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Economic, social, and environmental evaluation of energy development in the Eagle Ford shale play

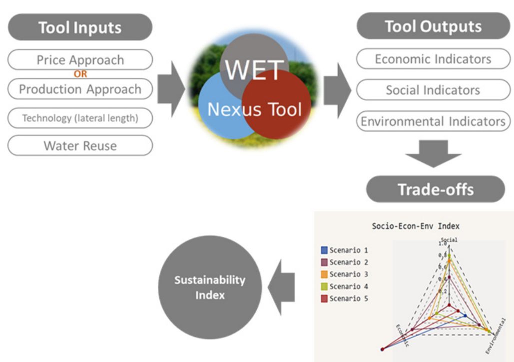
Rabi H. Mohtar [a,b,c,*], Hamid Shafiezadeh [d], John Blake [b], Bassel Daher [a,e]

[a] Department of Biological and Agricultural Engineering, Texas A&M University, United States of America
[b] Zachry Department of Civil Engineering, Texas A&M University, United States of America
[c] Faculty of Agricultural and Food Sciences, American University of Beirut, Lebanon
[d] Department of Economics, Texas A&M University, United States of America
[e] Water Management & Hydrologic Sciences, Texas A&M University, United States of America

HIGHLIGHTS

- Trade-off exist with different levels of energy development in the Eagle Ford Shale Play.
- Tools have a role in highlighting trade-offs to catalyze a dialogue among stakeholders.
- WET provides an assessment platform to quantify the impact of hydraulic fracturing.

GRAPHICAL ABSTRACT



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ABSTRACT

This research investigates the relation between water, energy, and transportation systems, using the growing hydraulic fracturing activity in the Eagle Ford shale play region of southwest Texas in which the local water systems and road infrastructure were not designed for the frequent transport of water into the production site and of produced gas and oil from the site as are often required for hydraulic fracturing. The research: 1) quantifies the interconnections between water, energy, and transportation systems specific to the Eagle Ford shale region; 2) identifies and quantifies the economic, social, and environmental indicators to evaluate scenarios of oil and gas production; and 3) develops a framework for analysis of the economic, societal, and long term sustainability of the sectors and 4) an assessment tool (WET Tool) that estimates several economic indicators: oil and natural gas production, direct and indirect tax revenues, and average wages for each scenario facilitates the holistic assessment of oil and gas production scenarios and their associated trade-offs between them. Additionally, the Tool evaluates these social and environmental indices, (water demand, emissions, water tanker traffic, accidents, road deterioration, and expected average employment times). Scale of production is derived from the price of oil and gas; government revenues from production fluctuations in relation to rise and fall of the oil and gas market prices. While the economic benefits are straightforward, the social costs of shale development (water consumption, carbon emissions, and transportation/infrastructure factors), are difficult to quantify. The tool quantifies and assesses potential scenario outcomes, providing an aid to decision makers in the public and private sectors that

* Corresponding author at: Department of Agricultural and Biological Engineering, Texas A&M University, 306 Scoates Hall, College Station, TX 77843-2117, United States of America.
E-mail address: mohtar@aub.edu.lb (R.H. Mohtar).

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allows increased understanding of the implications of each scenario for each sector by summarizing projected outcomes to allow evaluation of the scenarios and comparison of choices and facilitate the essential dialogue between these sectors.

1. Introduction

The United States has significant shale oil and gas reserves. The *Annual Energy Outlook 2014* of the U.S. Energy Information Administration (EIA), 2014 estimated that 610 trillion ft^3 of natural gas and 59 billion barrels of shale oil are technically recoverable there. The combination of newly developed technology, hydraulic fracturing, and horizontal drilling, together with the significant increase in oil and gas prices over certain periods of the past decade, have made extraction of shale oil and gas economically feasible. Large scale natural

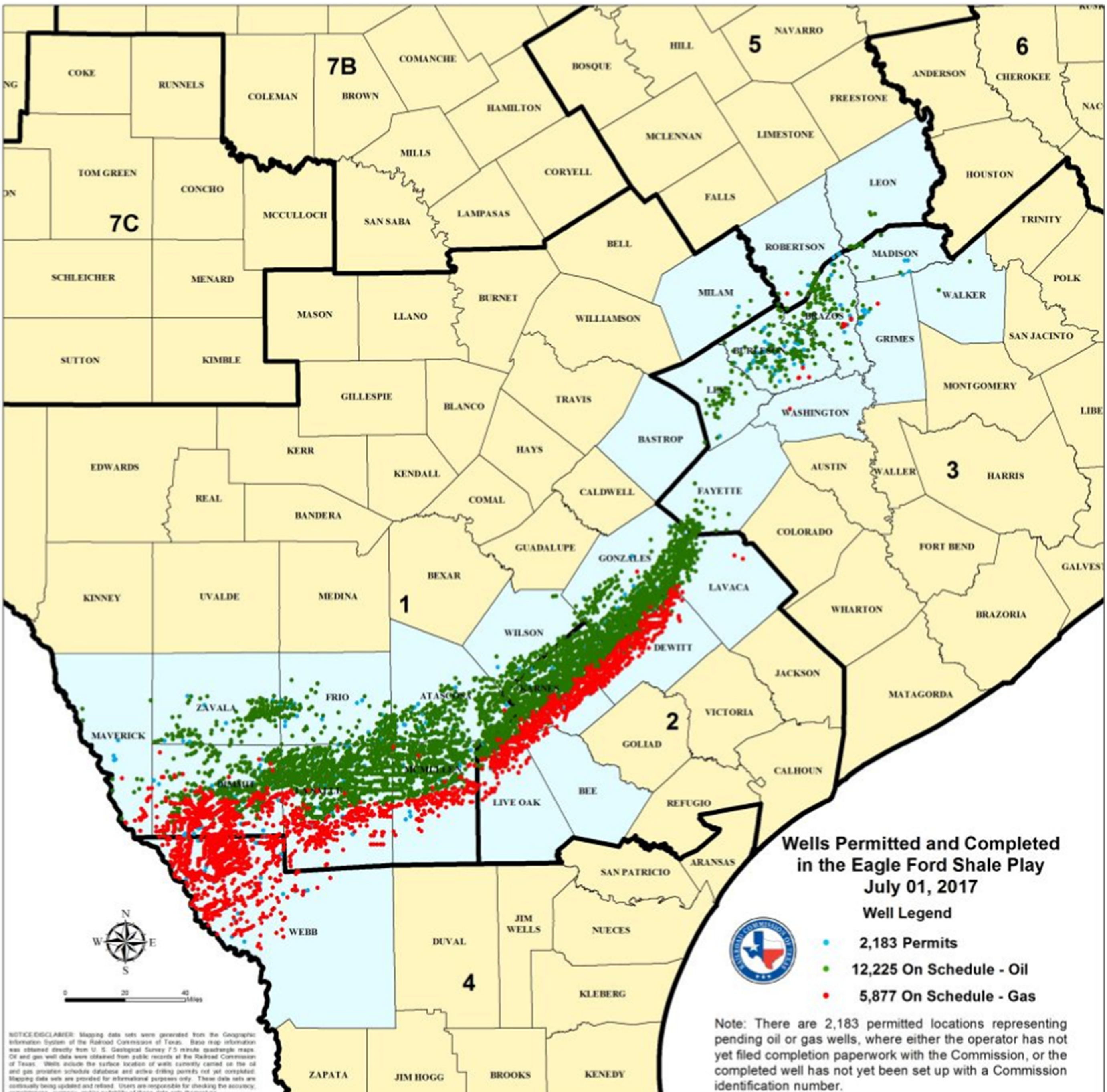

Fig. 1. Wells completed and permitted in the Eagle Ford shale play as of July 1, 2017.
(Source: Texas Railroad Commission, 2017).

gas production began with the Barnett shale in northcentral Texas, continuing to Woodford OK, Eagle Ford in southeast Texas, and the Marcellus and Utica shales in northern Appalachia (PA and NY). EIA reports significant shale oil and natural gas production from 2010 to 2016 (Figs. 1 and 2). Of these, Eagle Ford has become one of the major producers of shale oil and gas, transforming the economic and physical environment of southeast Texas. The Eagle Ford shale play is the focus of this paper.

