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Authors

Castro-Alvarez, Fernando
Marsters, Peter
de León Barido, Diego Ponce
et al.

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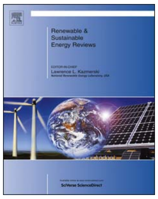

Sustainability lessons from shale development in the United States for Mexico and other emerging unconventional oil and gas developers

Fernando Castro-Alvarez[a,b,*], Peter Marsters[b,c], Diego Ponce de León Barido[b,c], Daniel M. Kammen[b,c]

[a] University of California Berkeley, School of Law, 94720, USA
[b] Renewable and Appropriate Energy Laboratory, University of California Berkeley, 94720, USA
[c] University of California Berkeley, Energy and Resources Group, 94720, USA

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ABSTRACT

Mexico's recent energy reform (2013) has provided the foundations for increased private participation in attempts to offset or reverse the country's continued decline in fossil fuel production. This country is currently on path to becoming a net energy importer by 2020. Conversely, in 2015, and for the first time in over 20 years, the United States (US) became a net oil exporter to Mexico. One of the strategies being pursued by Mexico to prevent an impending supply–demand energy imbalance is the development of shale resources using horizontal drilling and hydraulic fracturing techniques. Hence, an evaluation of the inherent risks associated with hydraulic fracturing is crucial for Mexico's energy planning and decision-making process. This paper draws lessons from the recent ‘shale boom’ in the US, and it analyzes and summarizes the environmental, social, economic, and community impacts that Mexico should be aware of as its nascent shale industry develops. The analysis seeks to inform mainly Mexican policy makers, but also academics, nongovernmental organizations, and the public in general, about the main concerns regarding hydraulic fracturing activities, and the importance of regulatory enforcement and community engagement in advancing sustainability. Furthermore, using the US as a case study, we argue that development of unconventional oil and gas resources in Mexico could lead to a short-term boom rather than to a dependable and sustainable long-term energy supply. Our analysis concludes with a set of recommendations for Mexico, featuring best practices that could be used to attenuate and address some of the impacts likely to emerge from shale oil and gas development.

1. Introduction

With the advent of hydraulic fracturing (fracking), the use of natural gas has increased considerably. As a result of the ‘shale boom’ in the United States (US), and the development of new fracking technology, other countries such as China, the United Kingdom, Turkey, Argentina, and Mexico are all evaluating the potential for exploitation of their indigenous shale resources [1–4] In 2013, the US became the largest producer of natural gas, which has led to some of the cheapest natural gas and oil in over two decades [5]. It is estimated that by 2020 the US will be producing 4.8 thousand barrels per day (4.8 mb/day), which will continue to support the growth of fossil fuel supply from regions not part of the Organization of Petroleum Exporting Countries (OPEC) [6]. While shale exploitation can provide some short-term localized economic benefits for resource-endowed nations, evidence from the US suggests these might be accompanied by a variety of environmental, social, and community-related problems [7]. Hence, the objectives of this paper are to shed light on the impacts of hydraulic fracturing, and to provide recommendations for best practices for consideration by Mexican policy makers as they endeavor to succesfully regulate this industry. We summarize the literature that explores these impacts and the best practices adopted in the US for their mitigation, while evaluating this information in the context of Mexico's desire to exploit its own shale resources.

In the US, the advent of hydraulic fracturing combined with horizontal drilling has changed the oil and gas industry dramatically [7]. Since 2008, the US has increased its production of oil and natural gas by almost 85 billion m^3/year, and crude oil by over 3 million barrels/day [10]. There are indications the US has received short-term localized economic benefits in areas of shale development. Communities sited near shale operations have experienced increases in employment, salaries, and per capita income during the initial stages of such operations [9]. However, the economic instability associated with price volatility and the panoply of environmental, social, and community impacts that emerge due to shale

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* Corresponding author at: University of California Berkeley, School of Law, 94720, USA.
E-mail address: fcastroa@berkeley.edu (F. Castro-Alvarez).

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development, complicate decision-making processes over whether unconventional oil and gas resources should be developed fully. Massive land clearing, water consumption, waste management issues, community impacts, and emissions of greenhouse gases and volatile organic compounds (VOCs) are only some of the many concerns that surround the exploitation of unconventional resources [10].

The rapid rise in drilling activity together with the adoption of new drilling methods in the US has meant that regulations have been slow to catch up [11]. Consequently, controversy arose over whether the existing oil and gas regulatory structure was sufficiently robust to avoid severe environmental impacts and to protect public health [12]. In effect, the existing rules and regulations were insufficient for these purposes. However, the Federal Government largely avoided the problem and it was left to the states to fill the regulatory gap, which has resulted in the implementation of different regulatory approaches for hydraulic fracturing across the US [13].

In the US, industry and operators have compiled considerable information regarding hydraulic fracturing processes, but they have usually been unwilling to disclose it given trade-secret concerns and the competitive benefits they derive from such practices [14]. Recently, academics, nongovernmental organizations (NGOs), and the government have all begun developing research to address the information asymmetry that exists between developers and the public.

1.1. Brief history of hydrocarbon development in Mexico

Mexico began intensive development of its hydrocarbon resources in 1904 [15]. At the turn of the 20th century, foreign oil companies, mainly from the United Kingdom and the US, commenced significant operations that led to Mexico becoming the second-largest oil producer in the world by the 1920s [16]. In 1938, President Lazaro Cardenas expropriated all the assets of the foreign oil companies operating in Mexico at the time. This action was prompted by constant threats from these foreign companies to leave the country and take their capital if the government forced them to sign a collective agreement with the “Petroleum Workers Union of Mexico,” which, among other things, demanded fair working conditions for the employees of the foreign companies [17]. The rationale advanced by the government was that oil, as an energy source, belonged to “all Mexicans,” and as such, government entities alone should exploit them for the sole purpose of benefiting the country [18]. Nevertheless, “Petroleos Mexicanos” (PEMEX), continued to engage in service contracts with some US oil companies until a 1958 regulatory law implementing Article 27 of the Mexican constitution definitively banned the practice [16].

During the 1980s, PEMEX consolidated and became one of the main contributors to Mexico's public finances, providing around 30% of the Federal Government's total income [19]. This was achieved largely because of the discovery in 1979 of Cantarell, the world's third largest oilfield at the time (just behind the Ghawar and Burgan oilfields of Saudi Arabia and Kuwait). This newfound bounty came with promises of jobs, technological development, commitment to industrialization, and sustainable city building. Above all, Lopez Portillo (and his team of experts) stressed that this windfall of wealth would be reinvested in Mexico to guarantee a future “beyond oil.” However, it took just 24 years for Cantarell to reach peak oil status. By 2004, Mexico's largest oilfield had reached its maximum rate of petroleum extraction, after which it entered a state of terminal decline [20,21].

Since its peak in 2004, Mexico's total oil production has declined by 27%. In 2014, Mexico produced an average of 2.8 million barrels/d of petroleum and other liquids, crude oil accounted for 2.4 million barrels (87% of the total output), with the remainder attributable to lease condensate, natural gas liquids, and refinery processing gain. Notably, crude oil production in 2014 was at its lowest level since 1986 and it has continued to decline [22]. This is evidenced by the fact that during 2015 the US became a net exporter of oil to Mexico, a situation that had not happened for over 20 years [23].

