A COMPARATIVE STUDY BETWEEN HYDRAULIC AND ELECTRIC FRACTURING TECHNOLOGIES

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Abstract: *Exploitation of shale gas in Tunisia is at a very early stage, but with the latest estimates suggesting potential resources of 389 Million Tonne of Oil Equivalent, it is observed by many as an exciting economic prospect. However, its environmental impacts are presently unknown. This is the focus of this paper, which estimates the life cycle impacts of Tunisian shale gas using hydraulic fracturing process for the first time. Hydraulic fracturing technology for unconventional gas is compared to electric fracturing alternative. A Life Cycle Assessment (LCA) approach was achieved throughout six stages for both hydraulic and electric fracturing technologies including site preparation, exploration, development, production, distribution and wells enclosure focusing on both exploration and development stages of the process. The SimaPro Software based on Impact 2002+ model 2.10 was used as an assessment tool to indicate quantitatively the environmental impacts. The results of LCA affirm that the process of hydraulic fracturing contributes to the impact category such as Climate Change, Human Health, Ecosystem Quality and Resources. The life cycle greenhouse emissions of Tunisia shale gas are estimated to be about 60 g* CO_2e/MJ *of the gas produced using hydraulic fracturing technology and around 20 g* CO_2e/MJ *of the gas produced using electric fracturing technology. The results of this research highlight the need for the use of another alternative method to minimize environmental impacts and the enormous amount of water used in hydraulic fracturing.*
Key words: *electric fracturing, electrical discharge, Hydraulic fracturing, Life Cycle Assessment, Shale gas.*

1. Introduction

The exploration and discovery of shale gas in Tunisia is a very recent phenomenon about which much remains unknown. In 2011, the official reserves estimate stood at 114000 billion cubic feet, and the technically recoverable in 2011 was estimated at 18000 billion cubic feet (or about 510 billion m^3) [1]. Two years later, these reserves have been increased and are now estimated at 23000 billion cubic feet [2] (about 650 billion m^3).
According to the International Energy Agency IEA estimations, this potential remains ten times higher than the proven reserves of "conventional" gas and the reserves technically exploitable in oil or shale oil are estimated at 1.5 billion barrels [3].

Regardless of the evident uncertainties in the recoverable reserve volume, shale gas resources could transform the Tunisian energy market and contribute significantly to the supply national security. [4]. However, while the economic potential is obvious, its environmental and social implications are currently quantitatively unknown, making it a controversial issue.

Limited literature is existing on its life cycle impacts separately from the Global Warming Potential (GWP) due to the immaturity of shale gas fracturing. Most such studies originate in the US where shale gas extraction by hydraulic fracturing is the only technique used. There are several alternatives such as Liquid Petroleum Gas fracturing, pneumatic fracturing, CO_2 fracturing and electric fracturing.

In this paper, we are interested in comparing environmental impacts related to the exploration and exploitation of liquid and shale gas in Tunisia using hydraulic fracturing and electric fracturing technologies. A tool that can be used in order to analyze the environmental impact of hydraulic fracturing and electric fracturing over its whole lifecycle is Life Cycle Assessment. LCA is a constantly improving methodology that contributes in getting a solid environmental management [5, 6].

The focus is on Tunisian shale gas whose exploitation is, at the time of writing, at a very early stage of development so that the results can help companies and policy makers understand broader environmental impacts of shale gas and make more informed decisions by taking in consideration the pollution[7].

2. Hydraulic fracturing process

The process of the exploration and extraction of shale gas consists of six stages, including site preparation, exploration, development, production, distribution and closing wells according to Fig. 1.
The shale gas life cycle begins with site preparation, which may include the establishment of proper supporting infrastructure for the well.

Then the exploration phase, which may include exploratory drilling during which any gas released is normally flared or simply vented to air. Drilling operations may be achieved with an electric equipment or a diesel-powered. Afterward a site is designated and a vertical well drilled, horizontal drilling gives access to a larger volume of the shale rock covering the trapped gas. This is pursued by hydraulic fracturing: the perforations are made in the steel casing of the well and pressurized fluid is injected into the shale. Again, this is usually achieved with diesel internal-combustion equipment.

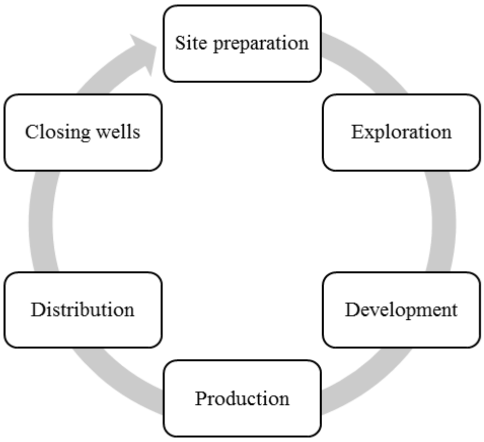


Fig. 1. Life Cycle Process of the production of shale gas.

