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Estimation of regional air-quality damages from Marcellus Shale natural gas extraction in Pennsylvania

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Abstract
This letter provides a first-order estimate of conventional air pollutant emissions, and the monetary value of the associated environmental and health damages, from the extraction of unconventional shale gas in Pennsylvania. Region-wide estimated damages ranged from $7.2 to $32 million dollars for 2011. The emissions from Pennsylvania shale gas extraction represented only a few per cent of total statewide emissions, and the resulting statewide damages were less than those estimated for each of the state's largest coal-based power plants. On the other hand, in counties where activities are concentrated, NO_x emissions from all shale gas activities were 20–40 times higher than allowable for a single minor source, despite the fact that individual new gas industry facilities generally fall below the major source threshold for NO_x. Most emissions are related to ongoing activities, i.e., gas production and compression, which can be expected to persist beyond initial development and which are largely unrelated to the unconventional nature of the resource. Regulatory agencies and the shale gas industry, in developing regulations and best practices, should consider air emissions from these long-term activities, especially if development occurs in more populated areas of the state where per-ton emissions damages are significantly higher.

Keywords: natural gas, Marcellus Shale, criteria pollutants, air quality, externalities
S Online supplementary data available from stacks.iop.org/ERL/8/014017/mmedia

1. Introduction

Recent technological innovations in natural gas extraction—namely the combined use of horizontal drilling and hydraulic fracturing—are enabling access to vast new natural gas resources contained in shale deposits across the United States (Kargbo *et al* 2010, Mooney 2011). The Marcellus Shale formation is the largest US shale gas deposit and has contributed significantly in recent years to increased US natural gas production (US DOE EIA 2012a, 2012b). The rapid development of this resource has been touted as both an economic boon (Considine *et al* 2011, Marcellus Shale Coalition 2012) and a potential environmental mistake for the region (PennEnvironment Research and Policy Center 2012). Environmental concerns often relate to risks to water resources (Ground Water Protection Council and ALL Consulting 2009, Mooney 2011). However, utilizing natural gas from shale deposits also produces air emissions of various types during extraction, transportation, and end use.

Increases in conventional air pollution may pose a threat to air-quality in shale gas extraction regions (Shogren

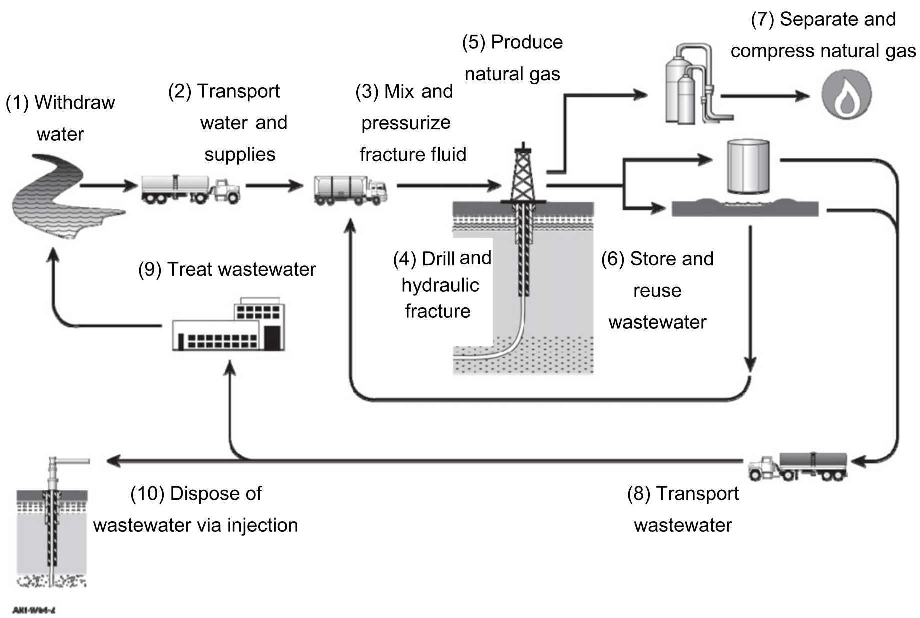

Figure 1. Major activities of shale gas extraction using horizontal drilling and hydraulic fracturing.