1.2. Current state of shale development in Mexico

The decline in hydrocarbon production has spurred support for the development of Mexico's unconventional resources as a means of reversing the situation. In 2011, the US Energy Information Administration reported that Mexico has the second-largest shale gas potential in Latin America and the fourth largest globally. With technically recoverable shale resources estimated at 545 tcf of natural gas, and 13.1 billion barrels of oil and condensate, Mexico's unconventional resources are potentially larger than its proven conventional reserves [24].

According to a public information petition made to PEMEX in 2014, at least 924 wells have been fractured hydraulically in Mexico since 2003 [25]. These wells are in the states of Coahuila (47 wells), Nuevo León (182 wells), Puebla (233 wells), Tabasco (13 wells), Tamaulipas (100 wells), and Veracruz (349 wells). However, the “Proyecto Aceite Terciario del Golfo: Primera Revisión y Recomendaciones” document (prepared in 2010 by the Mexican Ministry of Energy and National Hydrocarbons Commission) stated that 1323 wells have been fractured hydraulically in the specific areas of “Paleocanal” and “Chicontepec” in Veracruz and northern Puebla [26]. This inconsistency highlights the urgency for transparency in information, while illustrating the pressing need for a comprehensive regulatory framework aimed at protecting the local communities and the environment.

2. Lessons from hydraulic fracturing operations in the US

In this section, we provide a review of the literature and an analysis of the panoply of impacts associated with hydraulic fracturing in the US. Land impacts, atmospheric impacts, water impacts, community impacts, public health concerns, crime considerations, waste management, and administrative and environmental violations are evaluated.

2.1. Land impacts and issues

Oil and gas drilling activities require extensive use of land [27]. Hence, the primary major environmental impact of unconventional oil and gas development is associated with the requirement for land. This is estimated to be roughly 30,000 m^2 per well pad, including roads and associated infrastructure (i.e., equivalent to about seven football fields placed together) [28].

Hydraulic fracturing sites often intrude into forested land, agricultural land, and grassland [29]. Deforestation associated with this intrusion has been found to cause loss of habitat for animals and plants, and to increase the impacts of climate change because of associated land use changes [29].

The total infrastructure requirements are a function of the number of well pads and the size of the overall development; thus, the total impact is determined by the total number of well pads in a play [30]. In addition to direct impacts related to land clearance, there might also be indirect effects on ecosystems near the affected area due to the “edge effect” [31]. This edge effect relates to an ecosystem reducing its spatial “buffer zone” as a shale development encroaches.

Apart from issues associated with land clearance, spills of toxic oil and gas hydraulic fracturing fluids can have severe environmental impacts in neighboring areas. Adams [32] focused on simulating a spill of hydraulic fracturing fluid in an experimental forest. This study found the forest experienced significant mortality: “Two years after fluid application, 56% of the trees within the fluid application area were dead.”

In lieu of permanent infrastructure, many operators dig pits in the ground, line them with plastic or vinyl sheets, and use them to store water both before and after the hydraulic fracturing activity [33]. These pits can leak and subsequently kill aquatic life [34]. In addition to the massive volumes of fluids stored on site, chemicals and other additives involved in the hydraulic fracturing process also need to be stored and transported safely [31].

Long-term infrastructure (usually large metal tanks with volumes of up to several hundred barrels) generally needs to be installed to collect the water coproduced with the oil and gas [35]. It is important to note, however, that in extreme events such as flooding this long-term infrastructure has been shown to fail, resulting in spills of hydraulic fracturing fluid and hydrocarbons. This was demonstrated by the 2013 floods in Colorado, which resulted in the spill of an estimated 162 m^3 of hydrocarbons and produced water [36].

In terms of restoration (equipment removal and reseeding of the area around a well to allow vegetation to grow back), the time requirements and specific processes of reclamation are highly dependent on the particular conditions of the well and the environmental qualities of the area [31]. It is worth noting that because development is ongoing, large-scale restoration efforts do not yet exist; hence, details about the effectiveness of restoration remain vague.

2.2. Atmospheric impacts and issues

The main atmospheric impacts associated with hydraulic fracturing activities are related to the emissions of both greenhouse gases (primarily methane) that contribute to climate change and VOCs that affect air quality. It is worth noting that a compounding effect is caused by the high demands for energy associated with transportation and electricity related to the extraction of shale oil and gas, which result in increased local and greenhouse gas emissions [37].

The net impact of greenhouse gas emissions from hydraulic fracturing activities is a subject of great debate that focuses on two main issues: the emissions of greenhouse gases derived from electricity production and the magnitude of methane leakage [38]. Methane emissions can come from direct releases during venting or from unintended leaks [31]. A study conducted in the Denver–Julesburg Basin (Colorado, US) found that natural gas producers lose an average of 4% of the gas to the atmosphere, not including further losses attributable to the pipeline and distribution system [39].

These emissions could possibly outweigh any carbon reduction benefits derived from using natural gas to replace other fossil fuels such as coal and oil for electricity generation [38]. Tables 1 and 2, provided by US Environmental Protection Agency (EPA), show estimates of total annual methane emissions from oil and gas production.

During certain well operations (mainly completions, maintenance, and some emergencies), natural gas might be burned when it cannot be safely, profitably, or practically exploited [42]. These flaring practices, which are usually a consequence of a lack of access for transportation infrastructure, cause considerable emissions that are the product of wasted resources [51]. The exact scale and composition of emissions from flaring vary with gas type (sour or sweet), wind speed, and flaring equipment [43].

Localized emissions can also have significant impacts on the community and public health. These are mainly associated with VOCs, which are toxic precursors to ozone and include benzene, toluene, ethylbenzene, xylenes, BTEX, and n-hexane [44]. To provide an idea of the magnitude of the impacts related to the emission of VOCs, we introduce the results of a study by Macey, Breech, and Chernaik [45]. Their work analyzed the impacts on air quality specific to the development of unconventional oil and gas in the states of Wyoming, Arkansas, and Pennsylvania (US). They found that 16 of 35 grab samples and 14 of 41 passive samples had concentrations of VOCs that exceeded the Agency for Toxic Substances and Disease Registry (ATSDR) and/or EPA Integrated Risk Information System (IRIS) threshold levels (see Table 3). The chemicals that most commonly exceeded these threshold levels were hydrogen sulfide, formaldehyde, and benzene. Background levels of these chemicals are 0.15, 0.25, and 0.15 $\mu g/m^3$ for hydrogen sulfide, formaldehyde, and benzene, respectively. The samples that surpassed the health-based risk threshold levels were 90–66,000 times the background levels for hydrogen sulfide, 30–240 times the background levels for formaldehyde, and 35–770,000 times the background levels for benzene.

A recent study by Loomis and Haefele [46], translated the impacts of air pollution associated with hydraulic fracturing operations into dollar terms using data from Colorado, where about one third of the state population lives on one of three major shale plays. They found that the economic cost of the impact of VOCs ranges from $353 to $509 per ton emitted. Apart from VOCs, hydraulic fracturing operations are also associated with emissions of nitrogen oxides (NOx), sulfur oxide (SOx) and particulate matter with diameters of 2.5 μm ($PM_{2.5}$). Loomis and Haefele [46] found that the economic costs of NOx, SOx, and $PM_{2.5}$ emissions are $353–$821, $1058–$6343, and $1293–$19,825 (all in 2015 dollars) per ton emitted, respectively. These significant costs are borne by those communities sited nearest the unconventional oil and gas developments, regardless of whether they receive any quantifiable benefit from the hydraulic fracturing operations.

