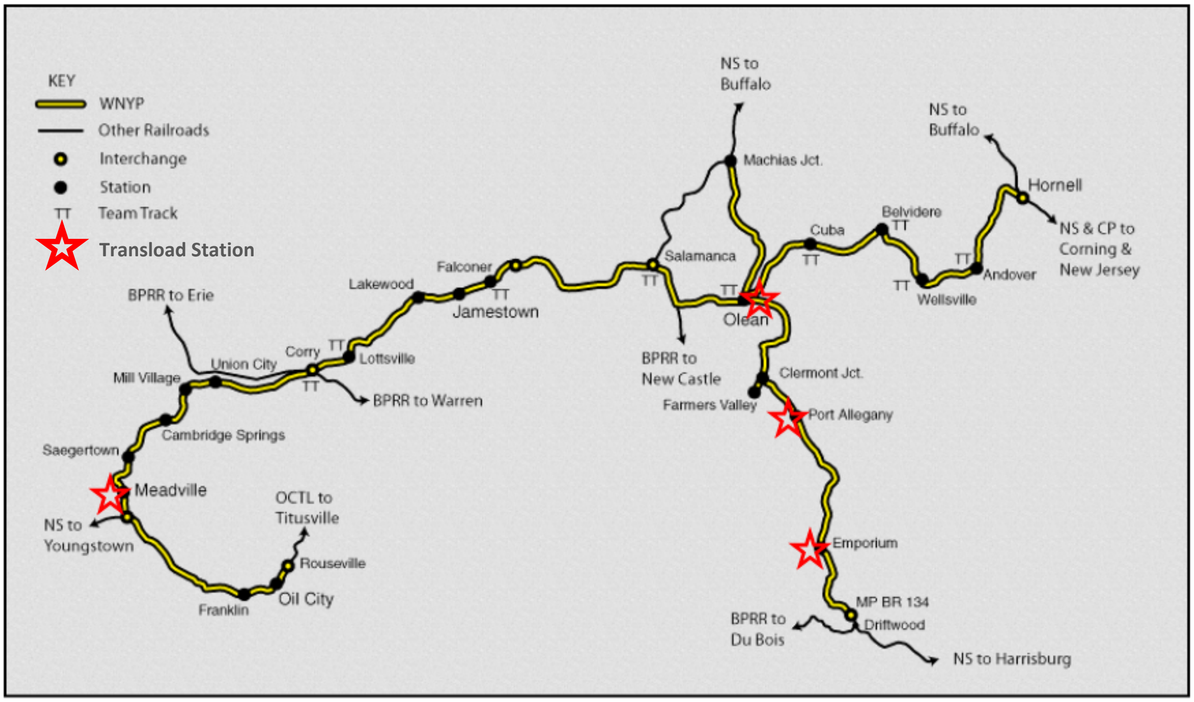
Figure 4. Railroads in the Marcellus Shale region (Canadian Pacific, 2014)



Transportation of Sand – Stage 3: Transload Station to HF Well

In order to estimate the average distance sand travels from transload station to HF well, the location of each transload station for each independent railroad in PA was identified and mapped out (see Figure 5 for example of an individual railroad map). In order to determine the average distance traveled by truck from a transload station to a HF well, visual inspection and Google Maps Driving Routes were used to identify the furthest points from the nearest transload station in six areas of the PA Marcellus Shale. The mean driving distance was 64 miles (range: 56 – 88 miles). Half the mean driving distance (32 miles) was used as the base case driving distance from transload station to HF well.

Figure 5. Western New York & Pennsylvania Railroad transload stations (Eagan)



Background –Transportation of Water

In the Marcellus Shale, approximately two-thirds of freshwater injected into a new hydraulically fractured well comes from surface water sources (e.g., rivers, ponds, lakes, etc.) (Gaudlip, Paugh, & Hayes, 2008; Penn State Cooperative Extension, 2011b; Penn State Public Broadcasting, 2011; Seydor, Clements, Pantelemonitis, & Deshpande, 2012; Yoxtheimer, 2011). Additional sources of freshwater include groundwater and water purchased from local public water suppliers (Gaudlip et al., 2008; Jiang et al., 2011; Penn State Cooperative Extension, 2011b; Penn State Public Broadcasting, 2011; Seydor et al., 2012; Yoxtheimer, 2011). Water is either transported to the drill site by truck or through temporary pipelines (Penn State Public Broadcasting, 2011).

