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ShaleXenvironmenT

Maximizing the EU shale gas potential by minimizing its environmental footprint

H2020-LCE-2014-1
Competitive low-carbon energy

D10.2
Sensitivity analysis of the LCA of the environmental footprint of shale gas in Europe

WP 10 – Life Cycle Assessment

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History of the changes

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1.1	31-08-2017	Carla Tagliaferri	First draft
1.2	15-10-2017	Alberto Striolo	Final version
1.3	16-08-2018	Andrea Paulillo	Revised version

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Key word list

Life cycle assessment, shale gas, sensitivity analysis, EUR

Definitions and acronyms

Acronyms	Definitions
ADP	Abiotic depletion potential
EUR	Estimated ultimate recovery
ISO	International Organization for Standardization
FAETP	Fresh water aquatic ecotoxicity potential
GWP	Global warming potential
LCA	Life cycle assessment
REC	reduce emission completion
TEPT	Terrestrial ecotoxicity potential

1. Introduction

1.2 General context

Following the boom of shale gas production in the US and the decrease in the US gas prices, increasing interest in shale gas is developing in many countries holding shale reserves. Many European countries, including UK, France and Poland are reported to hold recoverable resources of shale gas (EIA, 2013). However, controversies have arisen over whether European shale gas exploitation could parallel that in the US (Boersma, 2013; Oil&gas, 2013). Major concerns have been voiced about different European conditions compared to the US: different geology, higher population density, different laws governing land ownership and lack of relevant drilling expertise and infrastructure. Hence, the possibility of the establishment of a new global market for shale gas is still uncertain.

Some of the potential implications between shale gas development, global warming, policy and economics are reported in Newell and Raimi (2014). The debate on the potential of shale gas needs to include consideration of its impacts on the environment. Concerns about the environmental impacts of the extraction of shale gas, coupled with a strong nuclear lobby, have pushed some countries such as France to ban exploration and trials (Cooper et al., 2014). It is of major importance to identify the possible sources of pollution, quantify the environmental impacts of shale gas production, and compare shale gas impacts with those of other energy sources to inform the debate and the decision-making process. It is also crucial that the assessment is adapted to different contexts by taking into consideration specific conditions (e.g. policies, geological shale formations, technologies used, etc.).

LCA results are always associated with uncertainties, especially when the environmental impacts of emerging technologies are analysed. The process of shale gas extraction using hydraulic fracturing is still in the development stage in terms of both technology and regulation in the EU. Industry data is rarely publicly disclosed and field measurements are often proprietary so that the limited inventory data available are widely contested (Dale et al., 2013; Laurenzi and Jersey, 2013). This deliverable (10.2) builds upon deliverable 10.1 and aims at developing a robust life cycle assessment (LCA) analysis by investigating the sensitivity of the LCA model to critical parameters. These have been chosen based on discussions with other WPs of the SXT consortium. In the sensitivity analysis, each model parameter is changed by a specific amount and the effects on the LCA results are analysed. The results of the sensitivity analysis enable the identification of the most influential model parameters, i.e. those for which the highest quality data should be sourced, as well as providing input into the policy formulation guidance, developed in WP11.

This deliverable contributes to the project objective to understand whether shale gas has the potential of contributing to a clean and efficient energy market, necessary to continue to improve our standards of living and sustain our economy, without compromising the environment. In particular, along with the project's objectives it quantifies the environmental impact of a well during its lifespan (gaseous emissions, water quality, etc.).

1.2 Deliverable objectives

The key objective of deliverable 10.2 is to conduct a sensitivity analysis on the environmental impact of shale gas production (quantified in D10.1) by analysing the effects on the LCA results of changes in the following model parameters:

- EUR
- Fraction of flowback (Flowback fluids/ fracturing fluids injected)
- Fraction of the flowback fluids recycled
- Fraction of flowback disposed industrial treatment
- Potential completion emissions
- Potential workover emissions

2. Methodological approach

2.2 Life cycle assessment methodology

Life cycle assessment (LCA) is one of the most developed and widely used environmental assessment tools for comparing alternative technologies (Clift, 2013; Clift et al., 2000). LCA quantifies the amount of materials and energy used and the emissions and waste over the complete supply chain (i.e. life cycles) of goods and services (Baumann and Tillman, 2004). Moreover, it helps to identify the 'hot spots' in the system; i.e. those activities that cause the greatest environmental impacts and should be targeted in the first instance, thus enabling identification of more environmentally sustainable options (Clift, 2006).