Table 2
EPA Inventory Values (US EPA [41]).

Activity	Emission Factor	Unit
Hydraulic Fracturing Completions and Workovers that vent	41	Mg/comp or workover
Flared Hydraulic Fracturing Completions and Workovers	5	Mg/comp or workover
Hydraulic Fracturing Completions and Workovers with reduced emission completions	3	Mg/comp or workover
Hydraulic Fracturing Completions and Workovers with reduced emission completions that flare	6	Mg/comp or workover

Mg: Miligrams.
Emisssion factor: Emission factors listed in this table are for potential emissions.
Comp or workover: Completions or workovers.

Table 1
US methane emissions (Tg CO_2 Eq.), (US EPA [40]).

Activity	1990	2005	2008	2009	2010	2011	2012
Production Field Operations (Potential)	35	29	30	30	30	31	32
- Pneumatic device venting	10	8	9	9	9	9	9
- Tank venting	5	4	4	4	4	5	6
- Combustion & process upsets	2	2	2	2	2	2	2
- Misc. venting & fugitives	17	14	15	15	15	15	15
- Wellhead fugitives	0.5	0.4	0.5	0.5	0.5	0.5	0.5
- Production Voluntary Reductions	0	−0.8	−2	−1	−1	−1	−1
Production Field Operations (Net)	35	28	28	29	29	30	31
Crude Oil Transportation	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Refining	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Total	36	29	29	29	30	31	32

Table 3
ATSDR minimal risk levels and EPA IRIS cancer risk levels for chemicals of concern (units: μg/m^3) (Macey, Breech, and Chernaik [45]).

Chemical	ATSDR MRLs			Iris Cancer Risk Levels		
	Acute	Intermediate	Chronic	1/1000,000	1/100,000	1/10,000
Benzene	29	20	10	0.45	4.5	45
1,2 butadiene	x	x	x	0.03	0.3	3
Ethylbenzene	21700	8680	260	x	x	x
Formaldehyde	49	37	10	0.08	0.8	8
N-hexane	x	x	2115	x	x	x
Hydrogen sulfide	98	28	x	x	x	x
Toluene	3750	x	300	x	x	x
Xylenes	8680	2604	217	x	x	x

2.3. Water impacts and issues

The total volume of water used for hydraulic fracturing has also been at the center of much controversy because it has considerable impact on local communities in relation to its sourcing and transportation [47]. It has been estimated that a typical fractured well will consume an average of 6 million gallons of pressurized water [48]. The sourcing of water leads to reductions in its availability for other local requirements. A study by the EPA found that approximately 35,000 fractured wells across the US required around 70–140 billion gallons of water per year, which is approximately equivalent to the total amount of water used annually to support 40–80 cities with a population of 50,000 inhabitants [48].

One of the primary vehicles for potential societal harm from hydraulic fracturing is through water contamination [49]. This is because, even after hydraulic fracturing activities have ceased, large volumes of water contaminated with toxic and hazardous materials must be managed [50]. If these produced waters were to enter an aquifer in sufficient concentrations, it would render the aquifer unsafe for further use [51]. Regarding the chemical composition of these produced waters, Engle et al. [52] concluded that while the exact composition might vary, they will include most of the chemical constituents that were introduced into the well, except those consumed during the process (e.g., acids and some polymers). They will also contain proppants and potentially radionuclides that would have to be filtered out [52,66]. Table 4, from Hayes [53], presents the concentrations of constituents present in the flowback water of a well in Pennsylvania (US), within two weeks of it being fractured.

Regarding subsurface aquifer contamination, evidence suggests faulty well construction is the most likely cause of contamination. Darrah et al. [54] analyzed methane contamination within groundwater using noble gas isotopes. They concluded that cases of contamination were most likely due to poor cementing measures in the annulus of the well. Their study also suggested that migration from deep shales was unlikely. Sloppy cement jobs, seismic activity, or simply poor quality cement were all cited as possible causes of groundwater contamination. On the other hand, surface contamination is generally caused by spills, leaks, and accidental releases. Vidic et al. [55] and Vengosh et al. [56] found little evidence of shallow-water chemical contamination; strong evidence of methane contamination; some evidence of deepwater–shallow-water aquifer mixing; and significant issues regarding produced water management and accidental spills [31].

Table 4
Chemical composition of flowback water.

Parameter	Range	Median	Units
pH	4.9–6.8	6.2	No Units
Acidity	< 5–473	NC	mg/L
Total Alkalinity	26.1–121	85.2	mg/L
Hardness as CaCO3	630–95,000	34,000	mg/L
Total Suspended Solids	17–1150	209	mg/L
Turbidity	10.5–1090	233	NTU
Chloride	1670–181,000	78,100	mg/L
Total Dissolved Solids	3010–261,000	1,20,000	mg/L
Specific Conductance	6800 710,000	2,56,000	micromhos/cm
Total Kjeldahl Nitrogen	5.6–261	116	mg/L
Ammonia Nitrogen	3.7–359	124.5	mg/L
Nitrate-Nitrite	< 0.1–0.92	NC	mg/L
Nitrite as N	< 2.5–77.4	NC	mg/L
Nitrate as N	< 0.5 - < 5	NC	mg/L
Biochemical Oxygen Demand	2.8–2070	39.8	mg/L
Chemical Oxygen Demand	228–21,900	8530	mg/L
Total Organic Carbon (TOC)	1.2–509	38.7	mg/L
Dissolved Organic Carbon	5–695	43	mg/L
Oil & Grease (HEM)	< 4.6–103	NC	mg/L
Cyanide, Total	< 10	NC	ug/L
Amenable Cyanide	< 0.01	NC	mg/L
Bromide	15.8–1600	704	mg/L
Fluoride	< 0.05 - < 50	NC	mg/L
Total Sulfide	< 3.0–3.2	NC	mg/L
Sulfite (2)	7.2–73.6	13.8	mg/L
Sulfate	< 10–89.3	NC	mg/L
Total Phosphorus	< 0.1–2.2	NC	mg/L
Total Recoverable Phenolics	< 0.01–0.31	NC	mg/L
Sulfite	7.2–73.6	13.8	mg/L
Methylene Blue Active Substances (MBAS)	< 0.05–4.6	NC	mg/L

Samples were collected from 17 locations.
NC - indicates the median concentration was not calculated due to undetected results.
mg/L : Miligrams per liter.
NTU: Nephelometric Turbidity Units.

2.4. Community impacts

The visual and audible impacts of oil and gas extraction are among the most common complaints communities have regarding such development [57]. As with most impacts regarding shale development, they vary depending on the local conditions. Table 5, obtained from the US Bureau of Reclamation [58], presents the ranges of impacts from different noise sources including oil and gas development.

In addition, as evidenced in Table 6, many shale developments cause considerable increases in traffic with associated consequences. Increased levels of traffic exacerbate the risk of traffic accidents and augment local air pollution emissions, while also burdening the local community with additional wear of infrastructure. Moreover a study by Muehlenbachs and Krupnick [59] showed that for every well drilled in Pennsylvania (US), the number of fatal accidents in the studied county increased by 0.6% and the number of heavy truck accidents increased by 2%.