Most previous studies focus on the nexus of water and energy, citing the linkage between electricity production and water as the primary concern. The emerging technology of hydraulic fracturing (HF) for the production of oil and gas relies on million gallons of water. The rapid growth, globally, in shale production using HF, make it critical to consider the interlinkage of water as well. The technologies by which water is obtained by shale reserve producers and the heterogeneity of water governance across the areas in which shale resources are available becomes important because it may both affect the quantity and quality of water available, and can impact transportation infrastructure, such as roads and traffic. This paper is relevant to previous research on the interconnections between water and energy production, the importance of which has been widely discussed in an effort to preserve sustainable development around the globe (The United Nations world water development report, 2014: water and energy, and Scott et al., 2011). Different aspects of water use and management in hydraulic fracturing were discussed by Allen (2012), Jiang et al. (2014), and Nicot et al. (2012). Rahm and Riha (2014) note that HF produced oil and gas in Texas requires between 10,000 to 30,000 m^3 of water per well, depending upon the geology, depth of drilling, length of the horizontal portion of the wellbore, and other factors. The authors are unaware of any existing work addressing both the economic benefits of shale oil and gas production and its environmental consequences in one study. Moreover, the transportation sector, which is also affected by the quantity and mode of transport of the quantities of water required for the HF, has not been previously addressed.

The Eagle Ford shale play is roughly 50 miles wide and 400 miles long (Fig. 1), extending from Brazos to Webb County, Texas and entirely or partially passing under 23 additional counties. The development of economically feasible hydraulic fracturing technology has brought the Eagle Ford massive growth in the exploitation of its significant oil and gas reserves: 5172 million barrels (5.1 billion barrels) of proven reserve oil and 23.7 trillion cubic feet of proven natural gas (EIA, 2014a, 2014b). Despite the decline in the number of drilling permits issued between 2014 (5613 permits) and 2016 (447 permits), oil and gas production remain nearly constant as a result of the implementation of previously issued permits and increased productivity of existing wells.

This research investigated the interrelations of the water, energy, and transportation sectors as these relate to the Eagle Ford shale play and under scenarios of: 1) number of new wells (increasing or decreasing), 2) changing price in the oil and gas markets, and 3) variation in water reuse technology and percentage. Section 3 details the processes and quantification methodologies used for economic and societal indicators. Section 4 discusses several economic indicators, including: oil and natural gas production, direct and indirect tax revenues, and average wages- and socio-environmental indexes (water demand, emissions, water tanker traffic, accidents, road deterioration, and expected average employment rate). Based on the quantifications in Section 3, methodology is introduced that integrates the economic, social, and environmental indicators to assess the sustainability of a given scenario and provides a tool intended to facilitate holistic decision making for the region. Daher and Mohtar (2015) introduced a process and set of methodologies for defining the connections between the water, energy, and food sectors. Their basic framework is utilized and adjusted to incorporate the similarities and differences between the WEF Nexus (water, energy, food) and the WET (water, energy, and transportation) Nexus. A new framework is introduced to aid the analysis of potential scenarios and solutions for the oil and gas industry, thereby providing a useful aid to the public and private sectors; one which allows increased understanding of the implications of each scenario for each sector by summarizing projected outcomes to enable evaluation of the scenarios and comparison of choices, with the ultimate goal of facilitating the essential dialogue between the public and private sectors (Mohtar and Daher, 2016). The framework makes it possible to identify potential solutions for those future scenarios. Section 5 offers a framework and presents example solutions for use by decision makers. The research: 1) quantifies the interconnections between water, energy, and transportation systems specific to the Eagle Ford shale region; 2) identifies and quantifies the economic, social, and environmental indicators to evaluate scenarios of oil and gas production; and 3) develops a framework for analysis of the economic, societal, and long term sustainability of the sectors and 4) an assessment tool (WET Tool) that estimates several economic indicators: oil and natural gas production, direct and indirect tax revenues, and average wages for each scenario facilitates the holistic assessment of oil and gas production scenarios and their associated trade-offs between them.

2. Model development: quantifying interlinkages between water, energy, and transportation (WET)

2.1. Estimation of oil and gas production in the Eagle Ford

The first step in quantifying the factors impacting oil and gas development in the Eagle Ford shale play is understanding the trends of production. The Eagle Ford's short term oil and gas production and continuously increasing productivity makes precise estimates of oil

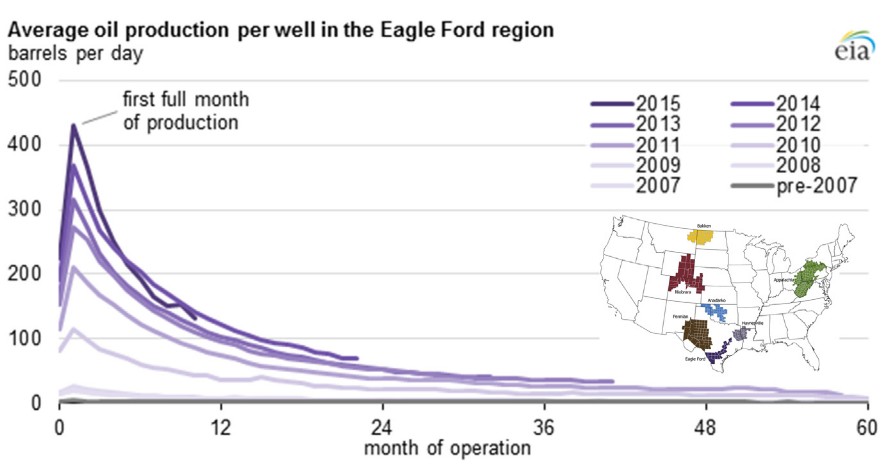

Fig. 2. Average oil production per well during the first 48 months of operation (EIA, 2015).

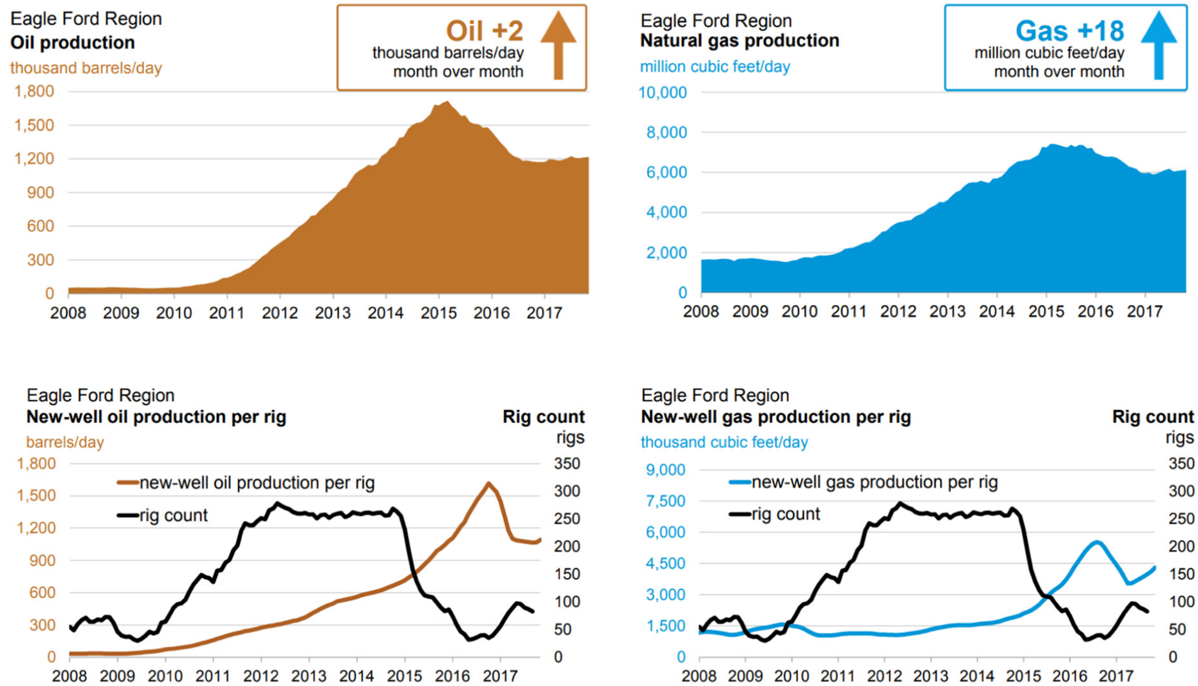

Fig. 3. Relation between rig count and oil and gas production in the Eagle Ford Shale, October 2017 Report (EIA, 2017).

and gas production unfeasible. While a given well's production declines after the first month of operation, the quantity of oil and gas produced in the Eagle Ford has increased annually: an outcome of improved drilling efficiency and the growth in the number of operational wells. Fig. 2 reflects the technological improvement and constant increase of first month production between 2007 and 2015.

Eq. (1) estimates the per well production of oil in the Eagle Ford (Center for Community and Business Research, 2012).

$$Oil(t) = 18.993t^{(-0.65)} \tag{1}$$

where 18.993 thousand barrels of oil per month is the initial production, and t is the number of months in production for each well. Eq. (2) provides a similar estimation for gas production:

$$Gas(t) = 147.850t^{(-0.585)} \tag{2}$$

where 147.850 million cubic feet (mmcf) of gas is the initial production for a well, and t is the number of months in production for each well.