International Standard Organization (ISO) 14040 (ISO 14040, 2006) provides standard guidelines on how to perform an LCA analysis for improving decision support. It consists of four stages:

i) Goal and scope definition
ii) Inventory analysis
iii) Impact assessment
iv) Interpretation

In the goal and scope definition, the purpose of the study is defined along with the following points:

i) what political or technical decision will depend on the results of the study;
ii) what processes are to be investigated (i.e. the system boundaries);

iii) the basis for comparison between different alternatives is (i.e. the functional unit).

During the inventory analysis phase all the environmentally relevant inputs and outputs of the process are identified on the basis of the functional unit. In the impact assessment phase, the inputs and outputs previously collected are classified in different groups according to the type of environmental impact they contribute to and assigned to specific impact categories. According to the mass flow, each environmental intervention is transformed into an environmental burden through a common unit, specific for the environmental category. The last phase includes the analysis of the results obtained in the previous phases and the drawings of the conclusions based on the points reported in the goal and scope definition.

For the impact assessment phase, this study adopts the CML method, version 4.6 (January 2016), which is based on the ISO standards (ISO 14040, 2006). The focus is on the impact categories shown in **Table 1**.

The *Global Warming Potential (GWP)* characterizes and calculates the impact of greenhouse gases based on the extent to which these gases enhance the radiative forcing. GWP values for specific gases, developed by the Intergovernmental Panel on Climate Change, express the cumulative radiative forcing of an emission over a given time period in terms of the quantity of carbon dioxide giving the same effect (Forster et al., 2007; IPCC, 2006). The *Abiotic Depletion (ADP)* addresses the problem of the diminishing pool of resources, focusing on the depletion of non-living resources such as iron ore, crude oil, etc. The abiotic depletion is usually measured in MJ when the deployment of energy sources is assessed. The *Toxicity* impacts include many types of indicators causing damages to different environments based on both the inherent toxicity of a compound and potential exposure. Toxicity categories indicate the toxicological impacts of pollutants emitted to the environment, such as neurological damage, carcinogenic, mutagenic, etc. The *fresh water (FAETP)* assesses the toxic effects of polluting compounds to water life, while the *terrestrial eco-toxicity potential (TETP)* is related to land-based ecosystems.

Table 1. Impact categories and indicators used in this study

Impact categories	Impact Indicator	Acronym	Characterisation model	Units
Climate change	Global warming potential	GWP	CML 2001 baseline (IPCC, 2007) (Apr. 2015)	kg CO_2eq
Resources depletion (fossil)	Abiotic depletion	ADP	CML 2001 baseline (Guinée, 2001) (Apr. 2015)	MJ
Ecotoxicity (freshwater)	Fresh water aquatic ecotoxicity potential	FAETP	USEtox model (Rosenbaum et al., 2008) (Apr. 2015)	kg DCB eq
Ecotoxicity (terrestrial)	Terrestrial ecotoxicity potential	TETP	USEtox model (Rosenbaum et al., 2008)	kg DCB eq

The ISO standards (ISO 14040, 2006) recommend that the environmental benefits of resources that are recovered should be accounted for by using the “system expansion” approach. According to this, the system boundaries are broadened to include the avoided burdens of conventional production processes.

A pragmatic distinction between the foreground and the background is followed in this study; the foreground is the set of processes whose selection or mode of operation is directly affected by decisions based on the study, whereas the background is defined as all other processes which interact with the foreground, usually by supplying or receiving material or energy.

Currently more than thirty software packages exist to perform LCA analysis, with differing scope and capacity: some are specific for certain applications, while others have been directly developed by industrial organisations (Manfredi and Pant, 2011). In this study, GaBi 7 has been used (Thinkstep, 2015); it contains databases developed by ThinkStep that incorporates industry organisations’ databases (e.g. Plastics Europe, Aluminium producers, etc.) and also regional and national databases (e.g. Ecoinvent, US NREL database, etc.).

2.2 Modelling assumption

2.2.1 Functional unit and system boundaries

The functional unit of this work is represented by the delivery of 1 MJ (low heating value) of natural gas to the final consumer at low pressure (<7 bar and >0.75 mbar gauge). Although the majority of data used in the LCA model are specific to the UK, the LCA results are considered to be representative of EU conditions. The overall system boundary is shown in **Figure 1**.