The potential pathways to exposure to the chemicals involved in hydraulic fracturing are numerous and they include drinking water, skin contact, soil and food, and the atmosphere [60]. The nature of the damage and the risk to health are largely dependent on the concentra-

Table 5
Noise ranges according to the US Bureau of reclamation [58].

Activity	Range in dBA	Timing Pattern
Site construction and rehabilitation (earth moving and agricultural equipment)	93 –108	Intermittent-Fluctuating sound levels-Typically day operations only
Oil/gas drilling/workover	100–130	Intermittent-Fluctuating sound levels-24 h/day operations-1 week to several months duration
Oil/gas fracturing operation	100–145	Intermittent-Fluctuating sound levels- Venting/flaring operations are loudest and most continuous-but last only 1–2 days-24 h/day operations-1 -2 weeks duration
Oil/gas operations	62–87	Long term-continuous sound levels-24 h/day–7 days/week-year round operations
Natural gas compressors	62–87	Long term-continuous sound levels-24 h/day- 7 days/week- year round operations- Low pitched sound
Highway traffic	80–100	Intermittent-Fluctuating sound levels-Generally heavier use during daylight hours
Developed recreational areas (Ldn)	50–65	Intermittent-Fluctuating sound levels-Generally more activity during summer daylight hours
Motor boating (including jet skis)	70–115	Intermittent- Fluctuating sound levels-Generally heavier use during daylight hours

Table 6
Number of truck trips per Well (NYSDEC 2011 [31]).

	Horizontal well with high-volume hydraulic fracturing		Vertical well	
	Heavy truck	Light truck	Heavy truck	Light truck
Light-duty trips	831	795	507	507
Heavy-duty trips	1148	625	389	310
Combined Total	1975	1420	905	817
Total Vehicle Trips	3950	2840	1810	1634

tion and vector of delivery, and on the toxicity potential of the compounds and its derivatives. This strongly suggests the need for full disclosure from operators in case of accidents. The chemicals of major concern have the following three characteristics: toxicity, persistence, and mobility [61]. Also of concern are other aromatic hydrocarbons, petroleum distillate products, amines, amides, and acids [31]. A study by Bloomdahl et al. [62] considered the exposure of workers to VOCs from produced water. It was found that the risk level was below the limits set by the Occupational Safety and Health Administration in most cases; however, they stressed the need for further research. Colborn et al. [63] focused on the chemicals involved in hydraulic fracturing and they attempted to select the most harmful chemicals. They found “many chemicals used during the fracturing and drilling stages of gas operations may have long-term health effects that are not immediately expressed”. On the topic of further research, Werner et al. [64] stated that the literature does not allow for any negative health impacts associated with hydraulic fracturing to be ruled out. McKenzie et al. [65] and McKenzie et al. [66] suggested that the impact of atmospheric emissions on human health warrant further study, emphasizing that they potentially have non-trivial effects on maternal health. Jenner and Lamadrid [67] studied the cost–benefit analysis of hydraulic fracturing in terms of direct comparison with coal. They concluded that any benefits rely on a thoroughly effective environmental management program. Finally, Eaton [68] determined that the risks were too great for the state of New York (US) and that a ban was appropriate given the lack of research. Indeed, in a public health review of hydraulic fracturing conducted in December 2014, the New York Department of Health came to the following conclusion:

> “The DOH [Department of Health] Public Health Review finds that information gaps still exist regarding various aspects of HVHF [High Volume Hydraulic Fracturing] activities. Well-designed, prospective, longitudinal studies are lacking that evaluate the overall effect of HVHF shale-gas development on public health outcomes. The existing science investigating associations between HVHF activities and observable adverse health outcomes is very sparse and the studies that have been published have significant scientific limitations. Nevertheless, studies are suggestive of potential public health risks related to HVHF activity that warrants further careful evaluation. Additional population-based research and surveillance, and more studies involving field investigations in locations with active HVHF shale-gas development, would be valuable” [69].

Crime has also increased in communities that surround these developments. James and Smith [70] showed that “shale-rich counties experienced faster growth in rates of both property and violent crimes including rape, assault, murder, robbery, burglary, larceny, and grand theft auto”. The study stressed that policymakers need to be prepared ahead of time in certain boomtown communities. Moreover, Haggerty et al. [71] explored this issue and found that while communities might benefit in the short-term from booms associated with hydraulic fracturing, communities with a long-term focus on oil and gas production experienced negative effects in terms of observed income, crime, and education.

The hydraulic fracturing boom in the US has been shown to have considerable social impacts for rural communities [72]. The advent of unconventional oil and gas development has meant that many rural communities, which have come to depend on these resources, face social and economic instability because of the effects of fluctuations in prices and industry practices [73]. Environmental pressures derived from unconventional oil and gas development further exacerbate the impacts of operators exiting the market as prices fluctuate [74]. As a consequence of the land clearance and the pollution of air and water resources during hydraulic fracturing activities, the potential to use the affected land for other purposes is diminished. This in part has been found responsible for the increased hardship faced by rural communities in the US, compared with metropolitan areas, particularly in terms of increasingly higher levels of poverty, widespread unemployment, and food insecurity [75].

2.5. *Waste management considerations*

An exemption by the US EPA means that many forms of drilling waste are not considered hazardous; thus, they can be disposed of without special management, even though they might contain toxic materials. The classification of materials as hazardous or not is determined by specific regulations from the US EPA [76]. Generally, waste is exempt from being treated as hazardous if it satisfies the following two questions. (1) Has the waste come from down-hole, i.e., was it brought to the surface during oil and gas E & P operations? (2) Has the waste otherwise been generated by contact with the oil and gas production stream during the removal of produced water or other contaminants from the product? If the answer to either question is yes, then the waste is exempt. It is worth noting that many environmental NGOs argue that this exemption should be reversed at the federal level given that it applies to most hydraulic fracturing waste, even that including pure chemicals and radioactive materials [77].

Most solid waste is disposed of in surface landfill. The total volume of waste varies greatly depending on the depth and geology of the plays. The NYSDEC [31] gives examples of vertical wells with depths of 2100 m producing 120 m^3 of cuttings and similar wells with horizontal sections producing 165 m^3. As these wastes are disposed in traditional landfill in the US, and given that they are legally exempt from hazardous waste laws, it is unknown what percentage of these wastes is actually harmful.

Oil and gas extraction operations produce large volumes of water together with the oil and gas [78]. This water is a mixture of fracture fluid, geologic water, and constituents picked up from within the shale itself. Its volume is determined by both the characteristics and quantity of the water injected and the geology itself [79]. The vast majority of this water flows back within the first two to eight weeks, but hundreds of liters of water can be produced daily during the lifetime of a well [31]. In the US, all water produced by oil and gas developments needs to be separated from hydrocarbons using filters or centrifuges [80]. This process generally removes the total suspended solids and it is required regardless of the fate planned for the water [31]. However, this process requires significant energy and hence, it causes considerable expense [81]. Because of the geologic variability, there is no single method for the management of produced water. Overall, cost is the primary factor that operators will consider when selecting the treatment and management methods to adopt. The costs of these methods are dependent on the quality of the water, its quantity, and the distance it needs to travel [103]. The main methods of water management, in descending order of most common use, are underground injection, recycling for future hydraulic fracturing operations, treatment through reverse osmosis, flash distillation, and treatment at a specialized centralized facility [82]. Although the exact number of failures of injection wells is unknown, a report by Lustgarten [83] showed that wells do fail and that they can cause contamination. In addition, it is worth noting that injected fluids will need to be sequestered for thousands of years; thus, long-term planning poses its own particular complications.