2011, Alvarez and Paranhos 2012, McKenzie *et al* 2012, Steinzor *et al* 2012). Such emissions can have direct physical impacts on health, infrastructure, agriculture and ecosystems. For example, short-term exposure to criteria pollutants such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) has been linked to adverse respiratory effects. Exposure to fine particulate matter (PM) and ozone (O_3) may increase respiratory-related hospital admissions, emergency room visits, and premature death. The expanded use of natural gas could arguably reduce net emissions from the electricity sector if used in lieu of coal (US EPA 1999, NRC 2010)[4]. However, shale gas extraction activities such as diesel truck transport and natural gas processing at compressor stations could lead to increases in air pollution in regions where extraction occurs.

Life cycle greenhouse gas (GHG) emissions from shale gas are often assessed to be greater than conventional natural gas. However, most studies also indicate that expanded use of shale gas could lower net GHG emissions relative to coal-based electricity (Burnham *et al* 2011, Fulton *et al* 2011, Hultman *et al* 2011, Jiang *et al* 2011, Venkatesh *et al* 2011, Lu *et al* 2012, Skone *et al* 2012, Weber and Clavin 2012). Additionally, any GHG benefits from shale gas use are not localized to the region where extraction occurs. While GHGs are an important consideration, this letter focuses on conventional, non-GHG air pollution.

A recent GAO literature survey found evidence that extraction activities pose risks to air quality. While some studies indicated degraded air quality at specific shale gas extraction sites, the data necessary to quantify aggregate impacts were not available (US Government Accountability Office 2012). Pennsylvania recently mandated reporting on some emissions to the Pennsylvania Department of Environmental Protection (PA DEP), but this data collection has just begun (Pennsylvania Department of Environmental Protection 2011). This analysis provides initial, first-order estimates of regional air emissions generated by Pennsylvania-based extraction activities[5] and associated ranges of potential regional monetized damages. These estimates must be considered in the context of other external costs and benefits of shale gas extraction and use, and should be refined as new data becomes available.

2. Estimating local emissions and regional damage from shale gas extraction activities

The major stages of shale gas extraction considered here are depicted in figure 1, and emissions occur across many of them (NYS DEC 2011). This analysis includes emissions associated with four shale gas-related activities:

- Diesel and road dust emissions from trucks transporting water and equipment to the site, and wastewater away (stages 2 and 8 in figure 1);
- Emissions from well drilling and hydraulic fracturing, including diesel combustion (stage 4);
- Emissions from the production of natural gas, including on-site diesel combustion and fugitive emissions (stage 5);
- Combustion emissions from natural gas powered compressor stations (stage 7).

[4] Emissions relative to renewable technologies are generally estimated to be lower than those of natural gas, so using natural gas in lieu of renewables would increase emissions.

[5] This analysis does not specifically address acute damages resulting from short-term, high levels of exposure near well-sites but rather focuses on region-wide damages from a general degradation in air quality.

Table 1. Air emissions damages, localization of effects, and relevant pollutants of concern.

Damage category	Damage location	Relevant emissions	Relevant stages	Inclusion in this analysis
Climate change	Local, regional, and global	GHGs: CO_2, CH_4, N_2O, O_3	• Stages 2, 8: transport • Stages 3, 4, 5: site activities • Stage 7: processing	No GHGs included in this study
Air quality	Local and regional	VOCs, NO_x, PM, SO_2, O_3, CO	• Stages 2, 8: transport • Stages 3, 4, 5: site activities • Stage 6: wastewater storage and reuse • Stage 7: processing	*Development activities*: (1) transport; (2) well drilling, hydraulic fracturing Ongoing activities: (3) production; (4) compressor stations *Pollutants*: direct: VOCs, NO_x, PM, SO_2; indirect: O_3 via VOCs and NO_x

We omit emissions from venting or flaring at well-sites (stages 4 and 5). The US EPA will prohibit this by 2015, requiring so-called 'green completions' which capture completions emissions rather than venting or flaring them (United States Environmental Protection Agency 2012), and many natural gas producers have already begun following this practice. Industry-reported emissions for venting are small relative to other sources; however flaring-emission estimates may have a more substantial impact[6].