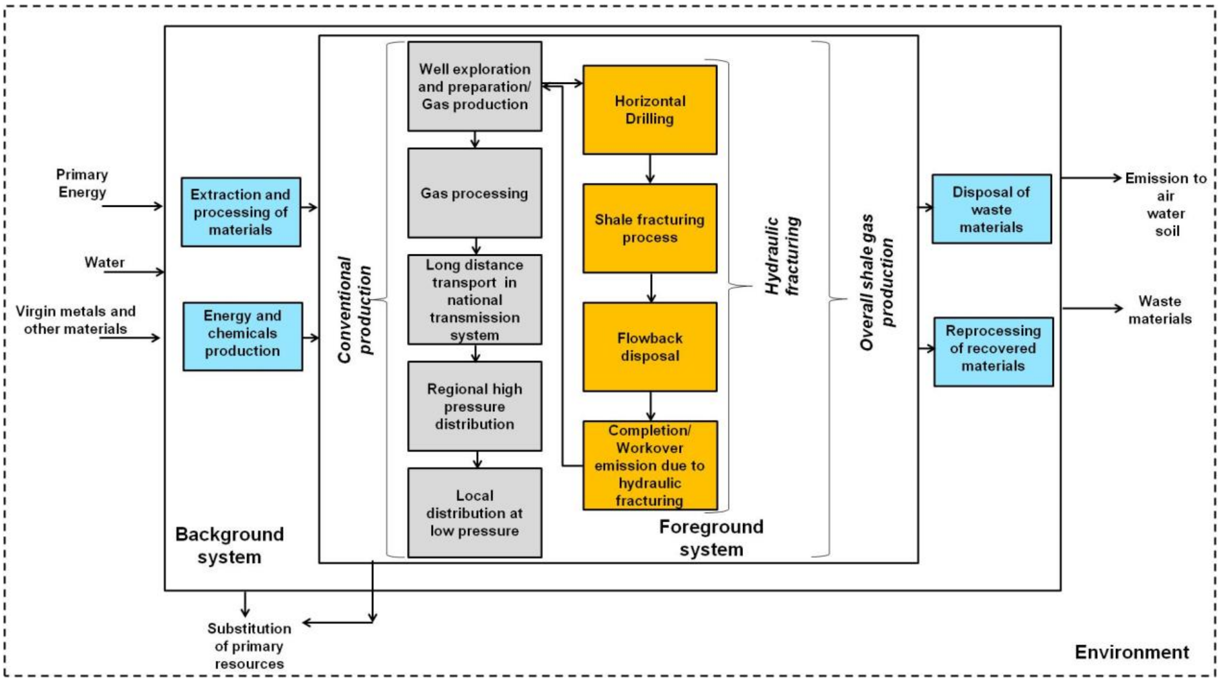

Figure 1. System boundary for shale gas. Yellow boxes represent the hydaulic fracturing process, grey boxes identify the conventional processes and the blue boxes refer to the activities of the background system.

2.2.2 Modelling of the base scenario

The modelling approach and the system boundary for the base scenario gas are shown in **Figure 1** and the main inventory data are reported in **Table 2** and **Table 3** The entire life cycle of shale gas production process has been considered in the modelling approach. This includes the indirect activities of energy, chemicals and water production and recovery and final disposal of waste material identified in the background of **Figure 1**. The background system exchanges energy and material with foreground system. This includes the entire supply chain of shale gas production, processing and distribution. The following stages have been considered in the LCA model:

1. *Well site exploration and investigation.*
2. *Well pad and road preparation and construction.*
3. *Well vertical drilling.* Production of materials needed for drilling; transport of materials; energy required during drilling and emissions from machinery; emissions during drilling; casing and cementing; disposal of drilling wastes.
4. *Hydraulic fracturing of the well*. Horizontal drilling; production and transport of water, chemicals and sand needed for fracturing; energy used during the hydraulic fracturing and emissions from machinery; disposal of wastes.
5. *Well Completion.* Energy and materials required; disposal of flowback and produced water from the well; emissions of natural gas during well completion, workovers, unloadings; re-fracturing.
6. *Production.* Processing and cleaning.

7. *Pipe construction and transmission.*
8. *Post production phase.* Decommissioning, plugging and removing of equipment.
9. *Distribution at high pressure.* Long distance distribution.
10. *Local distribution at low pressure.* Distribution to the consumers.

The operations of shale gas extraction, gas processing and distribution (gas field exploration, natural gas production, purification, long distance transport and regional/local distribution, operations required also in conventional gas production) rely on data from Ecoinvent database version 3.1 (Wernet et al., 2016). The Ecoinvent model has been modified by parameterisation of the estimated ultimate recovery (EUR) according to the value reported in **Table 2**.

Horizontal drilling, fracturing of the shale rocks, flowback water disposal and handling of emissions associated with hydraulic fracturing (operations specifically required for shale gas production) were also considered and added to the aforementioned conventional process operations. The main inventory parameters for these are reported in **Table 3**. The emissions from workover and completion are captured and gathered into the pipeline.
More information is available in Tagliaferri et al. (2016) and D10.1.

Table 2. Key assumptions of shale gas model.