A study by Maloney and Yoxtheimer [84] quantified the waste produced from hydraulic fracturing operations in the state of Pennsylvania (US). It was found that the total waste produced across the state included 5313 barrels of basic sediment, 9,065,470 barrels of brine water, 798,623 t of drill cuttings, 2,374,469 barrels of drilling fluids, 14,947 t of flowback fracturing sands, 7,878,587 barrels of flowback, and 5256 barrels of spent lubricants. Table 7 summarizes the total Marcellus Shale waste generated in Pennsylvania during 2011, separated by state, disposal method, and waste type.

Geologic formations that contain oil and gas deposits also contain naturally occurring radionuclides, which are referred to as naturally occurring radioactive material (NORM). Lopez [85] stated that hydraulic fracturing could create radioactive waste in the pipes, filters, produced water, and water treatment equipment. The main constituents of NORM are uranium, thorium, radium, and their decay products [86]. There is currently no consensus on regulatory limits in the US. However, currently, waste that does exceed limits is disposed of in injection wells, well bores during plugging, or sent to a landfill licensed to accept it [86]. What is troubling, however, is that given the amount of waste (estimated at > 27 t/d), there is a lack of capacity for its disposal [87]. For example, in North Dakota (US), filters known as “frac-socks” have overwhelmed the available disposal facilities, and this has led to numerous incidents of illegal waste dumping [87].

2.6. Violations (Pennsylvania case study)

To demonstrate the actual risks associated with operators' practices, we analyzed data from Pennsylvania (US) [88]. We evaluated 17,493 administrative (10,630 or 61%) and environmental health and safety (6863 or 39%) shale gas violations from the state of Pennsylvania (US) from 2010 to 2014. This data set does not include all the violations that occurred during that period for all the wells that exist in the state; therefore, it represents an underestimation of the actual number of violations that have occurred to date. The Pennsylvania data set includes 17,493 violations from 40 out of 67 counties and 546 townships in the state. The percentages of the total number of violations that occurred during 2010–2014 are 20%, 29%, 24%, 17%, and 10%, respectively. The data are divided into administrative and environmental health and safety violations. There are 180 unique violations, of which 99 are administrative (55%) and 81 (45%) environmental. Only 14,291 violations have well geolocation data (county and township).

Without distinguishing between administrative or environmental violations, the five most frequent violations are as follows: failure to plug a well upon abandonment (1720 occurrences or 9.8% of the total); failure to minimize accelerated erosion, implement an environmental safety (E & S) plan, and maintain E & S controls (1335 occurrences or 7.6% of the total); failure to properly store, transport, process, and dispose of residual waste (1314 occurrences or 7.5% of the total); failure to adopt pollution prevention measures required or prescribed by the DEP by handling materials that create a danger of pollution (771 occurrences or 4.4% of the total); and failure to submit well records within 30 days of completion of well (702 occurrences or 4.0% of the total).

Of all the violations analyzed, 6863 (39%) were environmental. The most frequent environmental health and safety violations include “failure to properly store, transport, process, and dispose of residual waste” (20%); “failure to minimize accelerated erosion, implement an environmental safety (E & S) plan, and maintain E & S controls” (20%); “failure to adopt pollution prevention measures required or prescribed by the DEP by handling materials that create a danger of pollution” (11%); “discharge of pollution materials to waters of the Commonwealth” (10%); and, “failure to properly control or dispose of industrial or residual waste to prevent pollution of the waters of the Commonwealth” (8%).

The cost of these top-five environmental violations is higher on average than the rest of the environmental violations. A top-five environmental violation is worth US$7812/violation, with other violations being worth US$568 less (US$7244). Of the top-five violations, the most expensive is the “discharge of pollution material to waters of the Commonwealth” (US$12,837/violation); followed by “failure to minimize accelerated erosion, implement an environmental safety (E & S) plan, and maintain E & S controls” (US$9782/violation); “failure to adopt pollution prevention measures required or prescribed by the DEP by handling materials that create a danger of pollution” (US $8942/violation); “failure to properly store, transport, process, and dispose of residual waste” (US$4266/violation); and “failure to properly control or dispose of industrial or residual waste to prevent pollution of the waters of the Commonwealth” (US$3590/violation).

Most (61%) of the violations in this analysis were administrative (10,630). The most frequent administrative violations include “failure to plug a well upon abandonment” (16%); “failure to submit well records within 30 days of completion of drilling” (7%); “failure to install, in a permanent manner, the permit number on a completed well” (6%); “failure to achieve permanent stabilization of earth disturbance activity” (4%); and “failure to submit annual production report” (5%). In contrast to the environmental violations, the top-five administrative violations are not the most expensive.

On average, the five most frequent violations are less expensive (US $2568/violation) than less frequent violations (US$5484/violation). Although “failure to plug a well upon abandonment” is the most frequent overall violation, the fine is relatively small (US$1307/violation). The most expensive top-five violation is “failure to achieve permanent stabilization of earth disturbance activity” (US$11,003/violation). This is followed by “failure to submit well records within 30 days of completion of drilling” (US$1476/violation); “failure to install, in a permanent manner, the permit number on a completed well” (US

Table 7
Marcellus Shale Waste (Maloney and Yoxtheimer [84]).

Total Marcellus waste generated in Pennsylvania during 2011 separated by state, disposal method, and waste type								
		Waste type						
Disposal State	**Disposal method**	**Basic sediment (bbl)**	**Produced water (bbl)**	**Drill cutting (tons)**	**Drilling fluids (bbl)**	**Flowback fracturing sand (tons)**	**Flowback (bbl)**	**Spent lubricants (bbl)**
MD	Brine or industrial waste treatment plant	–	114	–	363	–	–	–
NJ	Landfill	–	–	450	–	–	–	–
NY	Landfill	–	445	2,27,598	8598	443	1320	–
OH	Brine or industrial waste treatment plant	–	1,71,077	576	1,13,739	–	97,898	240
OH	Injection disposal well	–	23,48,701	–	47,412	–	1,40,063	–
OH	Landfill	–	–	1,49,118	6550	24	–	–
OH	Other	–	–	10,005	–	–	–	334
PA	Brine or industrial waste treatment plant	116	10,52,182	1834	4,69,871	210	5,31,970	3853
PA	Landfill	887	95	4,00,611	5946	13,877	1197	830
PA	Injection disposal well	–	5346	–	1110	–	110	–
PA	Municipal sewage treatment plant	–	26,379	–	14,466	–	6748	–
PA	Unknown	–	3,31,182	–	–	–	14,320	–
PA	Reuse other than road spreading	4311	22,16,889	405	12,24,431	–	37,74,078	–
PA?	Reuse other than road spreading	–	28,33,297	–	4,54,670	–	33,01,804	–
PA	Other	–	–	–	–	1	–	–
WV	Brine or industrial waste treatment plant	–	23,484	–	–	–	–	–
WV	Injection disposal well	–	10,305	–	23,775	–	3964	–
WV	Landfill	–	–	4815	1067	391	520	–
Unk	Injection disposal well	–	45,973	–	2473	–	4559	–
Unk	Landfill	–	–	3211	–	–	–	–
	Total intrastate transfer	5314	64,65,370	4,02,850	21,70,494	14,088	76,30,263	4683
	Total interstate transfer	–	25,54,127	3,92,562	2,01,504	858	2,43,765	574
	Unknown state	–	45,973	3211	2473	–	4559	–
	Total	5314	90,65,470	7,98,623	23,74,469	14,947	78,78,587	5256

"Unknown" indicates a treatment/disposal location was not indicated in the waste production report.
"PA?" indicates waste reports had no state disposal location, but it was assumed to be reused in Pennsylvania for analyses.
"Unk" no identifying record for state; bbl, barrels.