Flowback water recovery and reuse rates for the Marcellus Shale vary (see Figure 6 for a summary of the literature regarding the use of water in HF). It is generally accepted that approximately 10% of the injected water in Marcellus Shale wells returns to the surface as flowback water in the first 30 days following production (Penn State Cooperative Extension, 2011a; WRI, 2012; Yoxtheimer, 2011), and 35 to 40% is returned over the lifetime of the well (Gaudlip et al., 2008; Jiang et al., 2011; Johnson, 2013; NADO, 2010; Olawoyin et al., 2011). Estimates of the percentage of flowback water that is reused varies from 30% to nearly 100% (Clark et al., 2011; Jiang et al., 2011; Mantell, 2011; Penn State Cooperative Extension, 2010; Penn State Cooperative Extension, 2011b). Reused water is either reused at the same drill pad, is transported to another drill pad, or is taken to a recycling facility and brought back to the HF well for reuse. For the water that is disposed, the majority is either treated and discharged to surface water or injected into an underground disposal well. Regardless of the fate of flowback water, travel is done via truck (Penn State Cooperative Extension, 2010; Penn State Cooperative Extension, 2011a).

Figure 6: Literature review of water used in HF

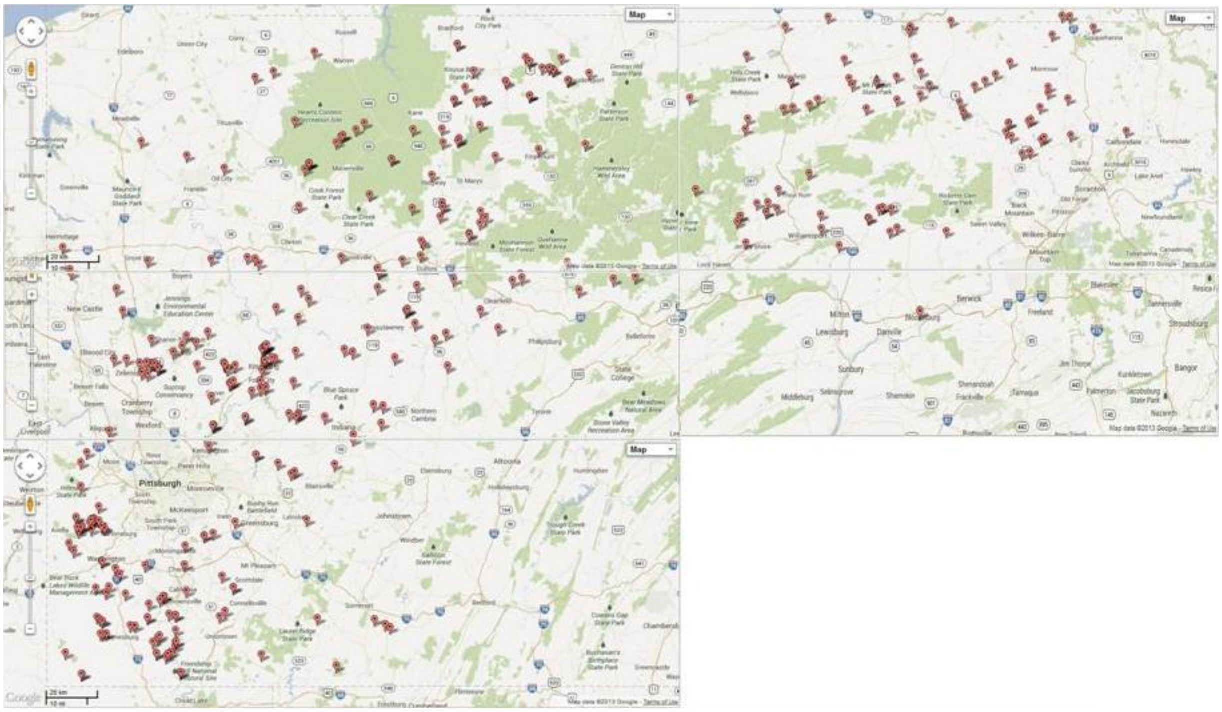
Source	Source of Water Withdrawal	% of Injected Water for New Well that is Reused Water	% of Injected Water that Returns to Surface as Flowback Water	% of Flowback Water that is Reused	% of Flowback Water that is Brought to Disposal Site	% of Injected Water Transported to Site that is Brought to a Disposal Site.	Specific to Marcellus Shale?
Mitchell, Small, & Casman (2013)	Almost all water is withdrawn from surface water sources						Yes
Johnson (2013)			20% in the first 60 days; 35-40% over life of well				Yes
WRI (2012)			~ 10% returns to the surface within one month				Yes
Seydor et al (2012)	~ 65% of the water comes from rivers, creeks, and lakes; 35% purchased from municipalities						Yes
Chesapeake Energy (2012)	Overall mix of water sources used depends on region and availability of sources near drilling sites						Yes
Yoxtheimer (2011)	Surface water sites: 71%; Public water supply: 29%	Freshwater: 85%; flowback water: 15%	10% in first 30 days				Yes
Penn State Cooperative Extension (2011a)			10% resurfaces in subsequent 30 days				Yes
Penn State Public Broadcasting (2011)	~ 65% of the water comes from rivers, creeks, and lakes; 35% purchased from municipalities						Yes