The fracturing fluid is a combination of water, chemical additives and proppant, this mixture being a fine-grained substance that aids to keep fissures open thus maximizing gas flow. Usually, the proppant used in fracking is a sand.

Hydraulic fracturing involves injecting high-pressure fluid to crack the rock. These cracks are held open by the fracturing fluid. It is artificially creating a network of small cracks around the well. This technique allows oil drain located along several tens of meters of the well. The amount of gas extracted from each well is low, needs providing a large number of wells to achieve a significant level of production and this is the development stage. The development stage consists of drilling and fracturing the largest number of wells that have proved interesting during the exploitation phase.

Following hydraulic fracturing, the well formation is complete. The well completion process often involves allowing gas to escape without capture in order to clear debris and return some of the fracturing fluid (flowback).

Following development stage, the life cycle is the same as that of conventional gas: a production well head is installed to gather the gas and transfer it to a processing plant before the distribution [8]. Before being fed into the national network, the gas is treated for distribution. Besides, the gas is dehydrated, typically using glycol dehydrators, to reduce the water content.

Once the well has reached the end of its lifetime it must be properly decommissioned and plugged in order to protect the surroundings and subterranean environment (closing well). The system boundary for assessing environmental profile of shale gas is shown in Fig. 2.

4. Electric fracturing process

The most extensively used technology to stimulate gas and oil reservoirs is hydraulic fracturing [9, 10].

Fracking by shock waves generated by electrical discharges in water is the proposed technology as an alternative method to hydraulic fracturing. The steps of the electric fracturing process are identical to those used in the exploration and exploitation of shale gas by hydraulic fracturing. Only the steps marked in red in Fig. 2 are different. Hydraulic fracturing is replaced by electrical fracturing and the treatment of flowback water is eliminated due to the non-use of large volumes of water and chemical products. Electrical fracturing is based on electrohydraulic shock wave fracturing reservoir technology. Underwater shock waves have exposed great prospects in the exploitation of unconventional gas. Shock wave is a strong compressive mechanical wave and is distinguished by high temperature, high pressure, and high energy density behind the shock wave front [11].

This high voltage discharge in the rock generates an acoustic wave to cause micro cracks in the rock to release the gas. Shock wave energy can be focused on the discontinuity of acoustic impedance produced by the network of microcracks or macrocracks, and then, the present fractures will be connected and extended. In addition, with the very high peak pressure, certain new fractures may similarly be created. Permeability will increase and the reservoir will be reconstructed with extra-connected cracks and greater surface area for exchange [12, 13]. The physical characteristics of shock wave are the source of the fracturing effects of reservoir. Two principal applications can be specified for rock fragmentation: The Pulsed Corona Electrohydraulic Discharges (supersonic discharge) and the Pulsed Arc Electrohydraulic Discharges (subsonic discharge).

Therefore, in order to attain a better application, it is important to combine the two discharge modes and to study the discharge processes and the characteristics of the associated shock waves [14, 15].

A schematic of the shock wave generation is shown in Fig. 3. The subsonic discharges are provided a 20kV voltage capacitor bank C of 4.2 µF and a peak current around 21 kA. The supersonic discharges are obtained from a High Voltage Pulsing Generator (Marx generator, Flying Capacitor Multilevel Converter, Cascaded H Bridge Converter) supplied with 50 kV dc.

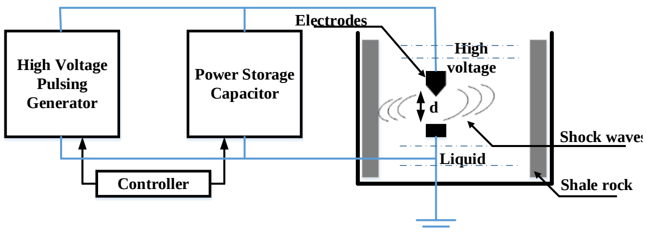


Fig. 3. Electrohydraulic shock wave generator for electrical fracturing process for shale gas.