Pollutants assessed were: volatile organic compounds (VOCs)[7]; NO_x; PM_{10} (<10 μm); $PM_{2.5}$ (<2.5 μm);[8] and SO_2.[9] We focus on these due to their adverse impacts and regulatory status; accordingly, they often appear in facility permitting and emissions reporting, and all are included in the model used here to monetize damages. Table 1 summarizes air pollutants and extraction activities included in this analysis.

3. Methods used to calculate air pollution damages

There is considerable uncertainty in emissions associated with shale gas development. This is due to a scarcity of emissions data and to actual differences in emissions caused by regional and site-specific variations in technology and processes[10]. The several estimation methods and data sources we use result in a wide range of estimates. For industry data used here, estimation methods are likely to have been used (e.g., an emissions factor approach) rather than empirical determinations. Such estimations often differ widely from empirical findings, especially for fugitive emissions (Chambers *et al* 2008, Pétron *et al* 2012), which are also subject to uncertainty (Levi 2012).

Our approach to estimating regional air pollution damages is modeled after another study of the external costs of energy production (NRC 2010). For each activity we have estimated emissions on a per well or per-unit-of-natural-gas-produced basis. Compressor station emissions are estimated per station. These emissions estimates allow us to obtain total statewide emissions, with resolution at the county-level, that we convert to statewide damages using the Air Pollution Emission Experiments and Policy (APEEP) model (Muller and Mendelsohn 2007, 2012). We first describe our approach for estimating emissions (sections 3.1–3.5) and then describe how these emissions were converted into monetary damages (section 3.6).

3.1. Estimates of air pollutant emissions from transport trucks

Diesel trucks used to transport water and supplies to and from the well-site emit air pollutants. Our assumption of the total number of per well truck trips is based on the New York State Department of Environmental Conservation's (NYS DEC) 2011 Environmental Impact Statement (EIS) (NYS DEC 2011). The corresponding implied diesel emissions were estimated with emissions factors in the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model (US DOE Argonne National Labs (ANL) 2012) and in a recent National Research Council study (NRC 2010) for light-duty and heavy-duty vehicles, respectively. Truck traffic can also result in considerable road dust, which we include based on estimates in the NYS EIS. Additional details are provided in section S.1 (available at stacks.iop.org/ERL/8/014017/mmedia). Table 2 provides the total per well transport emissions assumed.

6 For industry inventories that report venting, these emissions are less than 0.1% of VOCs from well drilling and hydraulic fracturing, as described in section 3.2. However, another source (NYS DEC 2011) estimates that total drilling, fracturing, and production PM emissions increase by 250% with flaring; NO_x and VOCs increase by 120%. Assuming these increases, and that all wells flare completions emissions and all PM from flaring is $PM_{2.5}$, additional damages are $5.7 million, or 18% of our high-bound total damage estimate.

7 The EPA defines VOCs to include organic compounds that undergo photochemical reactions in the atmosphere and does not include methane.

8 PM_{10} typically includes all particles less than 10 μm and $PM_{2.5}$ all particles less than 2.5 μm. Thus PM_{10} includes $PM_{2.5}$ in most reporting. In industry reports, there is considerable uncertainty in PM size, and it is often assumed that all PM is smaller than 2.5 μm (i.e. $PM_{10} = PM_{2.5}$). $PM_{2.5}$ has much larger health effects than PM_{10}; this assumption therefore implies the maximal damage.

9 In some cases sulfur oxides are reported as a mixture (SO_x); in our damage calculations, we treat all SO_x as SO_2.

10 In addition to differences in practices and technologies, well-specific variables that may influence emissions include length of well bore, number of fracturing stages, geographic location, and characteristics of the natural gas formation (e.g. wet or dry gas). For emissions reported by industry, we have little knowledge of estimation methodology.

Table 2. Range of assumed well-site development emissions in this analysis.