2.2. Relation of oil and gas prices to production

Shale oil and gas development is a function of market price, and hydraulic fracturing is an expensive process. It is not possible to precisely predict production based on price alone: price does impact *new* development of shale oil and gas but such development does not affect currently operating wells. Therefore, the authors used *rig count* (*RC*) as a proxy to estimate development changes and to better gauge growth in the oil and gas industry. RC does not reflect production, but is a good indicator of demand for products used in drilling and producing. RC also indicates the level of activity making useful in monitoring fluctuations in oil and gas prices. Fig. 3 shows a positive correlation between rig count and oil and gas production (EIA, 2017). This work uses the number of rigs in operation per month to estimate the number of new wells that were added in the same period. The Railroad Commission of Texas is responsible for issuing oil and gas drilling permits, and for reporting the number of new leases for oil production monthly. Each lease can include from a single to thousands of oil wells, and depends upon operator decisions regarding how many new wells to drill and when to do so. Thus, RC offers a best estimate indicator of newly developed wells.

A study by the Center for Community and Business Research (2012) showed current possible scenarios in the Eagle Ford shale play as:

- High development (over $100 per barrel): 18 wells per rig is assumed.
- Medium development ($80–$100 per barrel): 14 wells per rig assumed.
- Low development (under $80 per barrel): 10 wells per rig is assumed.

The study used the Baker Hughes RC to determine the number of rigs in operation at any given time. Data for crude oil prices were obtained from West Texas Intermediate (WTI-Cushing)[1] and data for natural gas prices were collected from Henry Hub price EIA.[2] To find the exact relationship between the RC and oil and gas prices, the EIA drilling oil and gas production monthly data were used for years 2007 to 2015. A log-transformation is most effective for estimating the number of rigs in relation to the price of oil and gas, such that (Table 1):

$$\ln\ (rig\ count) = \beta_0 + \beta_1(oil\ price) + \beta_2(gas\ price) + error \tag{3}$$

All variables are statistically significant, the estimation is:

$$\ln(rig\ count) = 4.134 + 0.021(oil\ price) - 0.229(gas\ price) \tag{4}$$

In practical terms, for each one-dollar increase in oil price and given that all other variables remain stationary, there is a 2.1% increase in the RC. Nevertheless, there is actually a negative correlation between gas price and number of rigs: as the price of natural gas increases, the number of rigs decreases. Based on Fig. 1, 12,224 of the 18,101 total wells are oil wells (represented by green dots). The remaining 5877 are gas wells (represented by red dots). This assumed correspondence was used for

[1] A crude stream produced in Texas and southern Oklahoma serves as a reference (marker) for pricing a number of other crude streams traded in the domestic spot market of Cushing, Oklahoma. https://research.stlouisfed.org/fred2/series/DCOILWTICO (accessed Sept, 2016).

[2] In March 2014, the Wall Street Journal discontinued publication of some of its commodity energy prices: downloadable, complementary data from EIA were used. http://www.eia.gov/dnav/ng/ng_pri_fut_s1_m.htm (accessed Sept, 2016).

Table 1
Results from the regression estimating oil and gas prices on ln (rig count) [Eq. (3)].

ln(rig count)	Coefficient	Std. Err.	t	P > |t|	[95% Conf. Interval]
Constant (β_0)	4.1338430	0.2109783	19.59	0.000	3.715166–4.552523
Oil Price (β_1)	0.0214674	0.0023932	8.970	0.000	0.016718–0.0262167
Gas Price (β_2)	−0.2288368	0.0221300	−10.34	0.000	(−0.272753) – (−0.1849206)

ease of interpretation. Otherwise, the number of rigs fluctuates over time, based on the price of oil and gas. This assumption is valid because the oil price during this period rose significantly compared to the price of natural gas. Eqs. (5) and (6) are derived by combining Eqs. (1), (2), and (3), and assuming that 65% of the rigs are for new oil wells and 35% for gas wells over a one-year period, such that:

$$Oil\ Production(bbl) = 0.65 \times RC \times OW \times \sum_{t=1}^{t=12} 18993t^{(-0.65)} \tag{5}$$

$$Natural\ Gas\ \ Production(bbl) = 0.35 \times RC \times GW \times \sum_{t=1}^{t=12} 147.85t^{(-0.585)} \tag{6}$$

where RC is the rig count as determined by the price in Eq. (3), OW is the number of new oil wells, and GW the number of new natural gas wells. For example, at a price of $110 per barrel for oil and $4 per mmcf for natural gas, Eq. (3) indicates approximately 247 rigs. Given this price for oil, 18 new wells per rig are indicated, 65% of the total new wells are assumed to be for oil production of 253 million barrels of oil per year, or 639,000 barrels per day.

2.3. Economic impacts of the Eagle Ford shale

Several variables can be tracked as economic indicators of oil and gas production in Texas. Based on data availability for this study, the authors considered: employment rate, total income, direct and indirect state government tax revenues. This sections briefly explains the role and impact of oil and gas production on state tax revenues, labor markets, and wages in the Eagle Ford area.

2.3.1. Tax revenue

Oil and gas production impact Texas revenue in two ways: directly, through tax on oil and gas products and indirectly, through other services related to oil and gas production. Other economic sectors affected by oil and gas production include sales tax: the main source of revenue for the government of Texas. The authors compared historical oil and gas production tax and sales tax with the total tax collections in Texas: more than 11% of the 2014 state revenue derived from oil and gas production (Fig. 4). Oil production taxes and regulation taxes are severance taxes, enforced on the removal of natural resources (including oil and natural gas). Oil taxes are the largest source of revenue for the state's Economic Stabilization Fund: which receives "one-half of 75 percent of oil production [tax] and natural gas production tax revenues in any fiscal year that exceeds fiscal 1987 collections, and one-half of any unencumbered general revenue surplus remaining at the end of each biennium" (Hegar, 2015). Oil production plays a major role in the prosperity and consistency of the Texas economy. State rates for oil production are 4.6% of market value, or 4.6 cents per barrel of oil produced, whichever is greater. Oil regulation tax is 0.1875 cents per barrel (Comptroller of Public Accounts). Both federal and local tax rate for oil production in Texas is zero.

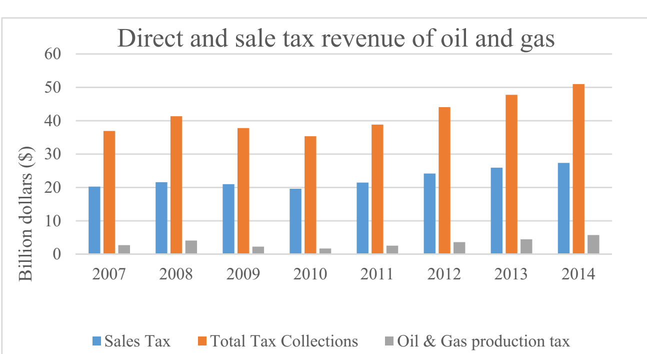

Fig. 4. Author's calculation of data from Texas Comptroller of Public Account.

Under the Texas tax structure, natural gas production is taxed at the market value of gas produced in the state. Current rates on natural gas production are 7.5% of market value, and 4.6% of market value for condensates. Fig. 5 compiles the data from the Texas Railroad Commission EIA drilling productivity reports and the Texas Comptroller of Public Accounts to show estimated tax revenue from the Eagle Ford shale oil and gas production.

2.3.2. Economic impact on jobs and wages

Different stages of oil and gas production impact the number of employees required for a given job site. Activities such as construction, hydraulic fracturing, drilling, and completion of wells all occur once, over a short period of time. However, production of oil and gas is a continuous activity over a period of years, depending on the productivity of a given well. The number of workers at each step varies with the variability of drilling costs per well and the value of oil and gas production. Quarterly Employment and Wages (QCEW) of the Texas Labor Market Information were used to capture all aspects of employment and wages resulting from oil and gas production in the Eagle Ford shale play (QCEW, Sept 2016). Quarterly data from 2010 to 2014 provide the annual average employment and total wages per quarter, for each county and industry. Fig. 6 shows the average employment per year in the Eagle Ford area; data can also be analyzed at the industry level. The authors report average total annual wages for five industries: construction, financial activities, natural resources and mining, leisure and hospitality, transportation and utilities.

Fig. 7 shows these five industries and the annual average total wages paid between 2010 and 2014 in the Eagle Ford region. Only natural resources and mining numbers are relevant; the others are included for reference. The average total wages for natural resources and mining have more than doubled in the same period, and speaks to the massive rise in oil and gas production in the Eagle Ford region.