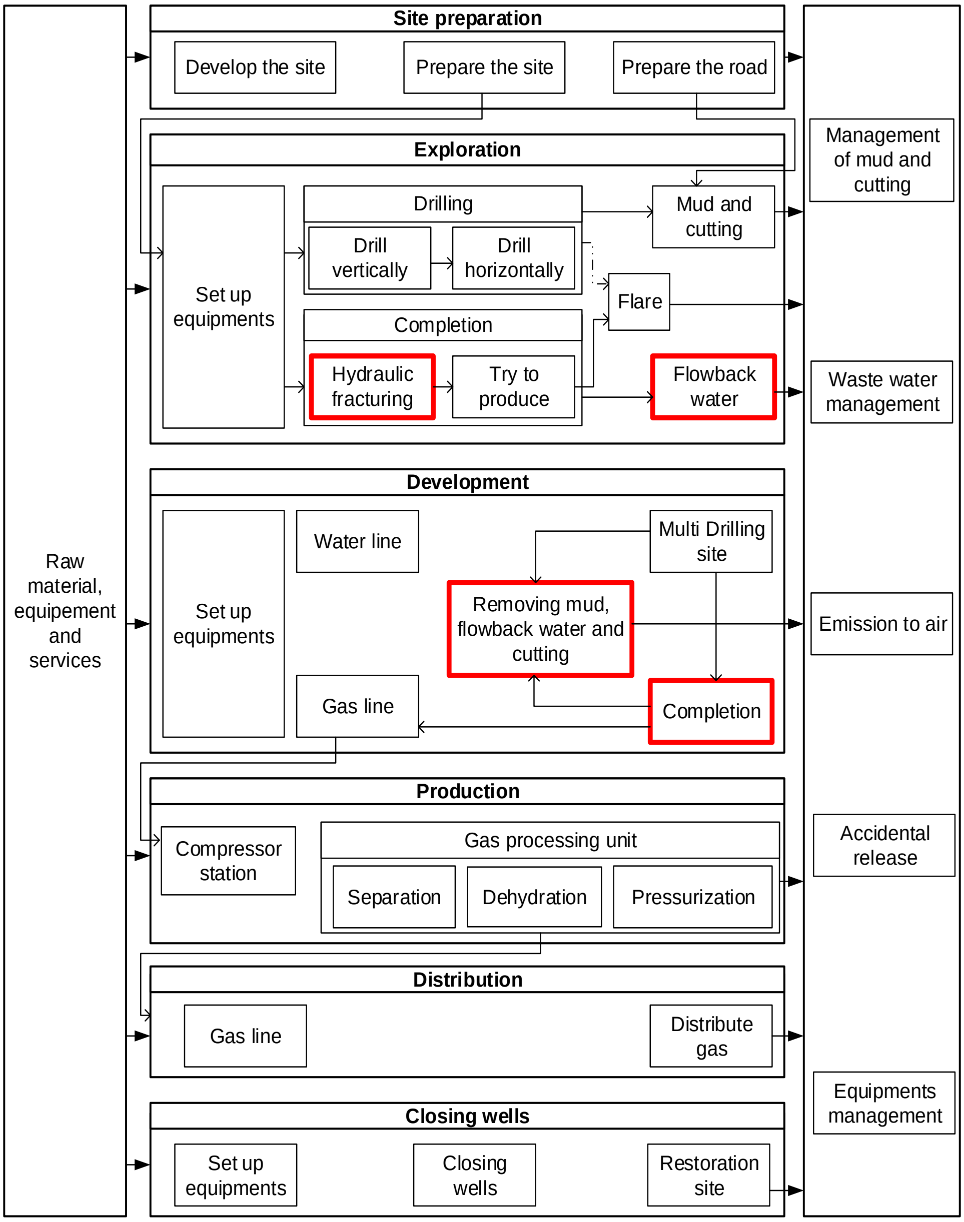


Fig 2. System boundary for assessing environmental profile of shale gas.

4. Evaluation criteria

The environmental impacts are estimated following the IMPACT 2002+ v.2.10 method. The latter, was used to connect the input and output material inventories to obtain the damage points of a specified boundary system. This method contains of 14 midpoint categories that can be assigned to four main damage categories namely, ecosystem quality, human health, climate change, and resources conferring to Fig.4 [16, 17].

All 14 midpoint impacts comprised in the IMPACT 2002+ are estimated to acquire a full picture of environmental consequences of shale gas, as opposed to the previous studies which considered mainly the GWP. The Evaluation criteria are detailed in the sections below and the results are presented and discussed in section 5.

A. Climate Change

The damage category Climate Change is the same category as the midpoint category GWP. Even if it is considered as a damage category, climate change is still expressed in "kg CO_2-eq". The GWP denotes the integrated radiative force measurement, over a time horizon, from 1 kg of a released substance and 1 kg of the reference gas [18].

$$GWP(x) = \frac{\int_0^{TH} a_x.[x(t)]dt}{\int_0^{TH} a_r.[r(t)]dt} \quad (1)$$

Where TH is the estimation time horizon, a_x is the radiative efficiency due to a unit increase in atmospheric abundance of the following substance in question, [x (t)] represents the time-dependent waning in abundance of the instantaneous substance release and the denominator includes the quantities of the reference gas.