Emissions activity	VOC	NO_x	$PM_{2.5}$	PM_{10}	SO_x
Total diesel and road dust development emissions (kg/well)	18–31	320–580	9.4–32[a]	9.8–32[a]	0.47–0.79
Total well-site development emissions (kg/well)	150–170	3800–4600	87–130	87–130[b]	3.8–110

[a] PM_{10} emissions were unavailable for heavy-duty trucks; in this case, it was assumed all diesel-related PM emissions were less than 2.5 μm. All road dust was also assumed less than 2.5 μm. Therefore aggregate PM_{10} counts differ from $PM_{2.5}$ only in light-duty vehicle emissions; at the high end of our range, this difference is not significant.

[b] Industry reporting often assumes all PM emissions are less than 2.5 μm and so PM_{10} counts are almost the same as $PM_{2.5}$.

Table 3. Range of assumed well-site production emissions used in this analysis.

Emissions activity	VOC	NO_x	$PM_{2.5}$	PM_{10}	SO_x
Total annual well-site production emissions per well (kg/well)	46–1200	520–660	9.9–50	9.9–50[a]	3.1–4.0

[a] Industry reporting often assumes all PM emissions are less than 2.5 μm and so PM_{10} counts are here the same as $PM_{2.5}$.

3.2. Estimates of on-site air pollutant emissions from well construction

Well development generates emissions at the extraction site during well pad construction, drilling, and hydraulic fracturing. The range of well-site construction emissions used in this analysis were estimated using data reported by three major regional shale gas producers, including one set of emissions reported directly to us and two sets obtained through PA DEP as part of its Air Emissions Inventory for the Natural Gas Industry (PA DEP 2011, Pennsylvania Department of Environmental Protection 2011, Ramamurthy 2012). Details on these data sets and how they were used are provided in section S.2 (available at stacks.iop.org/ERL/8/014017/mmedia); final values used in this analysis are provided in table 2.

3.3. Estimates of air pollutant emissions from shale gas production

The ongoing production of shale gas also generates emissions. Data were obtained from two major regional operators and were used to establish low and high values of production emissions estimates, shown in table 3. Production emissions obtained for this analysis were less consistent between sources than construction emissions, although values are typically within an order of magnitude. In addition to differences between producers, this range may also reflect differences in the operators' reporting assumptions (see section S.3 available at stacks.iop.org/ERL/8/014017/mmedia).

3.4. Estimates of air pollutant emissions from compressor stations

Emissions from compressor stations continue over the long term as natural gas is produced over the life of many wells. To estimate ranges of potential emissions from compressor stations, we reviewed permit applications for more than a dozen new facilities permitted in Pennsylvania in 2010 and 2011, as described in section S.4 (available at stacks.iop.org/ERL/8/014017/mmedia). We make use of the facility-wide potential-to-emit (PTE) emissions values, with ranges reflecting the lows and highs observed in our review. If most facilities are operating below capacity, they may fall at the lower end of the estimate; on the other hand, if they are not running optimally (e.g., frequent shut-downs and start-ups), the emissions could be even higher than indicated by PTE. Values in table 4 therefore represent a range of operating situations.

3.5. Aggregated air pollutant emissions estimates

We used per-facility emissions to estimate county-level and statewide emissions. We present total statewide aggregated emissions in table 5. These values represent the ranges of emissions in tables 2–4 applied to the following extraction activity assumptions for 2011: construction of 1741 wells; statewide shale gas production of nearly 1.1 trillion cubic feet; and operation of 200 recently developed compressor stations. County-level assumptions and values can be found in section S.5 (available at stacks.iop.org/ERL/8/014017/mmedia).

3.6. Estimating damages from air pollutant emissions

For each of the four activities included in this analysis, emissions per well or per million cubic feet were used to estimate county-level emissions because damage per unit of pollution varies greatly with location. These county-level emissions were then converted into county-level annual damages using the APEEP model (Muller and Mendelsohn 2007, 2012). APEEP is an integrated assessment model that uses information derived from the air quality and epidemiological literature[11]. APEEP converts tons of

[11] In considering the annual benefits of the Clean Air Act in 2000, APEEP gives a result of $48 billion compared to the US EPA's estimate of $71 billion. Muller and Mendelsohn argue that the US EPA work likely overstates benefits as it relies on air quality monitoring at sites that were out of attainment, sites likely to show greater changes in pollution levels than the country at large (2007). Note that in making the APEEP estimates, Muller and Mendelsohn use the US EPA's assumptions on value of a statistical life and concentration response function.