2.4. Water consumption in the Eagle Ford shale

A life cycle perspective provides the best method to account for direct and indirect water use in quantifying water consumption by oil and gas development and production. Fig. 8 shows the life cycle of water from construction to end of well life. Water is vital at each stage.

Total water use can be estimated using Eq. (6):

$$Water\ Use\ per\ Well = CW + DW + HFW + WCW - RW \tag{7}$$

where CW is construction water, DW is drilling water, HFW is water used in the hydraulic fracturing process, WCW is well closure water, and RW is recycled water from the produced and flow back waters.

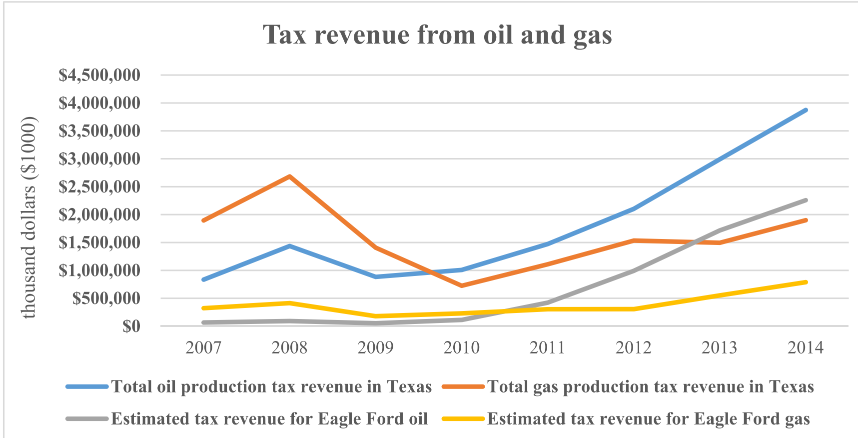

Fig. 5. Estimated tax revenue from oil and gas production in the Eagle Ford shale play (thousand dollars).

Only a few studies quantify water use in the Eagle Ford shale: most of the literature relates to the Marcellus shale. Fig. 9 demonstrates the water needed at each stage for a typical Marcellus well. In spite of the need for water at different stages of oil or gas production, the amount of water consumed by the hydraulic fracturing (HF) process is much larger than that needed for well preparation, drilling, gas/oil production, and well closure. The only publicly available data for water used in HF in the Eagle Ford shale is found at FracFocus, whose website is managed by the Ground Water Protection Council and the Interstate Oil and Gas Compact Commission, and whose missions revolve around conservation and environmental protection. The data on the FracFocus website is recorded on a completely voluntary basis from the private industry of driller: companies report their total base water volume. For this study, the authors collected, cleaned, and collated data from this website.

FracFocus data from 2012 to 2015, provided 9928 observations; on average, 5.6 million gal of water were used per well. Figs. 10 and 11 show the distribution of water use per well in the Eagle Ford shale from 2012 to 2015.

The literature was investigated to explain the different quantities of water used in the HF process: the quantity is a factor of geology, depth of drilling, and length of the horizontal portion of the wellbore (Rahm and Riha, 2014). This study focuses solely on the Eagle Ford shale, where both geology and well depth is constant, but the horizontal distance of the wellbore varies, significantly impacting water use. According to Arnett et al. (2014), a lateral length of 5000 ft is optimal for production. Given the 2012 data for the Eagle Ford Shale, Arnett et al. (2014) estimated the water needed per well, based on lateral length, using Eqs. (7) and (8):

$$\textit{Water Use per Well}_{gas} = 2.13 + 0.0022 \times \textit{lateral length} \quad (8)$$

$$\textit{Water Use per Well}_{oil} = -0.18 + 0.0025 \times \textit{lateral length} \quad (9)$$

Data from 2012 and 2013 indicate that a typical HF well in the Eagle Ford consumed about 4.2 million gal of water and had a 5000-ft lateral length, consistent with findings from FracFocus. Fig. 11a (2012) and b (2013) show almost identical consumption, but Fig. 14c (2014) and d (2015) reflect an increase in the average water consumption. This may be related to the lateral length of the wellbore, however, authors did not have access to data about lateral length, making it not possible to draw a conclusion.

Halliburton, a major HF company, reports that less than 14% of water used for HF returns as flowback water, meaning that the remainder is consumptive water: evaporated during production, lost underground, or embodied in a product, but in any case, resulting in a net loss of water from the watershed in which the water originates and thereby reducing the water available in that region. Thus, less than 14% of the water used in HF becomes available for treatment and reuse. The authors found no evidence of treatment of the flowback water, perhaps due to the high cost of treatment and the low quantity of flowback water. The conclusion is that current practices involve injecting flowback water into an underground formation for disposal; a conclusion that leads to further concern about groundwater quality, environmental contamination, and seismic

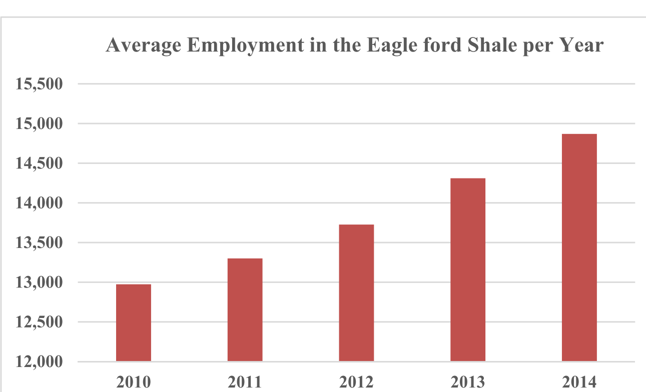

Fig. 6. Average employment in the Eagle Ford region.

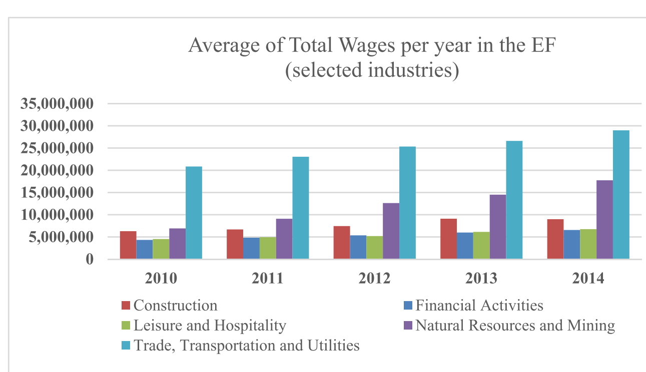

Fig. 7. Average total wage per year in the Eagle Ford Region for selected industries.

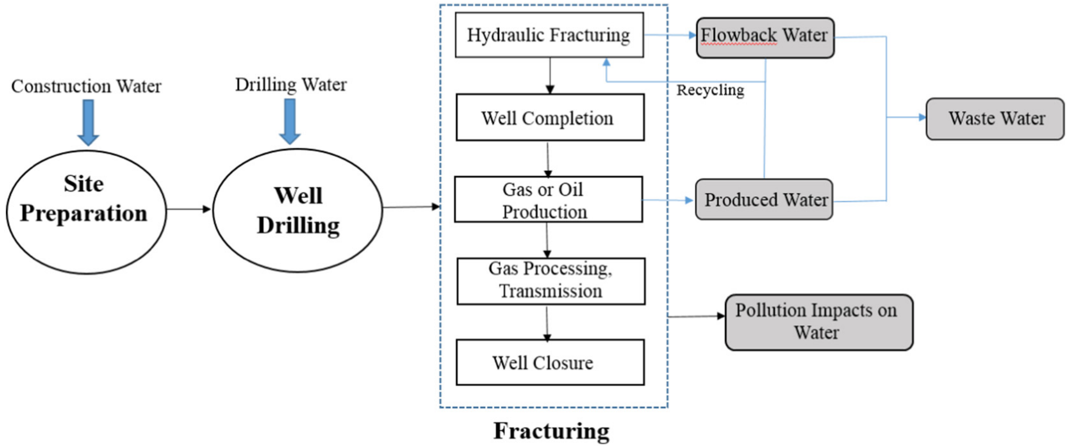

Fig. 8. Water Cycle in oil and gas production.