Parameter	Amount	
EUR	8.5E+07	m3 per well
Fraction of flowback (flowback fluids/ fracturing fluids injected)	2.5E+01	%
Fraction of the flowback fluids recycled	5.0E+01	%
Fraction of flowback disposed industrial treatment	5.0E+01	%
Completion emissions - Total amount of potential emission per well without flaring or REC (this is the difference between the emission from unconventional well and conventional wells)	1.6E+08	g CH4 per well
Workover emissions - Total amount of potential emission without flaring or REC (this is the difference between the emission from unconventional well and conventional wells).	3.3E+07	g CH4 per well

Table 3. Key inventory data of shale gas model.

Parameter	Amount	
Water used during hydraulic fracturing total	1.92E-04	m3/m3 of raw gas produced
Sand used during fracturing (silica, quarts sand)	2.55E-02	kg/m3 of raw gas produced
Additives		
Acid: Hydrochloric acid or muriatic acid	5.65E-04	kg/m3 of raw gas produced
Friction reducer: petroleum distillate	1.41E-04	kg/m3 of raw gas produced
Surfactant: isopropanol	1.41E-04	kg/m3 of raw gas produced
Cly stabilizer/controler: Potassium chloride	9.41E-05	kg/m3 of raw gas produced
Geling agent; Guar gum or hydroxyethyl cellulose	9.41E-05	kg/m3 of raw gas produced
Scale inhibitor: Ethylene glycol	7.06E-05	kg/m3 of raw gas produced
PH Adjusting agent: Sodium bicarbonate and sodium potassium hydroxide	1.88E-05	kg/m3 of raw gas produced

Breaker: Ammonium persulfate	1.88E-05	kg/m3 of raw gas produced
Crosslinker: borate salts	1.88E-05	kg/m3 of raw gas produced
Iron control: citric acid	7.06E-06	kg/m3 of raw gas produced
Bactericide/biocide: glutaraldehyde	1.88E-06	kg/m3 of raw gas produced
Corrosion Inhibitor: Formamide	1.88E-06	kg/m3 of raw gas produced
Amount of flowback water	5.46E-02	kg/m3 of raw gas produced
Flowback water disposal		
Fractions		
Recycled	2.73E-02	kg/m3 of raw gas produced
Disposal in proper industrial treatment plants	2.73E-02	kg/m3 of raw gas produced
Energy consumption		
Industrial treatment	3.43E-04	KWh/m3 of raw gas produced
Difference of materials used between conventional drilling and horizontal drilling		
Steel	1.29E-03	kg/m3 of raw gas
Portland cement	1.96E-03	kg/m3 of raw gas
Gilsonite (asphaltite)	-7.39E-05	kg/m3 of raw gas
Diesel fuel	1.51E-03	kg/m3 of raw gas
Bentonite	3.63E-04	kg/m3 of raw gas
Soda Ash	6.04E-06	kg/m3 of raw gas
Gelex	4.39E-08	kg/m3 of raw gas
Polypac	1.14E-05	kg/m3 of raw gas
Xanthum Gum	5.77E-06	kg/m3 of raw gas
Water throughput (Water volumes do not account for water associated with hydraulic fracturing activities)	6.31E-03	kg/m3 of raw gas
Surplus of emission due to wells horizontal drilling		
CO2	4.78E-03	kg/m3 of raw gas
SO2	4.85E-06	kg/m3 of raw gas
NOx	6.69E-05	kg/m3 of raw gas
PM	5.58E-06	kg/m3 of raw gas
CO	1.45E-05	kg/m3 of raw gas
NMVOC	2.11E-07	kg/m3 of raw gas
WELL COMPLETION- Potential emissions due to well completion without flaring or REC conventional wells		
CH4	1.91E+00	g CH4/m3 of raw gas
CO2	1.83E-01	g CO2/m3 of raw gas
C2H6	1.25E-01	g C2H6/m3 of raw gas
C3H8	6.12E-02	g C3H8/m3 of raw gas
N2	2.72E-01	g N2/m3 of raw gas
WELL WORKOVERS- Potential emissions due to well completion without flaring or REC conventional wells		
CH4	3.81E-01	g CH4/m3 of raw gas
CO2	3.65E-02	g CO2/m3 of raw gas
C2H6	2.50E-02	g C2H6/m3 of raw gas
C3H8	1.22E-02	g C3H8/m3 of raw gas
N2	5.42E-02	g N2/m3 of raw gas