Table 4. Range of compressor station emissions estimates used in this analysis.

Emissions activity	VOC	NO_x	$PM_{2.5}$	PM_{10}	SO_x
Total annual compressor station emissions (metric tons/facility)	11–45	46–90	1.4–5.5	1.4–5.5[a]	0–1.7

[a] Industry reporting often assumes all PM emissions are less than 2.5 μm and so PM_{10} counts are here the same as $PM_{2.5}$.

Table 5. Statewide emissions estimates for shale gas development and production in 2011.

	Statewide annual emissions (metric tons per year)				
Activities	VOC	NO_x	$PM_{2.5}$	PM_{10}	SO_x
(1) Transport	31–54	550–1000	16–30	17–30	0.82–1.4
(2) Well drilling and hydraulic fracturing	260–290	6600–8100	150–220	150–220	6.6–190
(3) Production	71–1800	810–1000	15–78	15–78	4.8–6.2
(4) Compressor stations	2200–8900	9300–18 000	280–1100	280–1100	0–340
Total[a]	2500–11 000	17 000–28 000	460–1400	460–1400	12–540

[a] These totals are reported to two significant figures, as are all intermediate emissions values in this document. The activity emissions may not exactly sum to the totals.

Table 6. Estimates of regional air pollution damages from Pennsylvania extraction activities in 2011.

Activities	Timeframe	Total regional damage for 2011 ($2011)	Average per well or per MMCF damage ($2011)
(1) Transport	Development	$320 000–$810 000	$180–$460 per well
(2) Well drilling, fracturing	Development	$2 200 000–$4 700 000	$1 200–$2 700 per well
(3) Production	Ongoing	$290 000–$2 700 000	$0.27–$2.60 per MMCF
(4) Compressor stations	Ongoing	$4 400 000–$24 000 000	$4.20–$23.00 per MMCF
(1)–(4) Aggregated	Both	$7 200 000–$32 000 000	NA

pollutant emitted into physical health and environmental damages, including mortality, morbidity, crop and timber loss, visibility, and effects on anthropogenic structures and natural ecosystems. The base APEEP model calculates age-specific health damages, recognizing that mortality risk and lost years of life will vary with age. Section S.6 (available at stacks.iop.org/ERL/8/014017/mmedia) provides additional details and damages for each county. The damage ranges given for each county are a result of the ranges in emissions estimates above; in addition, because of uncertainty in the size of PM, for activities 2–4 the low damage estimates assume none of the PM is $PM_{2.5}$ and the high damage estimates assume that all PM is $PM_{2.5}$. Complete damages by county and pollutant are found in tables S.11 and S.12 (available at stacks.iop.org/ERL/8/014017/mmedia).

4. Results

4.1. Regional shale extraction air pollutant damage estimates

The aggregated estimated regional damages associated with Pennsylvania shale gas extraction activities are shown in table 6. The total regional air-quality-related damages, at the level of development and production in Pennsylvania in 2011, ranged between $7.2 million and $32 million. These represent the sum of damages in all Pennsylvania counties. While per unit damages will vary greatly with location of the emissions, we also calculated the average per well or per MMCF damages. Some extraction activities occur in regions of Pennsylvania that influence the air quality of populated areas of other states; so while our estimates of emissions were confined to extraction activities in the state of Pennsylvania, these damages should be considered a regional impact, given that pollutants may cross the state border.

Development activities represent about a third or less of total extraction-related emissions (35–17% across the estimated range), whereas ongoing activities represent the majority of emissions (65–83% across the range). Compressor station activities alone represent 60–75% of all extraction-associated damages. Considering the relative importance of different pollutants, VOCs, NO_x, and $PM_{2.5}$ combined across all activities were responsible for 94% of total damages; across the range of estimates they contributed 34–33%, 59–20%, and 2–41%, respectively (shown by activity in table S.11 at stacks.iop.org/ERL/8/014017/mmedia).

4.2. Comparison of air pollutant emissions and damages to other industrial sectors in Pennsylvania

To assess the relative impact the shale gas industry might have on regional air quality, we compare the total emissions estimated for extraction activities in 2011 with net emissions from other major sectors of the Pennsylvania economy. We obtained data from the US EPA's 2008 National Emissions

Table 7. Magnitude of shale gas extraction industry relative to air pollutant emissions from other industrial sectors in Pennsylvania.

