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Perspectives for shale gas development in Europe: a case study in the province of Burgos, Spain

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Thesis submitted to the Faculty of Engineering, University of Porto
for the degree of Doctor of Philosophy in Environmental Engineering

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2018

Para a minha avó Antonia.

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Abstract

Shale gas or natural gas from shale formations is an energy resource that has changed the profile of the energy industry in recent years. The possible existence of large shale gas reserves coupled with the high dependency on natural gas imports have generated a great debate about its possible exploration in Europe. However, even though shale gas exploration techniques are not completely new in the oil and gas industry, such exploration faces great public opposition due to concerns over its impacts in the environment and public health.

As a background, this thesis presents an evaluation of natural gas markets from 2003 to 2014, as well as an extensive review of scientific articles addressing the environmental aspects of its exploration from 2010 and 2015. Following this, a well under licensing phase located in the province of Burgos, Spain, was considered as a case study to assess a possible development of shale gas exploration in Europe.

At first, a survey to evaluate public acceptance in province of Burgos and in Spain as a whole was performed. The results demonstrated that the general public is highly unaware of what shale is and presents great ambivalence in their opinions. A strong public opposition to its development was revealed, particularly in areas next to possible exploration zones.

Following this evaluation, a life cycle assessment (LCA) of extraction, production and distribution of shale gas to the final consumer was performed using the software Simapro 8.4.0.0. Results of LCA have demonstrated that well drilling casing and cementing, hydraulic fracturing, natural gas production, gathering, and processing are the most critical phases in shale gas production. A comparison to similar studies have failed to identify a consensus in different impact categories, with the exception of global warming potential and abiotic depletion of fossil fuels.

More research on shale gas is recommended since several gaps remain in the literature, such as the real recovery potential of basins, its social impacts and life cycle costs. On the other hand, innovation in extraction technologies and the possibility of carbon sequestration in depleted wells have the potential to dramatically change the environmental performance of shale gas in the future. Therefore, even though shale gas is not likely to be explored commercially in the short term, it remains an important energy asset that may be considered as an option for the European energy mix.

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Resumo

Shale gas, gás de folhelho ou gás natural a partir de formações do tipo *shale* ou folhelho, é um recurso energético que mudou o perfil da indústria de energia nos últimos anos. A possível existência de grandes reservas de gás de folhelho, juntamente com a alta dependência das importações de gás natural, fomentou um grande debate sobre a sua possível exploração na Europa. No entanto, ainda que as técnicas de exploração de gás de folhelho não sejam completamente novas na indústria de petróleo e gás, a sua exploração enfrenta grande oposição pública devido a preocupações com seus impactos no meio ambiente e saúde pública.

Como contextualização, esta tese apresenta uma avaliação dos mercados de gás natural entre os anos 2003 a 2014, além de uma extensa revisão de artigos científicos abordando os aspetos ambientais de sua exploração entre 2010 e 2015. Após esta revisão, um poço de gás de folhelho em fase de licenciamento localizado na província de Burgos, Espanha, foi considerado como estudo de caso para avaliar o possível desenvolvimento da exploração de gás de folhelho na Europa.

Inicialmente, foi realizada um inquérito para avaliar a aceitação pública na província de Burgos e na Espanha como um todo. Os resultados demonstraram que o público em geral declara desconhecimento deste recurso e grande ambiguidade nas suas opiniões. Foi revelada uma forte oposição pública à exploração de gás de folhelho, particularmente em áreas próximas a possíveis zonas de exploração.

Seguindo-se a esta etapa, uma avaliação do ciclo de vida (ACV) da extração, produção e distribuição do gás de folhelho foi realizada com o software Simapro 8.4.0.0. Os resultados da ACV demonstraram que a perfuração, a fraturação hidráulica (ou fraturamento hidráulico), a produção, o transporte até a central de processamento (ou *gathering)* e o processamento são as fases mais críticas na produção de gás de folhelho, durante a pré-produção. Uma comparação com estudos similares falhou em encontrar um consenso em diferentes categorias de impacto, com exceção do potencial de aquecimento global e depleção abiótica de combustíveis fósseis.

Este trabalho recomenda que mais pesquisas sobre o gás de folhelho sejam desenvolvidas, já que permanecem várias lacunas na literatura, tais como o potencial de recuperação real das bacias, os seus impactos sociais e os custos do ciclo de vida. Por outro lado, a inovação nas tecnologias de extração e a possibilidade de capturar carbono em poços depletados têm o potencial de mudar dramaticamente o desempenho ambiental do gás de folhelho no futuro. Portanto, ainda que a exploração comercial de gás de folhelho seja improvável no curto prazo, este continua a ser um importante recurso energético que pode ser considerado como uma opção para o *mix* energético europeu.

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Acknowledgments

Essa pesquisa envolveu muitos momentos de incerteza que solicitaram muita paciência e tempo dos meus orientadores. Por isso, meu agradecimento aos professores António Fiúza, Anthony Danko e Belmira Neto. À professora Belmira, em particular, agradeço a disponibilidade em embarcar com o trabalho já avançado e por todo o comprometimento com o estudo. Sem dúvida, essa contribuição especialíssima foi decisiva para a conclusão da pesquisa.

Pelos comentários enriquecedores, e muitas vezes desafiadores, agradeço especialmente a todos os revisores anónimos que contribuíram com os artigos submetidos. Também agradeço aos membros do júri de avaliação dessa tese, que gentilmente cederam seu tempo e disponibilidade para considerar esse trabalho.

Aos meus colegas da FEUP, Isabella, Joab, João e Raquel que tornaram os dias menos solitários e mais divertidos. Especialmente ao João, agradeço as muitas horas de debate e discussões académicas.

Dedico um agradecimento especial para o Gabriel Navarro, que com muita paciência ouviu muitas e muitas dúvidas sobre engenharia de poços. Sem essa ajuda preciosa e generosa muitas partes deste trabalho teriam sido muito mais penosas.

Ao André pela paciência e incentivo durante a realização desse trabalho. Obrigada por me tirar da FEUP quando necessário, por me obrigar a parar de trabalhar e por toda a ajuda e suporte. Seu otimismo fez toda a diferença!

Claro que uma tese também não se faz sem os amigos, que ajudam nos momentos de lazer e descontração, tão caros nesta fase. Por isso, estendo meus agradecimentos aos amigos do Porto (especialmente representados pela Laurem em pelo Guilherme) que me permitiram que essa cidade fosse minha casa. E claro, aos do Rio de Janeiro que sempre fizeram sentir que tenho uma casa.

Sem as presenças dos meus pais e do meu irmão a motivação e o incentivo para crescer, fazendo sempre mais e melhor, nunca teriam existido. Muito obrigada por serem meu porto seguro e me deixarem saber todos os dias como sou amada.

Agradeço a todos os meus colegas investigadores com quem tive o prazer de conversar presencialmente ou virtualmente pelas múltiplas contribuições e trocas de experiências. A gentil contribuição dessas pessoas muitas vezes tornou o caminho mais agradável.

Por fim, agradeço ao financiamento da Comissão Europeia, através do programa Erasmus Mundus no âmbito do projeto IBRASIL (*Inclusive and Innovative Brazil*) pelo suporte financeiro sem o qual não teria sido possível realizar este trabalho. Ainda agradeço o suporte da Reitoria da Universidade do Porto pelo trabalho de apoio e intermediação com as demais instituições vinculadas ao projeto.

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“(…)
Ithaka gave you the marvelous journey.
Without her you wouldn't have set out.
She has nothing left to give you now.

And if you find her poor, Ithaka won’t have fooled you.
Wise as you will have become, so full of experience,
you’ll have understood by then what these Ithakas mean.”

Ithaka, C. P. Cavafy

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Acronyms

ADP	Abiotic depletion potential
ADP-F	Abiotic depletion of fossil fuels potential
AMD	Acid mine drainage
AP	Acidification potential
CCGT	Combined cycle gas turbine
CMB	Coal bed methane
CV	Coefficient of variation
CWT	Centralized waste treatment
EIA	United States Energy Information Administration
EP	Eutrophication potential
EPA	United States Environmental Protection Agency
EU	European Union
EUR	Estimated Ultimate Recovery
FAETP	Freshwater aquatic ecotoxicity potential
GHG	Greenhouse gas
GWP	Global warming potential
HF	Hydraulic fracturing
HH	Henry Hub
HTP	Human toxicity
LCA	Life cycle assessment
LHV	Lower heating value
LNG	Liquified natural gas
MAETP	Marine aquatic ecotoxicity potential
MCS	Monte Carlo simulation
NBP	British National Balancing Point
NG	Natural gas
NGL	Natural gas liquids
NGP	Natural gas price
NORM	Naturally occurring radioactive material
ODP	Ozone layer depletion potential
OECD	Organization for Economic Co-operation and Development
PAH	Polycyclic Aromatic Hydrocarbons
PM_x	Particulate matter
POP	Photochemical oxidation potential
POTW	Public-owned treatment works
REC	Reduced emission completions
SD	Standard deviation
TETP	Terrestrial ecotoxicity potential

UK	United Kingdom
US	United States
USA	United States of America
VOC	Volatile Organic Carbon
WTI	Western Texas Intermediate

1. Introduction and background

Natural gas (NG) is a non-renewable energy source that is used for heat, fuel and electricity in many countries and it is considered a reliable, efficient and a clean burning fuel. NG plays an important role on the worldwide energy supply, accounting for 21% of global primary energy demand and 26.9% of primary energy demand in countries of the Organization for Economic Co-operation and Development (OECD) (IEA, 2017).

NG has maintained a share of about 30% on energy consumption in the EU-28 in recent years (Eurostat, 2016c). Although primary energy consumption in Europe has decreased by 4% between 1990 and 2014, NG consumption (including manufactured gases) increased by 17% and the quantity of imported natural gas nearly doubled over this period (Eurostat, 2016c). Final energy consumption of NG is largely divided over different sectors (Figure 1.1).

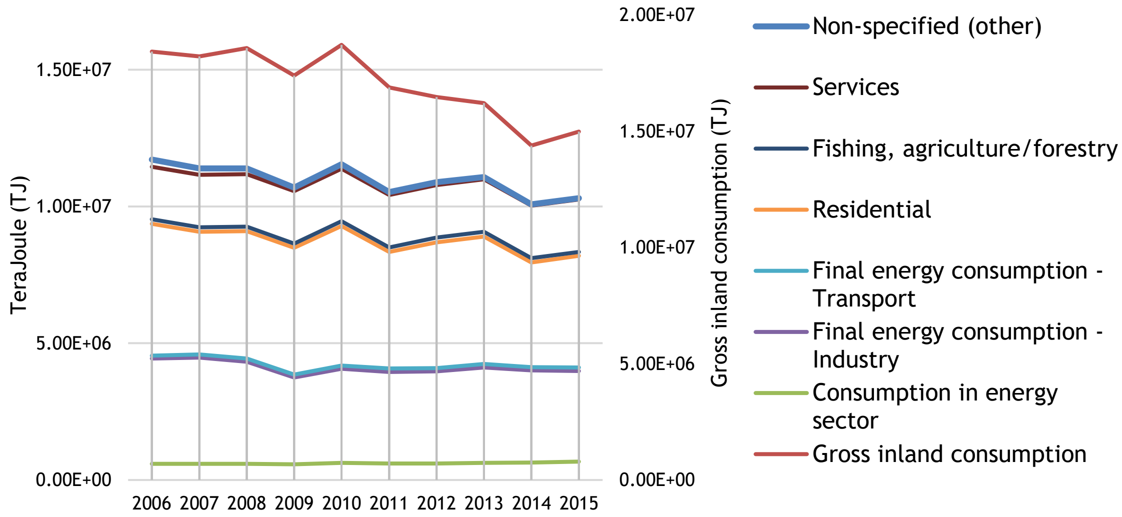

Figure 1.1: Final energy consumption of natural gas by sector. Source: Eurostat (2017).

The European Union (EU) has committed to decarbonize its energy mix and reduce 40% of its greenhouse gas (GHG) emissions in the 2030 Climate & Energy Framework (EC, 2017). NG is expected to maintain an important share in the fuel mix up to 2030 and beyond and is considered as a fuel bridging the current fossil-based energy matrix to a decarbonized energy system. However, Europe faces a strong dependency of foreign suppliers as currently more than two thirds of NG imports come from either Russia or Norway (Eurostat, 2016a, b), Figure 1.2, leading to vulnerabilities associated both to market and geopolitical issues.

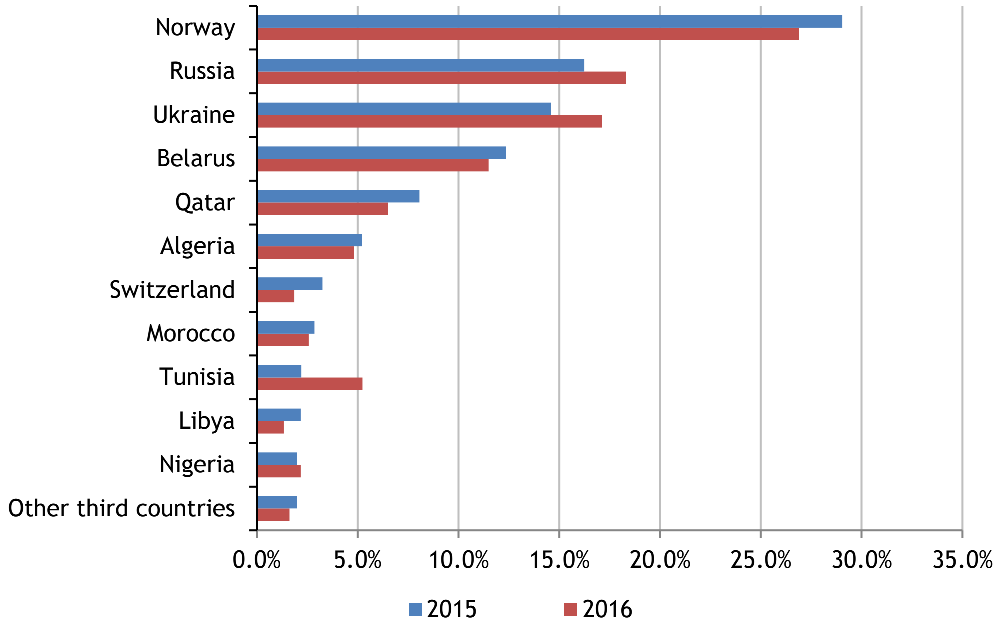

Figure 1.2: Percentage of extra-EU imports (entries) of natural gas by country of origin. Source: Eurostat (2017).

Therefore, EU policies are trending towards a greater flexibility in NG markets to reduce this exposure and the development of shale gas reserves could be one of the possible alternatives to contribute in this process. As a result, the debate of shale gas as an energy security issue has been increasing in recent years (Erbach, 2014; Johnson and Boersma, 2013a). In addition, in terms of safety, shale gas is perceived as an alternative in energy's portfolio driven by "high impact-low frequency" since the occurrence of major events in the energy industry, such as the spillage from the "Deepwater Horizon" platform in 2010 and the nuclear accident in Fukushima, Japan (2011).

The potential for unconventional gas production in Europe has been reported to be equivalent to 238 billion cubic meters of wet shale gas in Eastern Europe and 7,730 billion cubic meters of wet shale gas in Western Europe (EIA, 2015b), Figure 1.3. However, its exploration and exploitation are highly controversial because of the high global warming potential of methane leakage, the high volumes of water consumed in hydraulic fracturing and other environmental impacts.

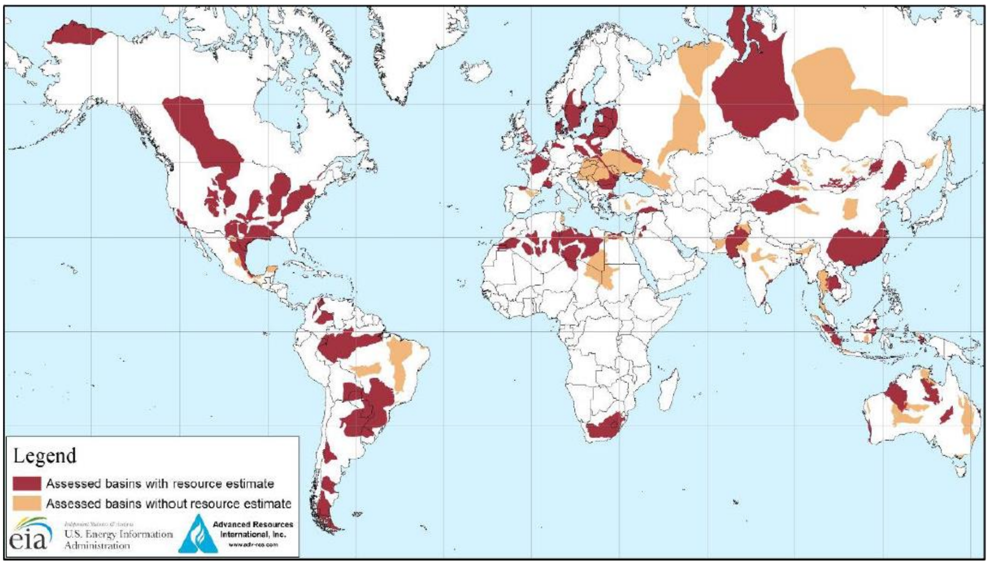

Figure 1.3: Map of basins with assessed shale oil and shale gas formations. Source: EIA (2013).

In Europe, several countries have banned or imposed a moratorium over fracturing and include Bulgaria, Czech Republic, France, Denmark, Germany, Ireland, the Netherlands, Ireland, Romania, Scotland and Switzerland (Brooks, 2015; Erbach, 2014; Johnson and Boersma, 2013a; KTWS, 2015). Some states and counties in Canada and in the United States of America (USA) have also imposed moratorium or banned fracking.

The United Kingdom (UK) is, by far, the country where studies and exploration are more developed within Europe, accounting for a representative number of published articles on the theme outside the USA (Prpich et al., 2016a). Shale gas is supported by the British government as a strategic resource to ensure energy security in the country, which is a major net importer of natural fossil fuels, specifically oil and gas from Norway and Qatar (DEEC, 2015a, b). However, it is considered that shale gas testing is still in an early phase in the UK, since flow testing and horizontal shale drilling have not been performed (EIA, 2015b) and no commercial production has started.

Due to the relative immaturity of shale gas over the World, there is limited literature on its life cycle impacts, which is even smaller outside the USA. Despite the potential of shale gas resources in the Iberian Peninsula, no published articles focusing on environmental aspects of its exploration and exploitation (including an evaluation of policies for this development) from this region were found (Costa et al., 2017b).

In Portugal, the Lusitanian basin is reported as a possible area with shale gas (IEA, 2012a), Figure 1.4. Some efforts have been made to characterize the existence of shale gas in this area (Baptista, 2011; Barberes et al., 2014; Sousa, 2015), but none of them are conclusive in presenting estimates of the existing resources and all of the studies indicate the need to perform more prospects and research in this area. Furthermore, the global assessment of shale resources performed by EIA (2013, 2015b) have not evaluated this zone, national data reporting performed prospections are poor and local experts affirm that it is very unlikely to find reserves with considerable recoverable resources (LNEG, 2015).

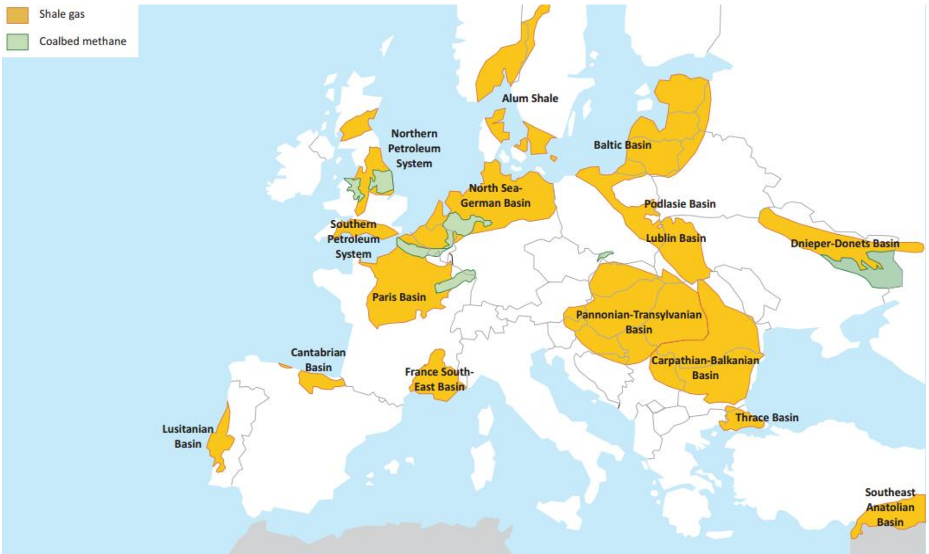

Figure 1.4: Shale gas potential in Europe. Source: IEA (2012a).

In Spain, the unproven technically recoverable wet shale gas is estimated at 237.9 billion cubic meters and is divided into two basins: (i) the Basque-Cantabrian Basin, in northern Spain, with potential for wet shale gas and condensate and (ii) the Ebro (Solsona) Basin, located to the southeast of the Basque-Cantabrian Basin, with potential for shale gas and oil (EIA, 2015c). The potential of Basque-Cantabrian Basin for oil and gas production has largely been reported in the press and in the academic literature since the early 2000's (Uphoff et al., 2002).

The Spanish government called for the exploration and exploitation of hydrocarbons in the country as a strategy to ensure the energy security of the country and reduce its accentuated energy dependence (DSN, 2015). It is estimated that the exploitation and exploration of shale gas could make the country independent of gas imports by 2030, and a net gas exporter by 2050 (Deloitte, 2014).

In Spain, as of June 2017, there were four active unconventional gas investigation permits under the responsibility of the national administration (MINETAD, 2017). In the Cantabria province, the Bigüenzo investigation permit included the Cadíalso 2, El Coto 2 and Sestero 1 projects (MINETAD, 2017). In the Burgos province, the Angosto 1 and Urraca investigation permits are represented by the Angosto A, Urraca 1, Urraca 2 and Urraca 3 projects (MINETAD, 2017). In Burgos, the Sedano investigation permit was also issued and extended in January 2016 until 2017, but the company waived its rights to the area in August 2016 (BOCYL, 2016; Planelles, 2016).

1.1. Brief history of shale gas and its exploration

Shale gas, shale oil, tight gas and coal bed methane are some examples of unconventional oil and gas resources. Unconventional resources are named this way due to some of its specific characteristics, such as porosity, permeability, fluid trapping mechanism, among others, including characteristics of the reservoir or rock formation which differ from the sandstone and carbonate reservoirs considered conventional (Broomfield, 2012), see Figure 1.5.

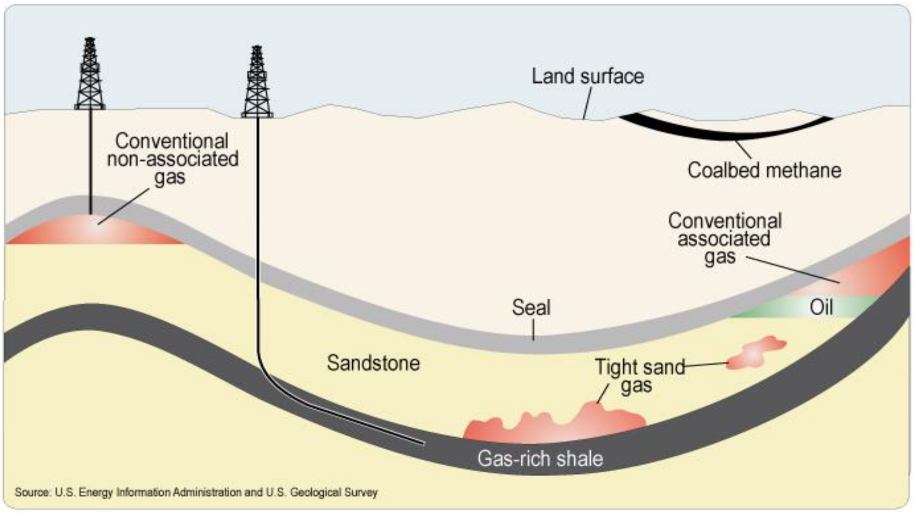

Figure 1.5: Geology of natural gas resources. Source: EIA (2011a).

It is worth mentioning that the concept of unconventional resources may change due to existing technologies and resource availability over the time. Although the distinction between 'conventional' and 'unconventional' fossil fuel extraction is somewhat arbitrary, it became particularly relevant in terms of legal framing in the European Commission Recommendation 2014/70/EU on hydrocarbons exploration and production using high volume hydraulic fracturing (EU, 2014a).

Shale is a fine grained sedimentary rock formed from the compaction of silt and clay-size mineral particles. Shale gas can be found in shale formations as gas sorbed onto kerogen and clay-particle surfaces, free gas in fractures and pores or dissolved in kerogen and bitumen and its systems can be classified as continuous-type biogenic (predominant), thermogenic, or combined biogenic-thermogenic (Curtis, 2002). It is typically a dry gas, but some formations produce wet gas, primarily composed of approximately 90% methane (GWPC, 2009).

The precise beginning of shale gas extraction technology is controversial. The first record on shale gas exploration comes from 1857, when Preston Barmore caused a rock fracture and a gas release by lowering gunpowder into a well in Canadaway Creek (NY) and dropped a red-hot iron down a tube (Morton, 2013). However, Montgomery and Michael (2010) reports that fracturing started in the 1860s when liquid nitroglycerin was used to stimulate shallow, hard rock wells in Pennsylvania, New York, Kentucky and West Virginia.

In addition to this controversy, Gandossi (2013) and the EPA (2004) report that the first shale gas experiment were done in 1947 on a gas well operated by Pan American Petroleum Corporation in the Hugoton field, the first industrial use in 1949 and the first large volume hydraulic fracturing in 1968. It is also reported in the literature that Halliburton was, in 1949, the company that conducted the first two commercial fracturing treatments in Stephens County (Oklahoma) and Archer County (Texas) (Montgomery and Michael, 2010).

More recently, NG gross withdrawals from shale formations were first monitored by the Unites States Energy Information Agency (EIA) in January 2007, when it corresponded to 8.72% of the total production (EIA, 2016c). Shale gas extraction also achieved the biggest growth in comparison to other gross withdrawals, since NG exploration series started to be disaggregated in 1993. As an example of the rapid expansion of shale gas industry in the USA, in the late 1990s, 40 drilling rigs (6% of total active rigs in the country) were capable of onshore horizontal drilling and this number grew to 519 rigs (28% of total active rigs in the USA) by May 2008 (GWPC, 2009).

1.2. Overview of shale gas exploration

Extraction of shale gas from these low permeability formations requires stimulation treatments, such as hydraulic fracturing and other types of well stimulation treatments, e.g. acid stimulation and acid fracturing. These treatments are being used extensively to increase oil and gas production and extract resources that would otherwise be inaccessible (Clark et al., 2013; King, 2012 ; Long et al., 2015a) and commonly referred to as unconventional oil and gas development. These treatments requires a wide variety of chemical additives (King, 2012; Stringfellow et al., 2014 ; Elsner and Hoelzer, 2016), which can have the potential to cause impacts on the environment and human health.

The word fracking (which is sometimes spelled as "fracing or frac'ing") was coined by the industry and refers to a specific stage in oil and gas development. However, due to the increased publicity around the domestic oil and gas boom, this terminology has often become synonymous with all aspects associated with the development of shale gas, including the construction of well pads, and all the related activity needed to support the industry, like pipeline construction and truck traffic.

The development of a shale gas play differs significantly from the development of a conventional feature, which is related to the differences in the reservoirs. In a conventional play, it is possible to exploit oil or gas from a relatively big area, requiring a small number of wells, while in shale plays wells are often drilled deeper and a bigger number of wells is required to assure the economic viability of the exploration field (CIWEM, 2016).

Typically, the shale gas development process encompasses the following stages: (i) mineral leasing, (ii) permits, (iii) road and pad construction, (iv) drilling and completion, (v) hydraulic fracturing, (vi) production, (vii) workovers and (viii) plugging and abandonment/reclamation (Spellman, 2012). This thesis considers the stages reported by the European Commission (Broomfield, 2012; Corden et al., 2016), which can be summarized as follows:

- Site identification and preparation: clearing and levelling an area and preparation of the surface to support movement of heavy equipment. Includes design and construction of access routes.
- Well design, drilling, casing, cementing, perforation: consists in the well drilling, positioning and cementing casing and tubing.
- Technical hydraulic fracturing: phase in which water with proppant and chemicals is pumped into the well at high pressure.
- Well completion.

- Well Production: in this phase NG Gas is extracted and put into supply.
- Decommissioning/abandonment.

1.3. Motivation, relevance and objectives

Structural changes in the energy sector are driven by complex decision-making processes, which include political, historical, social, environmental, technological changes, concerns and/or innovations. A possible shale gas exploration in Europe faces different challenges than in the USA, starting from the differences in geology, regulatory environment, public acceptance and management of environmental impacts.

A great debate on the possibility of exploring shale gas exploration in Europe has been raised in Europe in recent years and failed to represent a full picture of its acceptance and environmental impacts. This thesis represents an effort to assess different aspects of shale gas development, aiming to provide a more comprehensive understanding of several aspects related to shale gas development.

In the beginning of this study, some of the existing gaps over this issue were changes in NG gas markets in recent years, as well as a full disclosure and discussion of the extent of scientific literature on shale gas focusing on its environmental impacts. In addition, acceptance of public and the environmental impacts over the life cycle of shale gas were also poorly related outside the USA and UK.

This thesis intended to increase knowledge over these issues considering as a case study the investigation permit Urraca 1, located in the province of Burgos, Spain, as a case study for the evaluation of public acceptance and for the application of the life cycle assessment methodology. The choice of the case study location was made considering that this was one of the permits in the most advanced stage in the Iberian Peninsula (in the beginning of this research, the environmental licensing of the play was under appraisal).

1.4. Scientific literature output and other academic achievements

The main outputs of this thesis are represented by one conference article and three articles in international journals with peer review. The full references for this material (in order of presentation in this thesis) are:

- Costa, D., Garaffa, R., Branco, D. C., Danko, A., Fiúza, A., 2017. Price volatility across the Atlantic: The US and the European natural gas markets, 2017. 14th International Conference on the European Energy Market (EEM), pp. 1-5.
- Costa, D., Jesus, J., Branco, D., Danko, A., Fiúza, A., 2017. Extensive review of shale gas environmental impacts from scientific literature (2010–2015). Environmental Science and Pollution Research, 1-16.
- Costa, D., Pereira, V., Góis, J., Danko, A., Fiúza, A., 2017. Understanding public perception of hydraulic fracturing: a case study in Spain. Journal of Environmental Management 204, 551-562.

- Costa, D., Neto, B., Danko, A., Fiúza, A., 2017. Life cycle assessment of a shale gas exploration and exploitation project in the province of Burgos, Spain, submitted for publication in a peer-review scientific journal.

Other outputs from this work that have contributed to the development of this thesis, yet not presented here were several participations in conferences, namely:

- Costa, D., Góis, J., Branco, D. C., Danko, A., Fiúza, A., 2017. Panorama da exploração de gás natural não convencional (shale gas) no mundo, 8º Congresso luso-moçambicano de engenharia, Maputo, Moçambique.
- Costa, D., Neto, B., Danko, A., Fiúza, A., 2017. Life cycle assessment of shale gas production: a case study in Spain, Encontro Ciência 2017. FCT (poster presentation), Lisbon.

In addition, during the PhD, attendance in several conferences and other scientific events were registered. The most noteworthy are:

- Oral communication was performed in "Aula aberta – recursos energéticos convencionais e não convencionais (petróleo e gas)", organized by GEM (Grupo de Engenharia de Minas), Porto, Portugal – 2015.
- Participation in the IV Forum do Ambiente, Porto, Portugal – 2015
- Participation in the I Doctoral Congress in Engineering, Porto, Portugal – 2015
- Participation in the 2nd International Conferece on Energy and Environment: bringing together Engineering and Economics
- Participation in the Seminar "Oil and gas, safety and environment", Fing project, Porto, Portugal, 2015
- Participation in the V Forum do Ambiente, Porto, Portugal – 2016

In addition, different disciplines and courses were attended in an extracurricular basis at the Faculty of Engineering of the University of Porto (FEUP) and Faculty of Economics of the University of Porto (FEP). External courses were also attended, namely:

- Fracking: impacto sobre el medio ambiente, la economía y la sociedad de la fractura hidráulica, University of Burgos, 2017.
- Attendance in the courses "Life cycle assessment of bioenergy techonologies and energy systems" and "Life cycle assessment modelling of solid waste systems – application of the EASETECH Model" by the Techicnal University of Denmark, 2016.
- Metodología para el analisis de ciclo de vida – herramienta de software Simapro (80 hours) – Instituto Superior del Medio Ambiente, Madrid, Spain, 2015.
- Simapro user certificate program, EarthShift, 2015.

1.5. Thesis Outline

The thesis outline is based on the Venn diagram of sustainability. Therefore, it aims to address economic, social and environmental aspects of shale gas exploration and exploitation in Europe. This thesis is further divided into six chapters.

Following the current introduction, Chapter 2 corresponds to a conference paper published and presented in 2017. Chapters 3 to 5 refer to scientific articles which are either already published (Chapters 3 and 4) or submitted (Chapter 5).

The second chapter introduces shale gas impacts in the USA natural gas market and in the European market from 2003 to 2014. Through the evaluation of the price volatility over these years using data from Thomson Reuters DataStream, the main aspects influencing natural gas markets are discussed and reviewed. This chapter aims to contextualize the relevance shale gas has achieved in energy markets and why perspectives for a possible European were raised in recent years.

The third chapter reflects the state of the art of shale gas impacts in the world and the degree of consensus over different environmental compartments. In this chapter, the existing literature on shale gas from 2010 to 2015 is presented and is categorized and discussed into six impact categories.

The fourth chapter presents the first evaluation of public perception of hydraulic fracturing in Spain. Inhabitants of Spain and of Burgos province were considered in a survey, which revealed a strong rejection and unawareness of shale gas.

The fifth chapter is the core chapter of this research and makes use of the methodology of Life Cycle Assessment to evaluate the environmental impacts of shale gas investigation permit Urraca 1. Results were obtained for the characterization step and the CML-IA Baseline version 3.02 (CML-IE, 2016) was used to assess environmental impact categories. A sensitivity analysis as well as an uncertainty analysis using Monte Carlo Simulation (MCS) were also carried out.

Environmental impacts are assessed for the pre-production and production phases of shale gas exploitation and exploration. Pre-production considers the following stages: (i) site identification and preparation, (ii) well design drilling, casing, and cementing, (iii) hydraulic fracturing and (iv) well completion. The production phase the stages consist of (i) natural gas production, (ii) gathering, (iii) processing, (iv) transmission and distribution of gas until the final consumer, in production.

Finally, the sixth and final chapter of this research sums up the main recommendations and conclusions that can be derived from this work. In this chapter, the main perspectives for future work are laid out as well as suggestions for future research.

The thesis also contains three appendices. Each of them represents the supplementary material for the articles presented in Chapter 3, 4 and 5, respectively.

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2. Price volatility across the Atlantic: the US and the European Natural Gas Markets

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Abstract

Price volatility in the natural gas markets of the United States of America and the European Union have been the subject of several studies in recent years as these markets experienced important changes. The purpose of this study is to address and discuss market factors that have influenced price behavior. For this, the annualized monthly volatility for the "Henry Hub" (US Market) and the "London Natural Gas Index" (European Market) were calculated based on daily natural gas spot prices, from 2003 to 2014. The results show the different price behaviors and allow the comparison of these two markets.

Index Terms — international trade, natural gas industry, stock markets

2.1. **Introduction**

Natural gas (NG) is considered the fuel for the low-carbon transition and plays an important role on the global energy supply: it accounted for around 21.2% of the world's primary energy demand in 2014 (IEA, 2016). NG markets went through important changes in recent years due to the emergence of renewables, unconventional resources, and the increase of global liquefied natural gas (LNG) trade.

In recent years, some key points could be identified as determinants of natural gas prices (NGP) levels in the EU and US markets namely: (i) supply and demand balance, (ii) substitute fuels and renewables, (iii) LNG trade, (iv) NG transport infrastructure, (v) environmental policies and market aspects, (vi) extreme events, and (vii) shale gas development.

This paper examines the annualized historical NGP volatility of the European Union (EU), the EU-28, and the United States of America (US) based on recorded values of NGP trough time. Volatility is one of the most important factors affecting derivative products prices. Here this index is used as an initial step to evaluate and explain the main factors affecting NGP in these markets from 2003 to 2014.

In addition to this introduction, this article is divided into five sections. Section II introduces the background for this research. Section III presents the methodology applied and it is followed by its results, which are presented and discussed in Section IV. Finally, Section V presents concluding remarks.

2.2. **Background**

Despite the large internationalization of NG, there is not a single global benchmark for NGP. Price differentials in the markets over the World have narrowed since mid-2013, but still reflect their own demand-supply balances and pricing mechanisms, arbitrage options, cost of transport and local market aspects (IEA, 2014).

A main challenge in the NG markets is to establish price mechanisms that are both acceptable to consumers and to assure new investments in gas supply (IEA, 2014). International NG market prices are increasingly integrated and LNG may be a major reason for this, since it allows for the development of international arbitrage (Barnes and Bosworth, 2015; Brown and Yücel, 2009).

Today, the number of aspects that influence the NG prices has grown and are less predictable. Key points identified as determinant to price levels in the EU and in the USA markets are covered and discussed throughout the rest of this section.

2.2.1. Supply and demand balance

NG demand is increased by the level of economic activity and the demand for goods and services from the commercial and industrial sectors. In 2008, e.g., the economic crisis reduced the EU total demand of NG. Other factors, such as the migration of industrial plants to other regions and the low population growth contributed to stabilize the EU level of demand.

Moreover, the demand for NG and LNG in the Asian market is also a very important factor affecting prices in the EU. Also, countries with major shale gas reserves, like China, may increase domestic production and reduce demand for imports (Liu and Ma, 2017). The development of LNG demand, particularly from China, is pointed by Macmillan et al. (2013) as another key aspect affecting the supply in the EU.

Regarding the balance of supply and demand in the US, the exponential growth of domestic production due to the so called 'shale gas boom' has changed the market equilibrium. In November 2016, the US registered its first net outflow of one billion cubic feet (bcf) a day (Platts, 2016).

2.2.2. Substitute fuels and renewables

Substitutive fuels for NG for power generation are mainly coal and oil (Macmillan et al., 2013). When compared with these fuels, NG has the disadvantages of being harder to transport and store due to its low density (requiring liquefaction). However, NG is a cleaner and more reliable fuel. These characteristics, among others, historically led to the displacement of coal and oil products in residential and commercial sectors.