Source	Source of Water Withdrawal	% of Injected Water for New Well that is Reused Water	% of Injected Water that Returns to Surface as Flowback Water	% of Flowback Water that is Reused	% of Flowback Water that is Brought to Disposal Site	% of Injected Water Transported to Site that is Brought to a Disposal Site.	Specific to Marcellus Shale?
Penn State Cooperative Extension (2011b)	Permitted surface water sources: ~ 67%; Purchased from public water suppliers: 30%	Freshwater: 90%; Reused water: 10%		75%			Yes
Olawoyin et al (2011)			35%				Yes
Mantell (2011)		~ 10%	~ 10% to 15% recovered in first 10 days; < 200 gallons Per MMCF recovered over life of well.	Chesapeake Energy recycles/reuses nearly 100% of produced water via improved filtering processes			Yes
Jiang et al (2011)	Surface water: 50%; Local treatment plant: 50%		35–40%	30-60% Recycled and reused	40-70%		Yes
Gannett Fleming GFX Freight Solutions (2011)						~ 10-20%	Yes
Clark et al (2011)				95% of flowback assumed to be recycled			Yes
Penn State Cooperative Extension (2010)			13.5%	60%	40%	4%	Yes
Yoxtheimer & Gaudlip (2010)			10% in first 30 days; > 20% over life of well				Yes
NADO (2010)			~ 33%				Yes
Gaudlip et al (2008)	Surface water: 60-70%; Groundwater < 4%		35%				Yes
Halliburton (2014)			10% and 40%				No
Clark et al (2012)			10% to almost 300% over the life of the well				No
Kimball (2012)			15-35%				No

Transportation of Water: Freshwater to HF Well

Under 25 Pa. Code Chapter 110, the Pennsylvania Department of Environmental Protection (“PA DEP”) requires the registration of water withdrawal sources used for HF (PA DEP, 2014a). Data pertaining to registered water withdrawal sources are publically available for download from the PA DEP website. The data include 354 registered withdrawal sources in PA from January 2007 through October 2013 used for HF. Based on the GPS coordinates provided in the PA DEP data, figure 7 displays the spatial distribution of the 354 registered withdrawal sources used for HF throughout the PA Marcellus Shale. Surface water sources and groundwater sources account for 88% (n=311) and 12% (n=43) of the withdrawal sources, respectively.

Figure 7: Location of 354 registered PA withdrawal sources used for HF



To estimate the average driving distance traveled from withdrawal source to HF well, sixteen clusters of HF wells were analyzed in the areas of PA most densely populated with HF wells. Using the locations of the registered withdrawal sources and the registered HF wells, Google Maps Driving Routes were used to determine the furthest driving distance from a withdrawal source to an HF well in each analyzed cluster of HF wells. The mean driving distance was 15.8 miles (range: 7.5 – 27.9 miles). Half the mean (8 miles) was used as the base case driving distance from water withdrawal source to HF well.

Transportation of Water: Flowback Water

The Pennsylvania Oil and Gas Act requires unconventional well operators to submit production reports which detail each disposal of flowback water per PA HF well. Disposal water data are publically available for download from the PA DEP website. (PA DEP, 2014b) Twelve months of data from July 2012 through June 2013 contain 24,371 reports of the disposal of produced fluid, fracking fluid waste, or drilling fluid waste from 4,929 HF wells. Data include the GPS coordinates of HF wells, disposal methods, names and addresses of waste facilities, and quantities of disposal water. In this 12-month period, unconventional well operators in PA reported 32 million barrels of fluid waste, which is equivalent to 1.76 billion gallons (assuming 1 bbl = 55 gallons).

Assessment of Percentage of Initially Injected Water which Returns to the Surface as Flowback Water

PA DEP fluid waste data were also used to estimate the percentage of initially injected water which returns to the surface as flowback water. For the 4,929 HF wells which reported fluid waste from July 2012 through June 2013, all available PA DEP fluid waste data (from January 2006 through June 2013) were searched to capture every report of fluid waste associated with these wells in order to determine the total quantity of fluid waste per well to date. During this 7.5-year period, the mean quantity of fluid waste reported per well was 1.45 million gallons. Using 1.45 million gallons as the mean volume of returned flowback water per well and 4.29

million gallons (from the FracFocus dataset) as the mean volume of initially injected HF fluid per well (1.45/4.29 = 0.34), it is estimated that 34% of injected HF fluid returns to the surface as flowback water, which is consistent with the literature.