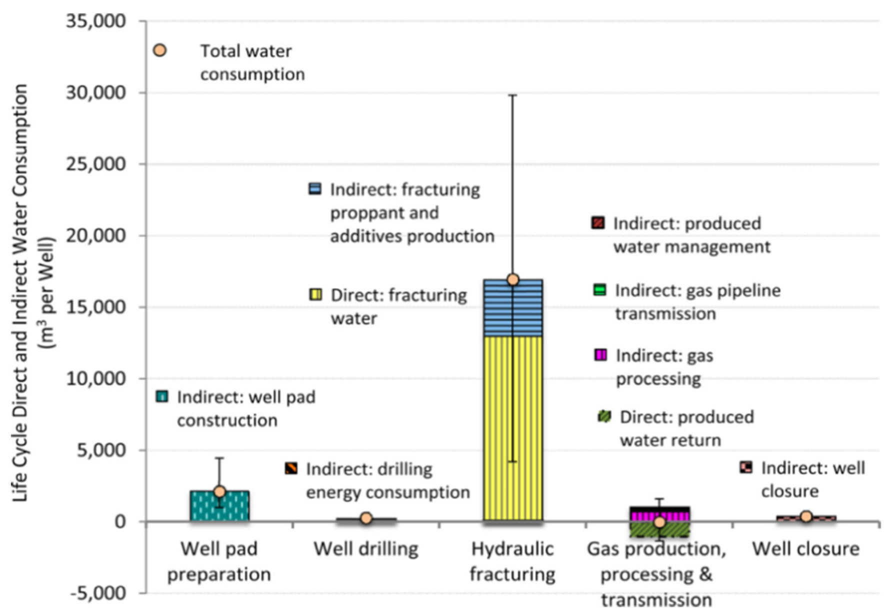

Fig. 9. Estimated life cycle direct and indirect water consumption for a Marcellus shale gas well. (Source: Jiang et al., 2014).

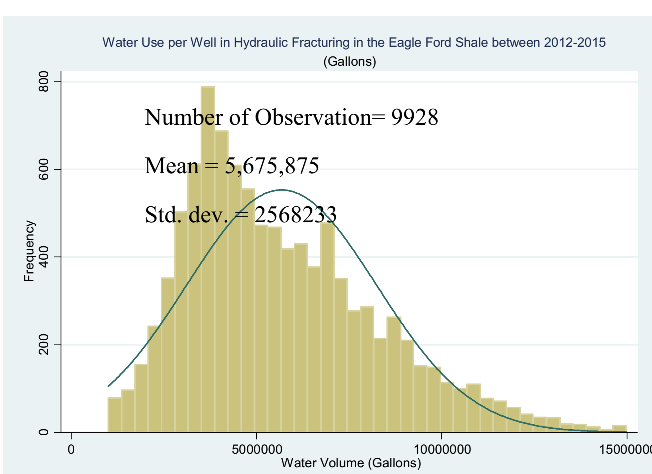

Fig. 10. Water use per well in HF (authors calculation from FracFocus data).

activity. Additional concerns arise regarding the type of water used for HF. Nicot et al. (2012) conclude that 80% of the water used is fresh water. The remaining 20% of water used in HF activity in the Eagle Ford is brackish water, which has avtotal dissolved solids (TDS) content of 1000 ppm or greater. There is no evidence that recycled or reused water is part of the processes. Multiple studies indicate that fresh water resources are 90% groundwater and 10% surface water (Rahm and Riha, 2014). Although important features to consider, they are not reflected in this tool.

2.5. Transportation in oil and gas production in the Eagle Ford shale

Transportation plays a major role in the day-to-day operations of oil and gas development and production. HF requires approximately 5 million gal of water per well; water that often must be transported over several miles to reach its destination. In most cases, tanker trucks are used, but there are rare exceptions in which an above ground, temporary pipeline is installed for water transport. For this study, only tanker trucks were considered. After injection into the formation, a portion of the water returns to the surface as flowback that must then either be disposed of or treated for reuse. Trucks or pipelines are again used to transport the flowback to its destination, either to be injected (disposal) or treated (reuse). Fig. 12 illustrates the stages in which trucks are used to transport either water or the product (oil or natural gas). The four factors measured regarding the increased development or production of oil and gas were: traffic, road deterioration, accidents and emissions.

2.5.1. Traffic

The initial two months of well life are known as the development phase. During the first year (site preparation to production), a single well requires approximately 4065 vehicles: about 3481 of which are used in the development stage and 1200 of these are large tankers or rig carrying trucks that carry machinery and materials for drilling and setting up the well pad. The remaining 2281 vehicles are smaller, lighter vehicles used primarily to transport workers. These numbers are approximated using the methodology proposed in a Naismith Engineering report conducted in DeWitt County, Texas (Naismith Engineering and DeWitt County Commissioners Court, Inc., 2012).

Eqs. (10), (11), (12), and (13) were derived by the authors to calculate the number of tanker trucks needed for water and product transport as described below. The number of trucks needed for transport of water is calculated by dividing the water needed per well (see water module) by the capacity of each truck (approximately 6000 gal). Author's discretion is used to imply that 20% of trucks are reused for the same well (multiplying by a figure of 0.80), as shown in Eq. (10).

$$\#of\ water\ Trucks\ per\ well = \frac{water\ need\ (gal)}{truck\ capacity\ (gal)} * 0.80 \quad (10)$$

The difference between the number of trucks needed per well for *water* transport and that for *oil* transport is the substance and quantity of water or oil transported. For simplicity, authors assume truck capacity remains constant, at 6000 gal per truck (Eq. (11)).

$$\#of\ oil\ Trucks\ per\ well = \frac{42 \times oil\ produced\ (bbl)}{truck\ capacity\ (gal)} * 0.80 \quad (11)$$

The 42 in the numerator is the conversion factor for one bbl of oil into gallons. An assumption was made that natural gas is never transported by truck and, thus could be ignored.

2.5.2. Road deterioration

Road pavement is designed in consideration of the impact of vehicle use, all axle loads are converted to the equivalent single-axle load. One measurement used to quantify this impact is the Equivalent Axle Load Factor or EALF: a typical county road has an annual wear and tear cycle of approximately 5000 EALF (TXDOT, 2014). The authors assumed here that each full truck contributed 1.7 EALF, while an empty truck contributed 0.014 EALF. Thus, the number of trucks was utilized to determine the contribution to road deterioration from oil and gas development. A base value of 150 EALF was assumed for the development stage of each well.

2.5.3. Accidents

A 2015 Texas Transportation Institute study (TTI, 2015 reflects a clear correlation between increased number of horizontal wells drilled