Limitations of coal and combined cycle gas turbine (CCGT) technologies, such as capacity factors and efficiency, are important aspects in the competition between coal and NG for electricity generation (Macmillan et al., 2013). This competition is increased due to coal prices in the global markets (IEA, 2016). In addition, more strict carbon dioxide emission policies and prices may also drive investments and competition between both fuels.

In recent years, renewables generation capacity is increasing significantly in the US and in the EU, as well as its share in primary energy production in both markets (EIA, 2017; Eurostat, 2014, 2016d). The intermittency of renewables is still a challenge to keep the grid's balance. However, the IEA (2016) points out that renewables can potentially surpass NG for power generation by 2040. Besides power generation, renewables still have a small share in the transportation and heating sectors. Its increase has the potential to reduce NG consumption as its participation in these applications continues to increase.

Meanwhile, the potential of LNG as a fuel for large vehicle fleets and ships is being investigated and can lead to increases in demand (Simmer et al., 2015). As of May 2015, there were 46 LNG terminals in the EU and 70 refueling stations for trucks (GIE, 2015). Despite the higher upfront costs for the vehicles and the refueling infrastructure expansion, the logistic for the growth of NG in road transportation, including buses and trucks, seems to be favorable (IEA, 2014).

2.2.3. LNG trade

LNG represents a great revolution for the integration of NG markets. The growing supply of LNG and its intrinsic technology flexibility, that allows its transportation to the highest bidder, are increasing the security of gas supply. Today, LNG exports from the US may increase global energy security, and, in the case of the EU, it may also reduce market vulnerabilities caused by unexpected disruption (Medlock et al., 2014).

LNG supply has influenced the spread of hub pricing in the EU (Macmillan et al., 2013). However, its demand as an alternative source of NG depends on the NG domestic production and pipeline imports Maxwell and Zhu (2011). Moreover, LNG prices also depend on Asian NG production. The entry of LNG suppliers in NG markets impact on NGP, once importers' production facilities are not restricted to a specific upstream producer, as occurs when NG is imported by pipeline (Dorigoni et al., 2010).

2.2.4. NG transport costs

Competitiveness of NG also depends on specific aspects related to its supply chain. NG transport operations and infrastructure are capital intensive and require upfront costs for facilities construction, either for long distance pipelines or liquefaction and re-gasification facilities. For instance, NG exports from the US will still keep a long-term basis (20 years or more) to obtain financing for the facilities investments (Ratner et al., 2015).

According to Barnes and Bosworth (2015), LNG trade has increased the opportunity for price arbitrage by reducing the associated transport costs. LNG chain costs have significantly decreased over time due to technological innovations (Dorigoni et al., 2010). Increasing the size of tankers and receiving terminals may generate economies of scale to firms. On the other hand, this increase may create barriers to entry, since investors with great economic capacity could enter the market (Ritz, 2014).

2.2.5. Environmental policies and market aspects

In terms of environmental policies, many researchers point out that NG emits less greenhouse gases (GHG) in comparison to coal over its lifecycle, when used as a fuel for the power sector (Fulton et al., 2011). New climate agreements, which create more restrictive rules, may induce demand of NG over coal for power generation.

In terms of market aspects, Ratner et al. (2015) state that US exports could pressure other countries to delink their NG exports price from oil, reducing costs and the exposure to oil prices. However, at this moment, declines in global oil prices have reduced the oil-indexed versus gas-indexed price differential. Increased opportunities for price arbitrage may also become a factor affecting NGP.

2.2.6. Extreme events

Extreme events may cause important shifts in energy markets. For example, the Fukushima Daiichi event in 2011, led Japan to close all of its nuclear power plants, causing major changes in its power generation mix, which deeply affected NG imports. This event transformed Japan in the largest LNG market in the world – currently it accounts for more than 35% of the global imports (BP, 2014; IGU, 2014). Due to public opposition, it is unlikely that nuclear power production will return to the same levels existing before the accident (McCurry, 2014).

2.2.7. Shale gas development

Shale gas in the EU is considered by many as an energy security issue, since shale gas reserves could significantly reduce NG import dependency (DSN, 2015; Erbach, 2014; Johnson and Boersma, 2013a). However, only a few exploration wells have been drilled in EU so far, making the technically recoverable estimates still unproved and subject to revision (EIA, 2013; Erbach, 2014).

In addition to technology advances, different economic parameters help to understand the growth of shale gas production in the US. One of the main aspects is the presence of a liberalized market as well as the previous existence of important NG facilities (such as pipelines), which reduced the need for upfront investment.

It is unlikely that a shale boom will reach the EU markets in the short or middle term due to environmental and energy policies in addition to the associated technical challenges (Costa et al., 2017b). So far, several European countries (as well as some regions in Canada and in the US) have banned or imposed a moratorium over fracturing (Johnson and Boersma, 2013a; KTWS, 2015) due to concerns over impacts to the environment and public health.

2.3. Methodology

The evaluation of historical volatility was based on daily spot NGP from 2003 to 2014, available on Thomson Reuters DataStream. Data were collected for the "Henry Hub" (HH), US Market, and the "London Natural Gas Index", European Market. These prices indexes were chosen as both can be considered representative and relevant indicators of price values in their respective markets.

In the next step, as described in Equation (2.1, a natural logarithm return was applied to evaluate the relative daily price changes. Then, the annualized monthly historical volatility of both series was calculated using the standard deviation of the daily logarithmic price returns as described in Equation (2.2). This approach is an efficient tool to assess the behavior of a time series and is widely applied in the literature (Moussa et al., 2017; Mu, 2007; Petrovich, 2014).

$$\Delta p_t = \ln({}^{p_t}/_{p_{t-1}}) \tag{2.1}$$

$$Volatility_t = \sqrt{\frac{\sum_{t=1}^{n_t}(\Delta p_t - \overline{\Delta p})^2}{n_{t-1}}}\sqrt{N} \tag{2.2}$$

Where P_t is the price in t; P_{t-1} is the price in t-1; n is the historical volatility period (the monthly trading days is assumed to be 21). N is the number of yearly trading days (assumed as 252).

Volatility indexes represent the expectation implicit in the price of existing options in the market. Volatility affects the derivative products prices and futures contracts, being an important measure of risk for investors – i.e., risk aversion investors are less prone to invest in a high price volatility environment.

High absolute volatilities indicate the tendency of relevant price changes. Volatility tends to have lower values whenever market presents a tendency.

2.4. **Results and Discussion**

The following section presents the results of the volatility analysis performed for the US and the EU markets. Results are therefore discussed based on events that have caused the main observed changes in the price time series and in the calculated volatility time series. US NG market.

2.4.1. US NG market

HH is a NG distribution hub located in Louisiana, US, which is an access point to the country main pipeline systems. In the US, gas prices are determined by gas-to-gas competition at trading hubs. The main drivers affecting US NGP from 2003 to 2014 were related to temperature changes, natural events (hurricanes) and the emergence of unconventional NG production. Figure 2.1 shows the calculated US NGP and the market volatility.

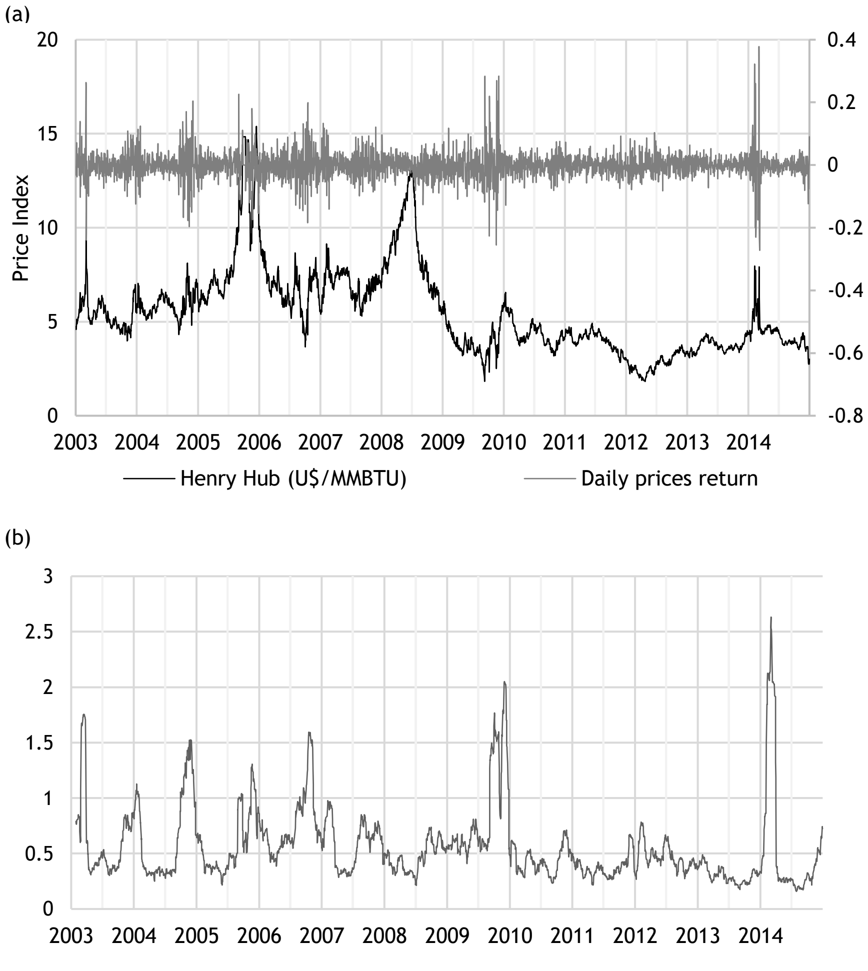

Figure 2.1: Henry Hub NGP and daily returns (a) and annualized monthly volatility (b).

From 2007[1] on, the exploration of unconventional gas reserves reduced HH spot prices, reflecting the market liberalization and the reduction of the reliance on offshore production

[1] Shale gas withdrawals were first reported in the national gross withdrawals in 2007 by the US Energy Information Administration [32].

(EIA, 2016b). The shale gas production growth has kept prices relatively low, though they increased temporarily in early 2014, because of higher demand from exceptionally cold weather.

NG wellhead prices in the US were experiencing ups and downs since 2001. A peak occurred in October 2005, when prices reached 10.33 US dollars per thousand cubic feet (tcf). In July 2008, the US NG wellhead price reached the maximum value since 1990 (10.79 US dollars per tcf). From July 2008 on, NGP have significantly decreased, due to the growth of shale gas gross withdrawals[2] (EIA, 2016b).

From 2009 on, HH spot prices decoupled from the Western Texas Intermediate oil price (WTI). Volatility in the NG market started to stabilize significantly from 2010 until 2014, with a slight increase in 2012 and an important peak in 2014. This fact can be attributed to the reduction in NG wellhead price caused by increases in shale gas supply (EIA, 2016b).

In March 2014, volatility reached the highest point in the historical series and the HH spot price reached 7.92 US dollars per tcf. In the beginning of that month, NGP volatility was influenced by seasonality, and intensified from September on because of a peak in NG inventories for the upcoming winter. In the following months, demand became uncertain and it depended on the unpredictable weather conditions (Alterman, 2012).

The US NG market can be defined as liquid and liberalized. Consequently, prices rely on supply and demand equilibrium. Despite these characteristics and the important role of speculation in this market, Alterman (2012) also showed that the occurrence of hurricanes[3] were an important factor to justify volatility in the US NGP.

In March 2014, a wave of cold weather and a reduction of stocks made storage levels 43.2% below March 2013 and 38.8% below the 5-year average, which lead to higher NGP (EIA, 2014). In a broader sense, price levels were significantly linked to offshore production disruptions, notably from 1997 to 2001 (Alterman, 2012). From 2014, price disruptions related to hurricane events became less sensitive but more severe.

2.4.2. European Natural Gas Market

NGP, daily returns and the annualized monthly volatility based on the London Natural Gas Index per therm (100,000 British thermal units or approximately 2.83 cubic meters) is shown in Figure 2.2. This series is used as a proxy to assess the British National Balancing Point (NBP)[4] price volatility.

[2] Since then, this production expanded and rose around 506% percent until December 2013 [32].

[3] The occurrence of different hurricanes (September 2002, September 2005, August 2007 and September 2008) reduced offshore production in the US, increasing NGP volatility.

[4] The Dutch Title Transfer Facility (TTF) and the NBP are the main NG trading hubs in the EU market.

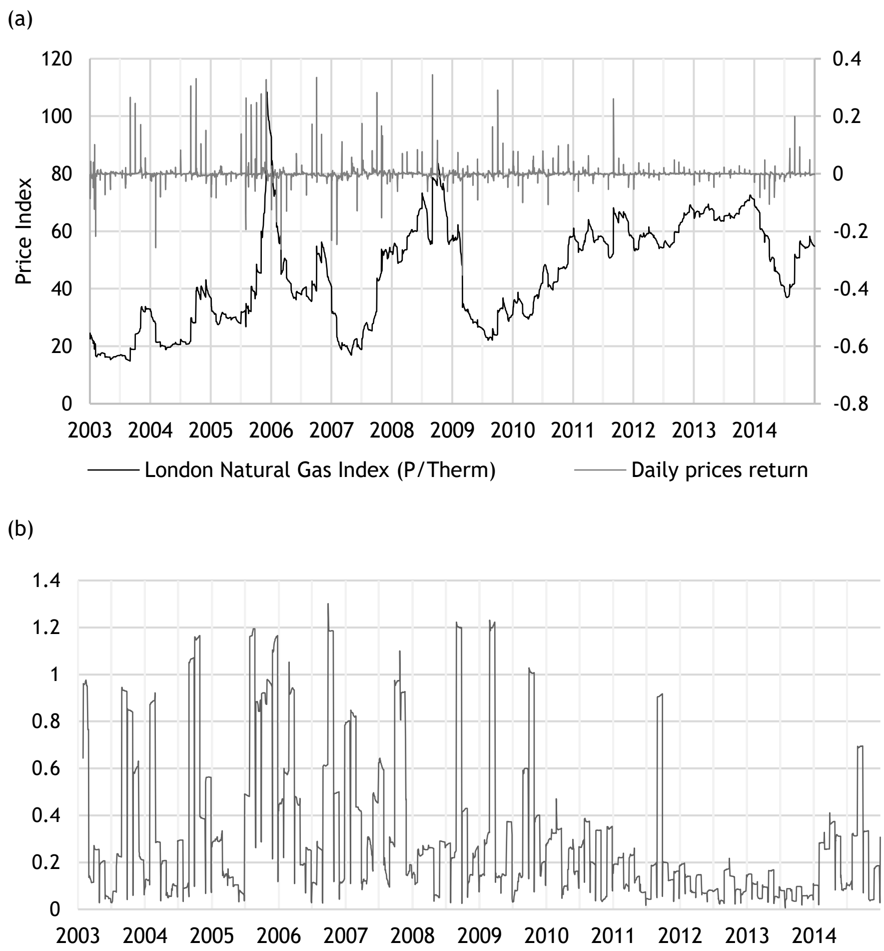

Figure 2.2: London Natural Gas Index NGP and daily returns (a) and annualized monthly volatility (b).

Regarding the EU market, there are three main drivers that influence NGP volatility, namely: (i) weather and seasonality, (ii) storage capacity, and (iii) import capacity. The results of the volatility analysis confirm that high volatility periods were observed between November 2005 and November 2011 due to several events related to these three factors. Price volatility is also related to the fact that the EU is highly dependent on energy imports. In 2012, the EU energy import dependency reached 53.4% in total fuels, and for NG the dependency reached 65.8% (EU, 2014b).

A period of great oscillation in NGP volatilities was observed between November 2005 and November 2010 in this market. Four events help to explain the increases in NGP during these years: (i) an early cold snap increased the demand, requiring an anticipated usage of NG stocks (November 2005); (ii) the conflict between Russia and Ukraine that led to temporary reductions in NG supply to some European consumers (January 2006); (iii) the production flexibility reduction caused by the low investments in new storage facilities, plus the decrease in NG supply caused by disruptions in production stations (between February and June 2006); and (iv) the unexpected warmer season that led the fall of NGP (between February and October 2007) (Alterman, 2012).

The volatility reduced in the period observed between December 2007 and May 2011, due to the following two events: (i) the increased Asian demand that led to a lower supply of LNG to Europe (during 2008); and (ii) the Russian gas supply interruption, caused by the political crisis between Russia and Ukraine, since the NG transits towards Western Europe through the Ukrainian territory (during 2009) (Alterman, 2012). In 2012, NGP in the EU were affected by the shortage of Russian NG, which can be attributed to political issues, excess Ukrainian withdrawals of Russian NG and the lack of stock capacity in Ukraine (Henderson and Heather, 2012).

Europe (EU-28) had relevant stock variations in the last ten years (Figure 2.3), which are strongly related to volatility peaks presented in Figure 2.2. Stocks variation is related to the seasonality of the demand, and acts as a buffer for volatility. The storage in the US differs from the EU market due to the geographical isolation of the country (Eurostat, 2015).

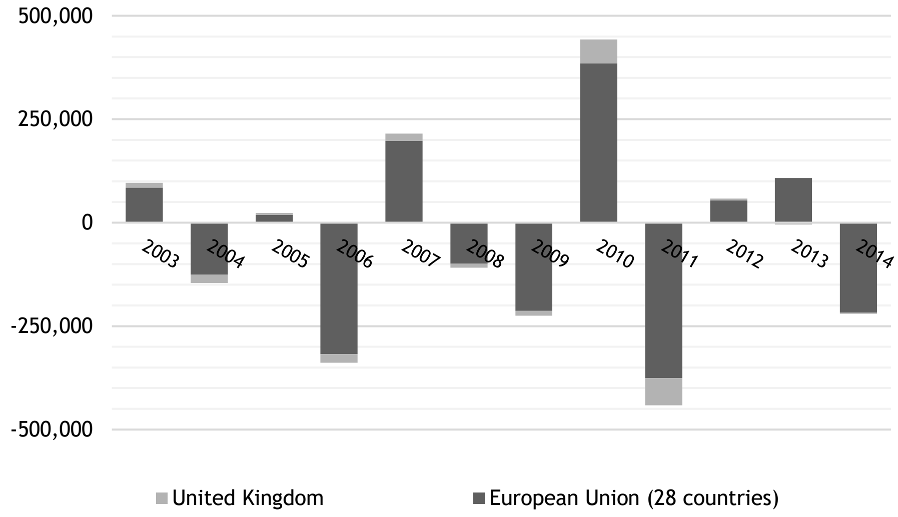

Figure 2.3: NG stock changes (TJ). Source: authors based on Eurostat (2015).

Differently from US markets, European markets have not experienced a growth of endogenous production of NG from unconventional resources. Changes in the European NG markets are likely to occur in the next years potentially as a result of a possible development of shale gas in the UK and the recent geopolitical changes in Europe.

2.5. Final Remarks

Results demonstrated that, from 2003 to 2014, the price of the US and EU markets became less volatile and NGP differential across markets have been reduced. In terms of price formation, NGP are increasingly detaching from oil prices and becoming more based on gas-on-gas competition.

The analysis explained volatility in NG markets and showed that periods of high price volatility occurred both in the US and in the EU markets mainly due to changes in ambient temperatures as well as due to extreme events, such as the Fukushima-Daiichi accident in Japan. Moreover, the development of trading hubs in Europe, geopolitical issues, the increase of the global LNG trade, the development of unconventional NG and the integration of renewable energy into the grid are all major challenges for these markets.

This paper does not address the effects of price volatility on demand, which is a limitation but is also out of the scope of this work. Future studies might also include autoregressive analysis to identify conditional volatility processes in these price series.

Acknowledgments

The authors acknowledge IBRASIL (Inclusive and Innovative Brazil project, an Erasmus Mundus Action 2 programme funded by European Commission) and CNPq (the Brazilian National Council of Scientific and Technologic Development).

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3. Extensive review of shale gas environmental impacts from scientific literature (2010-2015)

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Abstract

Extensive reviews and meta-analyses are essential to summarize emerging developments in a specific field and offering information on the current trends in the scientific literature. Shale gas exploration and exploitation has been extensively debated in literature, but a comprehensive review of recent studies on the environmental impacts has yet to be carried out. Therefore, the goal of this article is to systematically examine scientific articles published between 2010 to 2015 and identify recent advances and existing data gaps. The examined articles were classified into six main categories (water resources, atmospheric emissions, land use, induced seismicity, occupational and public health and safety, and other impacts). These categories are analyzed separately to identify specific challenges, possibly existing consensus and data gaps yet remained in the literature.

Keywords: shale gas, hydraulic fracturing, fracking, environmental impacts, bibliographic review, consensus

3.1. **Motivation and relevance**

Shale gas exploration and exploitation remains shrouded in controversy. From a policy point of view, there are two conflicting perspectives: while some view the shale gas revolution as a step back on the reduction on fossil fuel reliance, others claim that shale gas can be regarded as a transitional fuel, by substituting coal for electricity and heating. Furthermore, shale gas is also viewed as a way to decrease dependency on foreign sources of energy. However, doubts remain of the impact of shale gas exploration on climate change when its whole lifecycle is considered (Howarth et al., 2011a).

Controversy also arises from the point of view of its other environmental impacts and risks. While some find that the impacts and/or risks that shale gas exploration entails are unacceptably high and therefore should not be allowed under any circumstances, others believe that such impacts can be controlled and managed through a combination of reasonable and adequate regulation and risk assessments.

Regardless, it seems clear that initially observed environmental impacts were higher. a reflection of the infancy of a whole new industrial process, largely unregulated and unrefined at first. What remains uncertain, however, is whether recent developments and regulations (Cathles Iii et al., 2012; Howarth et al., 2012) were capable of sufficiently reducing or containing the negative impacts to acceptable levels. Therefore, the magnitude of both the environmental impacts and that of the novel procedures and regulations to reduce them are largely unknown.

To clarify these controversial aspects, a review of existing scientific literature is necessary. Although it may be considered that sufficient time has yet to pass for some environmental impacts to be noticeable, such reviews are important to identify existing consensus as well as identifying knowledge gaps, where research efforts should be focused. If accompanied by risk assessment and modeling, such analysis, even if preliminary in nature, can serve as guidance to policy makers in the short to medium term, while further research is performed to increase the validity of identified consensus.

Recently, some authors have examined the growth of shale gas scientific and technical literature (Li et al., 2015; Prpich et al., 2016b; Wang and Li, 2016). For example, Lee and Sohn (2014) evaluated the state of technological development of shale gas in China and the USA by comparing the evolution of the number of patents over time. In addition, a bibliometric review by Prpich et al. (2016b) focused on the environmental risk assessment for the requirements of United Kingdom regulators across the different production stages of shale gas exploration and exploitation while Li et al. (2015) performed a generic bibliometric analysis of the scientific literature. Nevertheless, a systematic analysis of the existing (or lack thereof) of consensus between different studies on shale gas environmental impacts as well as the impact of major mitigation strategies has yet to be made.

Considering the need to understand and identify what has been learned so far on the environmental impacts and risks, this article provides an extensive review of peer-reviewed publications in representative academic journals from 2010 to 2015 with the goal of examining the challenges and data gaps between research, current industry practices and impacts of shale gas exploration and exploitation.

3.2. **Methodology**

The objective was to initially use a generic search to perform the widest possible search and allow for the identification of articles that assess shale gas and hydraulic fracturing from diverse perspectives. Therefore, scientific papers were obtained using SCOPUS using a simple search based on the terms “shale gas” and “hydraulic fracturing", using the ‘or’ operator in article title, abstract or keywords for articles only and considering the ‘and’ operator for language equivalent to English. Articles missing key categories, such as the author’s name or location were excluded. Finally, a search of duplicates was conducted among the results obtained in each database.

3.2.1. Selection criteria, data collection and assessment

Articles were evaluated covering the more recent 5 years of academic research from 2010-2015. Extending this to an earlier timeframe was considered unnecessary since the so called ‘shale revolution’ in the USA began in approximately 2007, when it corresponded to 8.72% of the total production of natural gas (NG) in the country (EIA, 2015a). In addition, January 2007 was also the time when gross natural gas from shale formations were first reported by the U.S. Energy Information Administration (EIA). This assumption was further confirm by a simple search between 2005 and 2010 where no relevant environmental impact assessment studies were found and recent review studies (Prpich et al., 2016b).

Articles that discussed policies were only considered when they referred to environmental aspects and other impacts linked to shale gas. Similarly, discussions on energy security and shale gas extraction were excluded. Despite the fact that these other articles contribute to the discussion on shale gas development, they are considered outside the scope of this review, which focuses on the most relevant environmental impacts their management thus far.

In addition, studies focusing on the hydraulic fracturing process or stimulation technology, geology (such as fracture mapping, porosity modeling, among others), and wellbore integrity were not considered since these were also considered outside the scope of assessing environmental impacts.

Based on these criteria, the articles were classified as follows: (1) water resources, (2) atmospheric emissions, (3) land use, (4) induced seismicity, (5) occupational health and safety, (6) other impacts. The areas covered in each of these six criteria are listed in Table 3.1.

Table 3.1: Article classification criteria according to impact categories.

Impact category	Areas covered
Water resources	Groundwater and surface water contamination, depletion and water quality; wastewater treatment
Atmospheric emissions	Air releases and quality, climate change, greenhouse gas emissions (GHG) - including fugitive
Land use	Risk to biodiversity, noise impacts, increased traffic, waste management (including radionuclides)
Induced seismicity	Induced seismicity related to hydraulic fracturing and its practice
Occupational and public health and safety	Production accidents, spills, public health
Other impacts	Multiple impacts evaluation, socioeconomic impact, synergetic impacts

Articles related to occupational and public health and safety were grouped based on exposure pathways (water or air) since most studies focused on either exposure to contaminated groundwater (for the general public), produced water and spills (for workers), or continuous exposure to air contaminants. Few published works, if any, report a combined exposure risk to these different pathways.

For the sake of simplicity, not all articles are necessarily referenced, specifically if the content is not particularly relevant, novel or is limited in scope. After the articles were classified in one of the six impact categories, additional information for each article was also examined. These included the geographic location of the article's corresponding author and also ranking the data source.

The geographic location of the articles was examined since it may be considered as a proxy to identify which are the most active locations of shale gas research, irrespective of different stages of development and implementation. This geographic location was classified according to the location of the first author from each paper and mostly reflects institutional interest/commitment to shale gas research. This approach is not without its limitation: due to increasing multinational and multidisciplinary collaborative studies, some data obtained through this method may not be representative and thus this approach should be analyzed with care and seen as preliminary.

The geographic groups were then classified as follows: (1) USA, (2) Canada, (3) UK, (4) China, (5) Europe (including Russia but not the UK), and (6) Others, which included articles that did not belong to any of the other five groups.

Articles were also ranked according to the data source, as suggested in similar studies (Prpich et al., 2016b). This includes (1) primary data sources, (2) secondary data sources, and (3) theoretical studies. A description of each of the three ranking systems used are as follows:

- Primary data sources are those articles that collected, provided or evaluated direct measurements or field data. This provides new information on impacts caused by hydraulic fracturing from shale gas extraction. This includes laboratory experiments, modelling studies or even surveys.

- Secondary data research are those articles that offered reviews on shale gas production, but did not offer new data and only systematically discussed impacts caused by shale gas exploration and exploitation. Studies in this group provided critical reviews of the literature and have the potential to support policies and best practices for shale gas production.
- Finally, theoretical studies are those that adopted a mixed method approach, where a qualitative or quantitative evaluation of the topic was done with non-empirical data to support the assessment of impacts and risks. Both case studies and studies that evaluated or used raw data as a reference from third parties were classified here.

After the classification of all articles, a detailed analysis of the major environmental impact categories shall be presented in this study to assess existing consensus and major research data gaps divided in the following categories: water resources, atmospheric emissions (air quality and climate change), land use, induced seismicity and multiple environmental impact assessment (LCA and other studies).

3.3. **Results and discussion**

In total 3882 articles were identified based on the initial search parameters, of which 701 were identified as suitable for understanding environmental impacts. Out of these, 373 were not accessible or unavailable and were not included in this review. This left 328 articles that were included in the evaluation and were classified according to the six impacts defined in Section 5.3.2 for each year from 2010 to 2015 and the results of this classification is shown in Figure 3.1.

It is important to note that no articles were identified or obtained that fit the criteria prior to 2010, and therefore are not represented in the Figure 3.1. Reports on NG production from shale formations by the EIA (2015a) only began in 2007, which explains the lack of articles that fit the criteria for the search between 2005 to 2010.

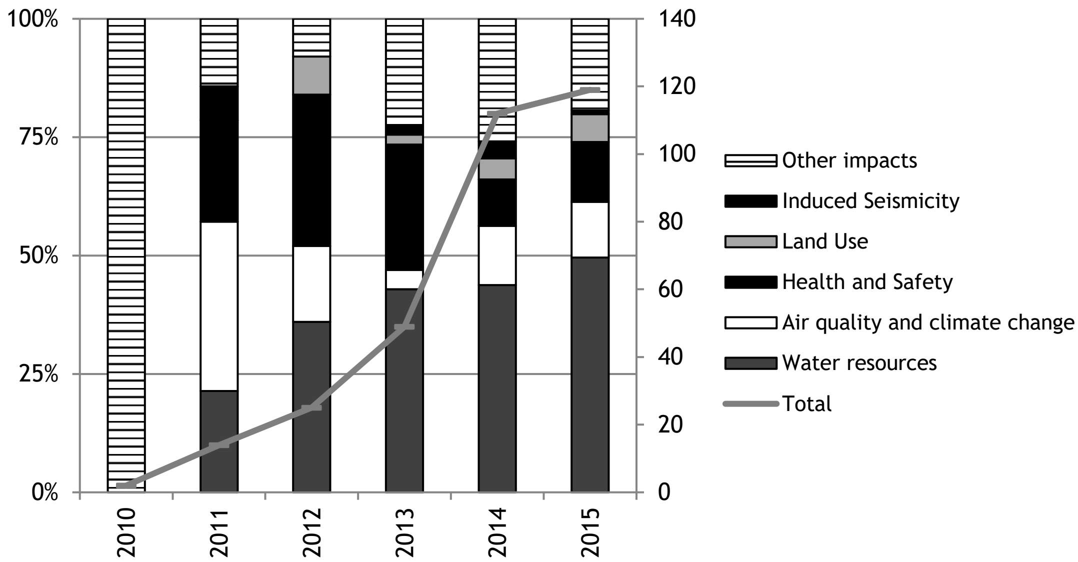

Figure 3.1: Evolution of included articles per impact category.

The growth of the number of articles during this time may reflect the production of NG in the USA, which grew an average of 43% between 2007 to 2011 and lead to a reduction of annual NG prices from 7.97 USD in 2008 to 2.66 USD in 2012 (EIA, 2015a). The combination of increased production and lower prices changed the North American energy market. In addition, the identification of technically recoverable shale gas reserves in other parts of the world lead to a debate on the viability of this technology to reduce the dependency on energy imports, particularly in Europe (EIA, 2013). Additionally, it may also represent a concomitant increase of public and scientific awareness of shale gas exploration and its potential impacts and risks.

An examination of Figure 3.1 further demonstrates a significant increase in number of shale gas articles between 2010 and 2015, from 2 in 2010 to 121 by 2015. Varying proportion were observed for four of the five topics during this timeframe, namely induced seismicity, land occupation, health and safety, and atmospheric emissions. Health and safety always showed the least percentage out of all six classifications and varied between 0% and 32% and there was a steady increase in the percentage of articles for water resources, from 0% in 2010 to 50% by 2015.

As the number of shale gas articles increased, so did the geographic coverage. As seen in Figure 3.2, only two regions were represented in 2010 (‘USA’ and ‘Others’). Afterwards, five regions were included by 2012, and all six were represented by 2013 and continued that way for 2014 and 2015. It should be noted that even though Argentina is currently one of the few countries commercially producing shale gas, no articles from this country were found.

Several regions saw significant increases in one year – from 2013 to 2014 – Canada, UK, Europe, and Others - and from 2014 to 2015 for China. Even though this is the case, the majority of shale gas articles from the studied timeframe was from the USA (around 79% of the articles), followed by Europe (6%) and the UK (5%). Cooperation among universities across countries is still low and accounted for only 39 articles, with approximately 77% of mixed nationalities involving the USA.

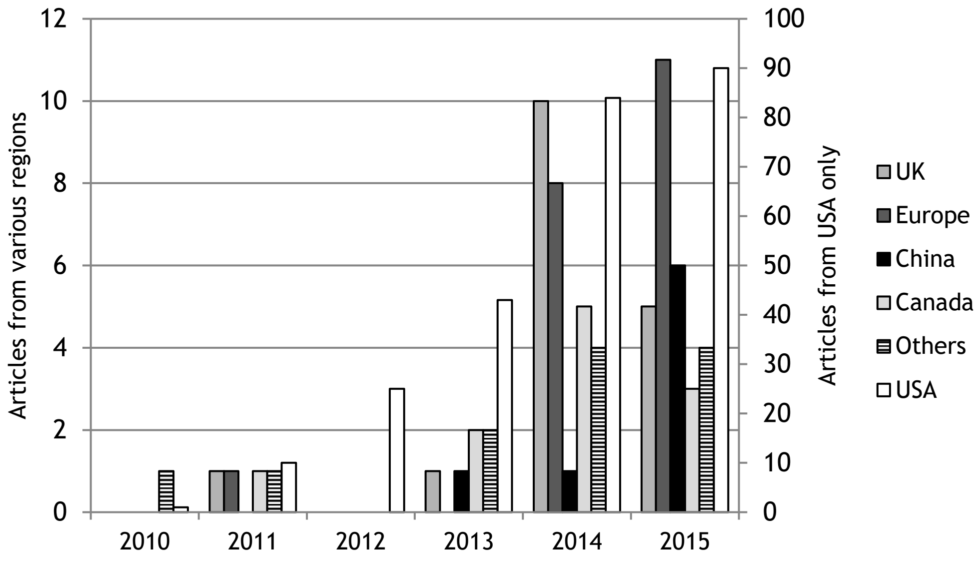

Figure 3.2: Geographic coverage of included articles – USA in secondary axis.

3.3.1. Water resources

This section discusses recent developments and current practices of water management in shale gas exploration and exploitation, including spills, water usage and treatment from the 141 included articles. Of these, primary data (Type 1) represented 33% in 2011 and a maximum of 81% in 2013, while secondary data (Type 2) peaked in 2011 at 67% but ranged between 7 and 22% in the remaining years. Finally, theoretical studies (Type 3) ranged between 10-44% of total number of papers in water resources category. Out of these 141 articles, only 17 were not from the USA with 7 from different European countries and 3 were from the UK and were published only in 2014 and 2015.

The hydraulic fracture water cycle can be described as having the following stages: 1) water acquisition, 2) chemical mixing, 3) well injection, 4) flowback and produced waters (wastewater) and 5) wastewater treatment and waste disposal (EPA, 2011b, 2015c). Water contamination issues associated with shale gas extraction are usually associated with the contamination of surface water, treatment and disposal of produced water as well as water management issues due to conflicting uses.

EPA (2010) reports water use of up to nearly 19 cubic meters per well, depending on its condition (depth, horizontal distance and geologic factors), the number of times the well is fractured and type of fracturing fluids used. Therefore, typical values vary significantly for each shale play (GWPC 2009). Discrepancies over the amount of water used in hydraulic fracturing are also found in different sources (Abdalla and Drohan 2010; Chang et al. 2014). From a lifecycle perspective, Clark (2013) demonstrated that water consumption per energy generated is different for each shale gas play evaluated. Nevertheless, it is always higher when compared to conventional gas produced in the same country.

Nearby water resources may come under pressure since hydraulic fracturing involves the pumping of large volumes of water into shale formations. This increased use in water resources may cause decreases in base flow to streams (Nicot and Scanlon, 2012), changes to the aquatic ecology (Gallegos et al., 2015) as well as conflicts with other industries that use this water, such as agriculture (Goodwin, 2014).

Therefore, the industry is examining ways to decrease their water requirements by reducing water intensity per well in shale gas explorations. However, increasing horizontal well length may lead to increasing water consumption per well (Nicot et al., 2014). It is important to note that net water use for shale gas exploration and exploitation was found to be within the range of other energy sources, namely coal (Goodwin, 2014; Nicot and Scanlon, 2012) and uranium mining (Nicot and Scanlon, 2012). Although, cumulative water consumption may result in extra pressure on water resources since demand rises but these impacts are regional (Jackson et al., 2015) and basin specific (Pacsi et al., 2014).

One alternative option of water for drillers is to use municipal or tap water, which do not require extensive pretreatment prior to use in shale gas operations. These water sources accounted for 29% of hydraulic fracturing water in parts of Pennsylvania (Abdalla and Drohan, 2010). Acid mine drainage (AMD) is another alternative water source for drillers in regions such as the Marcellus and Utica regions. This reduces freshwater demand but typically requires water treatment prior to its use for hydraulic fracturing (Abdalla and Drohan, 2010; Rodriguez and Soeder, 2015). Seawater and brine groundwater have also been successfully used in both onshore and offshore hydraulic fracturing (Rodriguez and Soeder, 2015). Both of these may be options for onshore projects in arid regions or in areas with water scarcity.

3.3.2. Shale gas wastewater – contaminants and sources

Wastewater derived from shale gas exploration and exploitation may be classified into three main types, which is based on different processes as well as different operational periods. The first type is drilling fluids. As the name suggests, it is wastewater resulting from the initial drilling of the well before any hydraulic fracturing or gas extraction can occur and it is normally used to cool and lubricate the drill bit and clean drilling cuttings (Lutz et al., 2013).

The second type is the flowback fluid. This represents the initial flow of wastewater immediately after hydraulic fracturing and it resembles the fracturing fluid the most and particularly contains organic compounds, even though it is a mixture of fracturing fluid and native existing fluids. It is estimated that 10 to 40% of the water injected into a well is returned to the surface as flowback water. Flowback fluid mostly occurs in the first 7 to 10 days but can be up to 4 weeks after hydraulic fracturing (Barbot et al., 2013; Haluszczak et al., 2013). It may represent 32.3% on average of the wastewater volume produced during the lifespan of a well (Lutz et al., 2013). Other names used to describe this wastewater type include: flowback brine and fracturing water flowback.

Finally, the third type is produced water. This comes from the recovery of naturally occurring fluid from the shale formation itself mixed with a small volume of fracturing fluid and flows through the entire lifespan of the gas well. Although it should be mentioned here that there is no standard definition of flowback fluid and produced water, they are often grouped together and the distinction between the two is difficult to make in many instances. Because of this, others authors have suggested the use of an additional term (transitional water) to distinguish between the two different phases (Bai et al., 2015).