$1617/violation); and "failure to submit annual production report," which has no cost (US$0/violation). Although it is not one of the most frequent violations, "pipeline installed less than 25 feet from the stream back without a wavier" is the most expensive administrative violation (US$91,666/violation).

2.7. *Economic impacts of price volatility on unconventional oil and gas development in the United States*

The unexpected collapse of crude oil prices in the second half of 2014 had a particularly high toll on the revenues of producers of unconventional oil and gas [89]. The price of Brent crude fell by more than 50% from US$115/barrel (bbl) in June to below US$50/bbl by early January in 2015, and up until 2016, it has shown no sign of bottoming out [90]. The main reason for this decline has to do with supply growth. While growth in global demand has diminished in recent years, supply (mainly non-OPEC, e.g., from countries like the US) has increased, leading to a surplus of oil in the market. In an analysis in November 2014, Citibank estimated that supply was exceeding demand by 700,000 barrels/day, which resulted in a build-up of oil inventories that inevitably drove oil prices down [91]. Moreover, the abandonment of OPEC's policy of reducing exports when prices weaken, which has been interpreted in the West as "an attempt to claw back market share from US shale oil producers," has exacerbated the outcomes of surplus in terms of current oil prices [92]. This issue has presented alarming challenges for developers of unconventional oil and gas, who are facing serious funding difficulties that have had an almost immediate impact on production [93]. Investors are becoming increasingly reluctant to invest in a market where the debt growth outpaces cash flow growth [94]. This "squeeze" in the funding of developers of unconventional oil and gas, coupled with an abrupt decline in profits from low prices, has forced many into massive layoffs and pay cuts (US companies have disclosed at least 86,405 job cuts attributed directly to falling oil prices, according to outplacement firm Challenger, Gray, & Christmas [95]).

In addition to a contraction of the oil sector, falling oil prices have been shown to have a number of indirect effects on oil-exporting economies where finances rely heavily on the oil sector, as is the case of Mexico [96]. It has been found that unless governments have ample buffers to safeguard spending, a significant loss of revenue could trigger abrupt fiscal consolidation [96]. Furthermore, a decline in oil prices generally deteriorates an economy's current account and precipitates currency depreciations [96]. Although these currency adjustments could result in opportunities in non-oil-related tradable goods in the medium term, financial constraints have been shown considerably more significant in the short term [96].

It is also worth noting that financial constraints have spurred efficiencies and cost reduction strategies across the US. Average drilling days are down from 14.2 to 4.3, and high-density fracking has led to a 39% increase in cumulative oil production [97]. In turn, these efficiency improvements have led to a higher rate of return on investments (some fracking companies have been able to achieve a higher rate of return on

US$65 oil in today's markets, compared with US$95 oil in 2012) [97]. However, there is no evidence that operators' incremental efficiencies have outpaced the current financial strain that many of them face across the market. Hence, the prospects for the oil industry in the current environment appear multifaceted [97]. The oil industry continues to face challenges, with under-investment leading to stagnating production and profit (which are of special concern for oil-exporting countries that rely heavily on the oil sector) [97]. However, the market is experiencing the benefits of emerging technologies, new resources, and the key role of the financial sector in the structure of oil production [97]. Nevertheless, the economic impacts associated with the volatility of the price of hydrocarbons, derived from reliance on unconventional resources, in combination with the rapid decline of production from shale plays and the limited amount of productive drilling areas, highlights that the development of unconventional oil and gas resources is temporary. It should be seen as a short-term boom in resources rather than a dependable long-term energy supply option [98].

3. Mexican vulnerabilities to shale development and best practices for their mitigation

As is clear from this analysis, the processes associated with hydraulic fracturing have resulted in considerable damage both to the environment and to certain communities. In the US, the complex cost–benefit calculations related to the development of unconventional oil and gas have resulted in intense political debate over the extent to which government should regulate such operations [99]. Nevertheless, public reaction to the impacts of this industry has been strong, leading to bans in some areas [13].

Mexico has high vulnerability to the impacts of this industry because of its specific circumstances. Therefore, if development of Mexico's shale resources continues, the best practices identified in the US should be incorporated in regulatory instruments to promote impact mitigation and to advance environmental protection efforts through regulation. This section briefly explores Mexico's vulnerability to the impacts of shale development, and it summarizes the best practices identified in the US aimed at mitigating such impacts.

3.1. Addressing land impacts through regulation

Mexico is one of the most biodiverse countries in the world; however, more than half its forest resources have been lost already [100]. The impacts of land clearance are common in association with hydraulic fracturing activities, and the calculation of financial compensation for land clearance and its associated edge effects can be complicated. Nevertheless, offsets might be an important policy for the compensation of losses. These would require a third party to quantify the impacts of land clearance and to propose offsetting projects to promote non-overall net loss of similar ecosystems [101]. Aside from land clearance, accidents and spills can occur during every stage of development of unconventional oil and gas resources.

Mexico has suffered spills due to hydrocarbon operations in the past. For instance, the widely cited Ixtoc oil spill, which occurred in the state of Campeche, had considerable impact on the species and ecosystems of the surrounding area through the effects of chemical toxicity [102]. The risk of a spill is high during every stage of the hydraulic fracturing operation. Therefore, if development of unconventional oil and gas resources continues, the following best practices should be implemented [103–108].

- Require operators to give immediate notice of any spill, fire, leak, or break to the appropriate agency followed by a full description of the event and the losses derived from it. Records on spills, fires, leaks, and any other accident should be made publicly available. Lack of compliance in both immediate notice or delay in the release of records should result in a fine.
- Require the submission of spill contingency plans by operators.
- Require approval of pits, tanks, and containers that are to be used to store drill cuttings, muds, and fluids to ensure they are of appropriate size and have the necessary characteristics.
- Develop drilling mud pit standards.
- Develop tank standards to ensure they are constructed to prevent corrosion and equipped with secondary containment systems and leak detection devices.
- Require operators to conduct studies to determine the radioactive levels of shale deposits.
- Provide mechanisms for operators and the public to report spills and accidents through the Internet (e-mail) and/or telephone (call or text/SMS) access 24 h/d, 7 d/week.
- Determine a process to assess any cleanup or remediation needs, which should be financed by the operators.
- Add radium to spill contingency protocols to ensure cleanups are adequately characterized.
- Consider financial and/or criminal liability derived from negligence in the operations of the developments depending on the severity of the impacts.