Travel Associated with Water Reused Without Being Brought to a Recycling Facility

Of the total reported fluid waste in the July 2012 through June 2013 PA DEP, 68.7% was reused without being brought to a recycling facility. In the Marcellus Shale, on average there are two HF wells per well pad (Penn State Public Broadcasting, 2011), though multi-well drill pads have been reported to have four to eight wells (Kimball, 2012; NADO, 2010).

To assess the distance traveled to bring reused water (which has not gone to a recycling facility) to a different well pad, FracFocus maps of HF wells were analyzed for three operators in the FracFocus dataset: Chesapeake Operating Inc., Consol Energy Inc., and Seneca Resources Corporation (see Table 6 for a full list of natural gas operators in the dataset). Clusters of HF wells were analyzed for each operator, and driving distances were assessed using Google Maps Driving Routes to determine the average shortest distance traveled between two HF wells of the same operator, assuming that reused water is brought to the nearest well pad. The average shortest distance driven to bring reused water to the nearest well pad of the same operator was estimated to be 1.5 miles.

Table 6. Number of HF wells if FracFocus dataset by natural gas operator

Natural Gas Operator	Wells per Operator	Percentage of Wells by Operator
Chesapeake Operating, Inc.	343	17.86%
Range Resources Corporation	210	10.93%
Shell Oil Company Affiliate	187	9.73%
Talisman Energy USA Inc.	171	8.90%
Anadarko Petroleum Corporation	147	7.65%
Cabot Oil & Gas Corp	107	5.57%
Chevron USA Inc.	77	4.01%
WPX Energy	76	3.96%
Chief Oil & Gas	71	3.70%
Consol Energy Inc.	67	3.49%
EOG Resources, Inc.	59	3.07%
EXCO Resources, Inc.	47	2.45%
XTO Energy/ExxonMobil	45	2.34%
EQT Production	42	2.19%
Seneca Resources Corporation	42	2.19%
Pennsylvania General Energy	41	2.13%
Southwestern Energy	41	2.13%
Energy Corporation of America	35	1.82%
Rex Energy	33	1.72%
Carrizo Oil & Gas, Inc.	28	1.46%
Atlas Energy, L.P.	11	0.57%
Snyder Brothers Inc.	10	0.52%
Hunt Marcellus Operating Company	9	0.47%
Ultra Resources	6	0.31%
Burnett Oil Co., Inc.	4	0.21%
Citrus Energy Corporation	4	0.21%
Triana Energy	4	0.21%
BLX, Inc.	2	0.10%
J-W Operating Company	1	0.05%
MDS Energy, Ltd	1	0.05%
Total	**1,921**	**100.00%**

Vehicle Carrying-Capacity Assumptions

The calculation of truck trips was based on quantities of sand and water used in the estimates, as well as various assumptions regarding train and truck carrying capacities.

According to Gannett Fleming GFX Freight Solutions (2011), an average rail car can carry 100 tons of sand, for which four to five trucks are needed to transport sand to HF wells (i.e., 20 – 25 tons per truck) (Gannett Fleming GFX Freight Solutions, 2011). In the Hart et al., (2013) study to assess transportation impacts from frac sand in Wisconsin, it was assumed that each unit train contained 100 rail cars, each rail car carried 100 tons of sand, and each truck carried 25 tons of sand (Hart et al., 2013). In our assessment we also assumed in all scenarios that each train contained 100 rail cars, and the carrying capacity of each rail car was 100 tons of sand. Our average estimate for sand transportation from mine to processing plant assumed each truck to carry 22.5 tons (range: 20 – 25 tons). According to Clark et al., (2011), the terrain in the Marcellus Shale region limits truck carrying capacity to 14.16 tons (Clark et al., 2011). Therefore, our average estimate for sand transportation by truck from transload station to HF well assumed a carrying capacity of 19.58 tons (range: 14.16 – 25 tons).

Regarding the transportation of water in the Marcellus Shale region, trucks to HF wells are said to have a carrying capacity of approximately 5,500 gallons each (22.9 tons) (Gannett Fleming GFX Freight Solutions, 2011). According to Hart et al., (2013), tank trucks can hold 5,465 gallons of water (22.76 tons) (Hart et al., 2013). However, as Clark et al., (2011) determined that the terrain in the Marcellus Shale region limits truck carrying capacity to 3,400 gallons of water (14.16 tons), our average estimate for water transportation by truck assumed a carrying capacity of 18.53 tons (range: 14.16 – 22.9 tons).