The GWP of all substance consequently expresses the pulse integrated forcing (of given small mass) of that substance relative to the pulse integrated forcing (of the same mass) of the reference gas during some time horizon. The numerator of Equation (1) is the absolute GWP of a given substance, thereby mentioned as the AGWP.

B. Human Health

The "human health" damage category is the totality of the midpoint categories human toxicity (carcinogenic and non-carcinogenic), ionizing radiation, respiratory effects, photochemical oxidation and ozone layer depletion. As for human toxicity, all of these midpoint factors can be expressed in $DALY/kg_{emission}$. Human health indicator is measured in Disability Adjusted Life Years (DALY). The Human Damage Factor (HDF) of substance i (HDF_i, in DALY per $kg_{emitted}$) is calculate as follows:

$$HDF_i = iF_I.EF_i = iF_I.\beta_i.D_i \qquad (2)$$

The intake Fraction (iF) denotes the fraction of chemical mass emitted resulting to food contamination, inhalation, or dermal exposure, is the fraction of mass of a chemical [19, 20], in kg_{intake} per kg_{emitte}. The Effect Factor (EF) is used to calculate the risk associated to the dose-response slope factor (β, in risk of incidence per kg_{intake}) and of the severity (D, in DALY per incidence).

For the EF, IMPACT 2002+ uses a different approach to determine the health effect metric for non-cancer toxicological impacts. The designated measure is the ED_{10}, the effect dose making a 10 % response over background. It is resulted from the health-risk-assessment concept of benchmark dose to evaluate a default linear low-dose extrapolation, as studied by [21] for cancer effects and by [22] for non-cancer effects.

C. Ecosystem Quality

The ecosystem quality damage category can be impaired by the release of substance that cause acidification, eutrophication, toxicity to wildlife, land occupation and also a variety of different types of impact. This category is measured in Potentially Disappeared Fraction (PDF) of species on a certain surface and over a given time [$PDF \cdot m^2 \cdot yr$].

The PDF can be generalized as [23]:

$$PDF = \left(S_{ref} - S_{use}\right) / S_{ref} \qquad (3)$$

Where:
S_{ref}: species diversity on the reference area type;
S_{use}: species diversity on the converted or occupied area.

In order to evaluate the Ecosystem Quality (EQ) damage, the PDF value is multiplied with the appropriate area and time span:

$$EQ = \frac{S_{ref} - S_{use}}{S_{ref}}.A.t \qquad (3)$$

Where:
A: the occupied area [m²];
t: time [years].

D. Resources

The damage category Resources is the result of the midpoint categories non-renewable energy consumption and mineral extraction. This damage category is expressed in MJ.

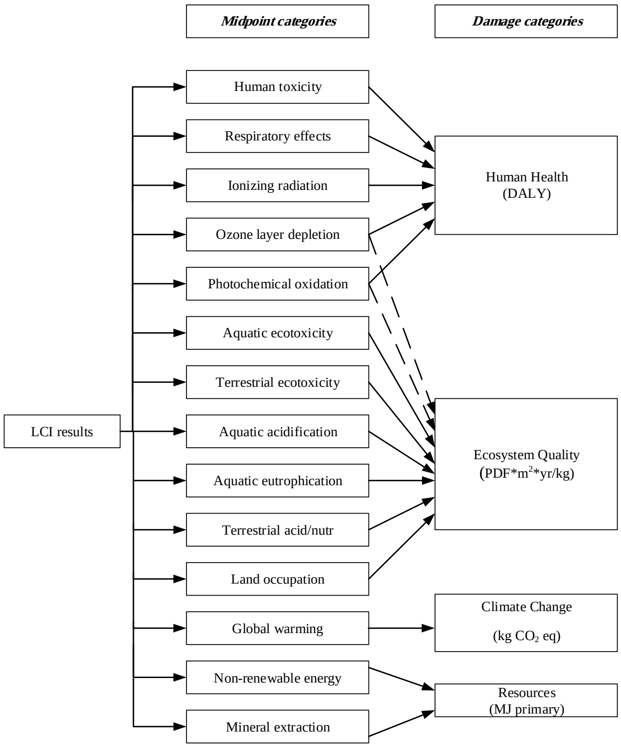


Fig. 4. Global scheme of the IMPACT 2002+ framework, connecting Life Cycle Inventory (LCI) results through the midpoint categories to damage categories.