The composition of flowback and produced water may vary significantly. Organic compounds that can be found in both flowback and produced water include surfactants (Thurman et al., 2014), low levels of volatile and semi volatile organic compounds (VOC and SVOC) (Akob et al., 2015; Lester et al., 2015b; Shih et al., 2015; Ziemkiewicz and Thomas He, 2015); low levels of Polycyclic Aromatic Hydrocarbons (PAHs) and other aromatics (Maguire-Boyle and Barron, 2014); high values of low molecular weight alkanes and alkenes and total organic carbon (TOC). An important aspect is the potential creation of halogenated and non-halogenated compounds as a consequence of the reactions between the fracking fluid and the rock matrix (Maguire-Boyle and Barron, 2014).

Naturally occurring radioactive materials (NORM) may also be found both in produced and flowback waters (Alley et al., 2011; Gregory et al., 2011). Although, a recent study mentioned that NORM concentrations may be higher in produced water (Shih et al., 2015). NORM found in these wastewaters may be dependent on the type of rock formation. Non-radioactive cations and anions (salts) also depend on rock formation, similar to NORM. However, in this case, other researchers mention that rock formation may not completely explain salt concentrations in early flowback fluids and concluded that unknown reactions between flowback and the source material lead to increasing cation concentrations (Barbot et al., 2013). Therefore, inorganics in early flowback waters may not be a result of mobilizing compounds that naturally occur within the rock matrix.

In contrast to that, cations and anions concentrations in late flowback and produced waters may be explained by simple dilution of the existing brine formations with the fracturing liquid rather than from the introduction of these compounds from the fracking fluid itself. This statement is based on the fact that the same conclusion was reached using independent samples in the Marcellus shale play from two different research groups and institutions within the same state (Pennsylvania) and with no author overlap (Barbot et al., 2013; Haluszczak et al., 2013). Although, it is still unclear whether these results apply only to the Marcellus shale gas plays or to other shale regions in the USA.

The above studies indicate that fracturing additives as well as the fracturing process have a small contribution to inorganics in these wastewaters. In fact, other researchers suggest that fracturing additives may only make a small contribution. not only to inorganic compounds, but also to organics and NORMs in flowback and produced waters (Ziemkiewicz and Thomas He, 2015). Although, it should be noted that organic compounds are more likely linked to fracking fluids in these cases (Akob et al., 2015; Orem et al., 2014)

Comparisons may be made between shale gas produced water to other sources of NG in order to provide context. Maguire-Boyle and Barron (2014) compared shale gas with coalbed methane (CBM) produced waters. Shale gas wastewater has a significantly higher TOC than CBM and slightly higher aliphatics but lower PAH and aromatics. As such, this may potentially mean that shale gas produced water is less toxic and more biodegradable in certain instances. Comparing with conventional gas, Pancras et al. (2015) reported higher lithium, potassium and boron values for shale gas produced water but lower copper and aluminum within the same gas region. Although, this similarity between conventional and shale gas produced water may only be limited to inorganic substances such as salts and heavy metals.

Contamination may not only be caused by the introduction and extraction of fracking fluids into the subsurface, it may also be a result of accidental spills or flaws in well construction. Recently, EPA published results of a systematic review of spills related to shale gas across 10 states in the USA from 2006 to 2011 (EPA, 2015d). From the 36,000 spills identified within the selected states, 33% could not be associated with hydraulic fracturing and only less than 1.3% (457 spills) was related to hydraulic fracturing.

Of that, flowback and produced water comprised 50% while 20% was from the fracturing fluid. In addition, almost half of the total number of spills (46%) originated from storage and were mostly caused by human error. Also, the majority of releases were a relatively small volume (13 m^3 or less) compared to the total amount of fluid used in hydraulic fracturing. Although, it is important to note that the number of spills increased three times from 2006 to 2011, and that approximately 70% of the spilled material was not recovered and 23% was from unidentified sources (for example, which individual well or wells caused the contamination).

Other authors also addressed issues associated with spills. For example, during 2008 and 2013, Brantley et al. (2014) that reported 32 spills (with a minimum volume of at least 1.5 m^3) originated from only 20 wells during a period when 6000 wells were drilled and 4000 were complete. Another study suggested that different processes in well drilling (the use of multi-well pad versus a single well pad) lead to fewer environmental spills per well (Manda et al., 2014).

Another source of contamination may be from the migration of methane and salts to groundwater as a result of the fractures that were made during the fracking process (Heilweil et al., 2015; Jackson et al., 2013a; Osborn et al., 2011). Although this may not happen at every site since other studies have not shown any evidence of significant migration (Kolesar Kohl et al., 2014; Molofsky et al., 2011; Nelson et al., 2015b; Warner et al., 2012; Warner et al., 2013b) and still others reported inconclusive results (Alawattegama et al., 2015; Hildenbrand et al., 2015a).

In addition to the above mentioned contamination processes, poor treatment of wastewater (at public centralized treatment plants) may lead to the discharge of untreated contaminants into surface water bodies (Bowen et al., 2015; Getzinger et al., 2015; Kassotis et al., 2014; Lutz et al., 2013; Pancras et al., 2015; Skalak et al., 2014; Warner et al., 2013a). These treatment processes will be addressed in the next section.

3.3.3. Wastewater treatment

Disposal of flowback and produced water is of particular concern because of their volume, high salinity, and the presence of other compounds, such as organics, inorganics, and

NORM, due to their ecotoxicological impacts. The main disposal methods reported in the literature include deep well injection, municipal wastewater treatment plants, and use as a deicing agent (due to the high salt content), amongst others (Maloney and Yoxtheimer, 2012a).

Deep well injection is the final destination of up to 95% of produced wastewater from conventional and unconventional onshore NG exploration (Lutz et al., 2013). However, this option may not be available in all the areas due to geological (for example, the Marcellus play) or infrastructure limitations. In this case, wastewater is sometimes transported to regions where deep well injection is available or sent to other treatment systems, such as municipal wastewater treatment plants.

Deep well injection may also be unavailable due to legal restrictions: in the US, for instance, North Carolina banned deep well injection (Adair et al., 2012), while West Virginia and Pennsylvania (with only three and seven disposal wells, respectively) highly restricted this practice (Lutz et al., 2013). In Europe different interpretations of the EU water framework directive have led to country or regionally specific bans all over Europe (Elsner and Hoelzer, 2016).

As an alternative, it was common to dispose wastewaters to be treated at municipal treatment plants. However, treatment provided by these facilities was impaired since they are designed to treat domestic wastewater and are not prepared to treat high salinity levels (GPO, 2016). This incompletely treated water was discharged and impacted surface waters (Mauter and Palmer, 2014a). As a result, the practice was formally banned by the EPA and pretreatment standards were established under the Clean Water Act for wastewater discharges to municipal treatment plants from onshore unconventional oil and gas (USGPO 2016). These pretreatments standards mainly focus on zero discharge to public-owned treatment works (POTW) and surface waters by diverting the wastewater mainly to deep well injection (where available) or centralized waste treatment (CWTs) facilities treating other industrial wastes. However, it remains unclear how many of these CWTs are capable of significantly reducing certain types of contamination, namely the high inorganic salt content. In addition, CWTs are capital intensive and require a large number of wells to be cost effective (Gómez et al., 2015). Construction of these CWTs is already a limiting factor in shale gas expansion at many locations in the US.

Since traditional wastewater treatment methods have a limited capacity to treat these wastestreams and deep well injection may not be an option, other methods have been suggested in the literature but only a select few have been used. These include microbial mats (Akyon et al., 2015), electrocoagulation (Ferrer and Thurman, 2015); oil/water separation; ion exchange; freeze thaw evaporation; thermal distillation coupled with crystallization, constructed wetlands; reuse for irrigation (Gregory et al., 2011); advanced oxidation (Lee et al., 2015); micro and ultra-filtration (He et al., 2014b) and reverse or forward osmosis (Hickenbottom et al., 2013).

Although, many of the above treatment options have a marked limitation that restricts their applicability in the field. For example, reuse in irrigation or treatment using constructed wetlands are severely limited by the plant salt tolerance to such high levels of salinity, which are often higher than seawater. Freeze thaw and thermal distillation are best applied in specific climatic conditions. Most remaining treatments are limited by very high costs and are energy intensive, such as reverse osmosis.

New technological developments are needed for more cost-effective treatments in order to provide valid options when deep well injection is not available. This is particularly true for salt removal due to the large volumes of wastewater. This also applies to the Marcellus play, where deep well injection is extremely limited. In addition, the climatic conditions there preclude the use of thermal distillation and evaporation as a treatment option. Another potential option may be the use of forward osmosis since it has been more extensively studied in recent years (Hickenbottom et al., 2013). This is because it may reduce costs when compared to reverse osmosis. Although, there is no evidence yet of the application of this technology in the field for this wastewater.

Produced wastewater also contains organics, which may be very diverse and complex and potentially difficult to treat. However, several articles refer to the high biodegradability of the wastestream, which is potentially due to high BOD/COD ratios and the high concentration of simple aliphatics (Kekacs et al., 2015; Lester et al., 2015b). Concerning toxicity, control tests were more toxic than the raw hydraulic fracturing fluid and produced water in an acute toxicity test (Microtox) with *Vibrio fischeri* (Steliga et al., 2015). This suggests that the added chemicals in the hydraulic fracturing process are not toxic to living organisms. However, the compositional variability and chemical complexity of the added organic compounds as well as lack of disclosure of fracturing fluid composition (Kekacs et al., 2015) hinder researchers' ability to assess both biodegradability and toxicity issues. As a result, further tests examining both chronic and acute toxicity appear to be warranted.

Finally, wastewater reuse is yet another wastewater management option and maybe applied directly or following dilution or pre-treatment. However, it may be limited by the chemical stability of viscosity modifiers and salt precipitation due to barium and calcium (Haghshenas and Nasr-El-Din, 2014). A series of simple pre-treatment steps may enhance reuse by precipitating most of these salts or controlling pH. Eventually though, treatment is no longer effective in removing these cations and reuse become unfeasible.

Based on the information examined in the articles, the preferred management strategy may be a compromise between water quality, economic constraints, and process performance. This suggests that one option may be to pretreat produced water followed by reuse. This may be done in conjunction with blending with makeup water and finally followed by deep well injection (where available).

3.3.4. Atmospheric emissions

This section discusses recent developments in monitoring of air quality and GHG and exploitation and impacts on health. From the total articles selected, 39 evaluated atmospheric emissions. More interest was shown in this topic initially as 36% percent of suitable articles focused on this theme in 2011. Although, there has been a steady decline in the percent overall contribution since then.

Research in this topic has predominantly been carried out in the USA (79% of articles tracked) over the examined timeframe but there has been an increased number of articles in 2014 and 2015 from 'Europe' and the 'UK. In addition, only Type 3 articles were identified in this area and totaled 65% on average. Finally, it is important to note that the last two years contributed to 72% of the total number of articles in this impact category from 2010-2015.

3.3.4.1. Air quality

The fast development of shale gas in proximity to residential areas and heavily populated areas has raised concerns on the impact of local and regional air quality. Although, there remains a lot of uncertainty over this issue to date. This may be related to the fact that air pollution generated by the shale gas industry is extremely difficult and costly to monitor. For example, sampling must take place over a long period of time in order to obtain robust results. Therefore, it is not surprising that only a small number of suitable articles (9) was found with reports of raw data emissions. In addition, no articles were found from 'Europe' that looked at this issue but this may be related to the very limited shale gas activity compared to other regions.

Of the articles that were published, comparisons between the studies were limited due to the extremely heterogeneous nature of the data collected, number of samples taken, the type and even the specific compounds that were analyzed, amongst others. Nevertheless, some general trends were found through the analysis of all three types of suitable articles.

Emissions are generally classified into the following categories: volatile organic compounds (VOCs), polyaromatic hydrocarbons (PAHs); particulate matter (PM_x); NO_x, SO_x, carbonyls – such as formaldehyde (Colborn et al., 2014), and ozone, a secondary pollutant resulting from the reaction of NO_x and VOC in the presence of solar radiation (Ahmadi and John, 2015; Edwards et al., 2014; Swarthout et al., 2015). One important contaminant that was only addressed in one article was radon. Walter et al. (2012) examined this issue from drill cuttings. Although, emissions from other waste materials (both solid and liquid) generated from shale gas exploration and exploitation have not yet been addressed in the literature.

There is a great variety of equipment that may be considered a source of air pollution either through combustion or fugitive emissions. For combustion, an assortment of equipment (generators, compressors, amongst others) utilize diesel engines during their operations, since they are traditionally used in shale gas exploration and operational activities and emit a variety of the air pollutants listed above (Rutter et al., 2015).

Litovitz et al. (2013) and Ethridge et al. (2015) inventoried combustion and fugitive emissions air emissions through a survey of various entities producing in the Barnett shale area. This included produced water storage tanks, piping component fugitive areas, blowdown vents, condensate storage tanks, engines, process vents, oil storage tanks, and heaters/blowers. The results showed that combustion emissions encompassed less than 10% of emissions while emissions from storage tanks, vents, and piping summed to almost 80% with 50% coming from just produced water storage tanks and piping. Heaters and boilers emitted the least (1.3%) (Ethridge et al., 2015). Additional studies are needed from the Barnett and other plays to determine if similar results are obtained.

Emissions occur of air contaminants during various phases of shale gas exploration and exploitation, including initial drilling, hydraulic fracturing, well completion and production operation. A recent study concluded that emission standards would not be exceeded in Poland during exploration activities despite the high level of NO_2 emissions (Bogacki and MacUda, 2014). Colborn et al. (2014) determined that emissions were higher during initial drilling.

Litovitz et al. (2013) estimated that well site preparation may emit between 150-170 kg VOCs; 3800-4600 kg NOx, 87-130 kg $PM_{2.5}$; 87-130 kg PM_{10} and 3.8-110 kg SO_x and 46-1200 kg VOCs; 520-660 NO_x; 9.9-50 kg $PM_{2.5}$ and PM_{10} and 3.1-4 kg SO_x per well during production. Although these values are estimates, it is important to highlight that emissions for site preparation values tend to be higher in NO_x and SO_x due to the influx of traffic to the facilities.

Emissions may also vary depending on seasonal effects, particularly for ozone formation (Edwards et al., 2014), and the shale play in question. For example, lower concentrations of VOCs were found for the Marcellus shale compared to the Barnett shale play (Goetz et al., 2015). Although, the authors noted that the results of air quality studies should be examined on a case by case basis and that caution should be used in generalizing the results. Finally, much like other fuels, the impact of shale gas on air quality can be significant. Although, it is important to note some studies (more recently Song et al. (2015) indicated that emissions remain lower than coal overall. This suggests that the commonly used policy of shale gas as a transitional fuel from coal should continue to play a part.

An important aspect with air pollution is that contaminants might be native to the shale basin that is being explored or exploited. For example, a recent study concluded that secondary organic aerosols from sources unrelated to oil and gas development were the cause of ozone formation (Rutter et al., 2015). In addition, emissions are not exclusive to unconventional shale gas exploration and exploitation or a direct result of the fracturing process. This is especially true in areas where conventional gas exploitation is also occurring. Therefore, it is important to obtain air quality measurements prior to the exploration and exploitation of shale gas in order to delineate the contribution of this activity to background air quality.

Public health risks to surrounding communities are still a controversial issue. Bunch et al. (2014) indicated that VOC levels due to fracking activities did not pose excessive exposure risks to their communities. Although, another study (McCawley, 2015b) showed a linked between respiratory effects from air contaminants to both the shale gas extraction itself and the heavy traffic associated during construction and exploration activities. This is due to emissions not only from PMs, VOCs, PAHs, but also crystalline silica (McCawley, 2015b). One study from the UK focused on inhalation of hydrocarbons from operational air emissions over the lifetime of a well and estimated increased health risks due to this exposure (Reap, 2015).

There are less studies on the impact to workers. Recently OSHA/NIOSH (2015) have reported that workers involved in hydraulic fracturing activities are exposed to dust with high levels of breathable crystalline silica. Rosenman (2014) also examined this issue and estimated appreciable risks after long term exposure.

Other studies examined exposure of both workers and communities with differing results. Several studies mentioned low to no substantial risks of exposure for both of these groups (Bunch et al., 2014; Ethridge et al., 2015; Goetz et al., 2015). Although, Paulik et al. (2015) and Colborn et al. (2014) alert to potential dangers. The different conclusions of these studies may be a result of monitoring different compounds. For example, Paulik et al. (2015) focused on only exposure to PAHs. In addition, it is important to note that permissible levels may not necessarily take into account segments of the population at higher risk of adverse health effects such as pregnant women and infants (Colborn et al., 2014).

Considering these potential risks, additional research efforts are needed since long-term direct measurements of air pollutants are extremely scarce (Goetz et al., 2015; Roy et al., 2014). This is especially true to obtain data for multiple years coming from different shale plays and regions while monitoring for the contaminants listed earlier in this section, especially radon. As such, data from these new studies would provide the basis for potential mitigation measures as well as the risk assessment of air pollutants to workers and public health in general. If measures are needed, two different strategies may be used (alone or in combination) for the protection of human health. These may potentially diminish exposure to pollutants either by best practices or mandated regulations by reducing pollutant load through technical improvements and mitigation strategies.

The first option would be the enactment of new regulations. Several regulatory measures have already been suggested in the literature with some already implemented. For example, at least 20 states in the USA have established setback requirements regulating the distance between exploratory areas and residential areas and range between 300 to 3000 meters (Richardson et al., 2013). Other proposed regulatory changes may include proposals to aggregate industry sources and the requirement to use Best Available Technologies (BAT) (Litovitz et al., 2013).

The second option would be the use of alternative chemicals and technologies that focus on limiting fugitive emission (Centner and Petetin, 2015). For example, one option to consider would be the implementation of dual fuel technologies, such as those that operate with diesel and NG (Thorn, 2015). Others include the use of complete combustion devices to reduce VOC emissions, incineration of aromatics and heavy hydrocarbons, the use high-bleed controllers (Centner and Petetin, 2015) or the application of selective catalytic reduction for NO_x emissions and diesel particulate filters for $PM_{2.5}$ (Roy et al., 2014).

3.3.4.2. Climate change

The climate change section will focus on the two main direct GHG resulting from shale gas exploration and exploitation, namely methane and carbon dioxide. However, measurements and/or estimates of these emissions are difficult to directly assess in the field due to a wide array of technical difficulties for three reasons. First, direct measurements of methane emissions are scarce and differ significantly. For example, Allen et al. (2013) reported emissions from well completions to be 98% lower than the national estimates by EPA. This discrepancy may not only be due to differences in methane source allocation, but also to restricted access to random sampling locations since those selected may have been potentially chosen by industry since they may have been the best performing (Howarth, 2014).

Second, methane leakage rate is an extremely important value for GHG estimations but is widely contested in the literature. Simply defined as the percentage of methane leaked over the total NG produced, methane leakage rate estimates vary from 0.42% (Allen et al., 2013) to ranges of 0.66-3.9% (Jiang et al., 2011b) and even as high as 3.6-7.9% (Howarth et al., 2011a). Furthermore, these estimates are likely to be play specific (Peischl et al., 2015) and dependent on final well lifespan (Howarth et al., 2012). Some reported values are contested as either being too low (0.42% indicated by Allen et al. (2013)) or too high (the upper limit of 7.9% indicated by Howarth et al. (2011a)). Third, an aspect that remains poorly discussed in the literature is the possibility of refracturing existing wells and their impact on GHG emissions (Jiang et al., 2011b; Stephenson et al., 2011a).

Although all of the issues listed above are extremely important, they represent only part of the total GHG emissions in the lifespan of a shale gas well. For the evaluation of total GHG emissions, life cycle assessments (LCA) are often performed for more accurate assessments (Burnham et al., 2012b; Howarth et al., 2011a; Jaramillo et al., 2007; Jiang et al., 2011b).

Heath et al. (2014b) developed a systematic review of eight LCA and concluded that emissions from shale gas averaged approximately 488 CO_2 equivalent /kWh. However, LCA also have significant variations in the chosen parameters, which are highly debated among authors in the reviewed literature. These parameters include GHG timeframe (Cathles Iii et al., 2012; Howarth et al., 2011a; Howarth et al., 2012), the end use of the produced shale gas and the considered methane leakage rate (as discussed above). These discrepancies not only limit an accurate assessment of total GHG emissions over the life cycle but also comparisons with other energy sources, such as coal.

It is important to note that different end uses (heating or electricity production) involve different considerations and potentially impact different input parameters and output results (Cathles Iii et al., 2012; Howarth et al., 2012). For example, Howarth et al. (2011a) concludes that shale gas GHG emissions are higher than coal for heating while other studies suggest that shale gas is substantially better than coal with 38-50% less GHG emissions but examined electricity production instead (Chang et al., 2015; Jiang et al., 2011b; Stephenson et al., 2011a). Similarly, conflicting results were also reported for conventional versus shale gas operations for GHG emissions. Heath et al. (2014b) concluded similar emissions for these energy source while other authors report an increase of 1.8 to 17% for shale gas over conventional gas (Jiang et al., 2011b; Stephenson et al., 2011a).

An important aspect that may impact and change the values obtained in these LCA are the proposed or implemented mitigation strategies in order to attenuate total GHG emissions. This focus has primarily been on initial well completion, since methane leakage may be extremely high during this process In order to mitigate these GHG emissions, a wide variety of technologies are available and are referred to as Reduced Emission Completions (REC) (Cathles Iii et al., 2012; O'Sullivan and Paltsev, 2012; Stephenson et al., 2011a).

One alternative option to venting is to recapture with the intention to sell. This option may be economically feasible considering that expected methane losses are much higher during well completion of shale gas than conventional gas because of hydraulic fracturing (O'Sullivan and Paltsev, 2012). From a regulatory standpoint, the EPA defined in 2012 that each well completion occurring after January 1, 2015 must employ REC in combination with a completion combustion device (flaring) (EPA, 2016).

Other technologies that may be considered are carbon capture and storage (CCS) in depleted shale gas reservoirs and the use of supercritical CO_2 as a working fluid in hydraulic fracturing. However, studies on CCS in depleted shale gas reservoirs (Wang et al., 2011) have yet to prove that the sequestration capacity is sufficient to offset overall GHG emissions from the industry (Edwards et al., 2015). Supercritical CO_2 has the potential to simultaneously reduce water requirements and sequester CO_2, thereby reducing two critical aspects of shale gas production (Middleton et al., 2015; Wang et al., 2012). However, additional tests are needed to determine the efficacy of this technology in the field.

3.3.5. Land use

Land use change can be defined as the conversion of land from one type of biome/management to another (IPCC, 2000). This impact category shows a wide range of impacts as demonstrated in the 15 examined articles from 2010 to 2015. This number represents approximately 5% of the total suitable articles in shale gas impacts. This classification is predominantly constituted by Type 1 articles (40% on average) and became more representative in 2014. The geographic locations were only from the USA, Canada, and the UK.

Shale gas exploration and exploitation involves various building activities in the selected area. Following the successful identification of potential areas using different methodologies, well pad construction not only requires the removal of soil and vegetation but also the transport, handling, and storage of chemicals and other materials for the building of gas pipelines, water extraction structures, and other operational facilities. All of these activities are liable to impact land use and cause habitat disruption, erosion, and increase noise pollution (Drohan et al., 2012; Moran et al., 2015a; Olmstead et al., 2013). Finally, road improvements may be required in order to handle the increased traffic during this phase. Although, this increased volume may potentially increase traffic accidents in the play area (Graham et al., 2015b).

Land use and area occupied by shale gas is highly dependent on a variety of factors, including the number of wells per pad, well pad size, and distance between them. While a larger number of wells per pad allow for less direct land coverage as support infrastructures are more concentrated, it also means wider spacing between well pads. This may impact pipelines and road construction needs as well as intensifying potential environmental impacts locally (Baranzelli et al., 2015).

The average building area for the different components involved in shale gas exploration and exploitation varied in the analyzed literature. The actual building area for wellpads have been reported or assumed to be between 1.2-3.55 ha for well pad with two or less wells (Baranzelli et al., 2015; Moran et al., 2015a) and between 2-9.93 ha for well pads with 8 to 16 wells (Baranzelli et al., 2015; Racicot et al., 2014). If adjacent infrastructures (compressor stations, storage areas for water, wastewater and chemicals) are included then the total building area varied between 3.56 up to 13.68 ha (Baranzelli et al., 2015; Kiviat, 2013).

Spacing between wells is also important in terms of proper land use allocation. This value is dependent on both legal requirements and technical issues of gas recovery when extracting from horizontal wells. Other authors report spacing requirements between 32 ha and 1024 ha for 2 and 16 wells per pad, respectively (Baranzelli, Vandecasteele et al. 2015). This spacing may also impact pipeline and road needs. Studies have reported average lengths per well between 2.3-2.8 km of pipeline (Evans and Kiesecker, 2014; Racicot et al., 2014) and 0.73 km of road (Racicot et al., 2014).

While all the aforementioned parameters may be reasonably estimated based on the observed density of already explored or exploited areas, indirect land use changes are far more complex to evaluate. In addition, this indirect land use is often difficult to measure as shale gas exploration and exploitation may also impact overall land use due to associated industries (Moran et al., 2015a). All of which results in values that are much more variable compared to other aspects. For example, Moran et al. (2015a) reported that 0.5 ha of natural forest was affected per well while Evans and Kiesecker (2014) and Kiviat (2013) reported values of 8.6 ha of indirect land use impacted and 15 ha of affected forest per well, respectively.

The resulting impact of shale gas exploration and exploitation construction activities mainly result in risks to biodiversity due to direct impact on habitat fragmentation and pollutant dispersion. These risks are still poorly investigated in literature, which may be due to the required time to observe these type of impacts.

Six articles evaluated damages to ecosystems were identified in this review, and pointed to the fact that many of the impacts caused by hydraulic fracturing were related to the poor management of chemicals, spills or the improper handle of flowback and produced waters and other materials (Kiviat, 2013; Latta et al., 2015). Shank and Stauffer (2015) and Latta et al. (2015) found similar results but focused on negative impacts to biodiversity. These studies showed that shale exploration led to reduced biodiversity and bioaccumulation of heavy metals in aquatic organisms and birds.

However, data on biodiversity impacts may be conflicting. For example, Shank and Stauffer (2015) found limited impacts on macroinvertebrate and fish while Stearman et al. (2014) did not find any relationship between analyzed species abundance and shale gas exploration and exploitation. Some reasons to explain the seemingly lack of relevant impacts on ecological systems are the effectiveness of protective measures but more importantly the lack of sufficient time to observe these impacts (Shank and Stauffer, 2015). This suggests that future research on ecological impacts is needed to truly assess the cumulative impact of shale gas over the entire life cycle of production.

Another aspect of land use relates to waste management and disposal. Mykowska et al. (2015) determined that the examined wastes have an estimated absorbed radiological dose lower than the average amount for individuals. However, previous studies with conventional oil producing site wastes suggest that NORM (including radium) may be present in produced sludges (Garner et al., 2015). The differences observed in potential risk between these two studies may reflect geological conditions in the different analyzed basins. Additional research appears to be warranted given the limited amount of information examining waste management derived from shale gas exploration and exploitation.

Land use may also be a highly contested issue amongst stakeholders in highly populated areas and is often highlighted as a limiting factor for expansion to Europe. As such, the Joint Research Centre (Kavalov and Pelletier, 2012) compared the population density in the Barnett play (38 inhabitants per km^2) with the population density of Europe (113 inhabitants per km^2) and concluded that this aspect may be a major barrier for large-scale development of shale gas in the EU.

However, the European Academies Science Advisory Council (EASAC, 2014) highlighted that the latest multi-well pads and horizontal drilling techniques reduced building surface areas. These new methods are now commonplace in the industry, even in heavily populated areas such as Pennsylvania, which has a population density similar to most of Europe. Additional research in land use impacts is needed in areas where shale gas is being explored, especially in highly populated areas where conflicting interests between constituents need to be addressed.

3.3.6. Induced seismicity

Induced seismicity refers to earthquakes stimulated by activities where human-introduced stresses are similar in amplitude to the ambient stress state (Rubinstein and Mahani, 2015). The link between induced seismicity and human activities (although of small magnitude) have been previously established for reservoir impoundment, conventional oil and gas field depletion, water injection for geothermal energy recovery, and waste water injections (Davies et al., 2013).

Based on the analyzed articles, it can be seen that studies on induced seismicity were rare between 2010-2015, with only eight such papers reported in relation to shale gas exploration and exploitation. However, unlike other impacts, three out of eight of these studies were conducted in Europe, a disproportionally large percentage compared to existing exploration there. This may be an indication that regulatory bodies and researchers in Europe are more sensitive to this issue based on a variety of factors, including occurrences of this issue in the USA.

The two main sources of induced seismicity in shale gas exploration and exploitation are hydraulic fracturing and the deep well injection of produced water. As previously mentioned, the link to induced seismicity and deep well injection was previously known, since this is practiced in conventional on shore oil and gas extraction (Rubinstein and Mahani, 2015). In the case of hydraulic fracturing, however, researchers initially thought that the volume of fluid used for fracturing, which is significantly lower than the volume disposed of in deep well injection, were unlikely to generate felt seismicity (Clarke et al., 2014).

The larger volume applied in deep well injection in conventional oil and gas is more likely to induce more frequent and larger earthquakes than hydraulic fracturing (McGarr, 2014; Rubinstein and Mahani, 2015). This counterintuitive observation is mainly due to the fact that both injection volumes and times are significantly lower with hydraulic fracturing when compared to deep well injection, despite higher pressure (McGarr, 2014; Rubinstein and Mahani, 2015).

Even though researchers originally thought hydraulic fracturing would not induce felt seismicity for to the reasons listed above, this does not apply to every single scenario or study as some report a direct link between the two (Clarke et al., 2014; Holland, 2013). For example, low-intensity earthquakes were detected in the UK due to hydraulic fracturing (Clarke et al., 2014; Johnson and Boersma, 2013a; Stamford and Azapagic, 2014) in 2011. This incident marked the first induced seismicity event in Europe associated with shale gas exploration and exploitation and lead to a Government suspension of shale gas extraction for 18 months (Clarke et al., 2014; Johnson and Boersma, 2013a; Stamford and Azapagic, 2014).

As a result, the UK now requires the identification of preexisting faults prior to exploration as well as detailed monitoring of induced seismicity during exploration (Milieu, 2013). Furthermore, more stringent regulations concerning the threshold for the suspension of operations when compared to other industries was applied to the shale gas industry in the UK (Westaway and Younger, 2014). This suggests that there are potentially higher regulatory barriers to shale gas exploration and exploitation in Europe compared to other geographic locations.

Despite these existing studies, there are still many questions and uncertainty between hydraulic fracturing and induced seismicity. One aspect is to examine whether the recent shale gas expansion has led to increased risks of induced seismicity due to the sheer increase in cumulative wastewater volume injected into existing or potentially new disposal wells. However, Rubinstein and Mahani (2015) indicated that the location of the largest increase in seismicity in Oklahoma was not correlated with a the deep well injection of spent hydraulic fluids. Although, additional studies should examine whether this applies to other plays as well.

An additional aspect concerns the link between induced seismicity by hydraulic fracturing and preexisting faults, which was recently established in several articles (Clarke et al., 2014;

Frohlich et al., 2011; Holland, 2013). This suggests that additional studies that include fault mapping is a potential option to mitigate this issue (Clarke et al., 2014). However, these unmapped faults are often only reactivated after the event occurs, making it difficult to obtain results in advance (Rubinstein and Mahani, 2015). In addition, detection methods remain in debate, which may potentially lead to the misidentification or mislabeling of regional natural earthquakes as induced seismicity due to hydraulic fracturing (Caffagni et al., 2014).

3.3.7. Multiple environmental impact assessment

This category encompasses articles that evaluated impacts that could not be placed into a single category (such as health risk assessment from multiple pathways or LCA that incorporate several impacts) or any impact category (for example, socioeconomic aspects). The total number of articles in this section was 69 during the analyzed period with the percentage between 5 to 35% and the majority coming from the USA. Further examination showed that none of these was a primary research article (Type 1), which indicated that no new data was obtained. Rather, these articles focused on analyzing existing trends.

Concerning multiple impact factor evaluation, life cycle assessment (LCA) is almost always used as the preferred method. This approach was used in several case studies in the UK (Stamford and Azapagic, 2014), China (Chang et al., 2015) and the USA (Laurenzi and Jersey, 2013b). Previous studies using LCA that were referenced in other sections of this review only examined singular compartments rather than a more holistic approach that encompassed multiple environmental aspects for all of the different stages of the life cycle.

Under different scenarios, Stamford and Azapagic (2014) concluded that shale gas may have negative environmental impacts several times higher than conventional NG. This was particularly true for human, marine, freshwater and terrestrial ecotoxicity. This is one of the few or potentially even the only study that considered impact categories such as acidification potential, element depletion, etc. As a result, this article has been prominently featured in traditional media and in the academic literature, even though it was only published in December 2014. However, it should be noted that the validity of the assumptions and by extension the conclusions in that study remain hotly contested (Stamford and Azapagic, 2015; Westaway et al., 2015b).

The importance of the LCA approach for a more accurate assessment of the different stages in shale gas exploration and exploitation cannot be overstated. Exploratory LCA may be seen as a tool for decision makers to identify bottlenecks in the process itself and to verify if shale gas production presents more environmental benefits in comparison to other energy sources in a given location. It should be noted that there is a critical lack of specific data, particularly for regions that have yet to be explored, and efforts to close these gaps are needed.

3.4. Concluding remarks

There has been an expectable and significant increase in the number of publications on shale gas exploration and exploitation and associated environmental impacts over the years.

This is a clear reflection of shale gas production growth in the US and the increased interest in mirroring this development in other regions coupled with increase awareness of potential environmental impacts. Although authors from the US represent a vast majority of the articles examined, several studies from countries which have yet to commercially produce shale gas were found, which suggests a precautionary approach to new regional development.

Regarding existing consensus (Table 3.2) that seem to emerge from the analysis made in this study, it is important to point out that these may not resist the test of time and are provisional at best. Yet, it is important to identify existing trends in the literature to enable more informed decision and policy makers.

Table 3.2: List of consensus that emerged from the analysis of this study and relative degree of consensus.

Consensus	Relative degree of consensus
- Wastewater characteristics is almost exclusively dependent on rock formation	High
- Migration of methane and salts to groundwater as a result of the fractures rarely occurs	High
- Contamination of surface water as a result of poor wastewater treatment is common	High
- Wastewater organic contaminants tend to be highly biodegradable	Medium
- Wastewater reuse after pre-treatment is a simple method to limit negative impacts	High
- Methane leakage percent lies within a 0.66 to 3.9% range	Medium
- Shale gas entire lifecycle GHG emissions are lower than coal for electricity generation	High
- Shale gas entire lifecycle GHG emissions are lower than coal for heating	Medium
- Seismicity from deep well injection is far more likely than from hydraulic fracturing	High
- Induced seismicity is connected to preexisting faults	Medium

No consensus can be tentatively allocated to air quality, resulting public health risks and land use as results are often contradictory with no obvious trend, partially due to limited studies exist due to the inherent difficulties associated with this type of studies.

As a result, it can be said that more studies within these areas are necessary. However, the observed larger number of studies on water resources might reflect a preliminary identification of this aspect as one of the most sensitive to negative impacts by shale gas exploration and exploitation (and also a bigger public concern). So, more studies on water resources cannot be neglected either.

Aside from the consensus detailed in Table 3.2, significant reductions in water contamination and treatment needs and GHG emissions (particularly in well completion) are expected due to new legislation and best industry practices as a result of advances in scientific knowledge and practical experience. Nevertheless, cost effective wastewater treatment remains a difficult challenge and there are no indications of a solution in the near future, particularly for salt removal. In addition, GHG emission estimations are highly debated as REC technologies have yet to be adequately integrated and characterized.

Finally, LCA appears to be a promising method for a precise overall impact assessment of shale gas but is currently limited in scope. This may be a reflection on the lack of sufficient raw data due to several propriety aspects and trade secrets of the applied technologies.

Future research efforts should focus on mitigation techniques as well as standardization practices to enable a more precise comparison between studies in order to establish a wider, stronger consensus on environmental impacts of shale gas exploration and exploitation.

Acknowledgements

Authors would like to acknowledge IBRASIL (Inclusive and Innovative Brazil project, an Erasmus Mundus Action 2 programme funded by European Commission) for the PhD grant.

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4. Understanding public perception of hydraulic fracturing: a case study in Spain

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Abstract

Public acceptance is crucial for the implementation of energy technologies. Hydraulic fracturing is a technology widely used in the USA for natural gas production from shale formations, but currently finds strong public opposition worldwide, especially in Europe. Shale gas exploitation and exploration have the potential to significantly reduce import dependency in several countries, including Spain. To better understand public opinion on this issue, this article reports a survey targeting both the entire Spanish population and the inhabitants of the province of Burgos, the location where shale gas exploration permits have already been issued. Results demonstrate that half of the Spanish population opposes shale gas, and this opposition increases in autonomous communities that are closer to possible exploration sites. The results also show that socio-demographic aspects are not strong predictors of opposition. In addition, Burgos' population show different behaviours toward shale gas that demonstrates that proximity and prospect of shale gas development affects opinion. Finally, there is still a great level of unfamiliarity with high volume hydraulic fracturing and shale gas in both populations sampled.

Keywords: public acceptance; risk perception; shale gas; hydraulic fracturing; construal level theory

4.1. **Introduction**

Shale gas, or natural gas (NG) stored in shale formations, is an unconventional resource that has been making a huge impact in the North American gas market (Cotton et al., 2014; EIA, 2016c). With shale gas development, the United States of America (USA) has shifted from a declining to a growing producer of NG (Cotton et al., 2014; EIA, 2016a). In contrast, the European Union (EU) has a great dependence on NG imports (Eurostat, 2016b), which have raised the question if exploitation and exploration of shale gas reserves could be an alternative to contribute to the security of NG supply (Erbach, 2014).

Even though the techniques employed are not completely innovative in the oil and gas industry, the rapid and vast expansion of shale gas production activities (both in terms of quantity of gas produced and exploration of new basins) has generated heightened concern over its environmental impacts and reliability of the existing regulatory structure (IEA, 2012b). Shale gas development in Spain and also in Europe remains uncertain and is still a controversial subject. Shale gas faces strong public opposition in Europe due to the unknown extent of its impacts in the environment and public health associated with its exploitation, which has led to protests and the introduction of bans in several countries (Costa et al., 2017b).

Acceptance is considered as an important constraint to unconventional gas development in the world, ultimately requiring a “social license to operate” (Brändle et al., 2016; IEA, 2012b). Currently, only a few studies assess the social acceptance of shale gas in Western Europe, except in the United Kingdom (UK) (Lis et al., 2015). The current study assesses public perception on shale gas development in a novel geographic context, contrasting a broad national perspective with opinions from a potential exploration area.