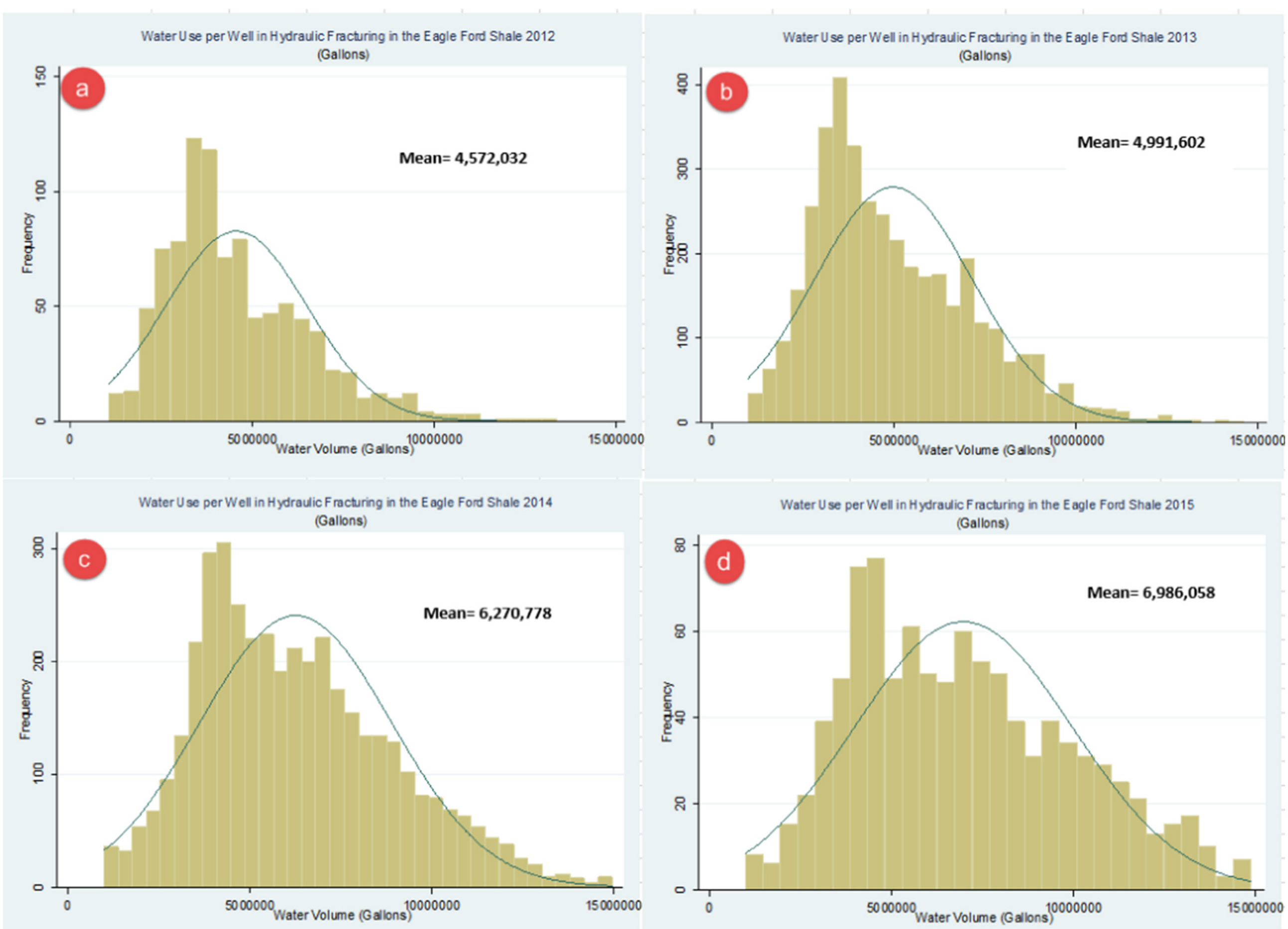

Fig. 11. Water use per well in the Eagle Ford shale per year.
(Source: FracFocus).

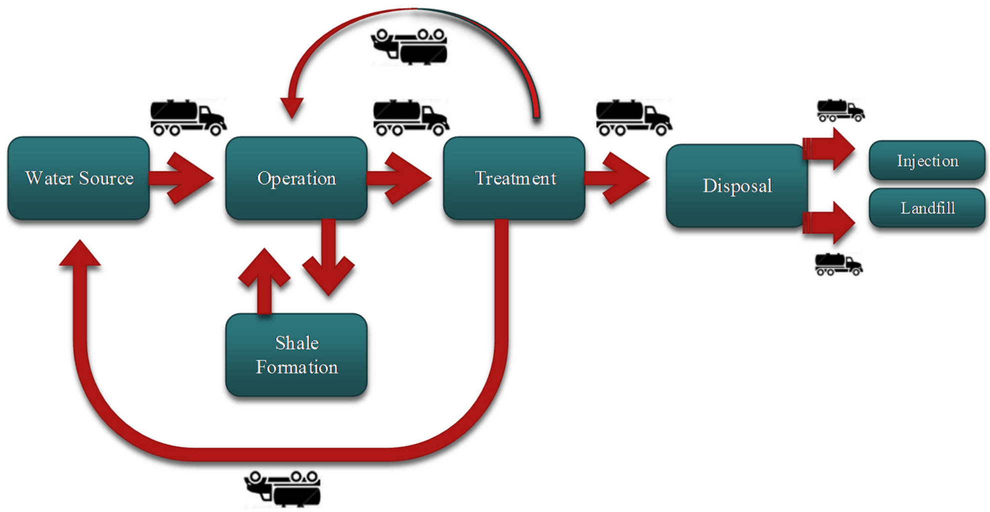

Fig. 12. Schematic of transportation in oil and gas development.

and number of serious accidents involving commercial motor vehicles (CMVs) on rural roads. Eq. (12) is used with regard to the focus of this study, the Eagle Ford shale play, in determining the number of accidents expected due to increased HF activity.

$$Number\ of\ crashes = 0.0349 * (number\ of\ new\ horizontal\ wells) + 7.9461 \quad (12)$$

2.5.4. Emissions

In general, truck transportation has a straightforward emission contribution and five factors are considered: number of trucks, distance (miles) traveled, type of fuel used, average miles per gallon (mpg) for each type of truck, and pounds of CO_2 equivalent produced per gallon of fuel burned. The number of trucks needed is determined from Eqs. (9) and (10); round trip distances were estimated for each vehicle at 40 miles, based on average reported values from companies and literature; type of fuel used is assumed to be diesel for tanker trucks and gasoline for standard service vehicles.; average miles per gallon is estimated at 6.5 mpg for tanker trucks and at 12 mpg for other vehicles (Davis et al., 2014); pounds of CO_2 equivalent, for each type of fuel, was extracted from the EIA website (U.S. Energy Information Administration, 2013), such that

$$lbs\ CO_2\ equivalent = \frac{distance\ traveled\ (mi) \times CO_2\ \ emissions\ coeffiencient\ (lbs\ CO_2/gal)}{miles\ per\ gallon\ (mi/gal)} \quad (13)$$

3. Water-energy-transportation (WET) tool and scenario development

This section reflects the use of the integrated economic, social, and environmental indicators (Fig. 13) to assess the sustainability of a given scenario by evaluating these aspects of possible oil and gas production in the Eagle Ford. Each factor referenced in Section 3.0 is quantified and weighted to provide an indicator of their importance relative to each other. This allows the user to compare the trade-offs associated with different projected pathways. The relations are then programmed into a web-based tool (Water-Energy-Transportation Tool) (WET, 2016) that allows the user to develop and assess the implications of different scenarios that are created in relation to a set of factors: amount of oil and gas produced, average lateral length used in production, and percentage of water reused. The scenarios are built using either the production approach or the price approach, as described below.

The ***production approach*** implies that a third party decides the percent by which oil and gas production is expected or desired to increase during the following12 month period. This approach is useful when the government owns the resources (oil and gas) and to an extent, determines how much energy to produce. Another example of this approach is a private industry considering the impact of a major increase in production on the market as a whole.

The ***price approach*** implies market-based control, in which price determines production. Since the region of study (Eagle Ford) more closely resembles a market-based environment with a low level of government intervention in production, the price approach is used to build example scenarios. The tool contains an ever-updating reference to the most recent prices for oil and natural gas. Additionally, users can see the history of prices to create more realistic scenarios.

The second component of the scenarios is the average lateral length of each newly drilled well, which as discussed, will significantly impact the quantity of water required. Lateral length is the choice of the operator and depends upon the feasibility of horizontal drilling distance. In the online tool, the ***lateral length*** default is 5000 ft, a number taken from other studies that consider the average optimal length of the horizontal portion of the well. There are indicators within the developing technology that operators tend to increase lateral length in an effort to produce more oil and gas: this results greater water use.

The third part of the scenario is the quantity of ***water reuse***. Other studies indicate that, on average, 10% of flowback and produced water are reused. Owing to the stress on water resources in arid areas and to the development of new technologies for water treatment, there is a trend toward increased water reuse. This makes it necessary to have a scenario for water reuse. As an example, available flowback and produced water in the Eagle Ford shale play, flowback represents less than 15% of the water used and the remaining 85% is consumed within the shale formation (Boschee, 2014). Flowback has reached as much as 40% in shales such as Marcellus.

There are a total of 11 outputs, including economic, environmental and social indicators. The economic indicators include estimated oil [bbl] and natural gas [Mcf] production, total revenue for government (direct taxes [$] and indirect revenue [$]), and average total wage [$]. Environmental outputs include water demand [gal] and emissions [lbs CO_2 equivalent]. The total number of additional trucks [#], the number of expected additional accidents [#], road deterioration [EALF], and