E. Water use

It should be noted that these four indicators (climate change, human health, ecosystem quality and Resources) do not cover all possible environmental impacts such as water use. For this reason, the comparison results will be presented in this section.
The total volume of fracking water for hydraulic fracturing process reported in literature ranges from 7500 to 29000 m^3 per well [24, 25].

This enormous amount of water will be greatly reduced during electric fracturing process because the amount of water required is equal to the volume of the well. In fact, for a well of 2000 m width and 10 cm diameter, the quantity of water required is less than 16 m^3.

5. Life Cycle Assessment comparison

Life cycle assessment (LCA) has been used as an evaluation means to calculate the environmental impacts over its life cycle, resulting the LCA methodology in ISO 14040/44 [26, 27].

The functional unit is defined as 1 MJ of shale gas, as it could be produced and distributed during 30 years in Tunisia. The system reference flow is 0.027 m^3 of shale gas produced and distributed.

SimaPro v7.3.3 has been used to perfect the life cycles of shale gas using hydraulic and electric technologies. The environmental impacts are assessed following the IMPACT 2002+ v2.10 methodology.

Table 1 present the quantitative effect on the environment. It is obvious that the steps of exploration, development, production and distribution have potential impacts on the shale gas life cycle, while site preparation and closing wells show that contributions are more marginal. It shows also that the indicator Resources is dominated by development stage. Fig. 5 and Fig. 6 shows the comparison between hydraulic and electric fracturing of shale gas for exploration and development stages respectively.

It is clearly shown by Table 1 that the exploitation of shale gas by hydraulic fracturing strongly affects the environment compared with electrical fracturing. In fact, the life cycle greenhouse emissions of Tunisia shale gas are estimated to be about 60 g CO_2e/MJ of the gas produced using hydraulic fracturing technology and around 20 g CO_2e/MJ of the gas produced using electric fracturing technology. Compared with the hydraulic fracturing technology, only the environmental impacts related to exploration and development stages will be reduced. The Human Health indicator value presents a reduction of 50% compared to hydraulic fracturing technology. The Ecosystem Quality and Climate Change values are divided by three compared to hydraulic fracturing technology. The Resources indicator is twenty times lesser than the previous Resources indicator.

The following paragraphs provide a more detailed analysis of the exploration and development stages.

The exploration and development stages contribute from 81.1% to 97.73% in the potential evaluated impacts of hydraulic fracturing process.

The exploration step includes the vertical drilling, horizontal drilling, hydraulic fracturing stage and production fracturing testing. Drilling is the activity that most influences the exploration stage. However, according to the environmental indicator, different activities contribute to the assessed potential impact. The most important are:

For the **Climate Change** indicator, the vast majority of the potential impact is caused by operations related to drilling (drilling fluid, operations of the drilling machinery, materials production wells) 56.9%, while 38.3% is due to the completion activities and 4.57% in equipment set up.

Table 1

Environmental contribution on the steps of the life cycle of the production of shale gas using Hydraulic Fracturing (HF) and Electric Fracturing (EF) technologies (method impact 2002+)

Fracking technologies	Fracking technologies	Human Health (DALY)	Ecosystem quality ($PDF*m^2*yr/kg$)	Climate change (kg CO_2 eq)	Resources (MJ primary)
Site preparation	HF	$2.31\ 10^{-11}$	$8.06\ 10^{-6}$	$2.2\ 10^{-4}$	$1\ 10^{-3}$
	EF	$2.31\ 10^{-11}$	$8.06\ 10^{-6}$	$2.2\ 10^{-4}$	$1\ 10^{-3}$
Exploration	HF	$1.41\ 10^{-9}$	$3.05\ 10^{-4}$	$9.13\ 10^{-3}$	$50.5\ 10^{-3}$
	EF	$1.18\ 10^{-9}$	$2.80\ 10^{-4}$	$5.66\ 10^{-3}$	$24.5\ 10^{-3}$
Development	HF	$3.23\ 10^{-9}$	$1.3\ 10^{-3}$	$3.9\ 10^{-2}$	1.06
	EF	$6.53\ 10^{-10}$	$1.55\ 10^{-4}$	$2.99\ 10^{-3}$	$12.8\ 10^{-3}$
Production	HF	$2.52\ 10^{-11}$	$3.15\ 10^{-6}$	$5.76\ 10^{-3}$	$7.65\ 10^{-4}$
	EF	$2.52\ 10^{-11}$	$3.15\ 10^{-6}$	$5.76\ 10^{-3}$	$7.65\ 10^{-4}$
Distribution	HF	$6.53\ 10^{-10}$	$7.9\ 10^{-5}$	$5.14\ 10^{-3}$	$23.6\ 10^{-3}$
	EF	$6.53\ 10^{-10}$	$7.9\ 10^{-5}$	$5.14\ 10^{-3}$	$23.6\ 10^{-3}$
Closing wells	HF	$6.48\ 10^{-12}$	$1.13\ 10^{-6}$	$8.12\ 10^{-5}$	$3.85\ 10^{-4}$
	EF	$6.48\ 10^{-12}$	$1.13\ 10^{-6}$	$8.12\ 10^{-5}$	$3.85\ 10^{-4}$
Total	HF	$5.36\ 10^{-9}$	$1.66\ 10^{-3}$	$5.93\ 10^{-2}$	1.14
	EF	$2.54\ 10^{-9}$	$5.26\ 10^{-4}$	$2\ 10^{-2}$	$6.3\ 10^{-2}$