WELL COMPLETION- Emission due to well completion including flaring or REC conventional wells		
CH4	3.82E-02	g CH4/m3 of raw gas
CO2	5.87E+00	g CO2/m3 of raw gas
C2H6	2.50E-03	g C2H6/m3 of raw gas
C3H8	1.22E-03	g C3H8/m3 of raw gas
N2	2.72E-01	g N2/m3 of raw gas
WELL WORKOVERS- Emission due to well completion including flaring or REC conventional wells		
CH4	7.61E-03	g CH4/m3 of raw gas
CO2	1.17E+00	g CO2/m3 of raw gas
C2H6	4.99E-04	g C2H6/m3 of raw gas
C3H8	2.44E-04	g C3H8/m3 of raw gas
N2	5.42E-02	g N2/m3 of raw gas

2.2.3 Modelling of the sensitivity analysis

To support the development of the sensitivity analysis, a parametric Excel-based tool has been developed to calculate the inventory data for the processes that are specific to shale gas production. The tool allows the user to calculate different inventories based on different values of critical model parameters, including the estimated ultimate recovery, the fraction of flowback fluids and their disposal method. The sensitivity analysis is performed by changing one parameter at a time, with all the other being equal to the base scenario. The base scenario and the eight different scenario analysed are explained below and in (Error! Reference source not found.):

- *S.0 (base scenario).* The LCA modelling for this scenario is described in section 2.1 and in deliverable 10.1. All gaseous emissions are assumed to be captured and collected into the pipeline. 50% of the flowback is disposed through industrial treatment while the remaining amount is recycled for reuse in other wells. The estimated ultimate recovery is assumed to be equal to 85 million m^3 (DECC, 2013; Stamford and Azapagic, 2014).

- *Scenarios 1-2* investigate a 20% increase/decrease in EUR, which is associated with an increase/decrease in re-fracturing jobs performed over the well's life. For the base case 3 fracturing jobs are considered; these are scaled linearly with the increase/decrease in EUR.

- *Scenarios 3-4* analyse the case for an increase and decrease in flowback fractions equal to 60% of the base scenario value.

- In *scenario 5,* 100% of the flowback is disposed through industrial treatment whereas in *scenario 6,* 100% of flowback is recycled for further fracturing jobs.

- *Scenarios 7-8* explore a 20% increase/decrease in the amount of completion/workover emissions associated with hydraulic fracturing. The potential emissions are assumed to be gathered into the pipelines as in the based scenario.

Table 4. Key inventory parameter of the scenarios analysed and transport distances

			EUR		Flowback fraction		Flowback fluids treatment		Completion/workover emissions	
Parameter	**Unit**	**Base scenario**	**S.1**	**S.2**	**S.3**	**S.4**	**S.5**	**S.6**	**S.7**	**S.8**
EUR	m3/well	8.50E+07	1.02E+08	6.80E+07	8.50E+07	8.50E+07	8.50E+07	8.50E+07	8.50E+07	8.50E+07
Processed gas recovered	m3/well	7.31E+07	8.77E+07	5.85E+07	7.31E+07	7.31E+07	7.31E+07	7.31E+07	7.31E+07	7.31E+07
Fraction of flowback (Flowback fluids/ fracturing fluids injected)	%	2.50E+01	2.50E+01	2.50E+01	4.00E+01	1.00E+01	2.50E+01	2.50E+01	2.50E+01	2.50E+01
Fraction of the flowback fluids recycled	%	5.00E+01	5.00E+01	5.00E+01	5.00E+01	5.00E+01	0	1.00E+01	5.00E+01	5.00E+01
Fraction of flowback disposed industrial treatment	%	5.00E+01	5.00E+01	5.00E+01	5.00E+01	5.00E+01	1.00E+01	0	5.00E+01	5.00E+01
Potential completion emissions	g CH4 per well	1.61E+08	1.61E+08	1.61E+08	1.61E+08	1.61E+08	1.61E+08	1.61E+08	1.93E+08	1.29E+08
Potential workover emissions	g CH4 per well	3.23E+07	3.23E+07	3.23E+07	3.23E+07	3.23E+07	3.23E+07	3.23E+07	3.88E+07	2.59E+07

3. Summary of activities and research findings

Figure 2 to **Figure 5** show the results of the sensitivity analysis on the environment impacts of shale gas production. Results are reported according to the functional unit of 1 MJ of gas delivered to the consumer.

All impact categories (i.e. AD, FAETP, GWP, TEPT) show the same trend: the EUR is the parameter that affects the most the LCA results on shale gas. An increase in the estimated ultimate recovery parameter determines a decrease in the environmental impacts and vice versa. Because commissioning of shale gas wells (which includes vertical drilling and hydraulic fracturing) represents the phase in the production of shale gas with the greatest environmental impacts, an increase in the ultimate recovery means that such environmental impacts are related to the production of more shale gas; this implies that the environmental impacts per unit of gas are lower. **Table 5** shows the results of Scenarios 1 and 2 (S.1 and S.2) as variations from the base scenario. The greatest variation is shown for the TEPT category in S.2 at 24% variation from the reference scenario.