In this scenario, shale gas exploration and exploitation in Europe and adjacent countries is often seen as a matter of energy security with strong influence of geopolitical issues, since it would increase domestic NG production and ensure both affordability and security of supply (Erbach, 2014; Johnson and Boersma, 2013a). Nevertheless, shale gas development in Europe calls for new strategies for risk analysis and governance in which public perception is an important factor to support the beginning of operations.

Consideration of public perceptions of energy undertakings has the potential to amplify perspectives and consequently reduce emerging externalities and conflicts between involved parties, as well as demonstrate support of democratic policy and decision making. Public acceptance is often neglected in energy studies even though it allows for a better understanding of the main factors driving opposition and how people can be convinced of the benefits of exploiting this energy resource (Sovacool, 2014b). This study offers a first approach to identify which are the main aspects driving acceptance of people from different regions in Spain when facing the possibility of a new energy technology exploration.

This article starts with a literature review followed by an evaluation of results obtained from two representative population samples, one from Spain (n=403) as a whole and the other from the Spanish province of Burgos (n=301). Data collection was based on a closed-end questionnaire addressed to Spanish residents in general and to Burgos province residents. Data were evaluated through descriptive analyses, followed by an exploratory factor analysis and the verification of the correlation between variables.

Out of the three dimensions of social acceptance (Wüstenhagen et al., 2007), namely socio-political acceptance, community acceptance and market acceptance, this study measures the community acceptance of the development of unconventional gas in Spain and in the province of Burgos. The conceptual framework for the discussion of results are based on the construal level theory, since it has already used in similar evaluations for acceptance of shale gas development (Clarke et al., 2016; Trope and Liberman, 2010; Trope et al., 2007).

4.2. **Background**

4.2.1. Public acceptance in literature

Understanding public attitudes to new energy sources like shale gas is vital to ensure the democratic establishment of energy policies and to assess community acceptance. Even though social acceptance is frequently neglected, it is crucial to the success of innovation in the energy industry (Wüstenhagen et al., 2007).

In recent years, the assessment of public perception towards shale gas development received great attention from scholars and national institutions, particularly in North America and in the UK (Thomas et al., 2017). This is shown by different surveys performed in academic studies in the USA (Boudet et al., 2014; Israel et al., 2015; Kreuze et al., 2016), Lithuania (Leonavičius et al., 2015), and the UK (Whitmarsh et al., 2015). Although not specifically related to hydraulic fracturing, it is also noteworthy that a recent study in France carried out the evaluation of public perception of coal bed methane, which is also an unconventional natural gas (Gunzburger et al., 2017).

Furthermore, the European Commission opened a public consultation on unconventional fossil fuels including shale gas from December 2012 to March 2013, and obtained a rejection range varying from 25% to 100% among individuals from European countries (EC, 2013b). The exception to this was Poland (EC, 2013b). Another study demonstrated that people interviewed in select countries (Denmark, Spain, Netherlands, Poland, Romania and the UK) have heard about shale gas projects and, with the exception of Poland, they still felt insufficiently informed about projects developed in their own countries (EC, 2015). Despite all of these and other efforts, such as the M4ShaleGas project, which also assessed public perception in European countries (Lis et al., 2015), shale gas development in European countries as well as public perception of it remains unclear.

In the UK, however, public acceptance is systematically monitored over time. Despite the imminent beginning of shale gas operations in the country, there is decreasing support, falling from 58.3% in 2013 to 46.5% in 2015 (O'Hara et al., 2015). This tendency can be observed over the years in the BEIS (2016) study, which showed that 48% of respondents said they neither supported nor opposed it and 33% opposed to it in 2016.

In Spain, only one study was performed by the industry, and tried to assess the perspective of public attitudes towards shale gas, even in a development scenario marked by opposition (which is discussed further in Section 4.2.3). This survey demonstrated that the majority of the Spanish population do not know what hydraulic fracturing or shale gas is, but that 61% support exploitation of hydrocarbons in the country (but not specifying which ones) (SIGMADOS, 2014).

More specifically in methodological aspects of shale gas acceptance in literature, labelling remains an issue when assessing public perception. Different studies explore the bias in public perception related to the usage of the wording 'fracking', 'hydraulic fracturing', 'frack', or 'shale gas development' (Brändle et al., 2016; Evensen et al., 2014; Stoutenborough et al., 2016). Since no consensus can be found in the literature as to which term can be considered neutral or otherwise unbiased, this research therefore adopted the term 'hydraulic fracturing' as it is older terminology and more technically precise when describing shale gas exploration (Evensen et al., 2014).

Much of the research on acceptance of new developments is based on the distance to exploratory areas. The effect of proximity to shale operation areas is observed and widely discussed in the literature. In the USA, awareness on shale gas development is considered higher in places closer to shale gas development or higher density development (Kriesky et al., 2013; Theodori et al., 2014; Thomas et al., 2017). The effect of how physical proximity may impact perceived ideas and public acceptance can manifest itself in two ways: the closer to the potential exploration site the higher the opposition (often regarded as the 'not in my backyard' or NIMBY effect) or the closer to the potential exploration site the stronger and better defined are the opinions on any given subject (in accordance to the construal level theory).

However, and particularly for the case of shale gas development, distance cannot be assumed as the only predictor since it is associated with neutral, negative and also positive support over different studies (Boudet et al., 2016; Clarke et al., 2016; Jacquet, 2014; Theodori et al., 2014). The effect of physical proximity for shale gas exploration was shown in Theodori et al. (2014) that found that members of the public living in areas with higher density of shale wells tended to be more familiar with the process of hydraulic fracturing than those who live in areas with low density of shale wells. This can actually indicate the extension of the concept of inverse NIMBY to shale gas exploration, which can also be affected by the variation of perception between proposed (heighten or potentially unrealistic fears of negative impacts) and existing explorations (Boudet et al., 2016).

As mentioned, the effect of physical proximity might also manifest itself in a stronger, better defined opinion regarding the implementation of shale gas development. Presumably, a combination of more exposure to information but mostly due to the fact that experiences that are closer to a person can be thought about in a more detailed and concrete manner due to proximity and potential impacts on its own life (Clarke et al., 2016).

Exposure to information and the level of knowledge are other aspects reported in literature as influencing public opinion. In the UK, it has been shown that participants change their attitudes when positive information about environmental or economic benefits are highlighted about shale gas (Whitmarsh et al., 2015). In a study conducted in the USA, after the provision of information participants changed perception on shale gas, level of knowledge and trust for information (Burger et al., 2015). Recently, a comparison between the UK and USA has demonstrated that the public in the UK show a lower acceptance of shale gas exploration and also greater levels of knowledge over this issue (Stedman et al., 2016).

Besides these issues, other stakeholders' acceptance is a crucial aspect to new technology implementation, since they can drive socio-political acceptance, and a considerable body of work has focused on evaluating their concerns and influence in energy development (Cotton et al., 2014; Crowe et al., 2015; Esterhuyse et al., 2016; Israel et al., 2015; Krupnick et al., 2013). To highlight the relevance of this approach (although outside the scope of this work), it is worth mentioning that experts are sharply divided over shale gas exploitation and exploration, especially regarding the risks related to hydraulic fracturing. In the USA, a good indicator of this is given by Krupnick et al. (2013) that interviewed specialists on shale gas in the USA from different sectors of society (NGOs, industry, academia and government), verifying poor agreement on the identification of environmental risks and their relevance in shale gas exploitation.

4.2.2. Natural gas consumption in Spain

Currently, NG production in Spain occurs in only five concessions. One of them is offshore and responsible for more than 84% of national production (MINETAD, 2016; MITC, 2011). However, in 2015, natural gas production in the country accounted for less than 1% of its consumption, explaining the high imports of the fuel by pipeline, mainly from Algeria, and also in LNG form, from a wide variety of suppliers (BP, 2016; CORES, 2016). In 2015, approximately 97% of the natural gas consumed in the country was from these imports (CORES, 2016). The same trend is observed in other European countries, which import more than 90% of their NG (Balitskiy et al., 2014).

In recent years NG accounts for approximately 20% of primary energy consumption in Spain (MINETAD, 2016). The demand profile corresponds to 36.3% of industrial consumption, 23.0% of residential/commercial consumption and 17.7% for electricity generation (MINETAD, 2016). In 2013, NG corresponded to 32% of industrial energy consumption, only exceeded by electricity (52%), an increase of 35% compared to 2009 for this sector (INE, 2016a).

4.2.3. Hydraulic fracturing in Spain

Shale gas exploration and exploitation appear to be viable in Europe based on the volume of technically recoverable reserves, which have been reported to be equivalent to 238 billion cubic meters of wet shale gas in Eastern Europe and 7,730 billion cubic meters of wet shale gas in Western Europe (EIA, 2015b) – estimates are reported as wet shale gas because they include natural gas plant liquids (NGPL), which may also be of economic interest. In Spain, the unproved technically recoverable wet shale gas is estimated at 237.9 billion cubic meters, divided into two basins: (i) the Basque-Cantabrian Basin, in northern Spain, with potential for wet shale gas and condensate and (ii) the Ebro (Solsona) Basin, located to the southeast of the Basque-Cantabrian Basin, with potential for shale gas and oil (EIA, 2015c).

According to a study of the potential economic impacts of shale gas in Spain, the exploitation and exploration of this resource could make the country independent of gas imports by 2030, and a net gas exporter by 2050 (Deloitte, 2014). In its Energy Security Plan, the Spanish government called for the exploration and exploitation of hydrocarbons in the country to ensure the energy security of the country and reduce its accentuated energy dependence (DSN, 2015). Despite the diversification of oil and natural gas suppliers in Spain, most of shipping routes involved in the transportation of these resources are located in the so-called maritime choke points – congested maritime pathways and/or routes subject to some kind of conflict like terrorism or piracy.

In Spain, as of June 2017, there were four active unconventional gas investigation permits under the responsibility of the national administration, as reported by the Ministry of Energy, Tourism and the Digital Agenda, the former Ministry of Industry, Energy and Tourism (MINETAD, 2017). In the Cantabria province, the Bigüenzo investigation permit covers the Cadíalso 2, El Coto 2 and Sestero 1 projects (MINETAD, 2017). In the Burgos province, the Angosto 1 and Urraca investigation permits are represented by the Angosto A, Urraca 1, Urraca 2 and Urraca 3 projects (MINETAD, 2017). In Burgos, the Sedano investigation permit was also issued and extended in January 2016 until 2017, but the company waived its rights to the area in August 2016 (BOCYL, 2016; Planelles, 2016).

The national ministry is only responsible for concessions affecting more than one autonomous community and these are approved by the central government. Other concessions within the country at the autonomous community level can be authorised by the local government. The existing permits in this category are presented in full detail in MINETAD (2015). However, in some of the other identified investigation permits, the usage of high volume hydraulic fracturing techniques is not explicitly stated and therefore not presented here.

Shale gas exploitation faces growing public opposition among individuals and civil organisations in Spain, who argue, among other allegations, that granting permits infringes local water resource legislation that they were obtained without conducting environmental studies and that public information and participation were not allowed (Benítez, 2015; Planelles, 2015; Rincón, 2016). In 2013, the La Rioja autonomous community's legislative assembly enacted a law forbidding hydraulic fracturing throughout its territory and similar laws were also passed in Navarra and Cantabria (BOE, 2013a, b, c).

More recently in 2015, 29 municipalities from Burgos and Soria proposed a law based on popular initiative to declare the autonomous community of Castilla y Leon free of fracking, which was denied by the local government (CCYL, 2014). On the other hand, some institutions (ACIEP, 2015b) and government members (EUROPAPress, 2014) are favourable to its exploitation under several arguments, including benefits from tax revenues and reduction of energy dependence.

4.2.4. Research questions and hypothesis

The main goal of this study is to understand how shale gas is perceived by Spanish inhabitants in general and to contrast this perception among people from different autonomous communities in comparison to people from Burgos province, the location where all the existing permits have been issued until now. As discussed in Section 4.2.1, the proximity to existing shale gas exploitation can impact perceived ideas and public acceptance and it is our aim to verify this effect or not.

Another objective of the study to verify if shale gas acceptance varies accordingly to the perceived risks and their magnitude related to its extraction as well as the willingness to accept shale gas in the face of new and positive information. Effects of risk communication and knowledge on shale gas can change perception about impacts of energy technologies, either increasing acceptance (Burger et al., 2015) or reducing it (Choma et al., 2016). In addition, the relationship between knowledge and acceptance founds profound difference across different countries (Stedman et al., 2016).

Participants were requested to evaluate typical pro-shale gas arguments and typical risks or counter arguments (further details are presented in Section 4.3 and in the Supplementary Material – SM). These questions were formulated to oppose each other and to be contrasting, particularly to the perception of existing information, opposition to shale gas development, economic benefits and willingness to change opinion when learning of new studies or the evidence that risks are manageable. We also hypothesised that those with more declared knowledge of energy sources would express stronger attitudes towards shale gas, either positive or negative. The relationship between knowledge (which also implies in the understanding of risks) and acceptance were shown to have profound differences in other countries (Stedman et al., 2016).

Considering the current context of the economic crisis in Spain, shale gas development could promote job creation and expansion of business opportunities, either directly (employment in operational or support activities) or indirectly (increase in services, etc.), even though they potentially can be temporary and local (Munasib and Rickman, 2015; Paredes et al., 2015; Taheripour et al., 2015). In light of this, we hypothesised that the acceptance of shale gas extraction could be linked to the perception of its benefits, mainly in the province of Burgos due to the prospect of its exploration.

The role of socio-demographics in predicting support or opposition to shale gas restricts some of the research hypotheses. Our hypotheses are based on the concepts of place attachment and identity, and considering that social and spatial proximity are likely to define concrete, low-level construals in population. Therefore, we expected opposition to be more likely among (i) people with previous experience in the energy sector, (ii) people living in Castile and León autonomous community or nearby, (iii) people with more residence time and (iv) residents of rural areas. Besides these aspects, we expected stronger shale gas opposition and less willingness to change opinion in the face of new studies amongst older people, which has been reported elsewhere to be more wary of new technologies (Boudet et al., 2014; O'Hara et al., 2015), and in people without higher education.

4.3. Methodology

Between February and July 2016, individuals from the 19 autonomous communities in Spain and Burgos province were contacted via different social networks in groups or associations related to the region where they lived. To avoid both positive and negative bias, the questionnaire was not sent or disclosed to people associated with pro and anti-fracking entities such as NGOs, trade associations and companies with an interest in the technology, even though other studies have considered this stakeholder approach in their methodology (Israel et al., 2015)

Besides to the contact through different social networks, regional authorities in Burgos were contacted, and the city government of Medina de Pomar, a municipality of Burgos, supported the survey dissemination. In Medina de Pomar, two shale gas investigation permits have been issued to date. In addition to this, two local newspapers were contacted and published brief items that described the ongoing research and called for participants.

Data evaluation consisted of extensive descriptive statistical evaluation of results, exploratory factor analysis, and multivariate data analysis to refine measures and attempt to explain variance among variables. Results of factor analysis were further explored by calculating Spearman's rank correlation coefficient to investigate the correlation among variables. Data were analysed using the software IBM SPSS Statistics, Microsoft Excel and R.

Results are therefore discussed based on the construal level theory, which postulates that individuals' thoughts and behaviour are influenced by psychological distance, which are traversed by mental construal processes (Trope and Liberman, 2010; Trope et al., 2007). The basic premise of the theory is that individuals use concrete, low-level construal's to near events and use more abstraction to the more psychologically distant events. Therefore, people experience different time, space, social distances, which hypotheticality may affect perception of the individual to the subject matter may have similar impacts (Trope and Liberman, 2010; Trope et al., 2007). For example, temporal, spatial, spatial, and probable proximity of shale gas development may determine pro or opposition groups as well as more awareness on this issue rather than in areas where its development is not likely.

4.3.1. Sampled populations and data gathering

The two populations targeted in this study were inhabitants of Spain and inhabitants from Burgos, the place where the most investigation permits have existed in Spain at the beginning of 2016. In total, 403 responses from Spain and 301 from Burgos province were obtained. As a result, 29 variables were considered with a total of 301 cases in Burgos, thus generating a case-per-variable ratio of approximately 10:1, and 403 cases in Spain with a case-per-variable ratio of approximately 14:1. It is assumed a variance as large as possible in the samples (p=q=0.5) and a confidence interval of 90%.

The research instrument consisted of a 19-question closed questionnaire in the Google Forms® platform, divided into three sections, and required an overall time of 5 to 10 minutes to complete. Questions and their coding are shown in the SM. A preliminary sample study was conducted to ensure that all questions had the same meaning to all participants and to ensure the time required was suitable for participants to answer all of the questions. The original questionnaire was first answered by volunteers, who noted some misunderstandings in the questions and other minor considerations, which were then rectified. To avoid labelling bias, the questionnaire just referred to 'hydraulic fracturing' as discussed previously.

The first part of the questionnaire included demographic and location characterisation, which are further summarized in the results section. In this section, other background information was included, namely previous experience in the energy sector, years and locale of residence. Questions in this group included age, gender, education (divided into three groups), area of residence, time of residence, employment in the energy sector and identification of autonomous community of residence (except for Burgos).

Sections 2 and 3 contained the questions related to the aim of the research itself. Section 2 elicited attitudes towards the environment and energy in two questions besides the perceived knowledge on energy sources. Reply options included 'yes', 'no' or 'I don't know' to (i) self-perception of environmental awareness, and (ii) concern about the country's dependence on foreigner energy resources. The level of knowledge of energy sources and technologies was evaluated in this section considering Likert scales (1=no knowledge at all to 5=expert). The energy sources listed were: conventional natural gas and oil, unconventional natural gas and oil, coal, nuclear power, and renewables (wind, solar, etc.) and bioenergy (biofuel, biomass, etc.).

Section 3 evaluated shale gas acceptance, risk perceptions and levels of knowledge, and also included a question of whether shale gas exploitation should be allowed in the country or not. It focused on the evaluation of perceived risks of shale gas, its impacts, and perception of economic benefits, to identify attitudes towards shale gas exploitation. This group consisted of 9 questions, of which 7 offered 'yes', 'no' or 'I don't know' responses while 2 were questions on a Likert scale (1=strongly disagree at all to 5=strongly agree) that aimed to identify:

(i) Impressions of shale gas impacts and acceptance. For this, it was asked if shale gas have more harmful environmental impacts than conventional gas and if shale gas exploitation in Spain be allowed.
(ii) Impacts on economy. To evaluate the perception of benefits, in this set the questions were if shale gas exploitation's benefits offset its risks and if the development of shale gas could benefit the economy.
(iii) Dependence on information and verification of the existence of enough information. For these, respondents were asked if they believed that there is enough information to have an opinion on shale gas, if more studies on shale gas should be performed? and if they Would change the declared opinion about shale gas development in Spain if impacts were proven to be negligible or properly manageable.

The authors are aware that questioning about a possible change of opinion could potentially be perceived as biased question, leading the participants to a more pro-shale gas stance by suggesting that existing (or perceived) uncontrollable environmental impacts shall eventually be manageable. However, the opposite bias can also be perceived by some participants, since the question may also be perceived as suggesting that shale gas exploration (where it is already implemented) currently does not have controllable impacts, leading some to mistrust regarding shale gas implementation due to a seemingly lack of technological maturity and faults in regulatory measures.

This question can be used as a proxy to evaluate how acceptance is linked to the existence of scientific information and if exposure to information matters when opposing to shale gas. In addition, the question intends to verify if scientific studies offer more controversy rather than support the resolution of controversies, as noted by different authors (Aklin and Urpelainen, 2014; Sarewitz, 2004). Therefore, the extent of negative answers to this question reveals that other factors rather than proven impacts may be affecting people, such as media, political views, etc., that can be further explored by other studies.

Questions in this section also intended to identify the perception of shale gas risks. The first question involved four main risks: (i) water contamination, (ii) atmospheric emissions, (iii) induced seismicity and (iv) lack of regulation. Finally, respondents were asked to identify if they believe that shale gas is a source of energy that can be considered (i) clean, (ii) reliable, (iii) cheap and if (iv) shale gas development could reduce the dependence on foreign energy.

4.3.2. Multiple linear regression, exploratory factor analysis, and correspondence analysis

In addition to the extensive descriptive statistics of the results, our approach was supplemented by three major steps: (i) multiple linear regression to identify predictors for shale gas acceptance alone, (ii) application of exploratory factor analysis to investigate data set structure (only the variables with a communality value greater than 0.4 were retained) and (iii) evaluation of the Spearman-rank correlation coefficient, which was meant to identify significant associations, positive or negative, between variables. Cronbach's alpha for Likert scales was calculated to test the reliability of answers, where values of 0.70 to 0.95 are considered acceptable (Tavakol and Dennick, 2011).

In general, a questionnaire's evaluation consists of connecting classification variables to the results to explain the observed behaviour or pattern, reducing the total number of variables to a more manageable number while retaining as much of the original variance as possible. Factor analysis is employed for being a multivariate data analysis tool for refining measures, evaluating constructs' validity, or testing hypotheses. The method consists of five steps: (a) defining the sample size, (b) calculating the KMO index and applying Bartlett's sphericity test, (c) extracting communalities and number of factors, (d) choosing rotation methods, and (e) analysing factor loadings, labelling and interpreting factors (further explained in the SM).

Finally, correlation between variables based on Spearman's rank correlation coefficient (r_s), or simply Spearman-rho, was adopted. This approach evaluates the strength and direction (either positive or negative) of the relationship between pair of variables.

4.4. **Results and discussion**

4.4.1. Descriptive evaluation of samples

Results from the first section of the questionnaire included location and other demographic aspects are shown in Table 4.1. For the statistical evaluation that follows, age groups from 55 years on up were grouped together, considering the small number of respondents. The demographic characterisation demonstrates great similarity among respondents from Burgos and Spain. Demographically, our samples can be said to be younger and more educated when compared to the general public.

Table 4.1: Descriptive statistics of participants.

Spain (n=403)	Sample (%)	Total population	Burgos (n= 301)	Sample
Gender				
Male	46.2	49.1	Male	47.5
Female	53.8	50.9	Female	52.5
Age[1]				
16-24	14.6	10.9	16-24	10.0
25-34	36.7	17.8	25-34	29.2
35-44	26.8	20.2	35-44	28.2
45-54	18.9	17.4	45-54	23.3
55-64	2.0	13.1	55-64	8.0
65-74	0.7	9.9	65-74	1.3
75 or more	0.2	10.7	75 or more	0.0
Highest academic qualification				
Primary school or less	1.0	21.5	Primary school or less	2.0
High school or similar	19.6	50.2	High school or similar	21.9
Bachelor's or higher degree	79.4	28.3	Bachelor's or higher	76.1
Autonomous community of residence				
Andalucia	16.6	18.1	Burgos province	100%
Aragón	2.2	2.8		
Asturias	1.5	2.2		
Basque Country	7.2	4.7		
Canaries	1.5	4.6		
Cantabria	4.7	1.2		
Castilla and Leon	13.6	5.2		
Castilla-la Mancha	2.7	4.4		
Cataluña	5.0	16.0		
Ceuta	1.0	0.2		

Spain (n=403)	Sample (%)	Total population	Burgos (n= 301)	Sample
Community of Madrid	18.4	13.9		
Community of Valencia	6.7	10.6		
Extremadura	1.7	2.3		
Galicia	6.5	5.8		
Islas Baleares	1.7	2.5		
La Rioja	2.0	0.7		
Melilla	1.5	0.2		
Navarra	3.5	1.4		
Region of Murcia	2.0	3.2		
Years living in this area				
Less than 1 year	7.4	Less than 1 year	4.0	
1-3 years	12.2	1-3 years	5.6	
4-6 years	8.2	4-6 years	7.3	
7-10 years	8.2	7-10 years	7.3	
More than 10 years	64.0	More than 10 years	75.7	
Residence area				
Rural	15.9	-	Rural	29.6
Suburban	10.7	-	Suburban	6.2
Urban	73.4	-	Urban	64.1
Employment in energy industry				
Yes, in the past	4.0	-	Yes, in the past	3.7
Yes, at this moment	4.0	-	Yes, at this moment	4.0
No	92.1	-	No	92.4

[1]: For the total population in Spain, values were normalized excluding the age group 0-15.

Although our results cannot be extrapolated to the entire Spanish population, it represents the opinion of educated people in the country towards shale gas exploitation and exploration and represent a step for theorizing about the opinion of other groups. Bias in educational levels may be related to the fact that respondents participated in the survey voluntarily, which can indicate that this matter is more sensitive to people with higher educational levels.

4.4.2. Attitudes towards environment, energy and perceived knowledge

Preliminary questions analysing attitudes towards the environment (Section 2 questions, please refer to the SM for the full list) indicate that variables are highly skewed. The question "Are you concerned about environmental preservation in your country?" received 98% of 'yes' answers for both Spain and Burgos. Concern for dependence on foreign energy resources was declared by 87% of the respondents in Spain and by 82.1% in Burgos.

Following this, Section 3, questions 3 through 8 (please refer to the SM for the full list) evaluated the reported knowledge of different energy sources for each sample. The results are shown in Table 4.2:. The reliability of the attitude scale is adequate (Cronbach's alpha for

Spain = 0.880 and for Burgos = 0.928). For both samples, most respondents claimed to know only ‘a little’ about most technologies. On average, participants were most familiar with renewable energy, followed by conventional oil and gas and coal.

Participants reported the least familiarity with unconventional oil and gas, respectively (Table 4.2). These results find comparison, although on a different scale, to the evaluated level of knowledge of shale gas in the UK and in the US. In these countries, a relevant number of participants (67% in the US and 28% in the UK) reported to not know or replied incorrectly when asked what shale gas is (Stedman et al., 2016). This trend is also observed individually in the UK in BEIS (2016). For this, we concluded that unconventional gas remains a largely unknown issue.

However, the percentage of people that evaluated their knowledge as very high is larger in Burgos than Spain for each category presented. That can be interpreted as a difference of exposure to media content and debate regarding energy, particularly shale gas, in recent years due to the predominant location of projects in the Burgos area in comparison to the rest of Spain. However, unconventional gas and oil received more than half of the choices in the categories ‘very low’ and ‘below average’ concerning all other energy sources in both samples.

Table 4.2: Perceived knowledge of energy sources.

Energy Source	Area	Very Low (%)	Below Average (%)	Average (%)	Above Average (%)	Very High (%)	Mean (1-5)	SD
Conventional natural gas and oil	(1)	6.20	15.88	45.41	27.05	5.46	3.10	0.94
	(2)	8.31	18.27	43.52	20.93	8.97	3.04	1.04
Unconventional natural gas	(1)	31.27	23.82	24.81	17.12	2.98	2.37	1.18
	(2)	21.26	25.58	26.25	18.27	8.64	2.67	1.24
Unconventional oil	(1)	30.77	28.54	26.80	11.17	2.73	2.27	1.10
	(2)	25.25	32.23	23.92	11.96	6.64	2.43	1.18
Coal	(1)	8.93	18.86	42.18	25.81	4.22	2.98	0.99
	(2)	8.31	17.61	42.52	23.59	7.97	3.05	1.03
Nuclear energy	(1)	9.68	18.86	43.18	24.32	3.97	2.94	0.99
	(2)	8.31	18.60	40.86	24.92	7.31	3.04	1.03
Renewable energy	(1)	3.47	13.65	39.21	32.51	11.17	3.34	0.97
	(2)	5.98	12.29	35.88	31.56	14.29	3.36	1.06

(1): Spain / (2): Burgos. SD: standard deviation.

The effect of proximity to shale gas is critical to the reported perceived level of knowledge and awareness of the population and it is possible to infer that this can be noted in the indication of perceived knowledge of participants living in Burgos. This finding is coherent with previous studies which observed that people living nearby or in high density shale gas exploration were more likely than those living in low well-density areas to report they had gained some degree of knowledge about hydraulic fracturing from the natural gas industry and regulatory agencies (Theodori et al., 2014).

This fact aligns with the construal theory, as people in Burgos are physically closer to potential exploration areas as well as socially which, accompanying by a more available information on the regional level, may help explain this seemingly better knowledge at least in a perceived way. This indicates that the people from Burgos might think of energy sources in a more concrete way as postulated by the construal theory.

4.4.3. Shale gas exploitation acceptance

Section 3 goes on to ask if shale gas should be allowed (question 10). In Spain, 52.4% of participants said no while 38% did not select an opinion. Confirming one of the research hypothesis, this demonstrates a relevant level of division among the population across different autonomous communities, which increased according to the proximity to existing shale gas investigation permits (Figure 4.1).

However, the majority of participants stated that there is not enough information to have a reliable opinion on shale gas (53.6%, result of question 13), that more studies should be performed (68.7%, result of question 14) and that their opinion could change according to results of further research on environmental impacts (49%, result of question 15). These results are compatible to other findings in that literature regarding the low familiarity of the public with shale gas development (Clarke et al., 2016; Graham et al., 2015c).

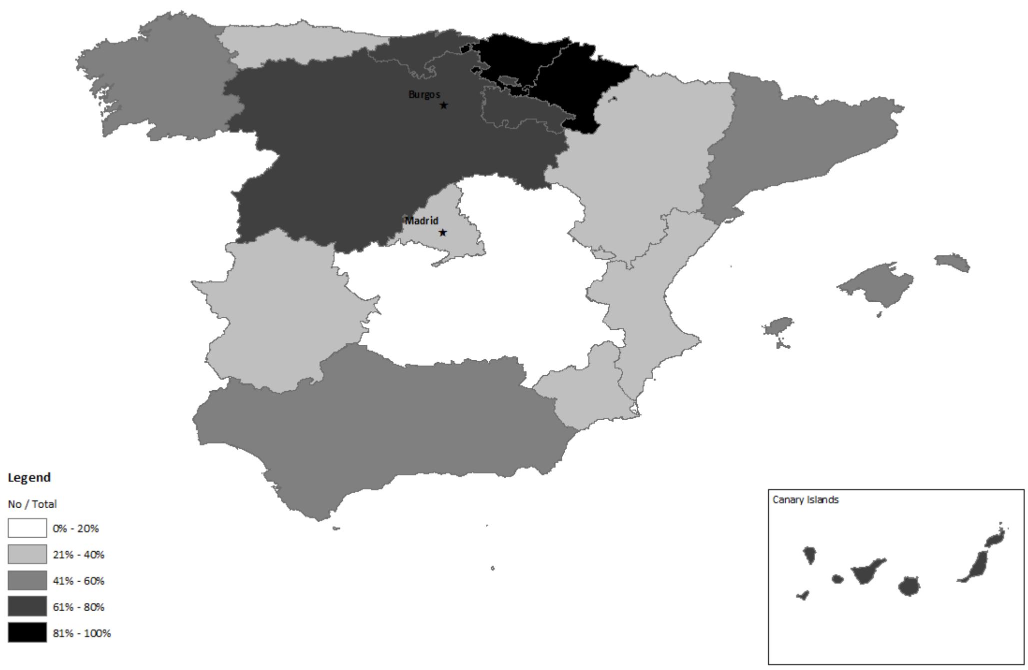


Figure 4.1: Shale gas rejection per autonomous community.

For Burgos province, the rejection of shale gas is noticeably higher (question 10). In the province, 70.8% of the respondents said that it should not be allowed in the country and 70.4% said that the impacts do not overcome the benefits of exploitation. In Burgos, 74.4% claimed that more studies should be conducted, but almost half (50.2%) said that even with more studies they would not change their opinion about shale gas exploitation. These differences in the willingness to change opinion on shale gas in face of new scientific studies demonstrates a certain level of scepticism for the population in Burgos, which suggest that more investigation on factors leading this opposition should be performed.

All of these questions (question 10 through question 14) also indicate that there is always a lower percentage of the public declaring no opinion on the subject in the Burgos region. As a result, this data demonstrates that in a physically and socially closer location to shale gas exploration projects there is a more concrete and well-defined opinion on the subject as postulated by the construal theory. This seemingly more stable and definitive opinion on shale gas is reinforced by the fact that the percentage unwilling to change opinion is higher in Burgos, even if the percentage of 'no opinion' is similar between both samples. Furthermore, this data also might indicate that opposition to shale gas when comparing regional to national public opinion can be narrower than previously thought, since the large differences observed can be a combination of actual opposition plus a dilution due to lower indecision at the regional level.

Acceptance by age groups did not reflect the expectation that older people would be more opposed to the introduction of a new technology in comparison to younger people for both samples by age groups (16 to 24 for group 1, 25 to 34 for group 2, 35 to 44 for group 3, 45 to 54 for group 4 and above 55 for group 5). In Burgos and Spain, acceptance with permitting shale gas was stronger in age groups 2 and 5. However, there was a relevant high level of indecision among younger age groups.

In total, only 23 people from Burgos declared having experience in the energy sector, either in the present or past (7.6% of the sample). Even though it is not representative, it is possible to sense some ambivalence towards shale gas, since nearly the same number of participants reported opposition (n=10) and support (n=9) for development, which neither confirmed or denied one of the research hypothesis. However, this group is known to be more assertive regarding this matter compared to the rest of the sample, since 'do not know' answers were much lower.

For Spain, this number is slightly higher, corresponding to a total of 32 (7.9% of the sample) and among them, the opinion on shale gas permission was almost perfectly divided in the three possible answers. These results contradict one of the research hypothesis, as experience in the energy sector did not have any particular relevance in defining shale gas acceptance in the samples.

However, when comparing both samples, the level of indecision among people who have worked in the energy sector (17.4%) is lower in the same group in Spain (34.4%) and opposition is higher (43.5% in Burgos and 37.5% in Spain). These results agree with the basis of construal level theory and other literature findings as they indicate that this group (which is less socially distant to shale gas development) have less ambiguous beliefs of support or opposition to shale gas (Clarke et al., 2016; Trope and Liberman, 2010; Trope et al., 2007). More specifically, comparing the results of this group between Spain and Burgos, there is also hints at the fact that former energy workers in Burgos also have stronger and more defined opinions than their remaining Spanish counterparts.

Opposition increased markedly according to longer residence time, confirming one of the research hypothesis. In Burgos, 77.3% and 75.4% of people living for 7-10 and for more than 10 years in the area, respectively, declared themselves against shale gas exploitation. For people living in rural areas, opposition was 86.5%, followed by 11.2% indecision. In Spain, opposition based on years of residence was more diversified and, ranged from 40 to 50% for all living years categories. For residence area (rural, urban or suburban) nearly 70% of professed rural residents declared opposition to shale gas development.

The comparison of results from both samples demonstrates that rural residents tended to be more contrary to this technology, since in a possible shale gas development scenario they would be more impacted (the majority of projects licensed are near less populated areas), confirming one of our research hypothesis. This effect can be explained not only by the proximity to the probable exploratory site in the construal level theory, but also by social representation theory, place attachment and impacts on human flourishing in rural communities (Clarke et al., 2016; Evensen and Stedman).

In order to obtain a deeper understanding of predictors to acceptance, multiple linear regression was performed (summarized in the SM) for both samples resulting in a coefficient of determination (adjusted R2) equivalent to 0.59 for Burgos and 0.68 for Spain. The evaluation demonstrated no significant correlation to demographic variables. Significant variables for both samples were observed for questions 9, 11 and 19, with positive correlation for acceptance, that showed that reported lack of knowledge on impacts of shale gas in comparison to conventional gas and benefits, and a lack of confidence in existing legislation are important predictors for rejecting shale gas.

Particularly for Burgos, 3 out the 4 pro-shale arguments (questions 20, 21 and 23), correlates negatively to acceptance, i.e., disagreement on these arguments determine more opposition to shale gas. For Spain, not believing that fracking would benefit national economy (question 12) and lack of information on it (question 13) are drivers for opposition. On the other hand, shale gas rejection is related to the perception that more studies are necessary (question 14).

These results seem to adhere to the construal level theory in the studied populations, despite the limitations of this concept which were discussed in different studies in the literature (Clarke et al., 2016; Komendantova and Battaglini, 2016). The construal level theory has frequently been used by different stakeholders to explain the possible gap in public opinion over an issue. Although people that are closer to shale gas development are more aware and concerned with its possible impacts and are also more exposed to information and debate over them, it is important to point out that different explanations other than geography can explain different declarations over an issue (Bell et al., 2013; Komendantova and Battaglini, 2016).

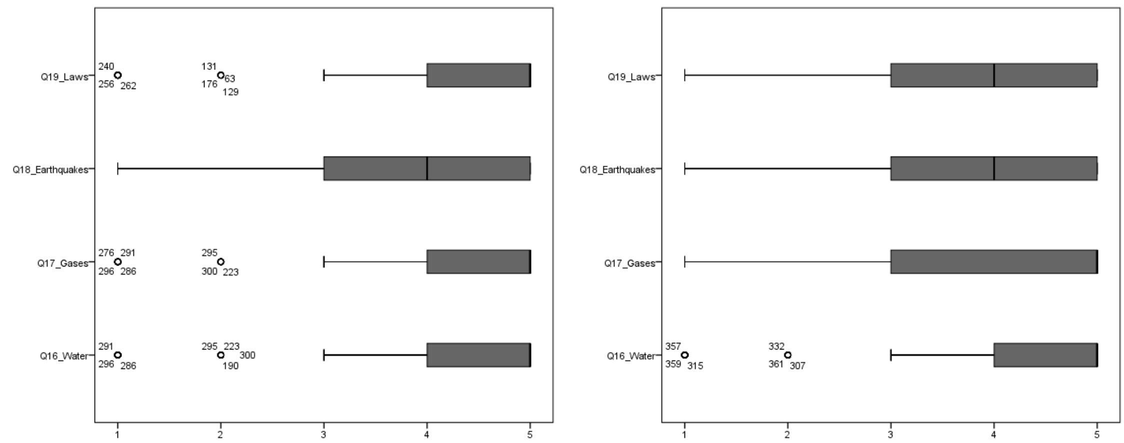
Particularly for Burgos, rejection was demonstrated to be more related to disagreement with pro shale gas arguments (which could have more direct impact over this population), representing a strong exposure to the fracking debate. This finding contradicts the hypothesis the possible economic benefits could be a driver for shale gas acceptance. Conversely, the rest of the country shows that rejection is related to the lack of information on it and possible economic outcomes, indicating that self-interest on exploration is also a possible social gap among the samples.

4.4.4. Perception of risks versus benefits of shale gas

Agreement on typical arguments used against shale gas development were presented to the participants on a Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree), results can be seen in Figure 4.2. The evaluation was based on results of questions 16 through 18 (Cronbach's alpha = 0.761 for Burgos and =0.716 to Spain). However, by removing question 19, Cronbach's alpha increases to 0.932 in Burgos and to 0.856 in Spain. This suggests that legislation is still a concern that is not fully explored in the fracking debate, yet it is influenced by proximity of exploration in the case of Burgos, which indicates that large differences of neutral responses when compared to Spain.