Table 7. Assumptions of Vehicle Carrying Capacities

Assumption	Material	Average Estimate	Range
Carrying capacity of trucks (mine to processing plant)	Sand	22.5 tons	20 – 25 tons
Carrying capacity of rail car	Sand	100 tons	100 tons
Carrying capacity of trucks (transload station to HF well)	Sand	19.58 tons	14.16 – 25 tons
Carrying capacity of trucks	Water	18.53 tons	14.16 – 22.9 tons

Life-Cycle Transportation GHG Emissions Factors

Table 8. Life-cycle transportation emission factors (grams per ton-mile)

Mode of Transportation	CO2	CO2e of NOx*	Total CO2e
Class 8b truck	187	797	984
Intermodal Rail	40	229	269

* Assumes emissions factors of 2.57 g/ton-mile for class 8b truck and 0.74 g/ton-mile for intermodal rail and a 100-year global warming potential of 310 (EPA, 2014).

GHG Emissions from deep well injection

GHG emissions associated with deep well injection of waste fluid were assessed using the EIO-LCA tool. “Support activities for oil and gas operations” was used as the surrogate sector for deep well injection, for which 650 t CO2e emissions are generated from $1M of production. According to Jiang et al., (2011), the estimated 2002 unit cost of deep well injection was $0.57 per gallon (Jiang et al., 2011). The EIO-LCA GHG emissions from deep well injection are a product of the cost of deep well injection and the emissions factor for support activities for oil and gas operations.

EIO-LCA tool to compute sand transportation GHG emissions for comparison

The EIO-LCA Purchaser Model incorporates transportation to final consumer. Using an emissions factor of 1,360 t CO2e emissions per $1M of “Sand, gravel, clay, and refractory mining”, the EIO-LCA purchaser model estimates that the production and transportation of sand used in the HF fluid generates 195 t CO2e per well (110 t CO2e per well for production, 85 t CO2e per well for transportation).

Results

Table 9. Average estimate – One-way trips and GHG emissions from transportation of sand, freshwater, and wastewater

Material	Travel	Means of Transport	Distance Traveled Per Trip (Miles)	Quantity Transported (Tons)	Total Ton-Miles (One-way)	Tons of Co2e Emissions per Well	Grams of CO2e per MJ		Carrying Capacity of Vehicle (Tons)	Number of One-Way Trips
Sand	Mine to processing plant	Truck	18.8	2,446	45,994	49.9	0.016		22.5	109
	Processing plant to transload station	Rail	929	2,446	2,272,789	674.9	0.212		100	0.25
	Transload station to HF well	Truck	32	2,446	78,288	84.9	0.027		19.58	125
Sand Total					**2,397,071**	**809.7**	**0.255**			**234**
Fresh Water	Withdrawal source to HF well	Truck	8	12,817	102,534	111.2	0.035		18.53	692
Flowback Water	Reused at different drill pad	Truck	1.5	3,130	4,695	5.1	0.002		18.53	169
	Waste fluid to recycling facility	Truck	110	963	105,962	114.9	0.036		18.53	104
	Waste fluid to injection disposal well	Truck	162	6660	107,827	116.9	0.037		18.53	36
Water Total					**321,018**	**348.1**	**0.110**			**1,001**
Total					**2,718,089**	**1,157.8**	**0.365**			**1,235**

Table 10. Average Estimate of GHG emissions by material, process, and process phase

Material	Process	Process Phase	t CO2e Emissions per Well	g CO2e Emissions per MJ
Chemicals	**Production and Transportation**		**46.1**	**0.014**
Sand	Production		110.0	0.035
	Transportation	Mine to processing plant	49.9	0.016
		WI to PA (Rail)	674.9	0.212
		Transload to HF well	84.9	0.027
	Transportation Total:		809.7	0.255
Sand Total			**919.7**	**0.290**
Water	Transportation Freshwater	Withdrawal to HF well	111.2	0.035
	Transportation Flowback Water	Reused at other drill pad	5.1	0.002
		Waste fluid to recycling facility	114.9	0.036
		Waste fluid to injection disposal well	116.9	0.037
	Flowback Water Total		236.9	0.075
	Treatment	Water recycling	0.9	0.0003
		Deep disposal injection	59.2	0.019
	Water Treatment Total		60.1	0.019
Water Total			**408.2**	**0.129**
Total			**1,374.0**	**0.433**

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