In **Human Health**, 74.5% of the potential impacts are due to drilling, 16.7% in hydraulic fracturing, 6.43% for sludge treatment and 2.35% in equipment set up.

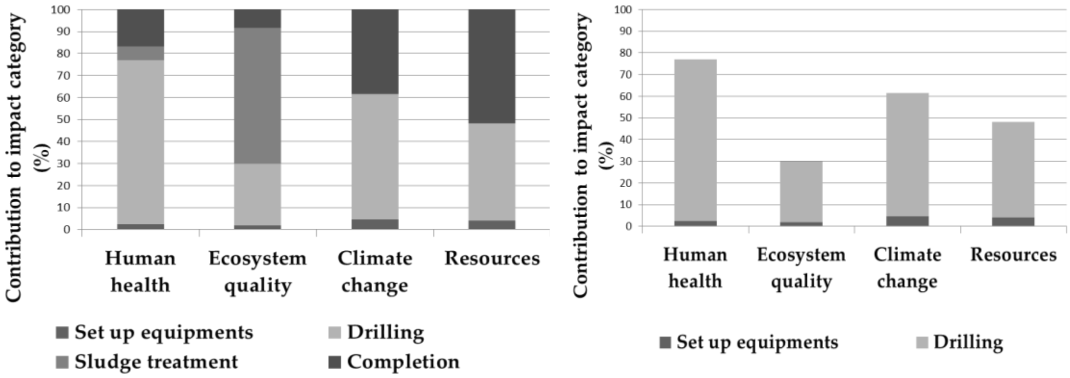
Ecosystem Quality indicator is mainly influenced by two activities. First, sludge treatment (62%) due to emission to the ground of the metals contained in sludge then drilling (27.9%). Finally completion (8.26%) and setting up of equipment (1.9%).

The use of **Resources** is strongly affected by completion (51.6%). Drilling and equipment set up account respectively for 44.2% and 3.91% of the result.

The development stage is to implement a greater number of wells on sites that have proved interest in the exploration stage. As for exploration, this step is strongly influenced by the drilling. Fracturing operations are also very important; direct consequence of the difference in the number of fractures per site. In more detail, we conclude that:

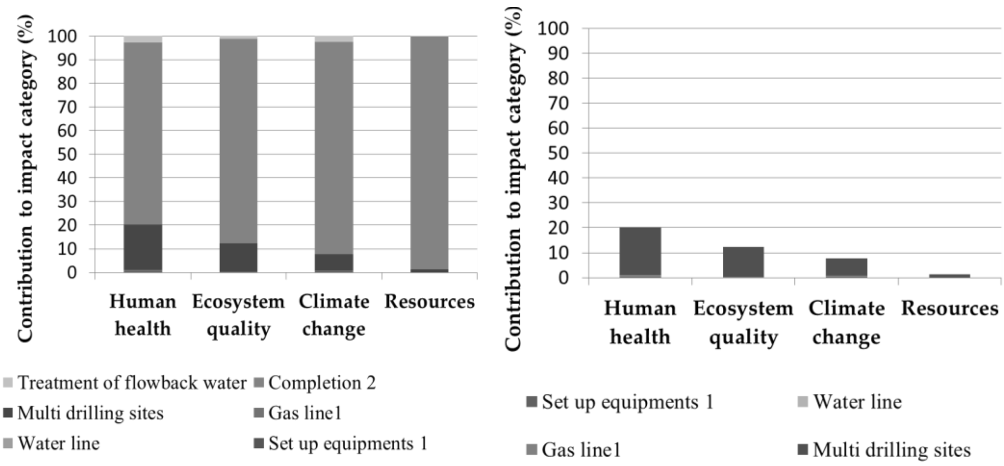
Climate Change indicator is influenced by the completion activities (89.9%) including drilling, fracturing, emissions of the flare and extraction of natural gas. Multi drilling site and treatment of flowback water have respectively 6.91% and 2.46% as an outcome. Water line, settings up equipment and gas line contribute slightly (less than 0.01% each) in the result of the Climate Change category.