These classes of risks were selected to avoid an excess of technical terms, especially because the literature shows that word choice matter when evaluating acceptance (Evensen, 2016). The risks presented were based on (i) the fact that it is extensively known that hydraulic fracturing requires large amounts of water, (ii) methane emissions from NG are a major concern for climate change, (iii) induced seismicity became a major concern since two seismic tremors, or minor earthquakes, occurred due to exploratory drilling by Cuadrilla Resources at its Preese Hall drilling site located near Blackpool, north England (Clarke et al., 2014; TRS and TRAE, 2012) and (iv) there is no sanctioned legal framework specific to unconventional gas extraction, so conventional hydrocarbon exploration and extraction requirements would apply (Ballesteros et al., 2013).

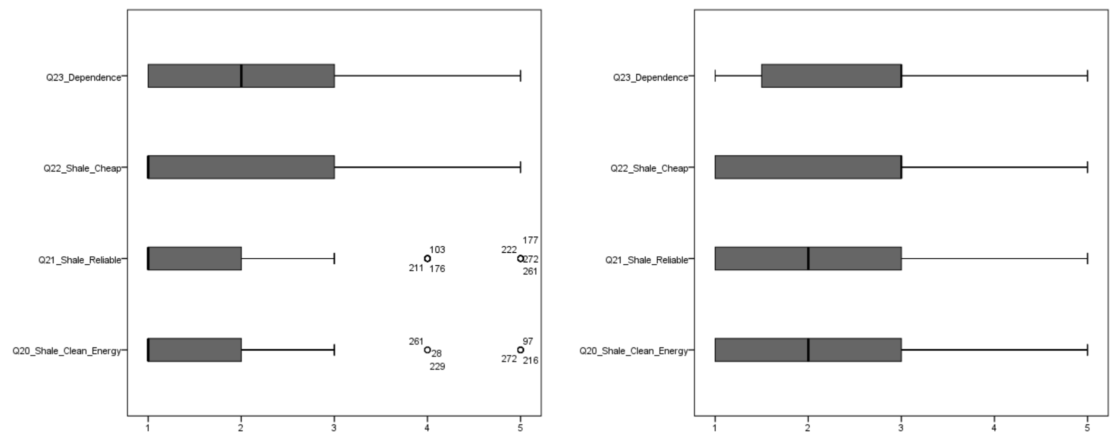
Results converged on the fact that people in Burgos showed more concern over the risks when compared to people in Spain. Lack of risk awareness can be due to the poor communication of impacts and benefits of shale gas and the inexistence of a reliable regulatory framework. In addition, no evidence of a comprehensible program of financial benefits and impact compensation was indicated for the areas and communities where shale gas projects are likely to be developed. The existence of such programs would change the provision of positive information on shale gas, potentially affecting the acceptance of its development, an effect which has already been demonstrated in the literature (Burger et al., 2015; Whitmarsh et al., 2015).



Scale: (1) Strongly Disagree / (2) Disagree / (3) Neutral / (4) Agree / (5) Strongly Agree. Numbers refer to participants id number.

Figure 4.2: Agreement with arguments used against shale gas development in Burgos (left) and Spain (right).

Analogously, agreement on typical arguments in favour of shale gas development were presented to the participants on a Likert scale (Cronbach's alpha = 0.911 for Burgos and =0.759 to Spain), ranging from 1 (Strongly Disagree) to 5 (Strongly Agree) in Section 3 (questions 20 through 23) – see Figure 4.3. The respondents were asked to rate their agreement to the following statements on shale gas as an energy resource: (i) it is a clean, (ii) it is a reliable, (iii) it is cheap and (iv) its development could reduce the dependence on foreign energy. Results demonstrated a greater scepticism about unconventional gas development for the Burgos region compared to Spain in general.



Scale: (1) Strongly Disagree / (2) Disagree / (3) Neutral / (4) Agree / (5) Strongly Agree. Numbers refer to participants id number.

Figure 4.3: Agreement with pro shale gas development arguments in Burgos (left) and Spain (right).

It was observed that 51.9% and 70.4% of respondents for Spain and Burgos, respectively, based on results from question 11 considered that the risks are insurmountable and the benefits are not sufficient to offset them. Even though risk is a concept that is also culturally biased (it is affected by ways of living and perception of each place) and difficult to quantify, these findings are consistent with results from the UK and in Canada, where similar surveys showed that risks associated with fracking were perceived as not possible to be compensated by its benefits (Thomas et al., 2017).

Risk perception can change overtime as a result of the complexities of the energy transitions in society (Sovacool, 2016). Based on the construal level theory, the rapid pace of shale gas development or the increased familiarity of it can determine low-level construals, i.e., less abstract. Therefore, evaluating risk perceptions and acceptance overtime is paramount. It has been previously shown that opinions on shale gas may become more divided (Mazur, 2014) or opposition can increase, as in the UK (BEIS, 2016) and in the US, (Perry, 2012) based on when it will be exploited or increased familiarity with it.

4.4.5. Exploratory factor analysis

For Burgos province, the 301 cases and 29 variables generated case-per-variable ratio of approximately 10:1, indicating a sufficient sample size, and a KMO index of 0.83. Bartlett's sphericity test indicated significant correlation between the variables (p-value < 0.05), allowing exploratory factor analysis. The Kaiser and Elbow criterion indicated the extraction of 4 factors, with a total of 45% of explained variance.

The table of communalities demonstrated that age, gender, education, place of residence, residence time, employment in energy industry, concern over environmental protection, concern over energy dependence, assertion of proper information on shale gas, need to develop more studies, possibility of changing opinion and perception of legal regulation did not explain behaviour patterns and variance in the sample. Removing these variables and extracting 4 factors, all communalities were significant, and the explained variance increased to 72%.

Following this, the four factors represented clusters of variables that significantly correlated and can be identified as follows: (1) extent of knowledge of energy sources – for all sources, (corresponding to questions 3 through 8, for both populations), (2) perception of shale gas benefits (corresponding to questions 20 through 23, for both populations), (3) perception of risks related to induced seismicity, GHG emissions and water (corresponding to questions 16 through 18, for both populations), and (4) perception that benefits could compensate exploratory risks, perception that shale could be beneficial to the national economy, opinion that shale gas exploitation should be allowed in the country, the perception that shale gas has more impacts on the environment (corresponding to questions 9 through 12, for both populations). Correlation among factors identified that factor 1 had mild positive correlation with the factor 3 and mild negative correlation with factor 4. Factor 2 was not strongly related to the others.

Similarly, for Spain the 403 cases and 29 variables generated a case-per-variable ratio of approximately 14:1, demonstrating sufficient sample size, and the KMO index was 0.82. Bartlett's sphericity test indicated a significant correlation between the variables (p-value < 0.05), allowing exploratory factor analysis. The Kaiser and Elbow criterion indicated the extraction of 4 factors, with a total of 43% of explained variance.

The table of communalities demonstrated that for Spain, the same variables which did not significantly correlate with any factor in Burgos were also excluded. The exclusion led to an increase of explained variance to 69%. Following this, also four clusters were observed that can be represented similarly to Burgos' factors (please refer to the SM). However, a difference in factor correlation was verified and only factors 1 (perceived knowledge) and 3 (perception of risks) correlated positively.

Results indicated both positive correlation between factors 1 and 3 for both Spain and Burgos, i.e., the more the respondents affirmed knowing about energy sources, the more concerned on shale gas impacts. On the other hand, the correlation between clusters 1 and 4 (acceptance) in the case of Burgos: the more respondents expressed knowledge, the more they reject any argument in favour of shale gas. The opposite correlation was found for Spain, although in this case it was not large enough to be considered statistically significant (r_s= -0.259) and this finding should be explored in similar studies in the country. In the light of the construal level theory, these findings can be explained by a low-level construal, in which individuals have more concrete opinion on concern due to the phycological distance.

4.4.6. Correlation between variables

Strong correlations between the knowledge of any energy source to any other were found for both Burgos and Spain (questions 3 to 8). These results reinforce the conclusions obtained in the factor analysis and the evaluation of Cronbach's alpha for the reliability of the Likert scale. In addition, the same trend was observed in the other two sets of questions that were based on Likert scales (questions 16 to 19 and questions 20 to 23).

Focusing more specifically on correlations between knowledge of shale gas as an energy source and remaining questions, there are several negative correlations for both Spain and Burgos for questions 9 through 13. For example, in both populations, the more knowledge on shale was claimed, the less likely the person was to accept shale gas exploitation, that benefits might offset risks, that shale exploitation is beneficial to national economy and finally that there is not enough information on the subject. This result answers one of the research questions, and finds comparison in the work of Choma et al. (2016) and the UK population assessed in the study by Stedman et al. (2016).

Perception of shale gas risks (except for the legal framework) and benefits among the proposed categories were all very related ($0.567<r_s<0.773$ for risks and $0.595< r_s<0.820$ for benefits) amongst themselves in both samples (i.e., different risks correlated highly with each other, as well as pro gas arguments), reinforcing the results of the factor analysis. As expected, there was strong tendency of risks being perceived as a whole and not compartmentalised into a single category. Particularly, correlations for counter shale gas arguments were stronger in Burgos and correlations for pro shale gas arguments were slightly stronger in Spain, thus demonstrating different levels of construals over samples.

The legal framework was the only variable from the arguments in favour of shale gas that was excluded from the factors (Section 4.4.5). With this in mind, we investigated its relationship with other variables in the Burgos province and Spain. For both samples, this variable had a mild negative correlation ($0.329<r_s<0.460$) with the set of questions on the pro-shale gas arguments (questions 20 to 23). This demonstrates that the perception of benefits is linked to the existence of a reliable regulatory framework, which induces the conclusion that better legislation would facilitate acceptance by the general public.

This can be accounted to possible drawbacks from shale gas which can be exacerbated considering there is no sanctioned legal framework specific to unconventional gas extraction (Ballesteros et al., 2013). To date there is no specific legislation or licensing procedures regarding unconventional gas activities at the EU level even though efforts to close these regulatory gaps have already been undertaken in the Commission Recommendation 2014 document (EU, 2014a).

Rejection of shale gas exploitation in Spain and Burgos (question 10) shows a strong positive correlation (r_s=0.707 for Burgos and r_s= 0.804 for Spain) with the view that benefits could compensate the risks (question 11), i.e., the more one believes it should not be accepted, the more it is believed that its possible positive economic effect on the country would not overcome risks. Mild positive correlations were ($0.300<r_s= 0.700$) observed in both samples when asked if shale gas have more environmental impacts than conventional natural gas (question 9), regarding the perception that benefits could offset risks (question 11) and that shale gas exploitation would benefit countries that exploit it (question 12). These results demonstrate that the perception that benefits can compensate risks does not explain opposition alone.

4.5. **Conclusions**

There is growing recognition of the need to understand public attitudes to energy sources, such as shale gas, and to consider these views in policymaking. This article fills the gap of the inexistence of an assessment of public perception of hydraulic fracturing in Spain. The results showed that shale gas development is a controversial subject and the responses obtained in this study can be particularly important for policymakers seeking to balance the needs of local communities grappling with unconventional oil/gas development with those of broader regional or national populations.

However, the present results should be considered albeit with some limitations. The methodological choice of a social network for recruitment used no incentives for participation, which may have caused the bias observed in educational levels. As such, this limitation should be considered when interpreting these results.

Based on a statistical evaluation, our results did not show important statistical correlations in demographic aspects of samples. Both samples showed important differences on perceived risks of shale gas, perception of benefits and its acceptance. Those living in a region where shale gas is more likely to occur were significantly less positive than those living where shale gas fracking is not viable, both in terms of autonomous communities and in rural areas.

According to our results, the strong rejection for shale gas revealed in the Burgos province at an individual level can be potentially explained by the proximity to the area, protection of rural areas, and mostly the lack of presentation of environmental compensation programs and practices. However, to date, the absence of a comprehensive program of financial and impact compensation for the areas and communities where shale gas projects are likely to be developed in Spain can be understood as another relevant driver of public rejection.

For both samples, opposition was more strongly associated with the level of knowledge about energy sources and the related risks. This implies the more alleged knowledge of energy sources, the more negative the perception of respondents on shale gas and, consequently, the more they oppose shale gas. This is a tendency that was already observed in the US and in the UK. In addition, statements about knowledge in Burgos presented a negative correlation with the perception of benefits, which is an indicator of rejection in this area.

This survey highlights the potential differences of opinion in regional versus national interest and rural versus urban settings but more importantly the degree of knowledge and high level of indecision among respondents. Our findings reveal a low level of perceived knowledge of shale gas and unconventional energy resources in both samples. However, awareness on shale gas activities is higher according to the proximity to shale gas development. This is consistent with similar evaluations in the USA and reveals a need for improvement of knowledge and risk communication among all individuals, which can be considered an important challenge to researchers and other stakeholders.

Communication among stakeholders is paramount to properly inform different aspects of new technologies and to evaluate arguments in favour or against them, allowing a better understanding of public attitudes to develop better policies and ensure a better allocation of resources in society. Risk communication efforts can help increase awareness of shale gas development impacts and promote a clearer understanding or more informed opinion, changing misperceptions associated with energy development.

Regulation and a comprehensive compensatory strategy for shale gas exploration remains an important issue in the EU and relevant drivers for public opposition. Policymakers and energy companies should not only consider the average evaluation of a technology, but should also take the general public into account in their decision-making process and communication strategy to avoid poor communication of risks and among stakeholders' increased opposition. Therefore, further efforts should continue to be made by the scientific community to support initiatives to evaluate and insert public opinion in energy decisions.

This study lays the groundwork for future studies in this field and for the establishment of new policies in Spain. It raises the issue that the implementation of technologies without proper risk communication would affect opposition. Future studies should focus on examining whether the provision of information would change perception and acceptance of shale gas development, which is similar to existing studies in the literature. Besides the regional aspect of the research, this work can also be used as a comparative reference for other European countries and to existing evaluations in the USA.

Further efforts should continue to be made by the scientific community to evaluate whether public acceptance is taken into account during decision making process on energy shifts overtime. Future energy systems will likely consist of multiple energy technologies and this may be taken into consideration when informing or evaluating acceptance of new technologies, assessing their shares and present their consequences to the security of supply. Considering this as a perspective, maintaining periodic surveys on public attitudes is an important strategy for environmental management.

Acknowledgements

We acknowledge IBRASIL (Inclusive and Innovative Brazil project, an Erasmus Mundus Action 2 programme funded by the European Commission) for the PhD grant. We also thank Filipe Barros and João Jesus for their support and contributions.

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5. Life cycle assessment of a shale gas exploration and exploitation project in the province of Burgos, Spain

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Abstract

Shale gas is an unconventional resource that has been generating a great deal of debate in Europe. Yet, their potential environmental impacts are poorly assessed in the literature. Therefore, this study is a life cycle assessment (LCA) of shale gas exploration using, as a case study, a gas well under appraisal located in the province of Burgos, Spain. The system boundaries assessed include pre-production, gas production and distribution to final consumption. Results, expressed per 1 MJ of processed natural gas, show that the most critical operations over shale gas life cycle are from pre-production (the well design, drilling and casing, as well as the hydraulic fracturing) and from production (natural gas production, gathering and processing). The comparison of the results obtained with results from similar LCA studies, shows a large variety for the environmental impacts categories due to the different modelling approaches and data used. The exception is found for global warming potential and abiotic depletion of fossil fuels. Ecotoxicity impact categories are also identified as the ones where larger uncertainties discrepancies across literature on shale gas and the impact categories to which the larger are observed. The model created was found to be relative sensitive to water usage and to the number of workovers with hydraulic fracturing and, to a lesser extent, to the estimated ultimate recovery, the gathering lines length and the rate of penetration of the drilling rig. The uncertainty analysis, on the other hand, reveals the relative uncertainty associated with toxicity related impact categories limiting drawing conclusions for these. Even though the environmental impacts remain controversial, shale gas in Europe remains as a strategic energy resource and the possibility of its exploitation and exploration should be considered by adopting a precautionary principle.

Keywords: life cycle assessment, shale gas, Spain, sensitivity analysis, Monte Carlo simulation

5.1. Introduction

Natural Gas (NG) is considered as a reliable, efficient and clean-burning fuel that can be used in a wide variety of applications. Its usage today spans more than 20% of the total world primary energy demand (IEA, 2016). Despite the existence of some uncertainty regarding the role of NG in Europe, it is frequently regarded as a transition fuel towards a low carbon economy (EC, 2011; Johnson and Boersma, 2013a).

Markets for NG have suffered important changes in recent years. These changes account for the large expansion of unconventional reserves in the United States of America (USA), more specifically shale gas, the internationalization and growing supply of Liquified Natural Gas (LNG) and the occurrence of extreme events (such as the Fukushima Daiichi event in 2011), which have changed the energy profile used in some countries (Costa et al., 2017a).

Due to the transformation of the energy industry in the USA following the so-called 'shale boom', the debate of shale gas production in Europe as an energy security issue have increased due to the high dependency on NG imports by European countries (Balitskiy et al., 2014; Erbach, 2014; Johnson and Boersma, 2013a). Although shale gas development may not transform Europe in a self-sufficient region for the NG supply, it could contribute to the reduction of imports in the upcoming years (Pearson et al., 2012).

Shale gas exploration and exploitation seems to be viable in Europe based on the extent of technically recoverable reserves, which have been reported to be equivalent to 15.5 trillion cubic meters of wet shale gas in Eastern Europe and 255.3 trillion cubic meters in Western Europe (EIA, 2015b). However, concerns of its environmental and public health impacts led to a strong public opposition among individuals from European countries that have been translated into bans to its exploration in several countries (EC, 2013a; Lis et al., 2015).

Although the environmental impacts of shale gas have been extensively discussed recently in literature, the majority of existing studies only evaluate single environmental categories (Costa et al., 2017b). This can be accounted to the relative immaturity of the shale gas industry worldwide and reflects in the relative scarce number of LCA studies available considering a wide number of impacts categories over the life cycle of a potential shale gas exploration in Europe.

To bridge this gap, this work assesses the potential environmental impacts of NG from shale formations (or simply shale gas) in Europe, through the life cycle assessment (LCA) methodology (ISO 14040:2006). A case study based on an investigation permit located in the Cantabrian Basin, located at Burgos province, Spain (BNK, 2014) was used as the basis for this work. In this study, the life cycle stages: pre-production, production, and distribution of shale gas to final consumer are evaluated. To better assess the model parameters, both a sensitivity and uncertainty analysis used are performed.

5.2. Background

5.2.1. Shale gas exploration in Spain and case study

The quantity of NG used in Spain in 2015 has served distinct demands, from which we can highlight the uses in industry (used a share of 36.3%), households (23.0%) and for electricity generation (17.7%) (MIET, 2016). Despite the fact that consumption increased over the past several years (Sedigas, 2017), approximately 97% of the NG consumed in the country was imported (CORES, 2016) by pipeline or in the liquefied form from a wide variety of suppliers (BP, 2016; CORES, 2016).

Due to the increase in NG demand, exploitation and exploration of shale gas has been identified as an alternative to reduce energy dependence in the country by 2030 and a way to make the country a net gas exporter by 2050 (Deloitte, 2014; DSN, 2015). Despite of the public opposition from the population (Costa et al., 2017c), the Spanish government has considered the exploration and exploitation of unconventional hydrocarbons in the country as an option to ensure energy security and to reduce its large energy dependence (DSN, 2015).

Until April 2017 there were four active investigation permits under the responsibility of the national administration in three Spanish provinces (MINETAD, 2017). The work carried out focuses on the investigation permit called Urraca 1, which is located in the province of Burgos (Spain) and used as a case study for this work (Figure 5.1) selection of Urraca 1 was done because it is the permit in the most advanced state of development in Spain. Although no decision on the exploration for this site has been taken, this permit was under the appraisal phase of the environmental impact study carried out for this project in the beginning of this research (ACIEP, 2015a; BNK, 2014). This is to say, a large amount of data specific from Urraca 1 is available and was used in the present study.

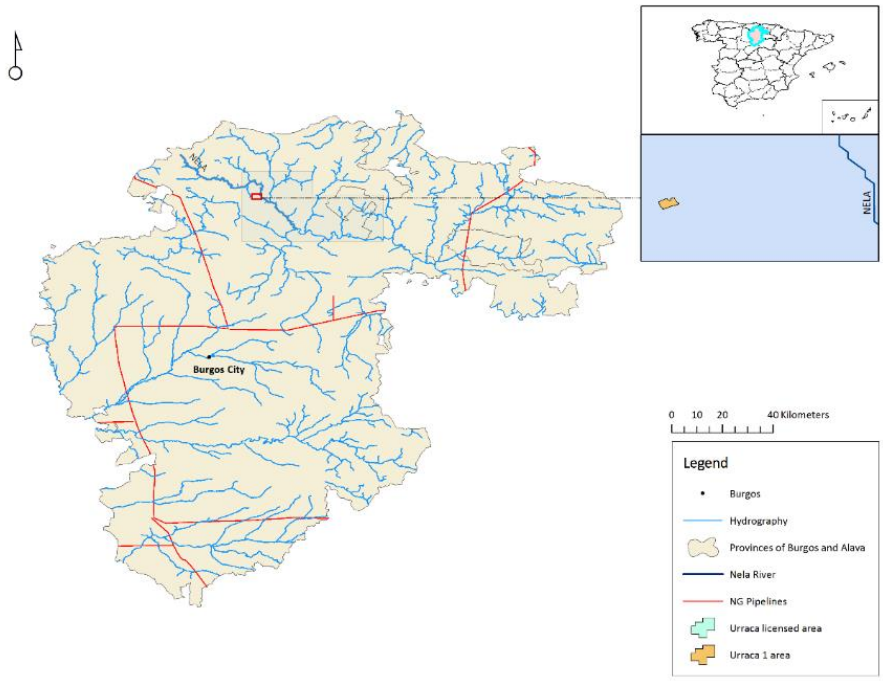

Figure 5.1: Localization of the site used as case study (Urraca 1) in the province of Burgos, Spain.

5.2.2. Life cycle assessment of shale gas in the literature

The interest in the investigation on shale gas is shown by an increase in the number of shale gas publications between 2010 and 2015, as well as a diversification of the geographical coverage (Costa et al., 2017b). It is important to note that there is also an increase in the number of articles looking at future explorations in Europe. The literature review also showed that only a small number of scientific studies focus on the evaluation of environmental impacts caused by shale gas production by taking a life cycle perspective.

Among the studies that used the life cycle perspective and assed the environmental impacts from shale gas, the review indicated that there are significant differences in the way the impact of shale gas production was assessed. These choices to assess environmental impacts can be grouped into differences in methodologic options or modelling parameters choice.

In the first group, one can account for the difference in the functional unit adopted. It may be the delivery of NG or the production of electricity in the use phase (Stamford and Azapagic, 2014; Stephenson et al., 2011b; Tagliaferri et al., 2016). This is also strictly related to the differences observed for the system boundaries considered in the review studies. Additionally, the number of impact categories assessed does vary. Most of studies focus on just one single environmental aspect, as the emissions of greenhouses gases (GHG) (e.g. Burnham et al. (2012b), Chang et al. (2014b); Howarth et al. (2011a); Laurenzi and Jersey (2013a), Jiang et al. (2011a), Jaramillo et al. (2007), or water (e.g. Jiang et al. (2014a) and Laurenzi and Jersey (2013a).

The second group refers to the different model parameters considered among studies (Chang et al., 2014b; Tagliaferri et al., 2016). An example is that the choice of emission factors for diesel consumption does not make a distinction between stationary and mobile emissions from combustion (Chang et al., 2014b; Tagliaferri et al., 2016). In addition, emissions factor considered may not reflect specific geographical emission (Chang et al., 2014b). Another example is the exclusion of Reduced Emission Completions (REC) during well completions in several studies (Chang et al., 2014b; Jiang et al., 2011a; Raj et al., 2016), even though this technology is being used on more than 90% of shale wells completions (ANGA, 2012; EPA, 2017; O'Sullivan and Paltsev, 2012).

Of the studies examined, only three evaluate LCA impacts from shale gas exploration and exploitation considering different environmental impacts categories, namely, Cooper et al. (2014); Tagliaferri et al. (2016) and Stamford and Azapagic (2014). However, all of them only refer to the context of the UK. When analyzing the selected studies, several aspects are identified to be lacking, such as a comprehensive and detailed description of operations and a detailed disclosure of data considering current field practices in shale gas exploration. Some examples include the disclosure of operation parameters used (e.g. drilling rig power, penetration rates of the drilling rig, cementing time), waste management practices (e.g. reuse of drilling mud and flowback water) and the exclusion of life cycle stages (such as site preparation and well abandonment).

To fill the identified gaps, this study assesses the environmental impacts from a shale gas investigation permit under appraisal phase, Urraca 1, located in Burgos province (Spain). This is done by using site specific parameters and providing details for them (e.g. details on the well drilling, casing and cementing operations), inclusion of overlooked life cycle stages in other studies (e.g. pad preparations and site abandonment), covering current and adequate waste management practices (e.g. recycle rates of drilling), and by making use of statistical distributions to analyze the influence of the variability of data (e.g. water consumption in hydraulic fracturing) in the assessed environmental impacts.

5.3. Materials and methods

5.3.1. Goal and scope definition, system boundaries and functional unit

This study assesses the environmental impacts associated with a shale gas exploration and exploitation project in the province of Burgos (Spain) under licensing phase (so called Urraca 1). The functional unit is 1 MJ of processed NG (considering its lower heating value – LHV). Unprocessed NG has a LHV of 41.4 MJ/m^3 and a density of 0.86 kg/m^3 (unprocessed NG) (API, 2009). Processed gas follows the requirements for transmission in Spain and has a LHV of 42.2 MJ/m^3 and 0.80 kg/m^3 (BOE, 2013d). The latter is delivered to the low-pressure distribution network, which is responsible for the supply of NG to the end-consumer. The closure of the well is also included in the assessed system boundaries. The use phase was excluded from the analysis. This is done since gas can have multiple final uses and make use of multiple technologies both in industry or households. This variety would make assessment very complex to be carried out due to the unavailability of ready to use data over the different equipment's used (both in industry and households) and their efficiency rates.

It is assumed that natural gas to be produced at Urraca 1 is dry (in other words, only natural gas is produced). Natural gas liquids (e.g. including ethane, propane, butane) are not considered to be produced at the site in this analysis. This is in line with other LCA studies on shale gas by considering the smaller contents of heavier hydrocarbons in the natural gas from shale formations (IEA, 2010) and due to the absence of data for gas composition, which is unknown.

The system boundaries analyzed (Figure 5.2) are based on studies for shale gas development in the European Union (Broomfield, 2012; Corden et al., 2016) and considers the pre-production and production phases. Infrastructures related to shale gas exploitation and exploration (e.g. site facilities, road accesses, and well drilling) are considered in the system boundaries to assess the environmental impacts associated with shale gas extraction (Frischknecht et al., 2007; Tillman et al., 1994).

Life cycles operations inside pre-production stage include site identification and preparation, well design drilling, casing, and cementing, hydraulic fracturing and) well completion. NG production is included in the production phase, which is followed by gathering, processing, transmission and distribution of gas until the final consumer. Well abandonment, i.e. the closure of the well, is considered after NG production phase. The provision of site utilities is included over the entire life cycle stages.

Activities excluded from the system boundaries are the phases of investigation and prospect, lease agreements, and licensing steps. The machinery manufacture and maintenance are also excluded from our system boundaries.

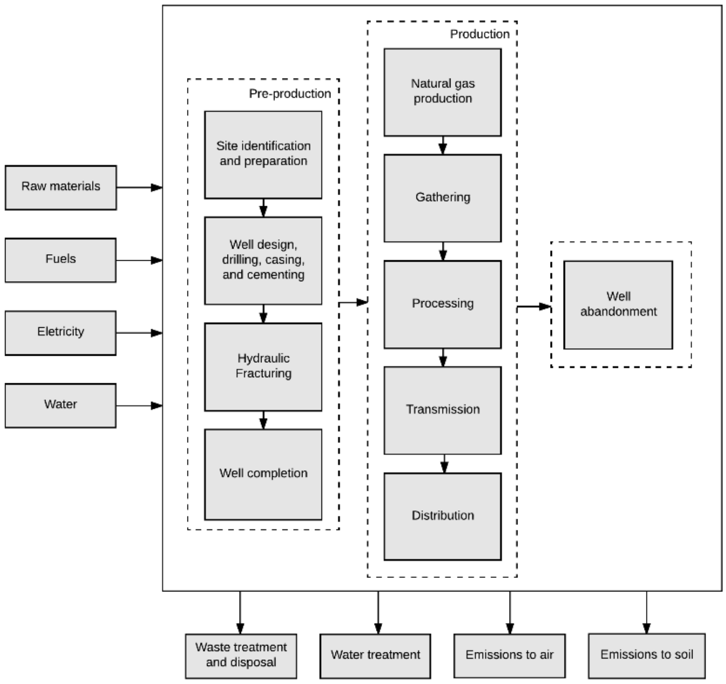

Figure 5.2: Life cycle phases of a shale gas exploration and exploitation project for a lifetime of 30 years. Dashed lines represent sub-phases accounted for the environmental impacts assessment.

5.3.2. Assumptions for relevant model parameters

Some assumptions were made due to the uncertainties associated with the parameters used in the modelling. Attention was paid to the composition of NG, the estimated ultimate recovery and the well production time. The estimated ultimate recovery (EUR) is the maximum expected production volume of a gas reserve. To assess the influence of variations on the above described model parameters over the environmental impact results, sensitivity and an uncertainty is carried out (further described in section 5.3.6).

In terms of raw NG composition, is assumed it has the same chemical composition of raw gas in Europe (50% sour gas), namely, 0.555 kg/m^3 of methane (CH_4) and 0.045 kg/m^3 of hydrogen sulfide (Schori and Frischknecht, 2012). The option underlining this composition is based on a worst-case scenario. It is assumed that the NG will require additional operation to remove hydrogen sulfide (NG processing, also known as sweetening) in order processed NG complies with the quality requirements of the Spanish transmission system (BOE, 2013d).

Uncertainty on the estimated ultimate recovery (EUR) exists due to the fact that most shale oil/gas wells sites in the world are still only a few years old (EIA, 2011b). The considered range of EUR values is consistent with values from other studies (Cooper et al., 2014; Heath et al., 2014a; Stamford and Azapagic, 2014; Stamford and Azapagic, 2015; Tagliaferri et al., 2016; Westaway et al., 2015b). EUR was assumed based on the production of four major plays in the USA (Marcellus, Barnett, Haynesville, and Fayetteville) (Clark et al., 2011a) to cover the different level of development of existent shale play areas. In the present study the central value for the EUR is considered as 39.6 Mm^3, representing a per-well weighted average of the lowest EUR value of shale gas plays in the USA.

The minimum EUR value considered reflects the minimum recovery volume that would be economically viable for a shale gas play (28.63 Mm^3) (Stamford and Azapagic, 2014; Westaway et al., 2015b). The maximum EUR value considered (85.0 Mm^3) was identified by using a conservative approach and reflects half of the largest recovery in the USA (Clark et al., 2011a).

In line with other LCA related studies, the total well operational time is fixed at 30 years (Clark et al., 2011b; Clark et al., 2013a; Cooper et al., 2014; NETL, 2014). However, for the purpose of the sensitivity analysis, 10 years is assumed to be a minimum duration to account for the minimum investment payback time (Weijermars, 2013).

5.3.3. System description

5.3.3.1. Pre-production

The pre-production phase begins with, site identification and preparation, which is often neglected in similar studies (Branosky et al., 2012). This phase includes the evaluation of the site and the construction of infrastructures and site access (CSUR, 2012). In Urraca 1 this phase includes site leveling, well cellar construction, repairing of roads, construction of a water impoundment, and surface pipeline to withdraw water and the gathering lines installation (BNK, 2014).

In respect to the well design, Urraca 1 is composed of one conductor casing, one surface casing, two intermediate casings and one production casing. Based on project data, the measured well depth is 5030 m and the true vertical depth is 3030 m.

The preparation of the well includes vertical and horizontal well drilling, casing and cementing. This process uses diesel, drilling fluids, chemicals for drilling fluid preparation and cement. The resulting effluents and drilling solid wastes include drilling fluids, drill cuttings and other wastes, for instance, cement wastes from casing (Piper et al., 2005). For reduction of diesel consumption in the drilling phase, the electrification of the drilling rig is regarded. This substitution has the potential of reducing impacts on fossil fuels depletion (Pearson et al., 2012; Stricklin, 2012) in sites that could have access to the power grid to avoid the use of diesel generators. However, this is still not a common practice in the field and may not be feasible in this early stage of shale gas development in Europe, specially taking into consideration the current scenario of limited availability of drilling rigs and other equipment (BH, 2017).

Following well drilling, casing and cementing, the hydraulic fracturing operations begins. Hydraulic fracturing is a reservoir stimulation technique, specifically used in unconventional wells (Halliburton, 2008). In the hydraulic fracturing process, high-pressure pumps are used to force the fracturing fluid downhole to fracture the rock and release its NG content in natural gas. Since the formation is fractured, the resulting fissures or fractures are filled with sand facilitating the flow of NG into the wellbore and subsequently to the surface (BLM, 2011). This process makes use of water and chemicals for the preparation of the drilling fluid, as well as diesel used in the related equipment. Outputs related to this process include wastewater from the returning drilling fluid and other liquids from the formation (as flowback water), emissions to the soil from the drilling fluid not returning to the surface and emissions from diesel combustion.

Well completion refers to various operations occurring at the wellbore prior to gas production. In this operation the excess of hydraulic fracturing fluids and the fracturing proppant, which are materials used to maintain induced fractures open, are removed (EPA, 2012). During well completion, NG emissions occurs due to the backflow of the fracture fluids and reservoir gas at high pressure to clean and lift excess proppant to the surface (EPA, 2011a). Reduced Emission Completions (REC) is a relatively recent technology used to capture and send to production part of the NG emitted during well completion. This operation is mandatory in the USA and it is done by making use of portable equipment (EPA, 2011d) that captures the gas released in completion in combination with a combustion device (flaring) that combusts the gas not captured (EPA, 2016; USGPO, 2016).

5.3.3.2. Production

NG production starts after the well completion. From the beginning of production of the well onwards, all life cycle phases are identical to onshore conventional gas production including the treatment technologies for gas (Stephenson et al., 2011b).

In the production phase, NG flows to surface and its production is initiated. During this phase NG fugitive emissions and produced liquid effluents are the main environmental aspects formed. Fugitive emissions occur due to the usage of pressurized equipment and unintentional leaks during operations. The amount of produced effluents is largely variable across the literature. Wastewater management strategies are similar to flowback water since they have similar composition (Boschee, 2015).

Flowback and produced water disposal from shale gas operations are of particular concern because of their volume, high salinity and its ecotoxicological impacts due to the presence of organics and inorganics compounds and radioactive material (Costa et al., 2017b). Typical end of life options for the above-mentioned wastewaters reported in the literature include: (i) deep well injection, (ii) treatment of municipal wastewater treatment plants, (iii) using as a deicing agent in roads, (iv) reuse and (iv) industrial treatments.

Even though deep well injection is the final destination of up to 95% of wastewater from NG onshore exploration (Lutz et al., 2013), this option is valid for all the production areas due to geological or infrastructure limitations. This option is considered unlikely to be available in the time length for the present study gas exploration. *D*ischarges of wastewater from onshore unconventional oil and gas extraction facilities to municipal sewage treatment plants were banned in the USA (GPO, 2016). The usage of wastewater as a deicing agent in roads is also unlikely to be used in Spain. Moreover, such usage raises some environmental concerns which still require further investigation related to the concentration of Ra-226 (Radon), Sr (Strontium), Na (Sodium), and Ca (Calcium) on sediments and soils proximal to roads (Skalak et al., 2014). Based on these facts, we have assumed that part of the flowback water is reused in the hydraulic fracturing phase and the remaining fraction, as well as the produced water, is transported to be treated in an existing industrial wastewater treatment facility adequate to treat such effluents.

The production of NG can be interrupted due to liquid unloading and workovers activities. Liquids unloading are a set of operation designed to clear excess fluid in the well. It can be considered a routine operation for conventional wells, but a rare event for unconventional exploration (Burnham et al., 2011; NETL, 2014) and therefore are disregarded in the present study.

Only a few exceptions (Clark et al., 2011a; NETL, 2014; Tagliaferri et al., 2016) do account for the occurrence of workovers. A workover is the process to perform maintenance or to re-fracture a well to accelerate the rate of production (French et al., 2014; Jacobs, 2014). The frequency of performing workovers with re-fracturing is extremely dependent on the characteristics of the reservoir and can be considered rare events in several plays (ICF, 2009b; NETL, 2014; NYDEC, 2009). Workovers with hydraulic fracturing in unconventional gas wells, are likely to occur every 10 years (EPA, 2009). For the purpose of the reference case for this study, it is assumed that no workovers with re-fracturing are occurring. However, in the sensitivity analysis the influence of the workovers on the impact results is assessed (Section 5.3.6).

Following production, gathering lines (formed by metals as steel and cast iron) transports the NG to a processing facility. In this study a total distance of 20 km is calculated in ArcGIS considering the minimum distance of the wellhead to a point located at the minimum distance to the existing transmission pipeline in the area that will transport gas to the processing facility. NG processing or treatment consists of the removal of contaminants from NG (e.g. oil, water and Sulphur) and separate NG liquids (NGL) (EIA, 2007) to ensure the quality of natural gas delivered to the transportation system (EIA, 2007).

Acid gas removal and dehydration are key NG gas treatment operations considered in this study (NETL, 2014). It is assumed that the produced NG is treated in adjacent areas used for another NG exploration in the country (PV, 2013). This is because the development of a single well, does not justify the investment of a dedicated treatment facility (BOE, 2013d; ENAGAS, 2013). After treatment, NG is transported from high-pressure gas transmission pipelines to a facility that reduces its pressure. From this point, NG is delivered for distribution in low-pressure distribution lines to the final consumer.

In well abandonment, tubes and equipment are removed from the well and the well is plugged with cement. The occupied area is converted to grassland for agricultural production, similarly to what occurs for many decommissioned sites in the UK (Boothroyd et al., 2016).

Fugitive emissions after well abandonment were not considered since these account for less than agricultural emissions that would occur in the reconstituted site (Boothroyd et al., 2016; Kang et al., 2014).

5.3.4. Inventory

The inventory analysis used SimaPro 8.4.0.0 to model the life cycle of shale gas. The Ecoinvent 3.1 database was employed as the principal source of background data (Wernet et al., 2016). Table 5.1 shows the set of key modelling parameters used and the aspects considered in the estimations for the shale gas life cycle inventory. Detailed inventory tables are, due to its extension, shown in the Supplementary Material (SM).