Total sector or comparison	VOCs	NO_x	$PM_{2.5}$	PM_{10}	SO_x
Shale gas extraction industry in 2011, from table 5 (metric tons)	2500–11 000	17 000–28 000	460–1400	460–1400	12–540
Total from EPA/NEI, all sectors reporting (metric tons)[a]	720 000	579 000	134 000	322 000	898 000
Shale extraction relative to total (%)	0.35–1.5	2.9–4.8	0.34–1.0	0.14–0.43	0.0013–0.060

[a] Combustion-based electric utilities and highway and off-highway vehicles generally constitute a large percentage of statewide emissions in EPA's 2008 NEI. For example, combustion-based electricity production, highway vehicles, and off-highway vehicles sectors statewide represent: 80% of NO_x (460 000 of 580 000 metric tons); 47% of $PM_{2.5}$ (63 000 of 130 000 metric tons); and 87% of SO_2 (780 000 of 900 000 metric tons). Combined, they are less significant for VOCs and PM_{10} (26% and 22% of statewide respectively).

Inventory (NEI) (US EPA 2008) and calculated statewide emissions (see section S.7 available at stacks.iop.org/ERL/8/014017/mmedia). These statewide totals are presented in table 7, along with the percentage of these total emissions that shale gas extraction activities in 2011 represent. Compared to total emissions from all industries reporting, the shale extraction industry in 2011 was producing relatively little conventional air pollution. Only NO_x emissions are equivalent to more than 1% of statewide emissions across the entire estimated range.

Extraction activities, however, are not evenly distributed throughout the state, so it is instructive to look at the magnitude of emissions in the few counties where activities were concentrated in 2011. More than 20% of wells were found in one county and nearly 50% were in the top 3 counties; the 10 counties with the most development constituted nearly 90% of wells in the state (see table S.8 available at stacks.iop.org/ERL/8/014017/mmedia). The statewide extraction industry also produced VOC[12] and NO_x[13] emissions equivalent to or larger than some of the largest single emitters in the state—GW-scale coal-based electric power plants. In the counties with the most activity, even the low-end of the NO_x emissions estimate ranges were 20–40 times higher than the level that would constitute a 'major' emissions source, although individually the new shale-related facilities are generally not subject to major source permit requirements. On the other hand, the magnitude of PM and SO_2 emissions are much less significant relative to existing major sources, as the statewide totals imply[14].

Although the correlation with emissions is not direct, the total regional damages from the shale gas extraction industry are also expected to be small relative to statewide air pollution emissions damages[15]. For comparison, we estimate that the largest coal-fired power plant in Pennsylvania—while not the state's most polluting facility—alone produced about \$75 million in damages in 2008. The four largest facilities—which included the top two SO_2 emitters in the state—produced nearly \$1.5 billion in damages in 2008. For the shale gas extraction industry, monetary damages were driven by significant levels of VOCs, NO_x, and $PM_{2.5}$, and the whole industry constituted less than 2%, 5%, and 1% for each of the pollutants, respectively, of total emissions in the state in 2008 from all industries reporting.

Because the relative damages will tend to be larger in the counties where shale gas extraction activities are concentrated, where population is relatively high, and where air quality is already a concern, it is also important to consider the county-level damage. For example, Washington County had the fifth largest number of wells (156) in 2011 but resulted in the highest damages, estimated at \$1.2–8.3 million. Damage in this county represented about 20% of statewide damages from the extraction industry[16]. And while not typical of 2011 development, this example illustrates the potential impact of extraction when located in relatively populated areas[17].

5. Discussion

We estimate that total regional air-quality-related damages, at the level of development and production in Pennsylvania in 2011, ranged between \$7.2 million and \$32 million (table 6). However, extraction industry damages will not be constant over time or evenly distributed in space, and there are important policy implications of when and where emissions damages occur. Development emissions damages range from about \$2.5 to \$5.5 million, but the majority of annual attributable emissions will continue for the life of the well and associated compressor facilities. This is true despite the relatively high level of development activity in 2011 and the relatively low number of actively producing shale gas wells, compared to what is expected in coming years. At the low end of our estimates, 66% of total damages in 2011 were

[12] The top five and top twenty VOC emitters produce 252 metric tons per year and 542 tons per year, respectively, in 2008.