In **Human Health**, 77.1% of the potential impacts are due to completion activities, 19.3% to multi drilling sites and 2.68% in the treatment of flowback water.



(a) (b)

Fig. 5. LCA comparison between hydraulic and electric fracturing of shale gas for exploration stage (a): Contribution to the environmental impact of shale gas exploration stage using hydraulic fracturing technology (Method Impact 2002+), (b): Contribution to the environmental impact of shale gas exploration stage using electric fracturing technology (Method Impact 2002+).



(a) (b)

Fig. 6. LCA comparison between hydraulic and electric fracturing of shale gas development stage (a): Contribution to the environmental impact of shale gas development stage using hydraulic fracturing technology (Method Impact 2002+), (b): Contribution to the environmental impact of shale gas development stage using electric fracturing technology (Method Impact 2002+).

Ecosystem Quality indicator is mainly influenced by the activities of completion (86.6%), multi drilling sites (11.9%) and treatment of flowback water (1.16%). Equipment installation, water line and gas line contribute slightly (less than 0.01% each) in the result of the Ecosystem Quality category.

The use of Resources is strongly affected by completion activities (98.5%) and multi drilling site (1.07%).

As regards the environmental impacts relating to the exploitation and exploration of shale gas by electrical fracturing, the most important are:

Climate Change indicator is mainly influenced by three activities. First, exploration stage (28.5%) due operations related to drilling (drilling fluid, operations of the drilling machinery, materials production wells) then production stage due to fugitive methane emissions (29.5%). Finally, distribution stage with the production and transportation of materials for the gas lines installation (25.9%). 15 % of the potential impacts are due to development stage, 1.1% in site preparation stage and 0.41% in closing wells.

In **Human Health**, 46.4% of the potential impacts are due to exploration stage, 25.73% in development stage and 25.73% in distribution stage. Site preparation, production and closing wells contribute slightly (less than 1% each) in the result of the human health category.

For the **Ecosystem Quality** indicator, the vast majority of the potential impact is caused by exploration stage (53.25%), while 29.36% is due to the development stage and 15% in distribution stage.

The use of **Resources** is strongly affected by exploration stage (38.8%). Distribution and development account respectively for 37.4% and 20.3% of the result. . Site preparation, production and closing wells contribute slightly in the result of the Resources category.

Conclusion

Through the exception of limited countries, especially the US, shale gas exploitation and exploration is at an early stage of development.

In Tunisia, while exploration begins to occur, extraction has not yet begun, but its potential has enthused controversy over its environmental impacts notably for climate change. The work reported in this paper has demonstrated that the life cycle greenhouse emissions of Tunisia shale gas are estimated to be about 60 g CO_2e/MJ of the gas produced using hydraulic fracturing technology and around 20 g CO_2e/MJ of the gas produced using electric fracturing technology. The Human Health indicator value presents a reduction of 50% compared to hydraulic fracturing technology. The Ecosystem Quality value are divided by three compared to hydraulic fracturing technology. The Resources indicator is twenty times lesser than the hydraulic fracturing Resources indicator.

Furthermore, hydraulic fracturing, based on the interaction between arc plasma and liquid, as a quasi-static process, cannot induce enough fractures in a rather large volume surrounding the borehole, and this will lead to decrease in well production after a period. However, the above problems may be resolved by the electrohydraulic shock wave fracturing reservoir technology. The authors shows that high pulsing voltage discharges in water induce a pressure wave to crack the shale rock and consequently minimize environmental impacts related to exploration and exploitation of shale gas using hydraulic fracturing technology.