A description is provided on how the inventory was built for the general supply of energy and water to the well site project construction and exploration. The following paragraphs also provide a summary of the most important aspects regarding air emissions (due to fossil fuel combustion), solid waste and wastewater management practices and at the end, the estimation used for distances from road transports. Energy used during pre-production is assumed to be supplied by portable generators, while the public energy network supplies any other stage of the life cycle. Water used during well drilling, casing and cement and hydraulic fracturing phases is abstracted from a local surface water source and transported by PVC pipelines using diesel powered pumps (Chang et al., 2014b). Water uses for site utilities in all phases is assumed to be from the public water supply.

Air emissions due to fuel combustion for all of the stationary combustion equipment (the drilling rig) and mobile machinery (pumps and hydraulic fracturing fleet) in the pre-production phase are calculated using emission factors taken from EMEP/EEA (EEA, 2016). Diesel consumption of 250 g per kWh is defined as a reference for diesel generators (Chang et al., 2014b; Clark et al., 2011a; EMEP/EEA, 2006, 2016a; Stephenson et al., 2011b).

The solid waste streams and wastewaters undertake specific treatments. Non-hazardous waste is sent to a waste facility located 55 km away for landfill disposal (AYTOBURGOS, 2017; BNK, 2014; JCYL, 2017). The same transportation distance for materials to be recycled is assumed. Hazardous wastes are waste mineral oil and drilling sludge. Waste mineral oil is transported for energy valorization to a facility located 94 km away from the project site (BNK, 2014; JCYL, 2017; SERTEGO, 2016). The drilling sludge is transported to a hazardous waste landfill located at 210 km distance after being temporarily stored (BNK, 2014; JCYL, 2017). The liquid streams resulting from site living are equivalent to domestic wastewaters and undergo treatment at the local municipal wastewater treatment facility. The flowback liquid and produced water are transported to an industrial effluent treatment facility located at a 73-km distance away.

Road distances were estimated considering the distances between the gas site project exploration and the currently existing facilities for waste valorizations/depositions (e.g. sanitary landfill, hazardous waste landfill facilities and energy valorization unit), wastewater treatment and transportation of raw materials. Raw materials, including diesel, are assumed to be obtained from the city of Burgos, located at 77 km from the project site.

Table 5.1: Key aspects estimated for the shale gas life cycle inventory.

Life cycle operation modelled	Key modelling parameters	Aspects considered in estimations	Main literature references used in parameters estimations
Site identification and preparation	Site area	(1) Total occupied area obtained from project specification (2) Identification of previous land type based on ArcGIS	MAGRAMA (2010)
	Diesel consumption in building equipment	(1) Literature data	Skolnik et al. (2013)
	Geotextile used	(1) Estimates for total area covered (pad areas and water impoundment) from project specification (2) Estimates for materials used from project data (3) Geotextile manufacturing process (extrusion of plastic films)	BNK (2014); BPF (2016); Chang et al. (2014b); Hischier (2007)
	Construction materials (cement, gravel, sand, limestone)	(1) Materials used obtained from project specifications (2) Estimates for solid waste rates based on literature	BNK (2014); Chang et al. (2014b)
	Gathering lines construction	(1) Distances (minimum) to the closest water body calculated in ArcGIS (2) Lines construction based on the database from Ecoinvent 3.1	ENAGAS (2017b)
	Construction of the water abstraction network	(1) Distances (minimum) to existing pipelines calculated in ArcGIS (2) Pipes manufacturing process (extrusion of plastic pipes) (3) Estimates for solid waste rates based on literature	Hischier (2007); MAGRAMA (2017)
Well drilling, casing and cementing	Energy consumption in drilling	(1) Energy used based on a triangular distribution built based on literature data by taking into account the rate of penetration (2) Estimative of the total power of the drilling rig based on current commercial technologies	Chang et al. (2014a); Drillmec (2017a, 2017b); EIA (2016d); Jiang et al. (2011b); Pavković et al. (2016)
	Drilling mud consumption and drilling waste	(1) Estimate based on well drilling geometry and well project specifications (2) Estimate of drilling mud recycling rates based on triangular distribution from literature data (3) Estimate of drilling fluid losses in well formation based on literature data	Ahmad and Rezaee (2015); BNK (2014); Chang et al. (2014b); Jiang et al. (2011a); Jiang et al. (2014a); Lindland (2006); Maloney and Yoxtheimer (2012a); Pettersen (2007)

Life cycle operation modelled	Key modelling parameters	Aspects considered in estimations	Main literature references used in parameters estimations
	Drilling mud composition	(1) Based on project specifications for water-based fluids and literature data for synthetic-based fluid	BNK (2014); HSE (2000)
	Equipment for drilling fluid circulation	(1) Based on well project specifications (2) Verification of equipment suppliers	BNK (2014); GN (2016); MI-SWACO (2004)
	Total casing requirements	(1) Based on well project specification and typical casing linear mass.	BNK (2014); ISO 11960:2004 (
	Cement usage and composition	(1) Based on well project specification and literature data	BNK (2014); Halliburton (2016); ISO 10426-1:2009 (
	Energy consumption in cementing	(1) Total cementing time estimated based on well design presented in project specifications (2) Estimate of energy consumption based on cementation truck power and cementing time	Chang et al. (2014b); Halliburton (2013, 2016); Lyons et al. (2005)
Hydraulic fracturing	Energy consumed during hydraulic fracturing	(1) Hydraulic fracturing time based on a triangular distribution built on literature data (2) Type and power of hydraulic fracturing fleet based on project specification and equipment availability	Chang et al. (2014b); EERC (2015); Jiang et al. (2011b); Stephenson et al. (2011b); Stewart&Stevenson (2016)
	Hydraulic fracturing fluid composition	(1) Hydraulic fracturing fluid material selected from the database from Ecoinvent 3.1	Wernet et al. (2016)
	Drilling fluid consumption	(1) Total water consumption based on a triangular distribution built on literature data (2) Fluid reuse rates based on a triangular distribution built on literature data	Chang et al. (2014), Stamford and Azapagic (2014), Yang et al. (2015), Vengosh et al. (2017), Clark, Horner, and Harto (2013)
	Flowback water production	(1) Flowback returning rate based on a triangular distribution built on literature data	Jiang et al. (2014a); Jiang et al. (2011b)
Well completion	Air emissions from completion	(1) Emission factor obtained from literature	EPA (2017)
	Gas recovery rate	(1) Total gas recovery rate based on a uniform distribution built on literature data	O'Sullivan and Paltsev (2012), EPA (2009), IPIECA (2014)
	Natural gas consumption in Reduced Emissions Completion equipment	(1) REC time based on a triangular distribution built on literature data (2) Natural gas consumption in REC equipment based on literature data	Allen et al. (2013); Chang et al. (2014b); EPA (2011d); Jiang et al. (2014a); NYDEC (2009); Sandlin (2012)

Life cycle operation modelled	Key modelling parameters	Aspects considered in estimations	Main literature references used in parameters estimations
	Gas emissions from venting	(1) Emissions estimated based on a mass balance considering the recovered and the flared gas	-
	Gas emissions from flaring	(1) Definition of flaring efficiency (2) Emission factor estimate based on the stoichiometry of the complete combustion of gas constituents	Caulton et al. (2014a); O'Sullivan and Paltsev (2012); Stephenson et al. (2011b)
Natural gas production	Total produced water	(1) Water amount based on a uniform distribution taken from literature data	EPA (2011c)
	Fugitive air emissions	(1) Emission factors taken from literature	API (2009)
Gathering	Fugitive air emissions	(1) Emission factors taken from literature	EPA (2017)
Processing	natural gas consumption and air emissions from gas processing (dehydration and sweetening)	(1) NG consumption and emissions from combustion and venting estimated based on literature process	NETL (2010, 2011, 2014)
Transmission	Fugitive air emissions	(1) Emissions estimated based in literature - National GHG Inventory database	MAPABA (2017)
	Materials consumed and emitted in transmission operations (e.g. fuels, water)	(1) Estimates of fuels and material consumption during transmission operations based the environmental performance of the Spanish NG transmission system	Enagas (2017a)
Distribution	Fugitive air emissions	(1) Emissions estimated based in literature - National GHG Inventory database	MAPABA (2017)
Well abandonment	Concrete usage	(1) Concrete usage taken from project specifications	BNK (2014)

5.3.5. Impact assessment

The methodology CML-IA Baseline version 3.02 (CML-IE, 2016) was used to assess the impact categories. This widely accepted method was chosen to allow a comparison of results with other LCA related studies. Results of the characterization step are presented in the contribution analysis (Section 5.4.1), which provides an overview of the relevant life cycle stages for the assessed environmental impacts (Heijungs et al., 2005). A sensitivity analysis and uncertainty analysis were carried out and are further described.

5.3.6. Sensitivity and uncertainty analysis

Sensitivity analysis is used to identify parameters in the model that mostly affect the results obtained for the environmental impact categories assessed. The selection of parameters took into consideration the ones identified to be the most variable in respect to operational conditions and also parameters for which information gaps on field practices were identified. In this study, the parameters were changed one at a time. Sensitivity analysis is performed by running the model for the minimum and maximum values for each ones of the 25 parameters identified as relevant. The values used for the sensitivity analysis are based on statistic distributions based in data collected from literature for each parameter.

A probabilistic uncertainty analysis was performed using Monte Carlo Simulation (MCS) implemented in SimaPro 8.4.0.0 assuming considering 10,000 runs (95% confidence interval). The uncertainty analysis considered the Ecoinvent 3.1 database (Wernet et al., 2016) and the distribution of parameters shown in Table 5.2.

Table 5.2: Parameters used in the sensitivity analysis (SA) for a shale gas exploration and exploitation project. Values are estimated based on triangular distributions considering the medium of the distribution equivalent to the median of the data, whenever possible. When this approach was not possible, the mode of the distribution was assumed to be the mean of the sample.

SA	Relation between parameters used and the life cycle stages	Parameter	Reference case value	Unit	Type of statistical distribution	Distribution parameters[1]	Sources of data
1	All life cycle stages	EUR	39.6	Mm^3	Uniform	a=28.3 b= 85.0	Clark et al. (2011a); Stamford and Azapagic (2014); Westaway et al. (2015b)
2		Sanitary landfill distance[2]	55	km	Uniform	a=38.5 b=71.5	Calculated in Google Maps considering existing facilities
3		Operation years	30	years	Uniform	a=10 b=30	Clark et al. (2011a); Clark et al. (2013a); Cooper et al. (2014); NETL (2014); Weijermars (2013)
4		Distance to Burgos[2]	77	km	Uniform	a=53.9 b=100.1	Calculated in Google Maps considering existing facilities
5	NG composition[3,4]	CH_4	0.555	kg/m^3	Uniform	a=0.555 b=0.610	Schori and Frischknecht (2012)
		CO_2	0.06	kg/m^3	Uniform	a=0.02 b=0.06	
		C_2H_6	0.075	kg/m^3	Uniform	a=0.04 b=0.075	
		H_2S	0.045	kg/m^3	Uniform	a=0 b=0.045	
		N_2	0.0365	kg/m^3	Uniform	a=0.013 b=0.0365	
		Propane	0.05	Kg/m^3	Uniform	a=0 b=0.05	
6	Pre-production: Site	Gathering line length	20230	m	Uniform	a=0 b=20230	Calculated in ArcGIS based on distance to

SA	Relation between parameters used and the life cycle stages	Parameter	Reference case value	Unit	Type of statistical distribution	Distribution parameters[1]	Sources of data
	identification and preparation						existing pipelines
7		Energetic valuation distance[2]	94	km	Uniform	a=65.8 b=122.2	Calculated in Google Maps considering existing facilities
8	Pre-production: Drilling, casing and cementing	Rate of penetration	13.13	m/h	Triangular	a=3.54 b=19.38	Chang et al. (2014a); EIA (2016d); Jiang et al. (2011b)
9		Casing weight	520	ton	Uniform	a=445 b=735	ISO 11960:2004 (
10		Mud volume[5]	2310	ton	Uniform	a=2302 b=4604	Chang et al. (2014b)5
11		Drilling rig power	3600	kW	Uniform	a=3600 b=6000	Chang et al. (2014b); Clark et al. (2011b); Drillmec (2017a, 2017b); Jiang et al. (2011b)
12		Drill mud recycle rate	76.3	%	Triangular	a=54 b=85	Jiang et al. (2011a); Jiang et al. (2014a); Lindland (2006); Maloney and Yoxtheimer (2012a); Pettersen (2007)
13		Hazardous landfill distance[2]	210	km	Uniform	a=147 b=273	Distance estimated with Google Maps considering existing facilities
14	Pre-production: Hydraulic fracturing	Hydraulic fracturing time	31.05	hours	Triangular	a=10 b=48	Chang et al. (2014b); EERC (2015); Jiang et al. (2011b); Stephenson et al. (2011b)
15		Water usage	14121	m3	Triangular	a=3096 b=46140	Chang et al. (2014b); Clark et al. (2013a); Stamford and Azapagic (2014); Vengosh et al. (2017); Yang et al. (2015a)
16		Flowback return rate	11.50%	%	Triangular	a=10 b=80	CSUR (2013); Groat and Grimshaw (2012); GWPC (2009); Haluszczak et al. (2013); Jiang et al.

SA	Relation between parameters used and the life cycle stages	Parameter	Reference case value	Unit	Type of statistical distribution	Distribution parameters[1]	Sources of data
							(2014a); Liu et al. (2015); Maloney and Yoxtheimer (2012a); Stamford and Azapagic (2014)
17		Flowback recycle rate	78.00%	%	Triangular	a=30 b=95	Jiang et al. (2014a); Jiang et al. (2011b)
18		Hydraulic fracturing fleet power[6]	24287	kW	Uniform	a=9134 b=25465	Chang et al. (2014b); Jiang et al. (2014a); Stephenson et al. (2011b)
19		Flowback treatment facility distance[2]	73	km	Uniform	a=51.1 b=94.9	Estimated with Google Maps considering existing facilities
20	Pre-production: Well completion	REC recovery rate	70	%	Uniform	a=70 b=90	EPA (2009); IPIECA (2014); O'Sullivan and Paltsev (2012)
21		Completion time	107.23	hours	Triangular	a=5 b=360	Allen et al. (2013); Chang et al. (2014b); EPA (2011d); Jiang et al. (2014a); NYDEC (2009); Sandlin (2012)
22	Production: Production	Produced water rate	47.62	m^3/m^3 of NG	Uniform	a=15.04 b=80.21	EPA (2011c)
23		Fugitive emissions of CH_4	9.184E-1	t $CH4/Mm^3$ of NG	Normal	SD= 3.71[7]	API (2009)
24		Produced water treatment facility distance[2,8]	73	km	Uniform	a=51.1 b=94.9	Estimated with Google Maps considering existing facilities
25		Workovers with hydraulic fracturing	0	events	Uniform	a=0 b=2	Clark et al. (2013a); EPA (2009); ICF (2009b); NYDEC (2009)

1: Standard deviation (SD) for normal distributions; minimum (a) and maximum (b) values for uniform or triangular distributions.

2: Distribution variables in transportation were calculated assuming that the transportation distances vary ±30%.

3: Natural gas composition is tested simultaneously. Composition reflects typical European natural gas composition. Concentration of Mercury (2.00E-7 kg/m^3), non-methane volatile organic compounds (0.04 kg/m^3), radioactive Rn 222 (400 Bq/m^3) are considered constant.

4: NG composition values are varied together.

5: Consider the sum of the three drilling muds considered.

6: Total combination of hydraulic fracturing fleet.

7: Uncertainty is based on a 95% confidence interval: [4.326E-1;1.404]; n=224.

8: The same facility is considered for produced water and flowback treatment.

5.4. Results and discussion

5.4.1. Contribution analysis

Results of the impact categories for the characterization step are presented in Figure 5.3. These results were obtained for each of the all life cycle stages and operations defined in the system boundaries. The absolute values calculated for each impact category assessed are presented in the SM.

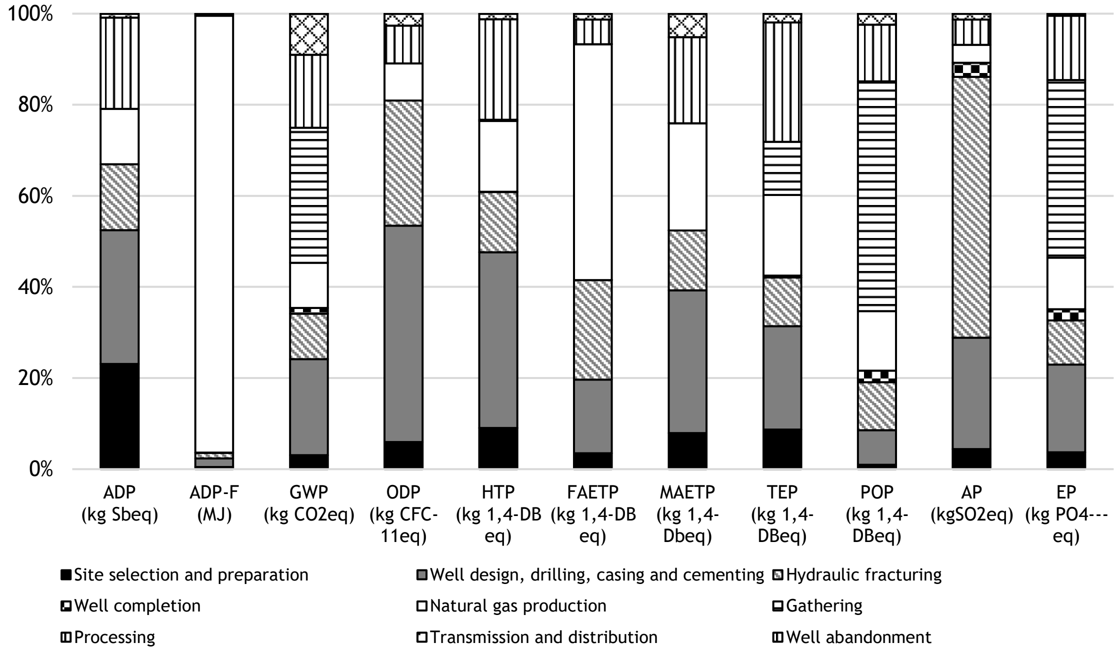

Figure 5.3: Results from the characterization step presented for each impact category and for all the life cycle stages evaluated through CML-IA baseline. Legend: ADP - abiotic depletion potential, ADP-F - abiotic depletion potential of fossil fuels, GWP100a - global warming potential, ODP - ozone layer depletion potential, HTP - human toxicity potential, FAETP - freshwater aquatic ecotoxicity potential, MAETP - marine aquatic ecotoxicity potential, TEP - terrestrial ecotoxicity potential, POP - photochemical oxidation potential, AP - acidification potential and EP - eutrophication potential.

With respect to the pre-production impacts, it is observed that the operations site selection and preparation, well design drilling, casing and cementing (hereafter called well drilling) and hydraulic fracturing are relevant contributors to environmental impacts. From these phases, well drilling is the largest contributor, since it contributes to a large variety of impact categories within the entire life cycle of shale gas development.

Site preparation together with well drilling are the major contributors to the abiotic depletion potential (ADP), explaining an overall contribution of 52% to this category. The main substances contributing for ADP are the consumption of copper, cadmium, nickel, lead and chromium. These are used for the construction of the metallic gathering lines in site preparation and in the manufacturing of the casing required in the drilling phase.

Two operations, namely, well drilling and hydraulic fracturing are the major contributors to ozone layer depletion potential (ODP) and acidification potential (AP), with, respectively, contributions of 75% and 81% to these categories. Impacts to ODP in both stages are due to emissions of fire suppression and refrigeration to the atmosphere in diesel manufacturing (such as Halon 1301, CFC-114 and Halon 1211). Contribution to AP is due to sulfur dioxide (SO_2), nitrogen oxides (NOx), nitrogen dioxide (NO_2) and ammonia (NH_3) related to the consumption of diesel in building machinery, in drilling rig and drilling fluid circulation during the drilling phase and by the hydraulic fracturing equipment fleet during the hydraulic fracturing process.

With respect to well drilling, the contributions of this operation for impact category, which are all smaller than 50%, are described as follows. First, we describe the contributions in which well drilling, are the largest contributor in the entire lifecycle. These impact categories are human toxicity potential (HTP) – about 39% of the overall contribution from SG production), marine aquatic ecotoxicity potential (MAETP) – 31% of total contribution, and abiotic depletion potential (ADP) – (29% of total contribution). These relevant contributions are explained by the following facts. Contribution to HTP is mostly related to benzene emissions to the air during the manufacturing process of well casings, while MAETP total contribution is explained by hydrogen fluoride and nickel emissions to the air and barium emissions to water from this same process. ADP contribution from this stage reflects the consumption different metals used in the manufacturing of casings and in the manufacturing of chemicals used to prepare drilling fluids.

Well drilling is also the second largest contributor to global warming potential (GWP) – with 21% of total contribution, terrestrial ecotoxicity potential (TETP) – with 23% of total contribution, and eutrophication potential (EP) – with 19% of total contribution. Approximately 59% of the contribution to GWP is related to diesel combustion in the drilling rig, energy generator to drilling fluid circulation, in the cement truck and to the transportation of raw materials. Half of the contribution to TETP is explained by mercury emissions to the air, chromium VI emissions to the soil, among other substances during the manufacturing of casings. The contribution to EP is related to diesel combustion in the different equipment related to this phase, as previously mentioned.

Hydraulic fracturing appears to have a relatively large contribution for some impact categories. The largest contribution is found for AP (57%). When looking at the entire lifecycle, hydraulic fracturing is the second largest contributor to ODP (28% of contribution) and for freshwater ecotoxicity potential (FAETP) – 22% of contribution). Results for hydraulic fracturing solely reveal that the contribution to FAETP is in its majority due to the injection of hydraulic fracturing fluid (that contributes to about 92% of the overall contribution to this category). When analyzing the impacts resulting from the injection of hydraulic fracturing fluid, it shows that they can be attributed to the treatment of the flowback water after the stimulation treatment (for which the contribution sums up about 49% to FAETP), to the preparation of hydraulic fracturing fluid (contribution of 21%) and to the emissions of flowback fluid to the soil (contribution of around 13%).

With respect to the production phase impacts, NG production, NG gathering, and processing are relevant contributors to the environmental impacts. All of these operations contribute to several impact categories, and the largest contributors to abiotic depletion of fossil fuels (ADP-F), GWP, FAETP, TETP, POP and EP.

This evaluation was carried out to allow a more environmentally oriented evaluation considering a fixed stock paradigm for natural gas reserves (Sala et al., 2016). Considering then that extraction of NG contributes to its depletion in nature, the gas production is the major contributor to ADP-F, representing 96% of the overall contribution of this category.

The remaining contribution is related to the consumption of diesel in the pre-production phase, which is largely used in machinery. The production phase is also the major contributor to FAETP (52% of the overall contribution). This contribution is mainly due to the treatment of the effluent over the life cycle of the well. More specifically, it is due to the treatment of the flowback water which is shown to have a contribution over 92% to this specific FAETP impact category.

The operation of gathering shows to be a relative large contributor to POP (50% of the overall contributions to this category), EP (39%) and GWP (30%). This is due to the fugitive emissions of raw NG over the production operational years.

Processing is the largest contributor to TETP (26%), the second largest contributor to HTP (22%) and the third contributor to a large number of impact categories, namely, ADP (20%), MAETP (19%), GWP (16%), EP (14%), POP (12%), ODP (8%) and AP (6%). The construction of the NG processing plant explains the most impacts to ADP due to materials employed in the construction of the processing facility. Operation of such plant explains the contributions of this operation to ODP, MAETP, TETP and AP in processing are mostly due to the provision of site utilities (particularly related to the provision of electricity and to the construction of the processing plant). GWP and EP are associated to NG combustion during processing, resulting in CH_4, dinitrogen monoxide (N_2O) and carbon dioxide (CO_2) emissions, NG venting and fugitive during treatment. Finally, contribution to POP and HTP are almost totally explained by fugitive emissions of ethane, propane and methane during the sweetening process.

With respect to the operations with comparative lower contribution to environmental impacts, the results show that in Pre-production, the operation that contributes the least to the impact categories is completion, which contributes to less than 3% for all impact categories. In the production phase, the operation showing the lower contributions is natural gas transmission and distribution (T&D), followed by well abandonment (WA). The contribution of transmission and distribution are, in majority, less than 5% to all impact categories. The exception is for global warming potential (GWP), for which the contribution is approximately 9% due to fugitive emissions during operations. Well abandonment contributes less than 1% for all categories.

5.4.2. Comparative discussion between results and similar studies

A comparative analysis between impact results obtained in this paper and results from other LCA studies for shale gas was carried out to highlight and discuss main differences and similarities (Figure 5.4). The three studies selected, which were previously discussed in Section 5.2.2, refer to European LCA related shale gas studies (Cooper et al., 2014; Stamford and Azapagic, 2014; Tagliaferri et al., 2016).

For all selected studies the values used for comparison refer to the base case scenario. In order to allow comparisons using the same boundaries and functional unit (1MJ of treated NG delivered in distribution lines), the use phase was excluded from Stamford and Azapagic (2014) and Cooper et al. (2014). The study from Tagliaferri et al. (2016) uses the same boundaries and functional unit considered in our evaluation.

All compared studies present similar values for ADP-F and GWP. The largest differences in results are obtained for the toxicity related categories (such as HTP, FAETP, MAETP and TETP). The initial focus at first, in the results for ADP-F and GWP. ADP-F impacts result from the abiotic depletion of natural gas followed by the consumption of diesel (drilling rig and hydraulic fracturing fleet). Comparisons for diesel consumption (as e.g. the fuel consumed in hydraulic fracturing) for this study and the others reviewed is not possible since these values are not available in the reviewed studies.

An accurate comparison for the GWP can only be made for total emissions in the pre-production phase considering other studies such as Jiang et al. (2011a) and Chang et al. (2014b). In our study, the emissions contributing to GWP for pre-production sums 4498 metric tons of CO_2e. This value is within the range of 1900–5000 metric tons of CO_2e estimated for the Marcellus shale (Jiang et al., 2011a) and is from the same order of magnitude of the 5500 metric tons of CO_2e estimated for China (Chang et al., 2014b).

Variations across GWP values from such studies may be accounted to the fact that, in opposition to the present study, both studies do not consider gas recovery systems during completion. Although our results are in line with values reported in the reviewed studies, the results for GWP are heavily dependent on EPA emission factors used for completion and for gathering line. Their usage led to similar results for all studies reviewed but may misrepresent European regional specificities. Therefore, the development of specific European emission factors seems to be an important gap to cover.

With respect to ADP, the results obtained in our study show a similar order of magnitude when compared to Stamford and Azapagic (2014). However, the work from Cooper et al. (2014) presents a larger value for this category which is due to the use of barite in the preparation of the single drilling fluid. Tagliaferri et al. (2016) does not present results for this environmental impact category.

The observed differences in the calculated ODP are due to different choices in modelling assumptions for the selected studies. Cooper et al. (2014) and Stamford and Azapagic (2014) explained their ODP results by the usage of fire retardants and coolants in NG transportation. The usage of such materials is not considered in our evaluation since they are used for long distance transportation systems (Schori and Frischknecht, 2012) and in our model the transportation occurs at a national level. Tagliaferri et al. (2016), without specifying in detail, the contribution causes, states that ODP are mainly due to the impact of construction of NG transmission network. In the present study, this construction was not modelled as it exists for the current scenario of NG consumption in Spain. As stated in Section 5.4.1, ODP impacts arise due to diesel production.

In our study, toxicity-related categories are mostly related to drilling and hydraulic fracturing, as described in Section 5.4.1. The relative smaller impacts, when compared to the other studies, are due to the consideration of recycle rates for drilling muds and flowback water. Even though reuse of these products are a common practice in shale gas wells (Maloney and Yoxtheimer, 2012a), the reviewed studies do not considered them.

The following paragraphs are used to analyze and discuss the differences verified for the toxicity related categories, namely, MAETP, HTP, TETP and FAETP. For the reviewed studies, drilling waste treatment options explain all toxicity related impact categories. Differences among these works are related to the different drilling waste disposal scenarios adopted, which is considered to be a mix of incineration, landfilling and landfarming in Cooper et al. (2014) or a mix of landfilling and landfarming in Stamford and Azapagic (2014).

In Tagliaferri et al. (2016), HTP and TETP are due to pipeline production for low pressure distribution and to onshore well drilling and gas production. An extended discussion of HTP is not possible due to the lack of details on the drilling process and on the single impacts. In particular, our results for FAETP are explained by the production of drilling fluids and disposal of flowback and produced waters. Both Stamford and Azapagic (2014) and Cooper et al. (2014) mention that the contribution to this impact is due to the treatment of drilling waste. In Tagliaferri et al. (2016), impacts are related to the disposal of flowback water.

In general, the obtained results for such impact categories are found to be smaller due to the reuse of drilling muds and flowback water in the process, leading to resources savings and to a lower amount of solid wastes to be treated. Comparation across toxicity impacts is not an easy task considering that the composition of materials (such as drilling muds, hydraulic fracturing fluid and composition of wastewaters) are not fully disclosed in the reviewed studies. To corroborate this fact the toxicity related impact categories also present the largest sensitivities as further explored in Section 5.4.3.

Regarding POP, the studies from Cooper et al. (2014) and Tagliaferri et al. (2016) have associated the impacts with fugitive and vented emissions of high hydrocarbons from natural gas to the atmosphere. In Stamford and Azapagic (2014), emissions contributing to this impact category are volatile organic carbon (VOC) emissions from the sweetening process. In our study POP is due both to VOC emissions during sweetening, but also to fugitive and vented emissions of high hydrocarbons during other operations as well completion, gathering and NG production.

AP is mostly explained by emissions from diesel combustion in vertical and horizontal drilling (Stamford and Azapagic, 2014; Tagliaferri et al., 2016). Similarly in our study, contribution to AP are mostly explained by diesel consumption during in site preparation, drilling and hydraulic fracturing. Cooper et al. (2014) state that AP is solely explained to the H_2S content of the extracted NG, particularly in the phase of electricity generations, and therefore it is not possible to draw comparisons with this study.

No consensus exists for the contribution to EP. Some authors explain the main aspects influencing EP as diesel consumption in diesel generators and drilling (Stamford and Azapagic, 2014; Tagliaferri et al., 2016). In our study EP impacts are due to nitrogen emissions to the atmosphere raw NG fugitive and vented emissions, as well as emissions from diesel consumption in drilling and hydraulic fracturing. The exception is presented in Cooper et al. (2014), which accounts for part of EP contributions to the disposal of drilling waste considering different strategies (landfill, land spreading and incineration).

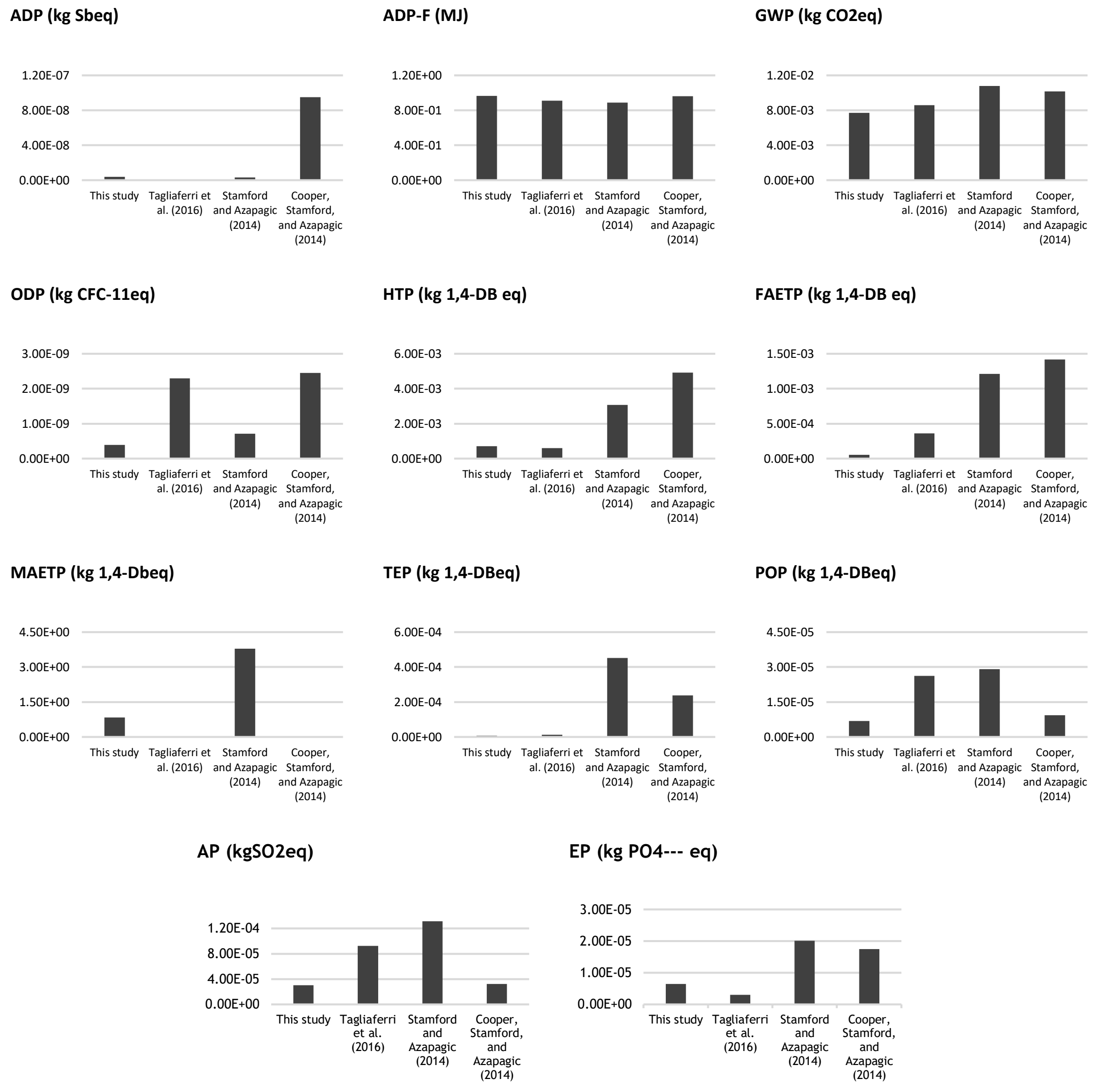

Figure 5.4: Comparison among LCA studies for shale gas considering the delivery of 1 MJ of natural to gas in distribution lines (logarithm scale). ADP – abiotic depletion potential, ADP-F – abiotic depletion potential of fossil fuels, GWP100a – global warming potential, ODP – ozone layer depletion potential, HTP – human toxicity potential, FAETP – freshwater aquatic ecotoxicity potential, MAETP – marine aquatic ecotoxicity potential, TETP – terrestrial ecotoxicity potential, POP – photochemical oxidation potential, AP – acidification potential and EP – eutrophication potential.

5.4.3. Sensitivity and uncertainty analysis

Sensitivity results of a set of 25 sensitivity cases are presented in Table 5.3. This analysis was done to evaluate the influence in impact category results of changes in a set of model parameters identified as relevant (see Section 5.3.6 for a detailed description of the sensitivity cases considered).

Results for the sensitivity analysis allows for the classification of parameters in three classes: (i) parameters for which at least one impact category changed by 30% or more), (ii) parameters for which at least one category changed between 6 and 29% and (iii) parameters for which at least one category changed by 5% or less.

Results show that hydraulic fracturing is the operation presenting the largest number of sensitive cases. Four out of six cases analyzed in hydraulic fracturing show to have sensitivity results varying more than 30% for at least one impact category. For the evaluation of the hydraulic fracturing operations, it is particularly notorious the limitation of available data and the large discrepancy among values reported in the literature for different aspects in this phase, especially for total water usage (SA15) and the flowback return rate (SA16).

For eleven parameters out of 25 analyzed at least one of the calculated impact categories varies by 30% or more. This occurs for the following parameters: the estimated maximum gas recovery EUR (SA1), operation years (SA3), NG composition (SA5), gathering lines length (SA6), rate of penetration (SA8), hydraulic fracturing time (SA14), water usage for hydraulic fracturing (SA15), flowback return rate (SA16), distance to flowback/produced water (SA18) and produced water rate (SA22) and the number of workovers during the hydraulic fracturing (SA25).

For four sensitivity cases out of the 25 analyzed, the sensitivity results obtained show that at least one category changed between 6 and 29%. These include the total drilling fluid requirement (SA10), drilling rig power (SA11), flowback recycle rate (SA17), and fugitive emissions from production phase (SA23).

For seven out of the 25 sensitivity cases analyzed, the sensitivity results show that at least one category changed by 5% or less. These are distance for raw material transportation (SA4), total weight of casing (SA9), drilling mud recycle rate (SA12), distance to drilling fluids and waste landfill (SA13), distance to flowback and produced water distance (SA19 and SA24), and the recovery of natural gas during well completion (SA20).

Finally, three parameters were not shown to influence the impact results for the variation range analyzed. These include transportation distances to sanitary landfill (SA2), transport to the energy valorization sites (SA7) and the well completion time (SA21).

The following discussion focus on parameters presenting the relative larger sensitivities, namely, SA1, SA3, SA5, SA6, SA8, SA14, SA15, SA16, SA18, SA22 and SA25. The relative large sensitivity for the EUR (SA1) is not surprising since it is strictly related to the well productivity affecting the total outputted energy. The sensitivity to yield differences again show that processes with larger productivities show to have less environmental impacts per energy output when compared to wells with lower productivities. The sensitivity for the cases operation years (SA3) and gathering lines length (SA6) are strictly related. That occurs since the adopted emissions factor for raw natural gas fugitive emissions in gathering lines (EPA, 2017) is dependent of the length of gathering lines and the total years of operations. NG composition (SA5) showed to affect mostly the GWP, POP and EP categories. This is explained by the fact that the variation in composition requires extra processing to reduce mainly the amount of H_2S

in gas and other contaminants such as CO_2, CH_4, N_2O, NOx, lead (Pb), particulates, SO_2, and VOC.

A consequence of the reduction of higher hydrocarbons is the reduction of POP from its emissions to the atmosphere in fugitive emissions during NG production and gathering. This also occurs for the reduction of N_2 content affecting EP due to reduction of N_2 emissions during the same phases. The rate of penetration (SA8) and hydraulic fracturing time (SA14) are both due to diesel consumption during drilling and fracking treatment by using equipment, such as pumpers, blenders and monitoring vans). The sensitivity results for water use in hydraulic fracturing (SA15) affects a large number of impact categories due to the increase in the consumption of hydraulic fracturing fluid volume and, consequently the increase in total flowback fluid volumes and the amount of chemicals consumed during its preparation. The sensitivity observed in SA16 reflects the large variation of this parameter in the literature and affects mostly FAETP due to the increase in flowback water volume and requirements for its treatment. S18 demonstrates that the total power of the hydraulic fracturing fleet reflects into savings of diesel consumed in such equipment.