[13] For example, the range of estimates of emissions of NO_x is comparable to or larger than the emissions of the top four NO_x emitters in the state. These top four facilities reported emissions of about: 23 500; 22 200; 16 200; and 15 800 metric tons per year of NO_x. The facilities are 2.7, 1.7, 2.0, and 1.9 GW coal-fired power facilities, respectively.

[14] For example, the top four emitters of SO_2 in the state produce from 90 000 to 170 000 metric tons each, so even the high end of the estimates of SO_2 for the extraction industry are equivalent to less than a per cent of these.

[15] Calculation of the statewide damages of all major emitters involves estimating damages for each source individually, due to county-to-county variability of the damage function as well as accounting for each emissions source location and height, and is out of scope for this analysis.

[16] These damages were equivalent to about 11% of the damages from the largest electricity plant.

[17] In this case, Washington County is just south of Allegheny County and the city of Pittsburgh; previous development in the state occurred in more rural north and central Pennsylvania.

attributable to long-term activities; at the high end, more than 80% of damages occur in the years after the well is developed. Nor are most emissions associated with well-site activities. More than half of emissions damages from this industry come from compressor stations, which may serve dozens of individual wells, including conventional ones. Our estimates indicate that regulatory agencies and the shale gas industry, in developing regulations and best practices, should account for air emissions from ongoing, long-term activities and not just emissions associated with development, such as drilling and hydraulic fracturing, where much attention has been focused to date. Even if development slows in the Marcellus region, as it did in 2012, the long-term nature of these emission sources will mean that any new development will add to this baseline of emissions burden as more producing wells and compressor stations come online.

Additionally, most development activities do not constitute 'major sources' under federal air-quality regulations. Especially for those counties that already suffer from high levels of air pollution (i.e., those in or near Clean Air Act non-attainment status), these new activities may make meeting federal air-quality standards more difficult. This issue was raised in the context of the Haynesville Shale region, where authors noted that emissions could 'be sufficiently large that (they)…may affect the ozone attainment status' (Kemball-Cook *et al* 2010). It may be hard to limit these emissions through mechanisms such as permitting restrictions, which typically do not apply to mobile and minor stationary sources. Existing regulations may therefore not be well-suited for managing emissions from a substantial number of small-scale emitters. Proposals to aggregate industry sources should be carefully considered in terms of the appropriate unit of aggregation (e.g., by company, by geographic region) and any unintended consequences or perverse incentive they may create. One approach to reducing air emissions is to require the use of Best Available Technologies (BAT); for compressors, these include lean-burn engines, non-selective catalytic reduction, or electrification, measures often found to be cost-effective (Armendariz 2009). The various costs of meeting or exceeding BAT in Pennsylvania will likely be estimated to support updated compressor permit requirements in Pennsylvania in 2013.

It is worth stressing that a substantial portion of emissions estimated here are not specifically attributable to the 'unconventional' nature of shale gas. Natural gas compressor stations are necessary to produce and distribute natural gas from any source, from conventional to biomethane. So while the emissions levels estimated are non-trivial, they may not differ substantially from any other large-scale industrial emissions that impact regional air quality; it is the scale of the resource extraction or industrial activity that is likely to matter most. Additionally, the magnitude of the potential damages must be considered in the context of other external costs associated with this industry, as well as in terms of the potential benefits of shale gas use.

While statewide emissions from the extraction industry are relatively small compared to some other major sources of air pollution in the state (e.g., SO_2 from GW-scale coal-fired power plants), these emissions sources are nevertheless a concern in regions of significant extraction activities. More detailed analyses, including regional data acquisition and consideration of site-specific variability, will be valuable in regions of intense extraction activity and for specific activities and pollutants shown in this analysis to be of most potential concern. And while significant uncertainty may exist for some potential risks of shale gas extraction, under current standard practices, shale gas extraction will be associated with non-trivial air pollution emissions.

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