References

1. U.S. Energy Information Administration. Annual Energy Outlook, 2011.
2. U.S. Energy Information Administration. Annual Energy Outlook, 2013.
3. U.S. Energy Information Administration/Advanced Resources International. World Shale Gas and Shale Oil Resource Assessment, 2013.
4. OXFORD ECONOMICS. The economic impact of liquid rich shale and shale gas exploration in Tunisia, 2013.
5. Curran, M.A.: Life cycle assessment: An international experience. In: Journal environment progress and sustainable energy, Vol. 19 (2000), No.2, summer 2000, p.65-71.
6. Khasreen, M.M., Banfill, P.F.G., Menzies, G.F.: Life Cycle Assessment and the Environmental Impact of Buildings: A Review. In: Sustainability, Vol. 1 (2009), No.3, September 2009, p.674-701.
7. Ziane, I., Benhamida, F.: Economic production with control pollution in thermal plants using simulated annealing optimization. In: Journal of Electrical Engineering JEE, Vol. 16 (2016), No.3, 2016, p.19-23.
8. AEA Technology plc. Climate impact of potential shale gas production in the Eu, 2012.
9. Jingchen, Z., Xiaobing, B.: Numerical simulation of hydraulic fracturing coalbed methane reservoir with independent fracture grid. In: Fuel, Vol. 143 (2015), March 2015, p. 543–546.
10. Guo, T., Zhang, S., Qu, Z., Zhou, T., Xiao, Y., Gao, J.: Experimental study of hydraulic fracturing for shale by stimulated reservoir volume. In: Fuel, Vol. 128 (2014), July 2014, p. 373–380.
11. Tang, W.H.: Shock Wave Physics. Beijing, China: Science Press, 2011.
12. Cao, J., Chung, D.D.L.: Defect dynamics and damage of concrete under repeated compression, studied by electrical resistance measurement. In: Cement and Concrete Research, Vol. 31 (2001), No.11, November 2001, p. 1639–1642.
13. Cao, J., Chung, D.D.L.: Minor damage of cement mortar during cyclic compression, monitored by electrical resistivity measurement. In: Cement and Concrete Research, Vol. 31 (2001), No.10, October 2001, p. 1519–1521.
14. Zhou, H., Zhang, Y., Li, H., Han, R., Jing, Y., Liu, Q., Wu, J., Zhao, Y., Qiu, A.: Generation of

Electrohydraulic Shock Waves by Plasma-Ignited Energetic Materials: III. Shock Wave Characteristics With Three Discharge Loads. In: IEEE Transactions on Plasma Science, Vol. 43 (2015), No.12, December 2015, p. 4017-4023.

15. Jabberi, H., Ben Ammar, F.: Electric fracturing using Flying Capacitor Multi-level Converters. International Review of Electrical Engineering, Vol. 11 (2016), No 3, June 2016, p. 230-238.
16. Koroneos, C.J., Nanaki, E.A.: Life cycle environmental impact assessment of a solar water heater. In: Journal of Cleaner Production, Vol. 37 (2012), December 2012, p. 154-161.
17. Frankl, P., Rubik, F.: Life Cycle Assessment in Industry and Business Adoption Patterns, Applications and Implications. Berlin: Springer Verlag, pp. 24-26, 2000.
18. IPCC Intergovernmental Panel on Climate Change, Climate Change The Physical Science Basis, 2007.
19. Bennett, D.H., Margni, M.D., McKone, T.E., Jolliet, O.: Intake Fraction for Multimedia Pollutants: A Tool for Life Cycle Analysis and Comparative Risk Assessment. In: Risk Analysis, Vol. 22 (2002), No.5, October 2002, p. 905-918.
20. Bennett, D.H., McKone, T.E., Evans, J.S., Nazaroff, W.W., Margni, M.D., Jolliet, O., Smith, K.R.: Defining Intake Fraction. In: Environmental Science & Technology, Vol. 36 (2002), No.9, May 2002, p. 207A-211A.
21. Crettaz, P., Pennington, D., Rhomberg, L., Brand, B., Jolliet, O.: Assessing Human Health Response in Life Cycle Assessment Using ED10s and DALYs: Part 1-Cancer Effects. In: Journal Risk Analysis, Vol. 22 (2002), No.5, October 2002, p.931-946.
22. Pennington, D., Crettaz, P., Tauxe, A., Rhomberg, L., Brand, B., Jolliet, O.: Assessing Human Health Response in Life Cycle Assessment Using ED10s and DALYs: Part 2-Noncancer Effects. In: Journal Risk Analysis, Vol. 22 (2000), No.5, October 2002, p.947-963.
23. Goedkoop, M., Spriensma, R.: The Eco-indicator 99: A Damage Oriented Method for Life Cycle Assessment, Methodology Report, second edition, Pré Consultants, Amersfoort (NL), Netherlands, 2000.
24. Wood, R., Gilbert, P., Sharmina, M., Anderson, K., Footitt, A., Glynn, S., Nicholls, F.: Shale gas: a provisional assessment of climate change and environmental impacts. Manchester: A report commissioned by The Cooperative and undertaken by The Tyndall Centre, University of Manchester, 2011.
25. American Petroleum Institute. Water management associated with hydraulic fracturing. Washington: American Petroleum Institute, 2010.
26. ISO. ISO 14040:2006: Environmental management – life cycle assessment – principles and framework. Geneva, Switzerland: International Organisation for Standardisation; 2006.
27. ISO. ISO 14044:2006: Environmental management – life cycle assessment – requirements and guidelines. Geneva, Switzerland: International Organisation for Standardisation; 2006.