During NG production, the produced water rate (SA22) affects FAETP, since the larger the volume of produced water during the production phase the higher the impacts of treatment which directly impact the FAETP. Finally, the number of workovers carried out during hydraulic fracturing (SA25) along with the well lifecycle is shown to affect a large number of impact categories due to the fact that it implies refracturing and recompletion of the well.

Table 5.3: Sensitivity analysis results, calculated for the characterization step, expressing relative changes for each impact category related to the reference case. Legend: ADP – abiotic depletion potential, ADP-F – abiotic depletion potential of fossil fuels, GWP100a – global warming potential, ODP - ozone layer depletion potential, HTP - human toxicity potential, FAETP - freshwater aquatic ecotoxicity potential, MAETP - marine aquatic ecotoxicity potential, TEP - terrestrial ecotoxicity potential, POP - photochemical oxidation potential, AP - acidification potential and EP - eutrophication potential.

Impact categories		ADP	ADP-F	GWP	ODP	HTP	FAETP	MAETP	TEP	POP	AP	EP
Life cycle stage	SA											
All phases	SA1 (%)	+44;-48	+2;-3	+29;-37	+39;-50	+31;-38	+20;-26	+35;-43	+37;-46	+30;-39	+39;-51	+31;-41
	SA2 (%)	0	0	0	0	0	0	0	0	0	0	0
	SA3 (%)	-9	-1	-23	-9	-5	-5	-17	-27	-35	-5	-28
	SA4 (%)	-1;+1	0	-1;+1	0	-1;+1	-1;+1	0	-1;+1	0	-1;+1	-1;+1
NG Composition	SA5 (%)	0	0	-11	0	-1	0	0	-4	-51	-1	-45
Site identification and preparation	S6 (%)	-21	-1	-31	-2	-7	-2	-7	-19	-51	-2	-40
	S7 (%)	0	0	0	0	0	0	0	0	0	0	0
Drilling, casing and cementing	SA8 (%)	+4;0	+3;0	+22;-3	+80;-10	+13;-2	+14;-2	+8;-1	+14;-2	+3;0	+34;-4	+35;-4
	SA9 (%)	-2;+7	0	-1;+4	-1;+3	-4;+11	-1;+2	-3;+9	-2;+5	-1;+2	-1;+3	-1;+2

	SA10 (%)	+5	0	+1	+6	+2	+3	+3	+1	0	+1	+1
	SA11 (%)	+1	+1	+5	+16	+3	+3	+2	+3	+1	+8	+8
	SA12 (%)	+5;-2	0	+1;0	+6;-2	+2;-1	+3;-1	+3;-1	1;-1	0	+1;-1	+1;0
	SA13 (%)	-1;+1	0	0	-1;+1	-1;+1	0	0	0	0	0	0
Hydraulic fracturing	SA14 (%)	0	0	-4;+3	-14;+11	-2;+1	-2;+2	-1;+1	-1;+1	-6;+5	-34;+28	-3;+1
	SA15 (%)	-11;+31	0;+1	-3;+10	-6;+16	-8;+23	-14;+41	-8;+24	-7;+21	-1;+4	-5;+15	-4;+12
	SA16 (%)	0;-8	0	0;-1	0;-4	0;+10	-1;+56	0;+8	0;-5	0;-1	0;-2	0;-1
	SA17 (%)	+1;0	0	0	0	+5;-2	+22;-8	+5;-2	0	0	0	0
	SA18 (%)	-1;0	0	-4;0	-13;+0	-2;0	-2;0	-1;0	-1;0	-6;0	-33;+1	-3;0
	SA19 (%)	-2;+2	0	0	-1;+1	0	0	0	0	0	0	0
Well completion	SA20 (%)	0	0	-1	0	0	0	0	0	-2	-2	-2
	SA21 (%)	0	0	0	0	0	0	0	0	0	0	0
Production	SA22 (%)	-4;+4	0	0	-1;+1	-8;+8	-33;+33	-7;+7	-1;+1	0	0	0
	SA23 (%)	0	0	-4;+4	0	0	0	0	-2;+2	-7;+7	0	-5;+5
	SA24 (%)	-2;+2	0	0	-1;+1	0	0	0	0	0	0	0
	SA25 (%)	29%	3%	22%	55%	27%	44%	25%	22%	26%	121%	24%

A MCS was performed due to the uncertainty associated with the estimation of several model parameters it was performed. This included all the variables used in the model (model inputs) to which a statistic distribution could be assigned (see Section 5.3.6 for a detailed description). The obtained results are summarized in Table 5.4.

The results show that the two largest coefficients of variation (CV) are found for TETP and FAETP. The large variability of the considered model parameters (presented in Table added to the large uncertainty for toxicity characterization factors (Jolliet et al., 2010) resulted in a large CV for TETP. High uncertainties for ecotoxicity categories is also verified in recent studies (Van Stappen et al., 2017), which can be accounted to the fact that toxicity impacts are calculated to have large uncertainties due to the uncertainties associated to the large number of substances contributing to such impact categories (Jolliet et al., 2015; Jolliet et al., 2010).

Table 5.4: Monte Carlo Simulation results for shale gas development in Spain. Legend: SD – standard deviation, CV – coefficient of variation and SEM – Standard Error of the Mean, CI – confidence interval.

Impact category	Average	Median	SD	CV	CI-2.50%	CI-97.50%	SEM
ADP (kg Sbeq)	3.82E-09	3.73E-09	7.66E-10	20.1%	2.58E-09	5.56E-09	7.66E-12
ADP-F (MJ)	9.65E-01	9.65E-01	4.68E-03	0.5%	9.57E-01	9.75E-01	4.68E-05
GWP (kg CO2eq)	7.71E-03	7.69E-03	1.76E-04	2.3%	7.41E-03	8.09E-03	1.76E-06
ODP (kg CFC-11eq)	3.92E-10	3.60E-10	1.61E-10	41.0%	2.12E-10	7.53E-10	1.61E-12
HTP (kg 1,4-DB eq)	9.84E-04	9.59E-04	6.41E-04	65.2%	-1.36E-04	2.21E-03	6.41E-06
FAETP (kg 1,4-DB eq)	7.18E-04	7.08E-04	6.25E-04	87.1%	-5.02E-04	1.95E-03	6.25E-06
MAETP (kg 1,4-Dbeq)	1.69E+00	1.64E+00	4.32E-01	25.6%	1.13E+00	2.53E+00	4.32E-03
TEP (kg 1,4-DBeq)	1.09E-05	1.05E-05	3.14E-04	2870.1%	-6.06E-04	6.24E-04	3.14E-06
POP (kg 1,4-DBeq)	6.90E-06	6.84E-06	2.61E-07	3.8%	6.63E-06	7.56E-06	2.61E-09
AP (kgSO2eq)	3.04E-05	3.02E-05	1.31E-06	4.3%	2.84E-05	3.33E-05	1.31E-08

Impact category	Average	Median	SD	CV	CI-2.50%	CI-97.50%	SEM
EP (kg PO4--- eq)	1.03E-05	1.01E-05	1.27E-06	12.3%	8.57E-06	1.32E-05	1.27E-08

5.5. Conclusions

This paper presents the first European LCA for an actual and real shale gas exploration and exploitation project in a specific site located in the province of Burgos, Spain. It includes a full disclosure of parameters affecting shale gas exploitation and exploration and has considered, for the first-time in the modelling the field practices, such as the recycling of drilling mud and hydraulic fracturing fluids.

The obtained results show that the most critical phases in the life cycle of shale gas are: well drilling casing and cementing, hydraulic fracturing, natural gas production, gathering and processing. Furthermore, the consumption of diesel, the water and chemicals used in hydraulic fracturing and the emissions of raw NG to the atmosphere are the major contributors to the environmental impacts.

Our results were compared to other relevant studies assessing shale gas development in Europe through the LCA methodology. This comparison demonstrates that there are still large discrepancies on the values calculated for the environmental impacts categories among different studies. For the GWP and ADP-F impact categories, the results obtained were found to be in line with the results from other studies, however, for toxicity categories (MAETP, FAETP, TETP and HTP) large discrepancies were found. This suggests that additional insights into the processes and materials used which contribute to these impact categories are needed.

Data gaps were identified and may result in the absence of coverage of relevant impacts. This is particularly important for the lack of specific data for sites in Europe. Due to this absence, the use of USA shale gas production data and estimates, partially explain the similarity of the results among LCA reviewed studies when it comes, for instance, to GWP. This is particularly relevant for the processes of hydraulic fracturing and well completion, for which data used are still strongly based on practices from USA shale gas production.

Another limitation relates to the LCA methodology in itself. Even though LCA is an appropriate tool for providing detailed information on the environmental impacts of a system, several non-LCA impacts relevant for the process of shale gas extraction are disregarded in this study. This includes impacts such as habitat disruption, induced seismicity, socio-economic perspectives, among others.

Limitations of the present study itself are related to the fact that we are looking at a project not yet implemented, and many aspects may be subject of change. However, for the purposes of the assessment the current best available technologies for shale gas extraction were accounted for as well as EUR estimates and NG composition. Another aspect to mention is that the possibility of production of sub-products from shale gas production (as NGL) is not known and it was not accounted. However, as the best as your knowledge, allocation of such products remains a challenge for the LCA of shale gas.

The results from the sensitivity analysis show that the discrepancies of the parameters reported in the literature can strongly affect total impacts of shale gas exploration and exploitation. The parameters with the largest sensitivity and that affect more than three impact categories were: the EUR, the gathering lines length, the rate of penetration, the water usage and the number of workovers. Results from uncertainty analysis based on the MCS show that impacts are largely variable due to limitations on information from the literature. It is important to note that water usage and the number of workovers with hydraulic fracturing are particularly sensitive to variabilities and site-specific conditions. Water usage is a very critical parameter due to its large reported variability and due to the fact that it is related to total hydraulic fracturing fluid consumption. The number of workovers is important since it determines the repetition of hydraulic fracturing and completion phases, having the potential to more than double impacts for the AP. Results from the MCS reflect not only the selected variables uncertainties but also the uncertainties related to the databases used in the project modelling. The CV were found to be particularly significant for the toxicity categories, particularly for TETP, which is due to the uncertainties associated with the large number of substances contribution to the toxicity potentials.

Even though this study relies on a case study, the data collected in the inventory as well as the environmental impact results can be extrapolated to other sites within the European context. Shale gas reserves remain a relevant and strategic resource for Europe to reduce its external dependency of NG. A future shale gas exploration in Europe should be conducted carefully considering both the environmental and social costs of its extraction. Thus, the potential threats and impacts related may be dealt with by adopting precautionary principles, calling for more research into this field in order to better evaluate identified uncertainties.

Acknowledgements

Authors would like to acknowledge IBRASIL (Inclusive and Innovative Brazil project, an Erasmus Mundus Action 2 programme funded by European Commission) for the PhD grant. We also would like to thank Angel Avardi, Filipe Barros, João Jesus, and Pedro Brancoli for their contributions.

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6. Final remarks and recommendations

Extraction of shale gas and other unconventional energy resources is still a recent practice in the World. The extraction of such resources has changed the profile of NG markets in recent years, leading to the question as to which extent its exploration could become a path to reduce dependency on external suppliers towards energy security in Europe.

However, its exploration is largely associated to its environmental impacts, even though techniques are not completely new in the oil and gas industry. Because of this, several efforts have been performed to better assess its impacts. Despite this increase in research on shale gas development, little information is available to perform a complete and accurate evaluation. This is particularly true in the European context and this study intended to bridge this gap towards a better understanding of shale gas production.

In this thesis, impacts of shale gas in the Iberian Peninsula have been addressed considering different perspectives: economic, social and environmental. From this evaluation one may conclude that shale gas is an important strategic resource in Europe and for this region in particular, due to the accentuated dependency from imports.

The evaluation of scientific literature on shale gas demonstrated an increase in the number of publications addressing environmental impacts of shale gas exploration and exploitation over the years. Despite some impact categories have presented some degree of consensus, studies related to air quality, resulting public health risks and land use, were demonstrated to be often contradictory.

It was demonstrated that shale gas remains a largely unknown resource even to people that are next to a possible exploration. This situation, combined with exposure to media information on possible shale gas impacts, demonstrated a strong opposition from the public that might represent an important barrier to shale development in Europe. In addition, opposition was more related with the level of knowledge about energy sources and its risks.

In the LCA it was demonstrated that overall impacts of shale gas in its life cycle are mostly accounted to well drilling casing and cementing, hydraulic fracturing, natural gas production, gathering and processing. The sensitivity analysis conducted revealed that eleven parameters generate at least 30% of changes in any impact category in the obtained results.

Such parameters are the estimated maximum gas recovery (EUR), operation years, natural gas composition, gathering lines length, rate of penetration, hydraulic fracturing time, water use for hydraulic fracturing, flowback return rate, distance to flowback/produced water and produced water rate and the number of workovers during the hydraulic fracturing).From those, EUR, the gathering lines length, the rate of penetration, the water use and the number of workovers are the most critical affecting more than three impact categories.

A Monte Carlo Simulation (10.000 runs) was conducted to evaluate total uncertainty associated to the model, including the uncertainties associated to the parameters considered and to the background database. Results show that the two largest coefficients of variation

(CV) are found for TEP and FAETP. However, the high uncertainties obtained for TEP call for caution when interpreting the results of this impact category.

The comparison with existing studies conducting a LCA of shale gas have demonstrated that there is still no consensus on total impacts, except for GWP and ADP-F. Results are particularly discrepant for toxicity categories (HTP, FAETP, MAETP and TEP). This can be accounted to the lack of information of some materials associated to the life cycle of shale gas, such as the hydraulic fracturing fluid and drilling mud composition. That translates into the need of a better disclosure of such materials in future studies.

Although a LCA study provides ample information about the environmental performance, there are several aspects to a system that are not assessed by this methodology. Some examples of associated risks are the growth of bacteria in drilling muds, induced seismicity and socio-economic perspectives, are examples of this.

Data gaps, such as the ones on fracking fluid composition and extension of well failures, and limitations of the methodology itself, limits the possibility of fully assessing potential impacts, especially on drinking water resources locally and nationally. As such, it is still not possible to fully describe the severity of impacts and to estimate the frequency of impacts on drinking water resources from hydraulic fracturing activities.

Despite the fact that shale gas is not likely to participate of the EU energy matrix in the short term, more research efforts in this energy resource are needed. Some issues remain unclear in the literature, such as the social impacts and life cycle costs of shale gas. Innovations on shale gas extraction technologies are likely to reduce its impacts over its life cycle. Particularly, the use of CO_2 as a fluid for hydraulic fracturing and the use of depleted wells to carbon capture storage are important innovations not only to reduce its contribution to climate change, but to transform it into a strategic resource.

Future research may not only focus on new strategies to recover shale gas, but also in the evaluation of LNG life cycle impacts, strategies to allow the entrance of biomethane in national grids and the investigation of impacts of synthetic natural gas. Biomethane is a particularly significant path in future research due to the possibility to reduce the carbon footprint of NG, as well as offering the option of a multiple and decentralized production.

To date there are still large and continuing uncertainties in shale gas resource estimates, including the extent of its reserves, which is translated into uncertain implications for the future of the shale gas industry and national energy policy. However, countries with shale gas reserves may see this resource as a strategic energy option to the diversification of their energy mix.

Appendix I

Supplementary Material of “Systematic review of shale gas environmental impacts from 2005-2015: perspectives for Europe”

This supplementary material provides all articles and respective classifications per environmental class and article type referred in the main manuscript.

Author	Location	Class	# Type
Abualfaraj et al. (2014)	USA	Water resources	3
Aguilera et al. (2014)	Others	Other impacts	3
Ahmadi and John (2015)	USA	Atmospheric emissions	3
Akob et al. (2015)	USA	Water resources	1
Akyon et al. (2015)	USA	Water resources	1
Alawattegama et al. (2015)	USA	Water resources	1
Allard (2015)	USA	Water resources	2
Allen et al. (2013)	USA	Atmospheric emissions	1
Alley et al. (2011)	USA	Water resources	2
Alley et al. (2014)	USA	Land use	2
Almond et al. (2014)	UK	Water resources	3
Altaee and Hilal (2014)	UK	Water resources	1
Balashov et al. (2015)	USA	Water resources	3
Bamberger and Oswald (2012)	USA	Occupational and public health and safety	2
Bamberger and Oswald (2013)	USA	Other impacts	3
Bamberger and Oswald (2015a)	USA	Occupational and public health and safety	3
Bamberger and Oswald (2015b)	USA	Occupational and public health and safety	3
Baranzelli et al. (2015)	Europe	Land use	3
Barbot et al. (2013)	USA	Water resources	1
Barth (2013)	USA	Occupational and public health and safety	3
Beaver (2014)	USA	Other impacts	2
Benavides and Diwekar (2014)	USA	Other impacts	3
Benavides et al. (2015)	USA	Other impacts	3
Bergeson (2014)	USA	Other impacts	2
Bergmann et al. (2014)	Europe	Water resources	3
Bernstein et al. (2013)	USA	Occupational and public health and safety	1
Best and Lowry (2014)	USA	Water resources	3
Bloomdahl et al. (2014)	USA	Occupational and public health and safety	3

Author	Location	Class	# Type
Bogacki and MacUda (2014)	Europe	Atmospheric emissions	3
Bowen et al. (2015)	USA	Water resources	3
Brantley et al. (2014)	USA	Water resources	3
Brasier et al. (2013)	USA	Occupational and public health and safety	1
Brooks (2013)	Others	Other impacts	3
Brown Iii (2014)	USA	Other impacts	3
Brown et al. (2015)	USA	Occupational and public health and safety	3
Bubna-Litic (2015)	Others	Other impacts	2
Bunch et al. (2014)	USA	Atmospheric emissions	1
Burnham et al. (2012a)	USA	Other impacts	3
Burton et al. (2014)	USA	Water resources	2
Caffagni et al. (2014)	Canada	Induced seismicity	3
Camargo et al. (2014)	Others	Water resources	3
Capo et al. (2014)	USA	Water resources	1
Carpenter (2013)	Others	Other impacts	3
Cathles Iii et al. (2012)	USA	Atmospheric emissions	3
Caulton et al. (2014b)	USA	Atmospheric emissions	3
Centner and Petetin (2015)	USA	Occupational and public health and safety	2
Chalupka (2012)	USA	Occupational and public health and safety	3
Chang et al. (2014b)	USA	Atmospheric emissions	3
Chang et al. (2014a)	China	Other impacts	3
Chang et al. (2015)	USA	Atmospheric emissions	3
Charman (2010)	Others	Other impacts	2
Chen et al. (2014)	USA	Other impacts	2
Chen et al. (2015)	China	Water resources	3
Cho et al. (2015)	USA	Water resources	1
Ciferno (2014)	USA	Other impacts	2
Clark et al. (2013b)	USA	Other impacts	2
Clarke et al. (2012)	USA	Occupational and public health and safety	3
Clarke et al. (2014)	UK	Induced seismicity	3

Author	Location	Class	# Type
Cluff et al. (2014)	USA	Water resources	1
Coday et al. (2015a)	USA	Water resources	3
Coday et al. (2015b)	USA	Water resources	3
Colborn et al. (2011)	USA	Occupational and public health and safety	2
Colborn et al. (2014)	USA	Atmospheric emissions	1
Coram et al. (2014)	Others	Occupational and public health and safety	2
Dale et al. (2013)	USA	Other impacts	3
Darrah et al. (2014)	USA	Water resources	1
Davis and Robinson (2012)	USA	Land use	3
Deller and Schreiber (2012)	USA	Occupational and public health and safety	3
Dernbach and May (2015)	USA	Other impacts	2
Down et al. (2015)	USA	Water resources	1
Drohan et al. (2012)	USA	Land use	1
Drollette et al. (2015)	USA	Water resources	1
Duda (2014)	Europe	Water resources	2
Edwards et al. (2014)	USA	Atmospheric emissions	1
Edwards et al. (2015)	USA	Atmospheric emissions	3
Engelder et al. (2014)	USA	Water resources	1
Esmaeilirad et al. (2015)	USA	Water resources	1
Ethridge et al. (2015)	USA	Atmospheric emissions	1
Evans and Kiesecker (2014)	USA	Land use	3
Farag and Harper (2014)	USA	Water resources	2
Ferrer and Thurman (2015)	USA	Water resources	1
Frohlich et al. (2011)	USA	Induced seismicity	1
Fry et al. (2015)	USA	Other impacts	3
Gabriel et al. (2014)	USA	Water resources	3
Gallegos et al. (2015)	USA	Water resources	2
Gao and You (2015b)	USA	Other impacts	3
Gao and You (2015a)	USA	Other impacts	3
Garner et al. (2015)	UK	Land use	1

Author	Location	Class	# Type
Gassiat et al. (2013)	Canada	Water resources	1
Getzinger et al. (2015)	USA	Water resources	1
Gilmore et al. (2014)	USA	Water resources	3
Goerman et al. (2013)	USA	Water resources	3
Goetz et al. (2015)	USA	Atmospheric emissions	1
Goldstein (2014)	USA	Occupational and public health and safety	2
Goldstein et al. (2014)	USA	Occupational and public health and safety	2
Goodwin et al. (2014)	USA	Water resources	3
Gopalakrishnan and Klaiber (2014)	USA	Other impacts	3
Grachev and Lobkovsky (2015)	Europe	Other impacts	2
Graham et al. (2015a)	USA	Occupational and public health and safety	3
Grant et al. (2015)	USA	Land use	1
Gregory et al. (2011)	USA	Water resources	2
Haddadian and Shahidehpour (2015)	USA	Other impacts	2
Haghshenas and Nasr-El-Din (2014)	USA	Water resources	1
Haluszczak et al. (2013)	USA	Water resources	1
Hao et al. (2015)	USA	Water resources	1
Hartley et al. (2015)	USA	Occupational and public health and safety	3
Hays et al. (2015)	USA	Other impacts	2
He et al. (2014a)	USA	Water resources	1
He et al. (2014b)	USA	Water resources	1
Heath et al. (2014a)	USA	Atmospheric emissions	3
Heath et al. (2014b)	USA	Atmospheric emissions	3
Heilweil et al. (2015)	USA	Water resources	1
Hickenbottom et al. (2013)	USA	Water resources	1
Hildenbrand et al. (2015a)	USA	Water resources	1
Hildenbrand et al. (2015b)	USA	Water resources	1
Holland (2013)	USA	Induced seismicity	1
Howarth et al. (2011b)	USA	Atmospheric emissions	3
Howarth et al. (2012)	USA	Atmospheric emissions	3

Author	Location	Class	# Type
Hu and Xu (2013)	China	Other impacts	2
Hultman et al. (2011)	USA	Atmospheric emissions	3
Jackson et al. (2013a)	USA	Water resources	1
Jackson et al. (2013b)	Canada	Water resources	2
Jackson et al. (2015)	USA	Water resources	3
Jiang et al. (2011b)	USA	Atmospheric emissions	3
Jiang et al. (2013)	USA	Water resources	1
Jiang et al. (2014b)	USA	Water resources	3
Jinjolia et al. (2015)	Europe	Other impacts	2
Johnson and Boersma (2013b)	USA	Other impacts	2
Johnson and Graney (2015)	USA	Water resources	1
Johnson et al. (2015)	USA	Water resources	3
Jones et al. (2013)	USA	Occupational and public health and safety	3
Jones et al. (2014a)	UK	Other impacts	2
Jones et al. (2014b)	UK	Other impacts	2
Jordaan et al. (2013)	USA	Other impacts	3
Joyner (2011)	USA	Occupational and public health and safety	3
Kassotis et al. (2014)	USA	Water resources	1
Kassotis et al. (2015)	USA	Occupational and public health and safety	1
Kekacs et al. (2015)	USA	Water resources	1
Kinchy and Perry (2012)	USA	Occupational and public health and safety	3
Kiviat (2013)	USA	Land use	2
Kolesar Kohl et al. (2014)	USA	Water resources	1
Kondash et al. (2014)	USA	Water resources	1
Korfmacher et al. (2013)	USA	Occupational and public health and safety	3
Korfmacher et al. (2014)	USA	Occupational and public health and safety	3
Kriesky et al. (2013)	USA	Occupational and public health and safety	1
Krogulec and Sawicka (2014)	Europe	Water resources	2
Kronenberg (2014)	Europe	Other impacts	2
Krupnick et al. (2014)	USA	Other impacts	2

Author	Location	Class	# Type
Kurwadkar (2014)	USA	Water resources	2
Latta et al. (2015)	USA	Land use	1
Laurenzi and Jersey (2013b)	USA	Other impacts	3
Lautz et al. (2014)	USA	Water resources	3
Lauver (2012)	USA	Occupational and public health and safety	3
Lave and Lutz (2014)	USA	Other impacts	3
Lee et al. (2011)	Others	Other impacts	2
Lester et al. (2015b)	USA	Water resources	1
Litovitz et al. (2013)	USA	Atmospheric emissions	3
Llewellyn (2014)	USA	Water resources	1
Llewellyn et al. (2015)	USA	Water resources	3
Loh et al. (2015)	USA	Water resources	1
Lu et al. (2014)	USA	Water resources	1
Lu et al. (2015)	China	Other impacts	2
Lutz et al. (2013)	USA	Water resources	1
Machowska (2011)	Europe	Other impacts	2
MacUda and Konieczyńska (2015)	Europe	Other impacts	2
Maguire-Boyle and Barron (2014)	USA	Water resources	1
Maloney and Yoxtheimer (2012b)	USA	Water resources	2
Manda et al. (2014)	USA	Water resources	3
Marks (2014)	USA	Occupational and public health and safety	2
Mash et al. (2014)	Others	Occupational and public health and safety	2
Mauter and Palmer (2014b)	USA	Water resources	3
Mauter et al. (2014)	USA	Water resources	3
McCawley (2015a)	USA	Occupational and public health and safety	3
McGarr (2014)	USA	Induced seismicity	3
McGinnis et al. (2013)	USA	Water resources	1
McGovern et al. (2014b)	USA	Water resources	3
McGovern et al. (2014a)	USA	Water resources	3
McKenzie et al. (2012)	USA	Occupational and public health and safety	1

Author	Location	Class	# Type
McPhillips et al. (2014)	USA	Water resources	1
Melikoglu (2014)	Europe	Other impacts	2
Meng (2015)	USA	Other impacts	3
Miller et al. (2013)	USA	Water resources	1
Molofsky et al. (2011)	USA	Water resources	1
Molofsky et al. (2013)	USA	Water resources	1
Moran et al. (2015b)	USA	Land use	3
Moritz et al. (2015)	Canada	Water resources	1
Muehlenbachs et al. (2015)	Canada	Other impacts	3
Munasib and Rickman (2015)	USA	Other impacts	3
Murali Mohan et al. (2013b)	USA	Water resources	1
Murali Mohan et al. (2013a)	USA	Water resources	1
Muresan and Ivan (2015)	Europe	Other impacts	2
Murray (2013)	USA	Water resources	1
Myers (2012)	USA	Water resources	3
Mykowska et al. (2015)	Europe	Land use	1
Namhata et al. (2014)	USA	Water resources	2
Nelson et al. (2015b)	USA	Water resources	1
Nelson et al. (2015a)	USA	Water resources	1
Newell and Raimi (2014)	USA	Atmospheric emissions	3
Nicot and Scanlon (2012)	USA	Water resources	2
Nicot et al. (2014)	USA	Water resources	3
Orem et al. (2014)	USA	Water resources	1
Orland and Murtha (2015)	USA	Other impacts	3
Osborn et al. (2011)	USA	Water resources	1
O'Sullivan and Paltsev (2012)	USA	Atmospheric emissions	2
Pacsi et al. (2014)	USA	Water resources	3
Pancras et al. (2015)	USA	Water resources	1
Paredes et al. (2015)	Others	Other impacts	3
Paulik et al. (2015)	USA	Atmospheric emissions	1

Author	Location	Class	# Type
Peischl et al. (2015)	USA	Atmospheric emissions	1
Penningroth et al. (2013)	USA	Water resources	1
Penning et al. (2014)	USA	Occupational and public health and safety	2
Perry (2012)	USA	Land use	3
Perry (2013)	USA	Occupational and public health and safety	3
Phan et al. (2015)	USA	Water resources	1
Piszcz et al. (2014)	Europe	Water resources	1
Popkin et al. (2013)	USA	Occupational and public health and safety	1
Post van der Burg and Tangen (2015)	USA	Water resources	3
Qin et al. (2015)	Others	Water resources	1
Rabinowitz et al. (2015)	USA	Occupational and public health and safety	3
Racharaks et al. (2015)	USA	Water resources	1
Racicot et al. (2014)	Canada	Land use	3
Rafferty and Limonik (2013)	USA	Occupational and public health and safety	3
Rahm and Riha (2012)	USA	Water resources	3
Rahm et al. (2013)	USA	Water resources	2
Rahm et al. (2015)	USA	Occupational and public health and safety	3
Raymond (2015)	USA	Occupational and public health and safety	2
Reagan et al. (2015)	USA	Water resources	3
Reap (2015)	UK	Occupational and public health and safety	3
Ren et al. (2015)	China	Other impacts	3
Rhodes and Horton (2015)	USA	Water resources	1
Rich and Crosby (2013)	USA	Occupational and public health and safety	1
Rich et al. (2014)	USA	Atmospheric emissions	1
Rivard et al. (2014)	Canada	Other impacts	2
Rodriguez and Soeder (2015)	USA	Water resources	2
Rosenman (2014)	USA	Occupational and public health and safety	2
Roy et al. (2014)	USA	Atmospheric emissions	3
Rozell (2014)	USA	Water resources	2
Rozell and Reaven (2012)	USA	Water resources	3

Author	Location	Class	# Type
Rubinstein and Mahani (2015)	USA	Induced seismicity	2
Rutter et al. (2015)	USA	Atmospheric emissions	1
Saberi (2013)	USA	Occupational and public health and safety	3
Saberi et al. (2014)	USA	Occupational and public health and safety	3
Sangani (2012)	USA	Water resources	3
Santillan et al. (2015)	USA	Water resources	1
Sari and Chellam (2015)	USA	Water resources	1
Sauvé (2015)	Canada	Occupational and public health and safety	2
Scanlon et al. (2014b)	USA	Water resources	3
Scanlon et al. (2014a)	USA	Water resources	3
Scanlon et al. (2013)	USA	Water resources	3
Schafft et al. (2013)	USA	Occupational and public health and safety	1
Shahriar et al. (2014)	USA	Occupational and public health and safety	3
Schmidt (2011)	Canada	Other impacts	3
Shank and Stauffer (2015)	USA	Land use	1
Sharma et al. (2015)	USA	Water resources	1
Shih et al. (2015)	USA	Water resources	1
Siegel et al. (2015)	USA	Water resources	3
Simon (2014)	USA	Water resources	2
Skalak et al. (2014)	USA	Water resources	1
Slizovskiy et al. (2015)	USA	Occupational and public health and safety	3
Small et al. (2014)	USA	Other impacts	2
Small (2015)	USA	Water resources	3
Soeder (2010)	USA	Other impacts	2
Soeder et al. (2014)	USA	Other impacts	2
Song et al. (2015)	China	Atmospheric emissions	1
Sovacool (2014a)	USA	Other impacts	2
Spataru et al. (2015)	UK	Atmospheric emissions	3
Stamford and Azapagic (2014)	UK	Other impacts	3
Stamford and Azapagic (2015)	UK	Other impacts	2

Author	Location	Class	# Type
Stearman et al. (2014)	USA	Land use	1
Steinzor et al. (2013)	USA	Occupational and public health and safety	1
Steliga et al. (2015)	Europe	Water resources	1
Stephens (2015)	USA	Water resources	2
Stephenson et al. (2011a)	UK	Atmospheric emissions	3
Sterling et al. (2014)	Canada	Water resources	3
Stohl et al. (2015)	Europe	Atmospheric emissions	3
Stoll et al. (2015)	USA	Water resources	1
Struchtemeyer et al. (2012)	USA	Water resources	1
Struchtemeyer and Elshahed (2012)	USA	Water resources	1
Sun et al. (2013)	USA	Water resources	1
Swarthout et al. (2015)	USA	Atmospheric emissions	1
Taheripour et al. (2015)	USA	Other impacts	3
Teasdale et al. (2014)	UK	Atmospheric emissions	3
Tereshin et al. (2015)	Europe	Atmospheric emissions	2
Thiel and Lienhard V (2014)	USA	Water resources	1
Thiel et al. (2015)	USA	Water resources	3
Thurman et al. (2014)	USA	Water resources	1
Townsend-Small et al. (2015)	USA	Atmospheric emissions	1
Uddameri et al. (2014)	USA	Other impacts	2
Umbach (2013)	UK	Other impacts	2
Vandecasteele et al. (2015)	Europe	Water resources	3
Vikram et al. (2014)	USA	Water resources	1
Walter et al. (2012)	USA	Atmospheric emissions	3
Wang et al. (2011)	Canada	Atmospheric emissions	3
Warner et al. (2012)	USA	Water resources	1
Warner et al. (2013a)	USA	Water resources	1
Warner et al. (2013b)	USA	Water resources	1
Warren (2013)	USA	Other impacts	2
Weber (2012)	USA	Other impacts	3

Author	Location	Class	# Type
Weber and Clavin (2012)	USA	Occupational and public health and safety	3
Weinstin (2014)	USA	Other impacts	3
Weltman-Fahs and Taylor (2013)	USA	Water resources	3
Wesley Burnett et al. (2015)	USA	Other impacts	2
Westaway and Younger (2014)	UK	Induced seismicity	3
Westaway et al. (2015a)	UK	Other impacts	2
White (2014)	USA	Occupational and public health and safety	2
Whyman (2015)	UK	Other impacts	2
Wilke et al. (2015)	Europe	Water resources	3
Willow and Wylie (2014)	USA	Other impacts	2
Witter et al. (2014)	USA	Occupational and public health and safety	2
Wold et al. (2014)	USA	Atmospheric emissions	2
Wolf et al. (2015)	USA	Water resources	1
Wright et al. (2014)	USA	Water resources	1
Yang et al. (2015b)	USA	Water resources	3
Yang et al. (2015c)	USA	Water resources	3
Yang et al. (2014)	USA	Water resources	3
Yao et al. (2015)	USA	Occupational and public health and safety	1
Ying et al. (2015)	USA	Water resources	1
Yu (2015)	China	Occupational and public health and safety	3
Yun et al. (2015)	Others	Water resources	1
Zavala-Araiza et al. (2015)	USA	Atmospheric emissions	3
Zhang and Yang (2015)	China	Other impacts	2
Zhang et al. (2014)	USA	Water resources	3
Zhang et al. (2015a)	USA	Water resources	1
Zhang et al. (2015b)	USA	Water resources	1
Ziemkiewicz et al. (2014a)	USA	Other impacts	2
Ziemkiewicz et al. (2014b)	USA	Other impacts	3
Ziemkiewicz and Thomas He (2015)	USA	Water resources	1

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Appendix II

Supplementary Material of “Understanding public perception of hydraulic fracturing: a case study in Spain”

1. Introduction

The present supplementary material refers to the article “Understanding public perception of hydraulic fracturing: a case study in Spain” and is divided into 4 sections, besides this introduction. Section 2 shows the questionnaire used in the research and its results. Section 3 presents the summary of the linear regression performed. Exploratory factor analysis methodology and the main assumptions considered are shown in Section 4, followed by the correlation between variables in Section 5.

2. Questionnaire

The questionnaire was built in Google Forms and replied by people from all autonomous communities in Spain and by people from the Burgos province. It considered 19 questions with 30 possible outcomes. Questions, their coding, and results are shown in Table II-1.

Table II-1: Questionnaire questions, coding, results (in percentage) and statistics, when applicable.