Mexico's environment has been affected seriously by ecosystem degradation. Recent studies have found that 50% of its territory has experienced some degree of degradation [109]. Ecosystem degradation does not only affect biodiversity, it poses risks to the quality of life of the people living in the surrounding areas who depend on the goods and services of those ecosystems [109]. Therefore, the following best practices should be considered when addressing restoration practices though regulation to ensure viable levels of ecosystem integrity are met after hydraulic fracturing operators exit the areas of extraction [110]:

- Establish the developer's obligation for restoration.
- Require a draft of a site restoration plan that includes achievable milestones toward this goal.
- Determine the provisions for removal and filling of pits and infrastructure used to contain and store produced fluids and wastes, and the removal of all drilling supplies and equipment.
- Survey infrastructure for NORM prior to removal and closure during restoration activities.
- Determine the timetable for compliance of the restoration activities, and establish sufficiently onerous fines to deter the possibility of late action and non-compliance, including the possibility of losing the right to develop hydraulic fracturing projects in the future.

3.2. Addressing atmospheric impacts through regulation

Methane leakage is already an issue of great concern in Mexico. In 2006, methane leakage was estimated to have reached 52,244,045 US tons in units of CO_2, 95% of which was attributed to the operations of the oil and gas sector [111]. However, some studies have suggested that the emission factors used to calculate methane leakage in Mexico could be improved because they likely underestimate leakage emissions [112]. The increase of shale development operations in Mexico has the potential to increase overall leakages associated with the oil and gas industry; this, in a country still struggling to quantify and regulate leakages from conventional oil and gas operations. Thus, hydraulic fracturing regulation should incorporate the implementation of the following best practices [113].

- Place specific limits on methane emissions from oil and gas developments, with consideration of leakage rates.
- Establish auditing and monitoring mechanisms to ensure compliance with these set limits.
- Ensure high-resolution data from the monitoring of methane

leakages, as well as other pollutants, is publicly available. Data from wireless sensor networks monitoring air quality within a worksite as well as in neighboring communities should be publicly available.
- Enact fines for non-compliance.

As for emissions of VOCs and associated air pollutants, some of Mexico's cities with the worst levels of air quality are located on or very near shale basins. For instance, the city of Monterrey, located over the Sabinas Basin, and very close to the Burgos Basin, already suffers from environmental contingencies due to poor air quality [114]. Development of unconventional oil and gas resources could worsen the air quality of this city further to the detriment of the health of its more than 1,000,000 inhabitants [115]. Therefore, considering the implementation of the following best practices should be explored [116].

- Set limits on emissions of VOCs and associated air pollutants derived from the findings of location-specific studies that evaluate geological characteristics and particular weather patterns.
- Establish monitoring mechanisms to ensure compliance with these set limits.
- Enact sanctions for non-compliance.
- Determine remediation mechanisms and include financial responsibility provisions for medical expenses derived from overexposure of impacted communities caused by developer's non-compliance.
- Require the implementation of “green completions” to reduce emissions of VOCs and associated air pollutants from well completions, by requiring developers to capture gas at the wellhead immediately after well completion, instead of releasing it into the atmosphere or flaring it off.

Flaring causes high point-source emissions, potentially wastes resources, and leads to unnecessary environmental damage. Nevertheless, this practice is preferred over venting. This is because the emissions of VOCs and hazardous air pollutants are reduced to 29 and 1 t, respectively, by flaring in comparison with venting; however, flaring of completion gases also results in the release of more than 1 t of NOx and almost half a ton of CO per well [42]. Recently, the practices of flaring and venting of gas have been increasing in Mexico. In 2016, gas flaring and venting represented 13.1% of PEMEX's total natural gas production, 30% more than in 2015 [117]. The total amounts of vented and flared gas can be expected to increase if Mexico decides to further pursue the development of its unconventional oil and gas resources. Hence, it is important to consider the following best practices in order to curtail the associated impacts [118,119].

- Establish the use of a flaring map that compiles nightly infrared data to display gas flares associated with oil and gas production to determine the sources.
- Require operators to submit gas capture plans as part of the permit process.
- Allow flaring only in cases where hydrocarbons are technically impossible to collect, regardless of economic feasibility issues.
- Require companies to pay full market value price for flared gas, and establish programs to direct the proceeds for the benefit of the surrounding communities.
- Track the amount of gas flared through audits, without relying on self-reporting mechanisms.
- Establish sanctions for illegal flaring and make enforcement data available to the public.

3.3. Addressing water impacts through regulation

The previously analyzed requirements for water by hydraulic fracturing operations, and the water pollution avenues such operations introduce, could affect the availability of an already strained resource. Mexico's renewable internal freshwater resources per capita have fallen dramatically in recent years from 10,062 m^3 in 1962 to 3262 m^3 in 2014 [120]. Hydraulic fracturing operations could exacerbate this decline and seriously compromise the access of the population to fresh water if the related avenues of water pollution are not addressed properly. Hence, if development of unconventional oil and gas resources continues, the following best practices should be considered to ensure safe levels of water quality and the prevention of subsurface contamination [121–123].

- Develop a baseline for water quality in regional water bodies as well as nearby communities before permitting operations to begin.
- Provide mechanisms to allow surface property owners to request water quality testing on any water well or surface water.
- Require the company to perform regular water quality monitoring both in regional water bodies as well as in nearby communities.
- Require water quality testing before and after well-stimulation treatment.
- Provide free and open access data to the public.
- Require restoration or replacement of any water supply affected by well operators. If disputes arise over the cause of the contamination, the burden of proof should fall on the well operators.

The following best practices should be considered to prevent subsurface contamination through well integrity [124–126].

- Develop casing and cementing codes to promote best practices to prevent subsurface contamination.
- Require pressure testing of wells before commencing well-stimulation treatments, following standards developed to ensure the tests simulate real pressure conditions.
- Provide for a period of cement evaluation after placement and before well-stimulation treatment, following standards developed to ensure the quality of the cement is sufficient to provide geologic and hydrologic isolation of the oil and gas formation during and after well-stimulation treatment.
- Require monitoring of each well that has had well-stimulation treatment to prevent and remedy any potential breaches.
- Determine testing schedules for wells undertaking well-stimulation treatment.
- Provide for the installation of pressure relief devices and for the reporting of any pressure release from these devices.

3.4. Addressing waste management concerns through regulation

The increase in seismic activity associated with hydraulic fracturing operations represents another source of danger for Mexico because of its inherent geological characteristics. Mexico is located at the intersection of four major crustal plates; thus, it is one of the most seismologically active regions on the planet and it has a long history of destructive earthquakes [127]. A recent seismological study conducted in Mexico, which analyzed data from the National Seismologic Service, found that areas where hydraulic fracturing operations had already taken place have suffered up to 10 times more earthquakes than before such operations commenced [128]. Therefore, the following best practices regarding produced water management should be considered [129–131].

- Require the use of methods to separate hydrocarbons from water. These methods should remove total suspended solids, and they should be required regardless of the fate of the produced water.
- Require the proposal and justification of the selected management method of produced water, providing for an extensive analysis of the feasibility and impacts of every other method available to ensure that cost is not the only factor considered in the decision.
- If disposal is to be done by injection, a permit application containing

studies of the characteristics of the well, fluid, and casing should be required. This should form part of a statement of purpose for the project, and it should include a map showing the injection facilities. Furthermore, details of the pressure and rate of injection, monitoring method to be utilized, method of injection, list of protection measures, treatment of water to be injected, source and analysis of injection liquid, and location and depth of each water-source well should be provided. Moreover, the requirement for monitoring of seismic activity derived from injection should be demanded to evaluate any potential impacts caused by earthquakes of relevant magnitude.
- If reuse for hydraulic fracturing is selected, requirements for the filtering and diluting of the water should be explored to prevent chemical interference between produced water and new fracturing fluids.
- If reuse for non-oil/gas uses is selected, reverse osmosis or flash distillation should be required. Treatment through publicly owned treatment works has not been successful in treating produced water fully; therefore, it is not recommended as a viable method.
- Auditing and establishing economic and/or criminal liability for negligence or intentional violations in these regards is of supreme importance to ensure water resource protection and remediation.