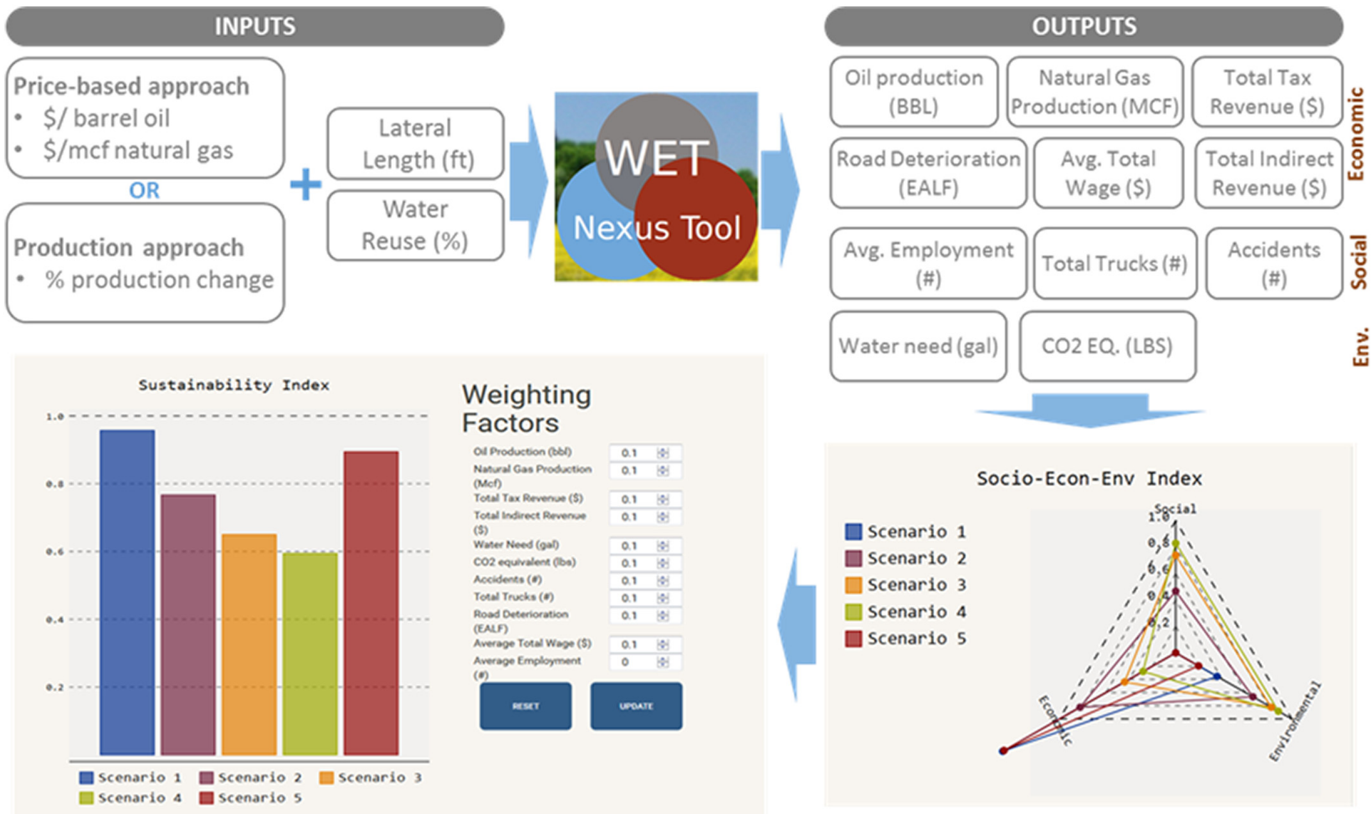

Fig. 13. WET Nexus tool structure.

average employment [# of jobs] round out the social indicators. The user assesses the different scenarios by comparing them in terms of their tradeoffs. Each output is normalized using the following equation:

$$\text{normalized value} = \frac{\text{calculated value} - \text{minimum value possible}}{\text{maximum value possible} - \text{minimum value possible}} \quad (14)$$

The maximum value possible produces a normalized value of 1 and the minimum value produces a normalized value of 0. These normalized values are calculated for each output. Negative perceived outputs (water need, number of trucks, road deterioration, CO_2 equivalent, and number of accidents) were manipulated to reflect the understanding that a lower normalized value for these outputs is positive for overall sustainability of the given scenario. Therefore, these values were converted to 1 minus the normalized value. In order to assess the different scenarios the social-economic-environmental (socio-econ-env) index was created and lumps together the individual economic, environmental, and social indicators for assessment of which scenario is more favorable toward which indicator. This was accomplished by taking the normalized values in each category, adding them together and then dividing by the number of indicators in the respective category, to produce a number between 0 and 1.

For example, the environmental indicator only has two outputs (water need and emissions). Therefore, if there was normalized water need value of 0.7 and a normalized emission contribution of 0.4, then the environmental indicator would be $(0.4 + 0.7)/2 = 0.55$. The higher the number, the more favorable the scenario with respect to a particular indicator. A perfect scenario would be one in which all three categories were maximized at values of 1. The issue, and reality, is that there are tradeoffs for increasing a given indicator at the expense of another indicator: the socio-econ-env index was created to assess these tradeoffs.

The final goal of the tool is to determine the overall sustainability of each scenario by weighing the various outputs, each of which is assigned a value between 0 and 1. The sum of the values assigned must equal 1, thus the user is equipped to carry out informed dialogue with experts, policy makers, etc. to determine the priorities for each output. When submitted, this will produce a bar graph showing which scenario is the most favorable or sustainable, given the chosen weights. If some of the outputs are not of concern to the user, these can be left at 0. Likewise, if only one output matters to the user, then it can be assigned a weight of 1 to see which scenario is most sustainable for that particular output.

3.1. Scenario assessment and evaluation

To demonstrate the tool, five scenarios were selected for comparison using the price based approach (Table 2).

Table 3 shows the output of the online tool. In addition to the raw numbers for the outputs, graphs are developed to represent what is seen in the table (Figs. 13 and 14–17).

Of the five scenarios, and as predicted by Eqs. (4) and (5), the fifth scenario (5) has the highest oil price; based on Eq. (3) (expected rig counts from combination of oil and gas prices), it is expected that the highest oil and gas production is reflected in the scenario with the

Table 2
Sample scenarios for energy development in the Eagle Ford shale play.

	Oil price	Gas price	Lateral length	Water reuse
Scenario1	$110	$3	5000	10%
Scenario2	$80	$4	5000	10%
Scenario3	$60	$4	6000	15%
Scenario4	$40	$4	6000	15%
Scenario5	$120	$2	7000	20%

Table 3
Sample scenarios outputs.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Oil production (bbl)	1,279,480,431	667,069,963	313,068,713	205,700,802	1,254,145,021
Natural gas production (mcf)	5,828,419	3,038,704	1,426,122	937,029	5,713,008
Total tax revenue ($)	$6,475,482,379	$2,455,729,078	$864,497,484	$378,770,585	$6,923,737,472
Total indirect revenue ($)	$3,136,417,299	$1,635,202,635	$767,431,922	$504,238,704	$3,074,312,076
Water need (gal)	59,853,750,767	31,205,353,643	17,427,305,933	11,450,555,941	80,818,776,904
Co2 equivalent (lbs)	2,087,761,401	1,088,475,358	561,974,726	369,243,707	2,453,530,452
Accidents (#)	792	417	200	134	777
Total trucks (#)	15,145,590	7,896,305	4,076,825	2,678,665	17,799,049
Road deterioration (ealf)	12,979,771	6,767,133	3,493,839	2,295,616	15,253,785
Average total wage ($)	$135,561,848	$90,869,824	$59,705,729	$39,229,459	$132,877,543
Average employment (#)	15,548	10,422	6848	4499	15,240

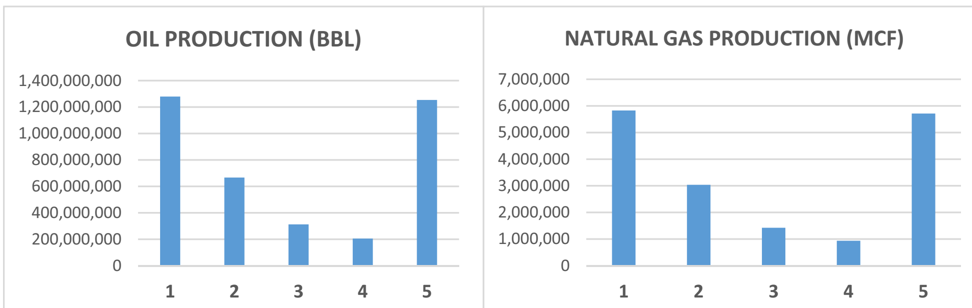

Fig. 14. Oil and natural gas production.

highest oil price. As the price of oil declines in the scenarios, less oil and gas production are expected; thus, it is unsurprising that scenario 4 has lowest level of production (Fig. 14).

As discussed, oil and gas production impacts Texas revenues in two ways: **direct tax on oil and gas production** and other **services related to oil and gas production**. Oil Regulation tax is 0.1875 cents per barrel; federal and local taxes are zero for oil production in Texas. Thus, higher production of oil impacts positively on direct tax revenue of the state, as reflected in Scenario 5 (highest direct tax revenue, approximately $7 billion) and Scenario 4 (lowest level of production, lowest tax revenue, $378 million) (Fig. 15). Another source of revenue directly correlated with oil and gas activity in the region comes from other services related to oil and gas production: Oil Well Service Tax, Oil and Gas Well Drilling Permit, Oil and Gas Compliance Certification Reissue Fee, etc. Thus, Scenario 5 is the highest and Scenario 4 the lowest income scenarios for the state. Water needed for hydraulic fracturing activity is correlated with the length of the horizontal portion of the wellbore, i.e. lateral length. Nevertheless, Scenario 4 requires the least amount of water, even though it does not have the shortest lateral length. This smaller water need is a result of much lower oil and gas production compared to the other scenarios. Even though the water per well is greater in scenario 4, the total amount of water is less due to the relatively small number of wells being drilled (Fig. 16).