With respect to workover and completion emissions, a 20% increase causes only a slight increase in the global warming category (approximately equal to 0.2%, see S.7 of **Figure 4**). This is due to the use of reduce emission completion (REC) devices that avoid the flaring or the direct release of methane into the atmosphere. It must be noticed that the analysis does not include the manufacturing of reduce emission completion (REC) devices as no inventory was available. However, this is not deemed to have the potential to significantly affect the results.

Finally, also the other parameters investigated, i.e. the fraction of flowback fluids and their disposal method, do not appear to affect significantly the LCA results.

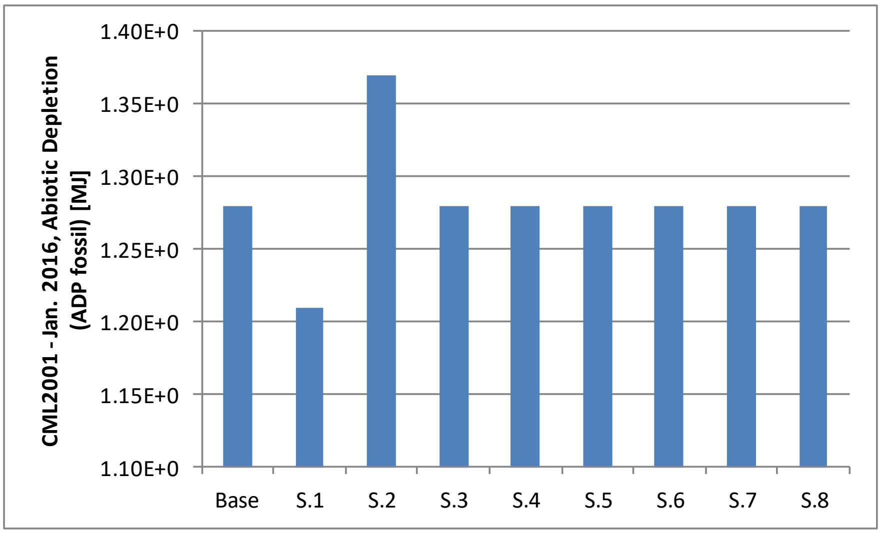

Figure 2. Sensitivity analysis on the impact of shale gas production on abiotic depletion potential.

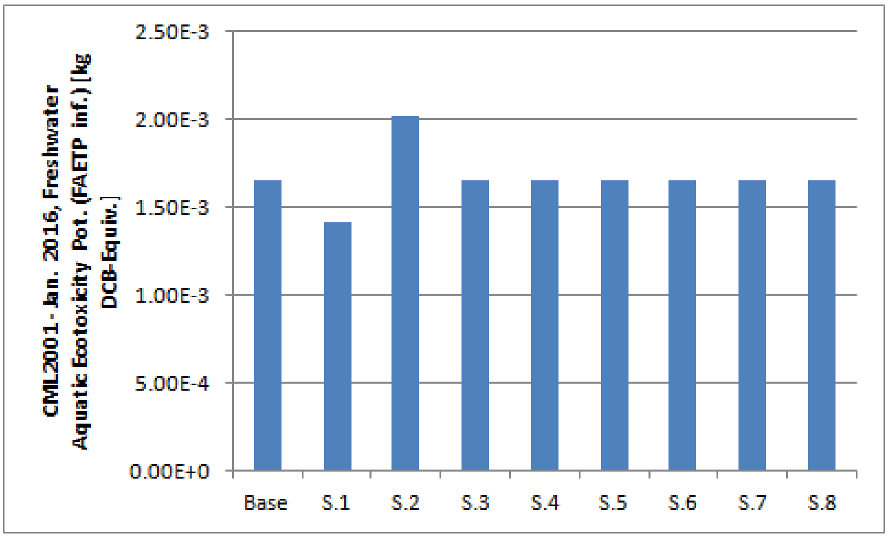

Figure 3. Sensitivity analysis on the impact of shale gas production on fresh water aquatic ecotoxicity potential.