Mexico is already struggling with the management of solid waste. For example, some studies have found there is a lack of control over the solid waste that is deposited in landfill, and that the daily covering of waste is inadequate [132]. The inclusion of solid waste derived from hydraulic fracturing operations could strain the capacity of local landfill sites further and exacerbate the negative effects of poor management in solid waste disposal facilities. Therefore, the following regulatory best practices should be considered [133–135].

- Determine which of the solid waste types associated with hydraulic fracturing should be categorized as hazardous. The US exempts waste coming from down-hole that would have otherwise been generated by contact with the oil and gas production stream during the removal of produced water or other contaminants from the products. However, this exemption is controversial. Thus, it is recommended that waste be categorized according to an objective assessment of its true harm and not given exemptions related to industry origin.
- Provide for waste sampling procedures to be conducted by operators to determine which generated wastes are hazardous and determining sanctions for negligent or intentional classification errors.
- Establish hazardous waste management methods and provide for sanctions for improper management.
- Promote source reduction, recycling, treatment, and proper disposal of non-hazardous waste.
- Determine management and disposal measures of NORM.

3.5. Enforcement recommendations

Regulatory Violations can result in devastating impacts on the environment and considerable risk to the health and safety of workers and the surrounding communities. A sound regulatory framework could be deemed worthless unless enforced effectively. Mexico has had difficulty in the past enforcing environmental provisions contained in laws and regulation instruments. For instance, the Mexican maquiladora program, which spurred the industrialization of the US–Mexico border, has been deemed the main contributor to the high levels of pollution in cities on the Mexican border because of the loose enforcement of laws [136].

A strong enforcement agenda should be pursued to deter unwanted activities, especially given the potential for catastrophic effects associated with the hydraulic fracturing industry. Thus, the following points should be considered when determining enforcement measures [137,138].

- Consider the creation of a new independent and transparent agency to oversee the shale gas industry, and ensure its presence in every state where there are shale plays. If such an agency were developed, it would be important for it to include representatives of the local communities, academia, and NGOs.
- Develop a formula to assign penalty amounts considering the impacts, intent, remediation costs, and profits and history of violators. Penalties should be proportional both to the gravity of the infringement as well as to the history of the violator. Cooperation by a violator could be recognized by reducing the total amount of a penalty to promote collaboration.
- Appoint a sufficient number of inspectors to supervise and audit the practices of unconventional oil and gas developers. To be able to conduct yearly inspections, the generally recognized number of inspectors required is one inspector per 1000 wells; however, to advance sustainability through enforcement it is important to consider increasing this number.
- Establish a public record to document every inspection. The record should be open access and readily available via the Internet.
- Provide for the shutdown of operations until violations are corrected.
- Establish mechanisms to allow reports of violations by the public.
- Audits, inspections, and fines should all be in the public domain.

3.6. Community engagement recommendations

Public engagement is crucial in the path toward sustainable development of shale oil and gas resources. Such engagement could promote better decision making, stimulate community trust, and ultimately reduce negative impacts by increasing accountability, which in turn deters negligent practices by act or omission [139]. A key requirement for successful community engagement is the ability to disclose to the public all relevant information regarding baseline data before hydraulic fracturing activities commence, the permitting processes, and all data on operational impacts gathered throughout the lifetime of shale resource exploitation projects [140].

In the US, it has been found that individuals living in regions that depend economically on extractive industries are likely to support hydraulic fracturing despite its numerous environmental consequences [141]. The economic hardship experienced by people living in the areas surrounding the Mexican shale basins is likely to pave the way for support for hydraulic fracturing, which will be viewed as a gateway to employment and economic development. In this context, it is important to protect the public through transparency in information and via engagement strategies aimed at protecting economically vulnerable populations susceptible to supporting the industry despite the risks. The following best practices should be explored when addressing community engagement and data disclosure through regulation [142,143].

- Promote proactive notification of project proposals to ensure adequate inclusion and reach via every possible channel, including leaflet drops, radio, television, social media (e.g., Facebook, Twitter), public displays, and house calls.
- Allow a period for information provision during which meetings should be held where operators and experts highlight the issues associated with the quality of life in areas of hydraulic fracturing development.
- Provide for printed materials in the languages of the local people to explain the issues regarding the development of unconventional oil and gas resources.
- Ensure the public has a chance to be involved in shaping plans through a mixture of participation channels in which they can offer opinion and interact (e.g., online, written, face-to-face meetings).
- Promote community involvement once exploration starts, including the management of community benefits by local people.

- Publish the contract and copy of the protocols and rules the operators must follow.

4. Concluding remarks

In the US, hydraulic fracturing outcomes have been twofold. Some communities have experienced economic benefit by welcoming this industry, which has contributed to the now contested boomtown phenomenon. In many instances, however, the development of unconventional oil and gas resources has resulted in considerable environmental and societal impacts, ranging from the disturbance of endemic species to the pollution of freshwater reserves.

This paper has shed light on the impacts of hydraulic fracturing, and it has provided recommendations for best practices to be considered by Mexican policy makers as they strive to enhance the regulations aimed at controlling the unconventional oil and gas industry. Enforced regulation could be the difference between building an economic success and damaging the environment further, while creating serious health threats for already vulnerable communities.

The US' shale development experience has served as a case study through which we have provided evidence of the panoply of environmental, social, and community impacts associated with hydraulic fracturing operations. These impacts, although not fully avoidable, could be mitigated through regulatory best practices uncovered by the governments, NGOs, and academics that have devoted substantial resources to analyzing ways to cope with and reduce the negative effects of hydraulic fracturing suffered by the US for years. We have summarized these best practices to alert Mexican policy makers to the available options, as they look to reap the benefits of the development of unconventional oil and gas resources at the lowest possible environmental and societal costs.

The fact that hydraulic fracturing is still a young technology leaves much room for research in terms of its impacts and possible remediation measures. Therefore, we would like to stress the importance of policy efforts aimed at promoting research and development to both advance sustainable practices and determine the geologic particularities of Mexican plays and the social, economic, and ecological characteristics of their surroundings.

Transparency in the processes and dynamism of the regulatory framework are crucial to keep up with the fast pace of growth of this industry and to ensure public preparedness for its activities. If policy efforts are directed toward the prevention and restoration of all potential associated impacts, hydraulic fracturing might offer high returns with low environmental and societal costs. However, if the potential impacts are not addressed carefully, the results could be devastating and the costs too high to countenance. Therefore, as Mexico moves forward with the exploitation of its unconventional oil and gas resources, it is of utmost importance to learn from the mistakes made in the US, which occurred primarily because of the unpreparedness of the regulators. Mexico has a privileged opportunity to apply the lessons derived from the US experience, which have been referenced throughout this paper, without suffering the consequences of this learning process.

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