Fig. 16 also shows the CO_2 equivalent (lbs) for all five scenarios. As expected, Scenario 5 has the highest production, directly impacting transportation needs. In this study, only emissions from truck transportation are considered, thus, a greater amount of trucks leads to a greater quantity of emissions. Scenario 5 has highest value in all three categories for accidents and total trucks. The more production there is, the more trucks are needed for transporting water and oil, and the higher likelihood of accidents and road deterioration.

A surprising result is seen in Fig. 17: Scenario 1 has a higher average employment than Scenario 5 and explained by the fact that oil and natural gas production is highest in Scenario 1 and because average employment is directly related to the number of rigs in operation (similar to oil and gas production).

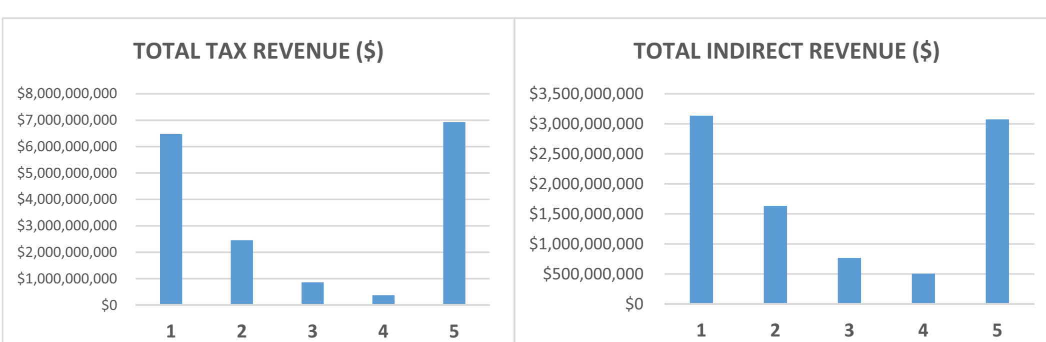

Fig. 15. Total tax revenue, indirect revenue.

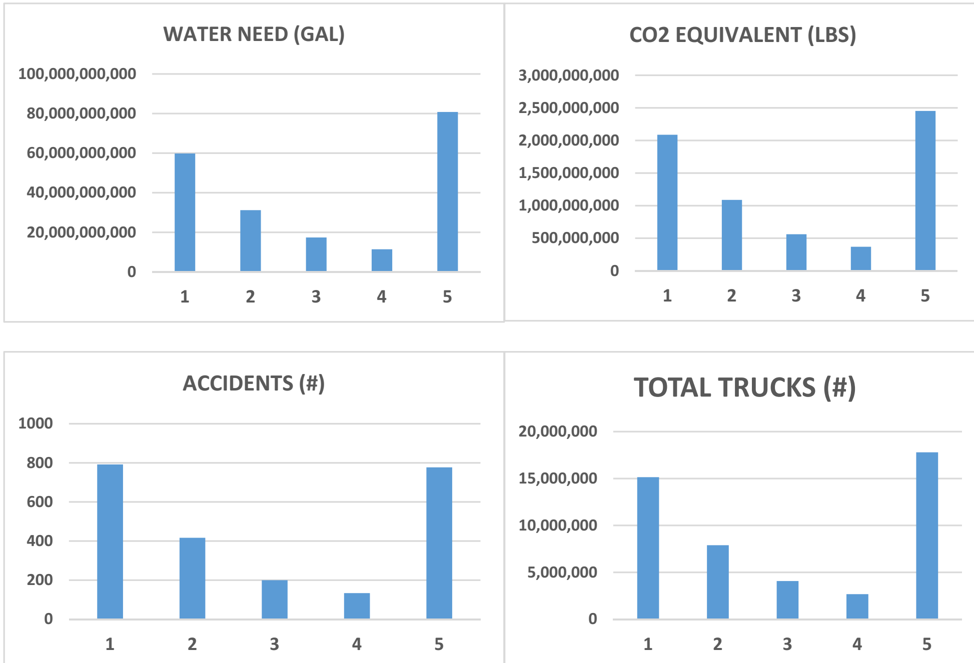

Fig. 16. Water need, CO2 emissions, accidents, and total trucks.

Overall, this tool allows the user to quickly compare different scenarios of oil and gas production: useful to policy makers interested in optimizing the industry and to field operators seeking the greatest profit possible. The tool is by no means an exhaustive collection of all data available on the oil and gas sector, but it does provide the opportunity to see the impacts of different choices in technology or policies.

4. Future work: a framework for policy analysis

This research demonstrates the consequences of shale production in the Eagle Ford under different scenarios of production. Not surprisingly, the data shows that the scale of production is derived from oil and gas prices: government revenues from production increase or decrease

Fig. 17. Road deterioration, average total wage, and average employment.

Table 4
Objective 1 breakdown analysis.

Goal	Impact Category	Status Quo	Desalinization	Regulate to use non-water base technology or brackish water	Change of water management institution or price of water
Efficiency	Cost for government	Very Low	Medium	Low	High
	Ease of Enforcement	Easy	High	Low	Medium
Equity	Fairness to Taxpayers	Low	Low	High	High
Preservation of water resource	The amount of water use	Low	High	High	High
Political feasibility	Likelihood of successful adoption	High	Medium	Medium	Very low

Table 5
Objective 2 breakdown analysis.

Goal	Impact Category	Status Quo	Pipeline for water transportation	Tax on road use	Tax on emission
Efficiency	Cost for government	High	High	Very low	Very low
	Ease of Enforcement	High	Low	Medium	High
Equity	Fairness to Taxpayers	Low	Low	High	High
Preservation road quality	Cost of road deterioration	High	High	High	High
Political feasibility	Likelihood of successful adoption	Medium	Low	Very low	Very low

with the boom or bust of the oil and gas market. The research also shows the connection between production, labor market, and average wages in the region. Although economic benefits are straightforward, social costs are more difficult to quantify and understand. Therefore, this section focuses on two objectives in suggesting alternative scenarios: (1) policy solutions that reduce fresh water consumption in the Eagle Ford and (2) policy solutions that reduce other social costs, such as road deterioration and emissions.

In determining governance options of the energy, water, and transportation Nexus in the Eagle Ford, possible policy scenarios must be compared with current policies (status quo). Four goals are considered in comparing status quo with other alternatives. A primary policy goal is efficiency: any policy alternative needs the intervention of government to either impose new rules or change current institutions. The cost to government and the ease of enforcement are considered. Second, the current policy poses a risk to water preservation in Texas, particularly in the Eagle Ford, where water is scarce and groundwater management is crucial to the sustainability of the communities living there. Similarly, road quality and safety risks decline in areas with shale production. Third, any policy alternative has implications for government revenues and expenditures, thus, fairness to tax payers should be considered. Fourth, political feasibility is always relevant to some degree in any policy alternative: radical alternatives that change social orders may be more difficult to pass and more likely to face social resistance.

Objective 1 Reduce the water consumption in Eagle Ford.

The framework of Weimer and Vining (2017) is used to present and examine four scenario alternative: (1) status quo, (2) change of water supply (desalinization), (3) using technology of non-water base or brackish water, and (4) change in water management institution (Table 4).

Objective 2 Reduce road deterioration and emissions in shale development.

The goal is to reduce possible social costs of shale development, such as road deterioration and emissions. This analysis also examines four scenario alternatives: (1) status quo, (2) change of water transportation (pipeline), (3) tax on road use, (4) tax on emissions, as seen in Table 5.

5. Conclusion

The developed tool quantifies the water-energy-transportation nexus of the Eagle Ford shale play and created sample scenarios to evaluate the impacts of shale oil and gas production. The tool estimates total oil and natural gas production, total direct and indirect tax revenue, and average wage under each scenario as economic indicators. The tool also evaluates socio-environmental indexes such as water need, emissions, expected average employment, traffic, accidents, and road deterioration. The tool can assist decision makers in the public and private sectors by increasing their understanding of the implications of each scenario on different sectors of the society and facilitating dialogue among public-private sectors that can assist them in reaching more optimal solutions.

The research indicates that the scale of production in the Eagle Ford shale region derives from oil and gas price: government revenue from production is a factor of the oil and gas market. The connection between production, labor market, and average wage in the region is estimated. In addition to economic indicators, analyzed by previous researchers, social and environmental factors were considered and quantified to provide a better understanding of the interlinked systems. This new framework is introduced as a springboard to future research that could help to answer questions surrounding what policies (scenarios) should be implemented to maximize the sustainability of the nexus of energy, water, and transportation in the Eagle Ford shale play.

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