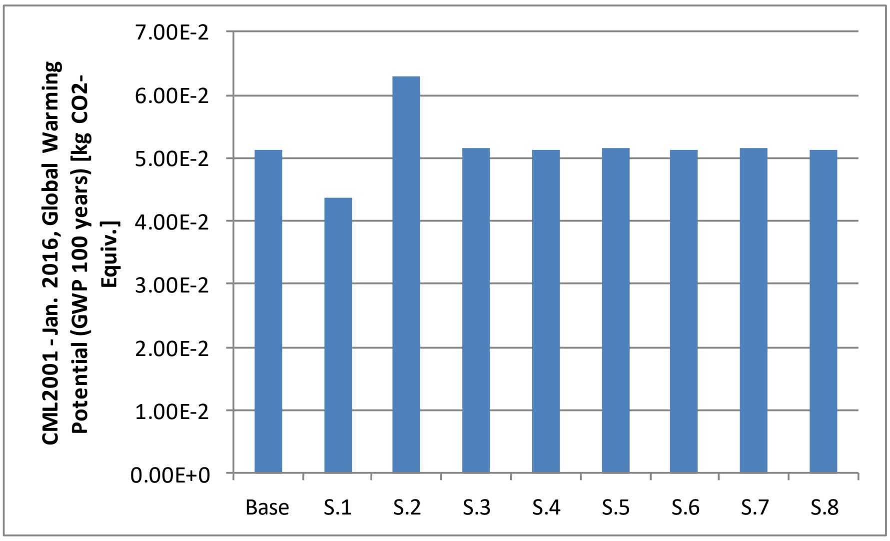

Figure 4. Sensitivity analysis on the impact of shale gas production on global warming potential assessed as CO_2-equivalent gaseous emissions.

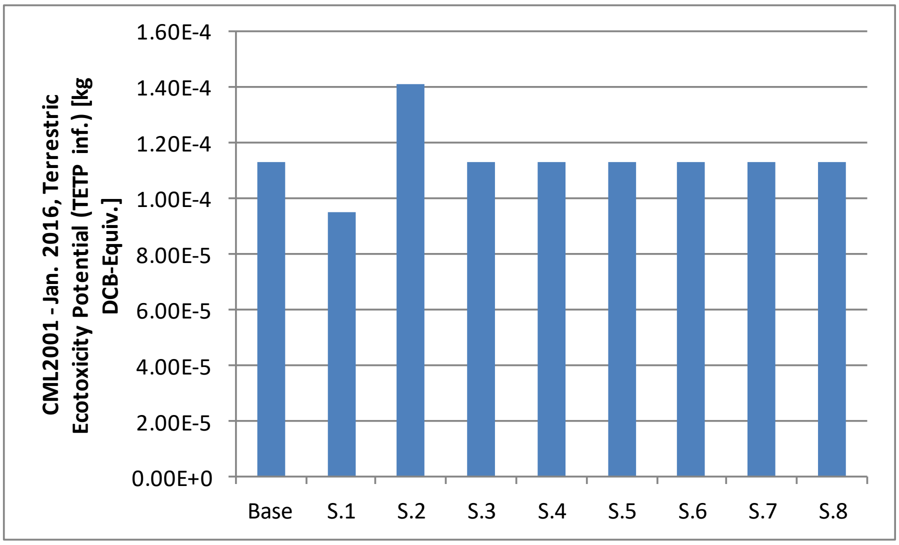

Figure 5. Sensitivity analysis on the impact of shale gas production on terrestrial ecotoxicity potential.

Table 5.Variation in the results for S.1 and S.2

Variation from base scenario (Base scenario-S.)/Base scenario [%]	**S.1** *(20% increase in EUR)*	**S.2** *(20% decrease in EUR)*
CML2001 - Jan. 2016, Abiotic Depletion (ADP fossil) [MJ]	-5.5%	7.0%
CML2001 - Jan. 2016, Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB-Equiv.]	-14.5%	22.4%
CML2001 - Jan. 2016, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	-14.8%	22.4%
CML2001 - Jan. 2016, Terrestrial Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	-15.8%	24.8%

Overall, the sensitivity analysis has shown that the LCA model developed within D10.1 and D10.2 is robust. With the exception of the EUR parameter, all other parameters have negligible effects on the LCA results. Furthermore, the variation in the LCA results (with respect to the base scenario) are always lower than the variation in the model parameter. This means that the LCA model does not feature non-linearities, i.e. changes in input parameters are not amplified in the results.

4. Conclusions and future steps

This deliverable analysed the sensitivity of the LCA model developed in deliverables D10.1 for quantifying the environmental impacts of shale gas exploration, production and transmission at low pressure to the consumer. The analysis focused on a number of model parameters including the estimated ultimate recovery (EUR), the fraction of flowback fluids, the flowback fluids disposal method, and amount of emissions from completions and workovers. A parametric excel-based tool has been developed to calculate the inventory data for the processes that are specific to shale gas production.

Overall, the analysis demonstrated that the LCA model is robust. With the exception of the EUR, all other parameters have negligible effects on the LCA results. The results of the sensitivity analysis will contribute to the development of the policy formulation guidance in WP11.

Because the sensitivity analysis does not take into consideration the uncertainty of the model parameters - but only the effects of a subjective variation in the model parameters (which here is performed on a one-at-a-time basis) on the LCA results - it is usually recommended to perform an uncertainty analysis as a second step in the interpretation of the LCA results. The uncertainty analysis quantifies how much each parameter contributes to the uncertainty of the results, therefore enabling the identification those parameter that are both the most uncertain and the most influential (i.e. to which the LCA model is most sensitive). The uncertainty analysis is considerably more challenging than the sensitivity analysis because it requires more data to be collected for each model parameter to be analysed. Further efforts should thus be directed to the collection or the estimation of uncertainty ranges and distributions of the model parameters, and the quantification of the uncertainty of the LCA results.

5. Publications resulting from the work described

Tagliaferri, C.; Clift, R.; Chapman, C.; Lettieri, P.; (2016) Shale gas: a life cycle perspective for UK production. The International Journal Of Life Cycle Assessment, doi:10.1007/s11367-016-1207-5.

6. Bibliographical references

Baumann, H., Tillman, A.-M., 2004. The Hitch Hiker's Guide to LCA. An orientation in life cycle assessment methodology and application. Lund, Sweden, Studentlitteratur.

Boersma, T., 2013. Four Questions on Shale Gas Development in Europe and the U.S [WWW Document].

Clift, R., 2013. System approaches: Life Cycle Assessment and Industrial Ecology, in: Harrison, R.M. (Ed.), Pollution: Causes, Effects and Control. The Royal Society of Chemistry, London.

Clift, R., 2006. Sustainable development and its implications for chemical engineering. Chem. Eng. Sci. 61, 4179–4187. doi:10.1016/j.ces.2005.10.017

Clift, R., Doig, A., Finnveden, G., 2000. The Application of Life Cycle Assessment to Integrated Solid Waste Management. Part 1 - Methodology. Process Saf. Environ. Prot. 78, 279–287. doi:10.1205/095758200530790

Cooper, J., Stamford, L., Azapagic, A., 2014. Environmental Impacts of Shale Gas in the UK: Current Situation and Future Scenarios. Energy Technol. 2, 1012–1026. doi:10.1002/ente.201402097

Dale, A.T., Khanna, V., Vidic, R.D., Bilec, M.M., 2013. Process based life-cycle assessment of natural gas from the Marcellus Shale. Environ. Sci. Technol. 47, 5459–66. doi:10.1021/es304414q

DECC, 2013. Potential Greenhouse Gas Emissions Associated with Shale Gas Extraction and Use.

EIA, U., 2013. Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States. US Dep. Energy/EIA, Washington, DC.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schultz, M., Van Dorland, R., 2007. Climate change 2007: The physical science basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Guinée, J., 2001. Handbook on life cycle assessment — operational guide to the ISO standards. Int. J. Life Cycle Assess. 6, 255.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change., Solomon, S. ed. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2006. 2006 IPCC guidelines ofr national greenhouse gas inventories [WWW Document].

ISO 14040, 2006. International Standard, In: Environmental Management – Life Cycle Assessment – Principles and Framework, International Organisation for Standardization, Geneva, Switzerland.

Laurenzi, I.J., Jersey, G.R., 2013. Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas. Environ. Sci. Technol. 47, 4896–903. doi:10.1021/es305162w

Manfredi, S., Pant, R., 2011. Supporting environmentally sound decisions for waste management: A technical guide to Life Cycle Thinking (LCI) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners [WWW Document].

Newell, R.G., Raimi, D., 2014. Implications of shale gas development for climate change. Environ. Sci. Technol. 48, 8360–8. doi:10.1021/es4046154

Oil&gas, 2013. A slow costly road to nowhere: shale gas development in Europe.

Rosenbaum, R.K., Bachmann, T.M., Gold, L.S., Huijbregts, M.A.J., Jolliet, O., Juraske, R., Koehler, A., Larsen, H.F., MacLeod, M., Margni, M., McKone, T.E., Payet, J., Schuhmacher, M., Van De Meent, D., Hauschild, M.Z., 2008. USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assess. 13, 532–546. doi:10.1007/s11367-008-0038-4

Stamford, L., Azapagic, A., 2014. Life cycle environmental impacts of UK shale gas. Appl. Energy 134, 506–518. doi:10.1016/j.apenergy.2014.08.063

Tagliaferri, C., Clift, R., Lettieri, P., Chapman, C., 2017. Shale gas: a life-cycle perspective for UK production. Int. J. Life Cycle Assess. 22, 919–937. doi:10.1007/s11367-016-1207-5

Thinkstep, 2015. GaBi 6 software-system and databases for life cycle engineering. Stuttgart, Echterdingen (see www.pe-europe.com).

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. doi:10.1007/s11367-016-1087-8