Questions and classes		Categories	Variable coding	Spain		Burgos	
				Results	Mean/SD	Results	Mean/SD
Section I							
Gender	1	Male	GENDER	46.2		47.5	
	2	Female		53.8		52.5	
Age	1	16–24	AGE	14.6		10.0	
	2	25–34		36.7		29.2	
	3	35–44		26.8		28.2	
	4	45–54		18.9		23.3	
	5	55 or more		2.9		9.3	
Higher academic qualification	1	Less than high school	EDUCATION	1.0		2.0	
	2	High School		19.6		21.9	
	3	Bachelor's or higher degree		79.4		76.1	
Autonomous community of residence	1	Andalusia	COMMUNITIES	16.6		NA	
	2	Aragon		2.2		NA	
	3	Asturias		1.5		NA	
	4	Cantabria		4.7		NA	
	5	Castile and Leon		13.6		NA	
	6	Castilla-la Mancha		2.7		NA	
	7	Catalonia		5.0		NA	
	8	Ceuta		1.0		NA	
	9	Community of Madrid		18.4		NA	
	10	Valencian Community		6.7		NA	
	11	Extremadura		1.7		NA	
	12	Galicia		6.5		NA	
	13	Balearic Islands		1.7		NA	
	14	Canary Islands		1.5		NA	
	15	La Rioja		2.0		NA	
	16	Melilla		1.5		NA	

		17	Navarra		3.5		NA	
		18	Basque Country		7.2		NA	
		19	Region of Murcia		2.0		NA	
BURGOS PROVINCE		20	Burgos	BURGOS	NA		100	
Years living in this area		1	Less than 1 year	RESIDENCE_TIME	7.4		4.0	
		2	1-3 years		12.2		5.6	
		3	4-6 years		8.2		7.3	
		4	7-10 years		8.2		7.3	
		5	More than 10 years		64.0		75.7	
Residence area		1	Rural	RESIDENCE	15.9		29.6	
		2	Suburban		10.7		6.2	
		3	Urban		73.4		64.1	
Employment in energy industry		1	Yes, in the past	ENERGY_EMPLOYMENT	4.0		3.7	
		2	Yes, at this moment		4.0		4.0	
		3	No		92.1		92.4	
Section II								
I am concerned with environmental protection in my country.		1	Yes	Q01_Preservation	98.8		98.0	
		2	No		0.7		1.0	
		3	I do not know/NA		0.5		1.0	
I am concerned with the foreign energy dependency in my country		1	Yes	Q02_Foreign_Energy	86.8		82.1	
		2	No		6.7		11.6	
		3	I do not know/NA		6.5		6.3	
Classify how much you know about of each energy source	Conventional gas natural and oil	1	Very Low	Q03_Energy_G_P	6.2	Mean: 3.10 SD: 0.943	8.3	Mean: 3.04 SD: 1.042
		2	Below Average		15.9		18.3	
		3	Average		45.4		43.5	
		4	Above Average		27.0		20.9	
		5	Very High		5.5		9.0	
	Unconventional natural gas (e.g. shale gas, tight gas, coal bed methane)	1	Very Low	Q04_Energy_Shale	31.3	Mean: 2.37 SD: 1.176	21.3	Mean: 2.67 SD: 1.238
		2	Below Average		23.8		25.6	
		3	Average		24.8		26.2	
		4	Above Average		17.1		18.3	
		5	Very High		3.0		8.6	
	Unconventional oil	1	Very Low	Q05_Energy_P	30.8	Mean: 2.27 SD: 1.096	25.2	Mean: 2.43 SD: 1.180
		2	Below Average		28.5		32.2	
		3	Average		26.8		23.9	
		4	Above Average		11.2		12.0	
		5	Very High		2.7		6.6	
	Coal	1	Very Low	Q06_Energy_Coal	8.9	Mean: 2.98 SD: 0.987	8.3	Mean: 3.05 SD: 1.031
		2	Below Average		18.9		17.6	
		3	Average		42.2		42.5	
		4	Above Average		25.8		23.6	
		5	Very High		4.2		8.0	
	Nuclear	1	Very Low	Q07_Energy_Nuclear	9.7	Mean: 2.94	8.3	Mean: 3.04
		2	Below Average		18.9		18.6	

		3	Average		43.2	SD: 0.988	40.9	SD: 1.030
		4	Above Average		24.3		24.9	
		5	Very High		4.0		7.3	
	Renewables (wind, solar, etc.) and bioenergy (biofuel, biomass, etc.)	1	Very Low	Q08_Energy_Renewable	3.5	Mean: 3.34 SD: 0.966	6.0	Mean: 3.36 SD: 1.060
		2	Below Average		13.6		12.3	
		3	Average		39.2		35.9	
		4	Above Average		32.5		31.6	
		5	Very High		11.2		14.3	
Section III								
The exploitation of shale gas has more negative environmental impacts compared to conventional gas exploitation....		1	Yes	Q09_Gas_Exploitation	51.6		65.8	
		2	No		6.7		6.3	
		3	I do not know/NA		41.7		27.9	
Should the extraction of shale gas be allowed in Spain?		1	Yes	Q10_Permission	9.7		7.6	
		2	No		52.4		70.8	
		3	I do not know/NA		38.0		21.6	
Benefits associated with shale gas could offset the risks of exploitation?		1	Yes	Q11_Risks	11.7		9.6	
		2	No		51.9		70.4	
		3	I do not know/NA		36.5		19.9	
Do you believe that shale gas development would be beneficial to the economy of the country that make its exploitation and exploration?		1	Yes	Q12_Benefits	20.6		16.3	
		2	No		40.0		58.1	
		3	I do not know/NA		39.5		25.6	
Do you think that there is enough reliable information to have an opinion on hydraulic fracturing?		1	Yes	Q13_Frack	31.3		38.5	
		2	No		53.6		56.8	
		3	I do not know/NA		15.1		4.7	
Do you think that further studies on hydraulic fracturing should be developed?		1	Yes	Q14_Studies	68.7		74.4	
		2	No		16.6		20.6	
		3	I do not know/NA		14.6		5.0	
Would you change your opinion on shale gas and hydraulic fracturing if studies demonstrate that environmental impacts are insignificant or manageable?		1	Yes	Q15_Changes	49.1		33.2	
		2	No		32.5		50.2	
		3	I do not know/NA		18.4		16.6	
Please rate the following questions about the exploitation of shale	I am worried about the risks of water pollution	1	Not much	Q16_Water	5.0	Mean: 4.34 SD: 1.092	7.3	Mean: 4.29 SD: 1.202
		2	Little		2.7		3.7	
		3	Somewhat		10.2		7.0	
		4	Much		17.1		17.3	
		5	Very much		65.0		64.8	
	I am concerned	1	Not much	Q17_Gases	4.2	Mean: 4.16	8.3	Mean: 4.05
		2	Little		4.2		4.3	

gas, considering hydraulic fracturing as its extraction technique.	about emissions of greenhouse gases and other pollutants	3	Somewhat		17.1	SD: 1.113	11.6	SD: 1.241
		4	Much		20.3		25.6	
		5	Very much		54.1		50.2	
	I am concerned about the risks of earthquakes	1	Not much	Q18_Earthquakes	6.0	Mean: 3.85 SD: 1.246	8.6	Mean: 3.86 SD: 1.284
		2	Little		10.2		7.3	
		3	Somewhat		19.9		16.6	
		4	Much		21.1		24.6	
		5	Very much		42.9		42.9	
	I do not believe that the current regulations are sufficient to prevent the risks associated with hydraulic fracturing	1	Strongly Disagree	Q19_Laws	6.2	Mean: 3.94 SD: 1.218	8.6	Mean: 4.28 SD: 1.270
		2	Disagree		6.0		3.7	
		3	Neutral		22.3		7.6	
		4	Agree		19.1		11.6	
		5	Strongly Agree		46.4		68.4	
I believe that shale gas….	… is a clean energy source	1	Strongly Disagree	Q20_Shale_Clean_Energy	42.7	Mean: 2.09 SD: 1.106	69.4	Mean: 1.57 SD: 0.955
		2	Disagree		16.6		9.3	
		3	Neutral		32.5		18.3	
		4	Agree		5.2		1.0	
		5	Strongly Agree		3.0		2.0	
	… is a reliable energy source	1	Strongly Disagree	Q21_Shale_Reliable	36.5	Mean: 2.24 SD: 1.114	67.4	Mean: 1.64 SD: 1.057
		2	Disagree		16.1		10.6	
		3	Neutral		38.0		15.3	
		4	Agree		6.0		3.7	
		5	Strongly Agree		3.5		3.0	
	… is a cheap energy source	1	Strongly Disagree	Q22_Shale_Cheap	32.3	Mean: 2.39 SD: 1.172	56.8	Mean: 1.83 SD: 1.093
		2	Disagree		15.6		13.3	
		3	Neutral		37.7		22.6	
		4	Agree		9.4		4.7	
		5	Strongly Agree		5.0		2.7	
	… can reduce the dependency from foreigner energy sources	1	Strongly Disagree	Q23_Dependence	25.1	Mean: 2.61 SD: 1.209	47.5	Mean: 2.05 SD 1.215
		2	Disagree		17.1		17.9	
		3	Neutral		37.7		21.6	
		4	Agree		12.2		7.6	
		5	Strongly Agree		7.9		5.3	

3. Summary of multiple linear regression

This section presents the summary of multiple linear regression for Burgos and Spain samples, Table II-2 and Table II-3, respectively. The multiple linear regression considered shale gas opposition (Q10) as dependent variable and all other questionnaire questions as independent variables. In the tables, all significant correlations are highlighted.

Table II-2: Multiple linear regression results - Burgos.

```
Coefficients:
                        Estimate Std. Error t value Pr(>|t|)
(Intercept)             0.891600   0.331877   2.687 0.007666 **
AGE                     0.005646   0.020095   0.281 0.778962
GENDER                  0.039980   0.044907   0.890 0.374102
EDUCATION              -0.052501   0.040630  -1.292 0.197400
RESIDENCE               0.002482   0.024120   0.103 0.918101
RESIDENCE_TIME         -0.003397   0.018573  -0.183 0.854999
BURGOS                 -0.144119   0.072690  -1.983 0.048416 *
ENERGY_EMPLOYMENT      -0.001728   0.053312  -0.032 0.974168
Q01_Preservation        0.069951   0.096150   0.728 0.467534
Q02_Foreigner_Energy    0.038601   0.037136   1.039 0.299528
Q03_Energy_G_P          0.017343   0.039055   0.444 0.657350
Q04_Energy_Shale       -0.026785   0.029994  -0.893 0.372645
Q05_Energy_P           -0.024452   0.030947  -0.790 0.430132
Q06_Energy_Carbon      -0.040905   0.039800  -1.028 0.304973
Q07_Energy_Nuclear      0.048665   0.035400   1.375 0.170358
Q08_Energy_Renewable   -0.032605   0.038431  -0.848 0.396958
Q09_Gas_Explotation     0.116626   0.030391   3.837 0.000155 ***
Q11_Risks               0.480138   0.060306   7.962 4.69e-14 ***
Q12_Benefits            0.013599   0.045435   0.299 0.764931
Q13_Frack               0.064948   0.040095   1.620 0.106429
Q14_Studies             0.001882   0.037817   0.050 0.960339
Q15_Changes             0.004192   0.032132   0.130 0.896290
Q16_Water              -0.039112   0.036940  -1.059 0.290626
Q17_Gases               0.036127   0.034894   1.035 0.301439
Q18_Earthquakes         0.014091   0.030038   0.469 0.639372
Q19_Laws                0.052386   0.017737   2.954 0.003417 **
Q20_Shale_Clean_Energy -0.108344   0.036939  -2.933 0.003644 **
Q21_Shale_Reliable      0.170911   0.038463   4.444 1.29e-05 ***
Q22_Shale_Cheap        -0.037091   0.032473  -1.142 0.254377
Q23_Dependence         -0.053510   0.028078  -1.906 0.057733 .
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.335 on 271 degrees of freedom
Multiple R-squared:  0.6297,     Adjusted R-squared:   0.59
F-statistic: 15.89 on 29 and 271 DF,  p-value: < 2.2e-16
```

Table II-3: Multiple linear regression results - Spain.

```
Coefficients:
                         Estimate Std. Error t value Pr(>|t|)
(Intercept)            -0.0257624  0.3088850  -0.083  0.93357
AGE                     0.0221787  0.0181449   1.222  0.22236
GENDER                 -0.0286051  0.0379865  -0.753  0.45190
EDUCATION               0.0230819  0.0436942   0.528  0.59763
RESIDENCE              -0.0217632  0.0246859  -0.882  0.37856
RESIDENCE_TIME          0.0009939  0.0137483   0.072  0.94241
Communities             0.0053238  0.0034897   1.526  0.12797
ENERGY_EMPLOYMENT      -0.0596773  0.0460543  -1.296  0.19584
Q01_Preservation        0.1794669  0.1124067   1.597  0.11120
Q02_Foreigner_Energy   -0.0079090  0.0345263  -0.229  0.81894
Q03_Energy_G_P          0.0411353  0.0325739   1.263  0.20744
Q04_Energy_Shale       -0.0053096  0.0297025  -0.179  0.85822
Q05_Energy_P           -0.0040326  0.0289715  -0.139  0.88937
```

```
Q06_Energy_Carbon      -0.0097531  0.0308511  -0.316  0.75208
Q07_Energy_Nuclear     -0.0039032  0.0333929  -0.117  0.90701
Q08_Energy_Renewable   -0.0313599  0.0314913  -0.996  0.31998
Q09_Gas_Explotation     0.1322164  0.0296958   4.452 1.12e-05 ***
Q11_Risks               0.5050026  0.0440054  11.476  < 2e-16 ***
Q12_Benefits            0.1550840  0.0375141   4.134 4.41e-05 ***
Q13_Frack               0.0987951  0.0321139   3.076  0.00225 **
Q14_Studies            -0.0624493  0.0269884  -2.314  0.02121 *
Q15_Changes             0.0359525  0.0266934   1.347  0.17884
Q16_Water               0.0322833  0.0287757   1.122  0.26263
Q17_Gases               0.0269493  0.0289435   0.931  0.35240
Q18_Earthquakes        -0.0052490  0.0200764  -0.261  0.79389
Q19_Laws                0.0332153  0.0168803   1.968  0.04984 *
Q20_Shale_Clean_Energy  0.0133191  0.0301141   0.442  0.65854
Q21_Shale_Reliable      0.0117708  0.0353654   0.333  0.73945
Q22_Shale_Cheap        -0.0391928  0.0267667  -1.464  0.14397
Q23_Dependence          0.0294510  0.0243030   1.212  0.22635
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.3559 on 373 degrees of freedom
Multiple R-squared:  0.7042,     Adjusted R-squared:  0.6812
F-statistic: 30.62 on 29 and 373 DF,  p-value: < 2.2e-16
```

4. Exploratory factor analysis

Spearman (1904) developed the factor analysis technique, which considers the creation of only one factor, to try to understand the causal relationship between human intelligence and students’ grades obtained in several disciplines. His single factor model was later generalized by Thurstone (1931) to multiple factors, with the purpose of building a method which did not restrict the number of general factors that are operative in producing the inner correlation between several variables observed.

The methodology consists on the following steps: (A) sample size, (B) KMO index and Bartlett’s sphericity test, (C) extraction, communalities and number of factors, (D) rotation methods and (E) analysis of loadings, label and interpretation of factors. Step A consists in analysing the relationship between variables (questions) and the number of cases (respondents), to improve the factor analysis construction and interpretation. From step B to step E, common instructions to perform a reliable factor analysis are described. These steps are considered solely as guides, because the literature can diverge in various aspects related to the recognition of which are the best practices.

4.1. Sample size

Several rules of thumb have been suggested to determine the sample size required to use factor analysis with reliable results. One of these rules suggest that the sample size be determined as a function of the number of variables being analysed, ranging from two subjects per variable to 20 subjects per variable, with at least 100 subjects needed (Stevens, 2009).

As a general rule Hair et al. (2010) suggest that the minimum is at least five times as many subjects as the number of variables, but the researcher should always try to obtain the highest cases-per-variable ratio (for example 20 to 1) to minimize the chances of driving factors that are sample specific and not subject to generalization. Unless the data shows a high level of communality (0.60 or greater) for the measures used in a factor analysis, a sample of at least 100 subjects should be used.

4.2. KMO index and Bartlett's Sphericity test

A precaution that researchers contemplating a components analysis with a small sample size (around 100) should take is to apply the Kaiser-Meyer-Olkin (KMO) index and Bartlett's sphericity tests. The KMO index, in particular, is recommended when the subjects to variable ratio are less than 1:5. The KMO index ranges from 0 to 1, with 0,50 considered suitable for factor analysis.

The Bartlett's Sphericity procedure tests the null hypothesis that the variables in the population correlation matrix are uncorrelated. If one fails to reject with this test, then there is no reason to do the factor analysis because the variables are already uncorrelated. The Bartlett's Sphericity test should reject the null hypothesis at the 0,05-significance level to consider a factor analysis as suitable (Stevens, 2009; Williams et al., 2010).

4.3. Extraction, communalities and number of factors

The most common extraction methods in factor analysis are: Principal Components Analysis and Principal Axis Factoring. The decision whether to use one or the other is strongly debated among researchers. However, if the variables have high reliability, or if there are 30 or more variables, both techniques can be appropriate (Williams et al., 2010). However, Russell (2002) indicated that results based on principal axis factoring are more accurate in reproducing the population loadings and therefore, it should be the preferable method of factor extraction.

One drawback is that the Principal Axis Factoring can produce final communalities higher than one. SAS (2009) indicates that since communalities are squared correlations, one would expect them to always lie between 0 and 1. If the communality equals 1, the situation is referred to as a Heywood case, and if communality exceeds 1, it is referred as an ultra-Heywood case. An ultra-Heywood case implies for some factor a negative variance, which renders a factor solution invalid.

A communality is the extent to which an item correlates with all other items. The higher values of communalities the higher the correlation. If communalities for a particular variable are low (between 0.0 and 0.4), then that variable may struggle to load significantly in any factor and should be removed from the analysis.

Rencher and Christensen (2012) suggest four types of criteria to choose the number of factors to retain: Fixed percentage of explained variance; the Kaiser's Criterion and the Scree Plot Test (Elbow Criterion). The fixed percentage of explained variance method, keeps as many factors as are required to explain some percentage of variance. There is no general consensus about a fixed threshold but it is considered reasonable that any model should have at least 50% of the variance in the variables explained by the common factors (Williams et al., 2010).

Kaiser's Criterion method, developed by Kaiser (1960), extracts only factors with eigenvalues greater than 1. However, Hayton et al. (2004) oppose this arbitrary choice of the threshold of 1 because it tends to overestimate the number of factors to be extracted.

The Scree Plot test or Elbow Criterion, developed by Cattell (1966), employs the plot of the eigenvalues against the order of extraction of the factor. The obtained curve indicates the number of factors to be extracted (Hair et al., 2010). Williams et al. (2010) proposed the following 2 steps to interpret a Scree Plot: (i) draw a straight line fitting the smallest eigenvalues. The point where a departure from this line occurs highlights where the break occurs and (ii) the point above this break (not including the break itself) indicates the number of factors to be retained.

4.4. Rotation Methods

The interpretation of factors can be improved by rotation methods and two major approaches are available: orthogonal (the factors are maintained uncorrelated) and oblique (the factors can be correlated). The most used orthogonal rotation is the varimax method, and the most used oblique rotation is the direct oblimin method (Stevens, 2009).

Hair et al. (2010) affirms that there are no specific rules to select a particular orthogonal or oblique rotational method. As a rule of thumb, orthogonal methods are preferred when the goal is data reduction and oblique methods are best suited when the goal is to obtain theoretically meaningful factors.

Stevens (2009), recommends that researchers should be aware that although an oblique solution is more reasonable, it makes the interpretation of the factors more complicated, because two matrices need to be examined: the factor pattern matrix (the elements indicates the importance of that variable to the factor with the influence of the other variables), and the factor structure matrix (the elements are the simple correlations of the variables with the factors; that is, they are the factor loadings). For orthogonal factors, these two matrices are the same.

4.5. Analysis of loadings, label and interpretation of factors

Loadings (Pearson correlation between the variable and the factor), determine which variables will be considered as an element of any given factor. Usually their values can range from -1 to +1, but the interpretation considers only their absolute value. In other words, a load with a value of -0,88 and another with a value of +0,88 possess the same level of significance.

To choose which are the values that should be considered for the interpretation of the loadings (of any factor), Hair et al. (2010) recommends loads above 0.3. Guadagnoli and Velicer (1988) indicated that if the average of the four largest loadings is greater than 0,60 or the average of the three largest loadings is greater than 0,80; then the factor can be considered meaningful.

After obtaining the final set of factors, a label must be given to each construct based on the variables that fundamentally identify the factor. Interpretation involves the researchers' ability in associating the variables and the construct, which can be a subjective, theoretical, and inductive process. Usually, at least two or three variables must load on a factor so it can be given a meaningful interpretation (Williams et al., 2010). Russell (2002) suggests that should be at least three variables per factor, and preferably four or more.

4.6. Exploratory factor analysis results

4.6.1. Burgos

Examining step A of the methodology, 29 variables will be considered with a total of 301 cases, thus generating a case-per-variable ratio to approximately 10:1. In Step B, Table II-4 indicates a KMO index of 0.83 and the Bartlett's Sphericity test indicates that there is significant correlation between the variables (p-value<0.05). Therefore, it can be concluded that a factor analysis procedure can be done with the current data.

Table II-4: Data Adequacy (KMO and Bartlett's Test) - Burgos.

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.83
Bartlett's Sphericity Test	Approximated Chi-Square	4680.844
	Significance	.000

In Step C, the Principal Axis Factoring was chosen in order to explore the structure of variables. Both Kaiser and Elbow Criterion indicates the extraction of 4 factors, as seen in Figure II-1, with a total of 45% of explained variance.

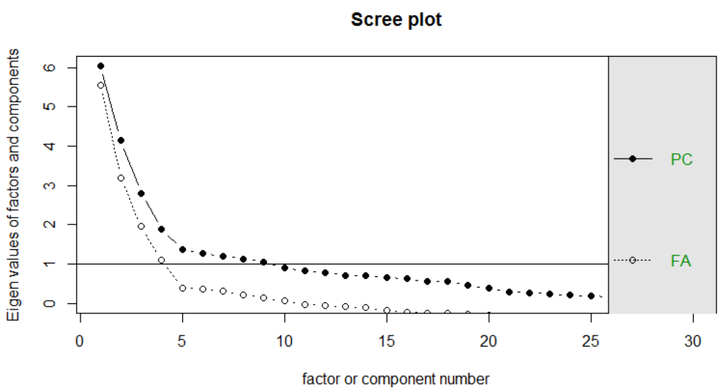

Figure II-1: Scree Plot for Burgos.

Table II-5 shows the extraction made by the Principal Axis Factoring. The variables: AGE, GENDER, EDUCATION, RESIDENCE, RESIDENCE_TIME, ENERGY_EMPLOYMENT, Q01_Preservtion, Q02_Foreigner_Energy, Q13_Frack, Q14_Studies, Q15_Changes and Q19_Laws are not well represented in the common factor space and they are expected to not correlate significantly with any factor, therefore, these variables will be removed. Removing the aforementioned variables and extracting 4 factors, see Table II-6, all communalities are significant and the explained variance increased to 72%.

Table II-5: Table of Communalities (removed variables highlighted) - Burgos.

	h2
AGE	0.122
GENDER	0.122
EDUCATION	0.042
RESIDENCE	0.076
RESIDENCE_TIME	0.046
BURGOS	0.079
ENERGY_EMPLOYMENT	0.145
Q01_Preservation	0.055
Q02_Foreign_Energy	0.021
Q03_Energy_G_P	0.782
Q04_Energy_Shale	0.669
Q05_Energy_P	0.646
Q06_Energy_Coal	0.763
Q07_Energy_Nuclear	0.712
Q08_Energy_Renewable	0.771
Q09_Gas_Exploitation	0.496
Q10_Permission	0.618
Q11_Risks	0.773
Q12_Benefits	0.528
Q13_Frack	0.240
Q14_Studies	0.052
Q15_Changes	0.190
Q16_Water	0.871
Q17_Gases	0.841
Q18_Earthquakes	0.741
Q19_Laws	0.189
Q20_Shale_Clean_Energy	0.633
Q21_Shale_Reliable	0.790
Q22_Shale_Cheap	0.719
Q23_Dependence	0.715

Table II-6: Communalities following variable removal - Burgos.

	h2
Q03_Energy_G_P	0.79
Q04_Energy_Shale	0.65
Q05_Energy_P	0.62
Q06_Energy_Coal	0.78
Q07_Energy_Nuclear	0.72
Q08_Energy_Renewable	0.77
Q09_Gas_Exploitation	0.47
Q10_Permission	0.60
Q11_Risks	0.83
Q12_Benefits	0.56
Q16_Water	0.85
Q17_Gases	0.86
Q18_Earthquakes	0.76

Q20_Shale_Clean_Energy	0.69
Q21_Shale_Reliable	0.84
Q22_Shale_Cheap	0.73
Q23_Dependence	0.69

Figure II-2 indicates the existence of 4 clusters of variables that significantly correlates, corroborating with the indication of the Scree Plot. In Step D, it was decided the usage of an oblique rotation, once if factors do not correlate results should be similar to the ones obtained by an orthogonal rotation.

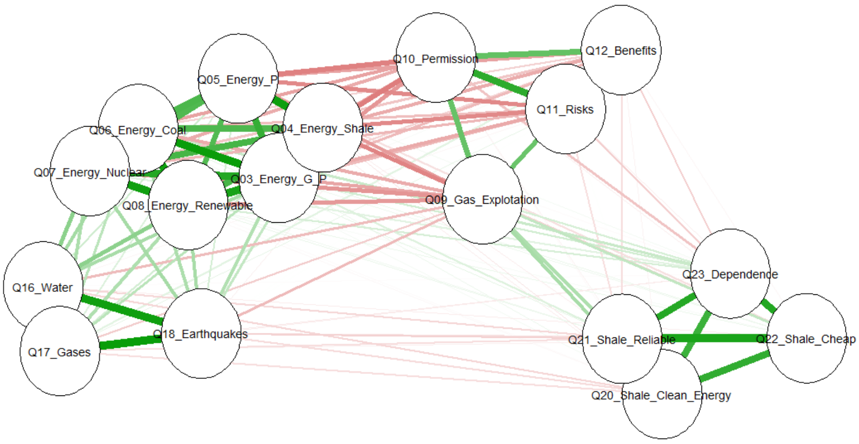

Figure II-2: Correlations Between variables - Burgos sample.

In Table II-7 only the significant loads (equal or greater than 0.3) are represented. Correlation of factors can be seen in Table II-8; one can note that the factor 1 has mild positive correlation with the factor 3 and a mild negative correlation with factor 4. Other correlations were not significant.

Table II-7: Loadings - Burgos.

	PA1	PA2	PA3	PA4
Q06_Energy_Coal	0.904			
Q03_Energy_G_P	0.890			
Q08_Energy_Renewable	0.872			
Q07_Energy_Nuclear	0.829			
Q05_Energy_P	0.718			
Q04_Energy_Shale	0.714			
Q11_Risks				0.943
Q12_Benefits				0.735
Q10_Permission				0.720
Q09_Gas_Exploitation				0.531
Q17_Gases			0.939	
Q16_Water			0.903	
Q18_Earthquakes			0.869	
Q21_Shale_Reliable		0.905		
Q22_Shale_Cheap		0.858		
Q20_Shale_Clean_Energy		0.825		
Q23_Dependence		0.820		

Table II-8: Correlation of factors (significant correlations highlighted) - Burgos.

	PA1	PA2	PA3	PA4
PA1	1.00000000	0.03309117	**0.321811418**	**-0.380008537**
PA2	0.03309117	1.00000000	-0.121356912	-0.018519863
PA3	0.32181142	-0.12135691	1.000000000	0.005259786
PA4	-0.38000854	-0.01851986	0.005259786	1.000000000

4.6.2. Spain

Examining step A of the methodology, 29 variables will be considered with a total of 403 cases, thus generating a case-per-variable ratio to approximately 14:1. In Step B, Table II-9 indicates a KMO index of 0.82 and the Bartlett's Sphericity test indicates that there is significant correlation between the variables (p-value<0.05). Then it can be concluded that a factor analysis procedure can be done with the current data.

Table II-9: Data Adequacy (KMO and Bartlett's Test) - Spain.

Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.82
Bartlett's Sphericity Test	Approximated Chi-Square	5396.447
	Significance	.000

In Step C, the Principal Axis Factoring was chosen in order to explore the structure of variables. Both Kaiser and Elbow Criterion indicates the extraction of 4 factors, as seen in Figure II-3:, with a total of 43% of explained variance.

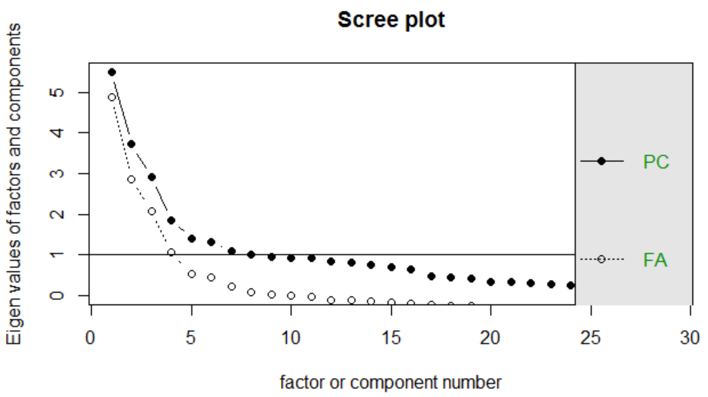

Figure II-3: Scree Plot for Spain.

Table II-10 shows the extraction made by the Principal Axis Factoring. The variables: AGE, GENDER, EDUCATION, RESIDENCE, RESIDENCE_TIME, ENERGY_EMPLOYMENT, Q01_Preservtion, Q02_Foreigner_Energy, Q13_Frack, Q14_Studies, Q15_Changes and Q19_Laws are not well represented in the common factor space and they are expected to not correlate significantly with any factor, therefore, these variables will be removed. Removing the aforementioned variables and extracting 4 factors (Table II-11), all communalities are significant and the explained variance increased to 69%.

Table II-10: Table of communalities (removed variables highlighted) - Spain.

	h2
AGE	0.069
GENDER	0.042
EDUCATION	0.013
RESIDENCE	0.039
RESIDENCE_TIME	0.033
ENERGY_EMPLOYMENT	0.087
Q01_Preservation	0.032
Q02_Foreign_Energy	0.014
Q03_Energy_G_P	0.694
Q04_Energy_Shale	0.651
Q05_Energy_P	0.528
Q06_Energy_Coal	0.665
Q07_Energy_Nuclear	0.697
Q08_Energy_Renewable	0.613
Q09_Gas_Exploitation	0.652
Q10_Permission	0.718
Q11_Risks	0.748
Q12_Benefits	0.666
Q13_Frack	0.283
Q14_Studies	0.078
Q15_Changes	0.071
Q16_Water	0.730
Q17_Gases	0.768
Q18_Earthquakes	0.519
Q19_Laws	0.183
Q20_Shale_Clean_Energy	0.695
Q21_Shale_Reliable	0.845
Q22_Shale_Cheap	0.702
Q23_Dependence	0.644

Table II-11: Table of communalities - Spain.

	h2
Q03_Energy_G_P	0.70
Q04_Energy_Shale	0.62
Q05_Energy_P	0.51
Q06_Energy_Coal	0.69
Q07_Energy_Nuclear	0.71
Q08_Energy_Renewable	0.62
Q09_Gas_Exploitation	0.63
Q10_Permission	0.74
Q11_Risks	0.77
Q12_Benefits	0.66
Q16_Water	0.72
Q17_Gases	0.83
Q18_Earthquakes	0.51
Q20_Shale_Clean_Energy	0.70

Q21_Shale_Reliable	0.86
Q22_Shale_Cheap	0.73
Q23_Dependence	0.65

Figure II-4 indicates the existence of 4 clusters of variables that significantly correlates, corroborating with the indication of the Scree Plot. In Step D, it was decided the usage of an oblique rotation, once if factors do not correlate results should be similar to the ones obtained by an orthogonal rotation.

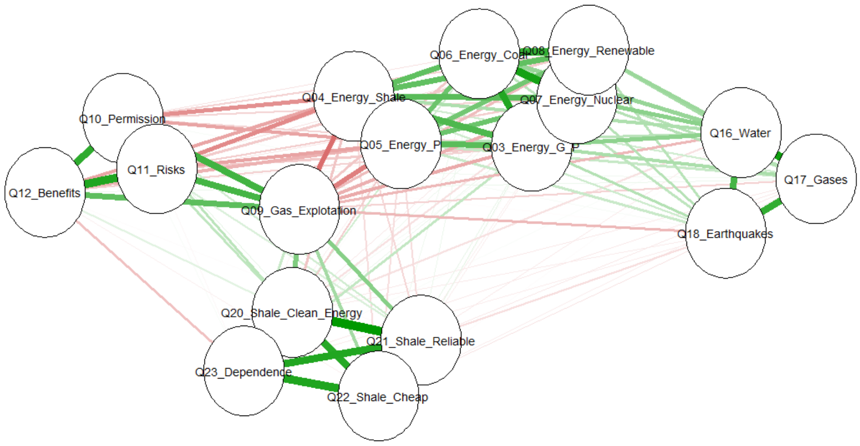

Figure II-4: Correlations Between variables - Spain.

In Table II-12: only the significant loads (equal or greater than 0.3) are represented. The correlation of factors can be seen in Table II-13, in which can be noticed that the factor 1 has mild positive correlation with the factor 4.

Table II-12: Loadings - Spain.

	PA1	PA2	PA3	PA4
Q07_Energy_Nuclear	0.851			
Q06_Energy_Coal	0.848			
Q03_Energy_G_P	0.811			
Q08_Energy_Renewable	0.781			
Q04_Energy_Shale	0.675			
Q05_Energy_P	0.621			
Q11_Risks			0.880	
Q10_Permission			0.854	
Q12_Benefits			0.833	
Q09_Gas_Exploitation			0.639	
Q17_Gases				0.930
Q16_Water				0.814
Q18_Earthquakes				0.714
Q21_Shale_Reliable		0.922		
Q22_Shale_Cheap		0.861		
Q23_Dependence		0.812		
Q20_Shale_Clean_Energy		0.809		

Table II-13: Correlation of factors (significant correlations highlighted) - Spain.

	PA1	PA2	PA3	PA4
PA1	1.00000000	-0.02294307	-0.259417719	0.372854725
PA2	-0.02294307	1.00000000	0.148388125	-0.095755939
PA3	-0.25941772	0.14838812	1.000000000	-0.005186136
PA4	0.37285473	-0.09575594	-0.005186136	1.000000000

5. Correlation between variables

Correlation between variables were based on Spearman's rank correlation coefficient. Please refer to Table II-14 and Table II-15 to access these data.

Table II-14: Spearman's rank correlation coefficient - Burgos.

	AGE	GENDER	EDUCATION	RESIDENCE	RESIDENCE_TIME	BURGOS	ENERGY_EMPLOYMENT
AGE	1.000	-0.075	-0.299	-0.218	0.133	-0.056	-0.028
GENDER	-0.075	1.000	0.011	-0.024	0.047	-0.028	0.278
EDUCATION	-0.299	0.011	1.000	0.155	-0.097	0.094	-0.077
RESIDENCE	-0.218	-0.024	0.155	1.000	-0.007	-0.038	-0.021
RESIDENCE_TIME	0.133	0.047	-0.097	-0.007	1.000	-0.111	0.152
BURGOS	-0.056	-0.028	0.094	-0.038	-0.111	1.000	-0.202
ENERGY_EMPLOYMENT	-0.028	0.278	-0.077	-0.021	0.152	-0.202	1.000
Q01_Preservation	-0.010	0.041	0.045	0.019	-0.027	-0.047	0.041
Q02_Foreigner_Energy	-0.007	0.020	0.009	-0.064	0.053	-0.043	0.009
Q03_Energy_G_P	0.020	-0.171	0.057	-0.105	-0.021	0.161	-0.244
Q04_Energy_Shale	0.141	-0.175	0.000	-0.277	-0.007	0.166	-0.164
Q05_Energy_P	0.094	-0.244	0.002	-0.203	0.017	0.149	-0.249
Q06_Energy_Carbon	0.035	-0.154	0.073	-0.060	0.016	0.101	-0.196
Q07_Energy_Nuclear	-0.014	-0.158	0.084	-0.143	0.000	0.030	-0.136
Q08_Energy_Renewable	-0.076	-0.151	0.113	-0.079	-0.003	0.051	-0.182
Q09_Gas_Explotation	-0.169	0.121	0.091	0.187	-0.136	0.001	-0.008
Q10_Permission	-0.068	0.219	0.000	0.108	-0.007	-0.223	0.178
Q11_Risks	-0.135	0.215	0.076	0.094	0.019	-0.160	0.184
Q12_Benefits	-0.089	0.166	0.115	0.026	-0.011	-0.133	0.246
Q13_Frack	-0.135	0.113	-0.026	0.241	-0.049	-0.073	0.089
Q14_Studies	0.110	-0.071	0.082	-0.077	-0.011	-0.086	-0.008
Q15_Changes	0.087	0.094	0.103	-0.162	0.076	-0.100	0.113
Q16_Water	-0.101	0.026	0.051	-0.118	0.044	-0.072	0.132
Q17_Gases	-0.039	0.118	0.042	-0.041	0.013	-0.080	0.136
Q18_Earthquakes	0.003	0.176	-0.006	-0.136	0.046	0.012	0.102
Q19_Laws	0.052	0.095	0.055	-0.130	0.132	-0.148	0.188
Q20_Shale_Clean_Energy	-0.191	-0.075	0.068	0.109	-0.158	0.127	-0.070
Q21_Shale_Reliable	-0.185	-0.174	0.047	0.134	-0.139	0.109	-0.147
Q22_Shale_Cheap	-0.267	-0.110	0.067	0.181	-0.096	0.044	-0.088
Q23_Dependence	-0.224	-0.219	0.068	0.116	-0.073	0.102	-0.179

Table II-14: Spearman's rank correlation coefficient – Burgos (continuation).

	Q01_Preservation	Q02_Foreigner_Energy	Q03_Energy_G_P	Q04_Energy_Shale	Q05_Energy_P	Q06_Energy_Carbon
AGE	-0.010	-0.007	0.020	0.141	0.094	0.035
GENDER	0.041	0.020	-0.171	-0.175	-0.244	-0.154
EDUCATION	0.045	0.009	0.057	0.000	0.002	0.073
RESIDENCE	0.019	-0.064	-0.105	-0.277	-0.203	-0.060
RESIDENCE_TIME	-0.027	0.053	-0.021	-0.007	0.017	0.016
BURGOS	-0.047	-0.043	0.161	0.166	0.149	0.101
ENERGY_EMPLOYMENT	0.041	0.009	-0.244	-0.164	-0.249	-0.196
Q01_Preservation	1.000	0.245	0.050	-0.006	0.001	-0.008
Q02_Foreigner_Energy	0.245	1.000	0.041	0.010	0.014	0.022
Q03_Energy_G_P	0.050	0.041	1.000	0.635	0.635	0.799
Q04_Energy_Shale	-0.006	0.010	0.635	1.000	0.786	0.564
Q05_Energy_P	0.001	0.014	0.635	0.786	1.000	0.579
Q06_Energy_Carbon	-0.008	0.022	0.799	0.564	0.579	1.000
Q07_Energy_Nuclear	-0.033	0.031	0.710	0.586	0.556	0.736
Q08_Energy_Renewable	0.015	0.063	0.745	0.589	0.545	0.781
Q09_Gas_Explotation	0.128	-0.012	-0.281	-0.397	-0.328	-0.259
Q10_Permission	0.060	0.069	-0.333	-0.451	-0.426	-0.314
Q11_Risks	0.026	-0.010	-0.287	-0.408	-0.394	-0.229
Q12_Benefits	0.022	0.019	-0.238	-0.289	-0.314	-0.174
Q13_Frack	0.065	-0.047	-0.286	-0.399	-0.359	-0.264
Q14_Studies	0.135	0.161	0.042	0.125	0.140	0.096
Q15_Changes	-0.045	0.103	-0.021	0.046	0.014	0.021
Q16_Water	-0.214	-0.006	0.248	0.264	0.168	0.266
Q17_Gases	-0.146	0.026	0.212	0.161	0.136	0.193
Q18_Earthquakes	-0.153	-0.001	0.230	0.206	0.150	0.244
Q19_Laws	-0.150	0.002	-0.079	0.096	0.046	0.011
Q20_Shale_Clean_Energy	0.163	-0.028	0.055	-0.133	-0.091	0.039
Q21_Shale_Reliable	0.145	-0.009	0.086	-0.124	-0.073	0.066
Q22_Shale_Cheap	0.104	-0.021	0.039	-0.172	-0.144	0.065
Q23_Dependence	0.041	-0.051	0.110	-0.068	-0.030	0.167

Table II-14: Spearman's rank correlation coefficient – Burgos (continuation).

	Q07_Energy_Nuclear	Q08_Energy_Renewable	Q09_Gas_Explotation	Q10_Permission	Q11_Risks	Q12_Benefits
AGE	-0.014	-0.076	-0.169	-0.068	-0.135	-0.089
GENDER	-0.158	-0.151	0.121	0.219	0.215	0.166
EDUCATION	0.084	0.113	0.091	0.000	0.076	0.115
RESIDENCE	-0.143	-0.079	0.187	0.108	0.094	0.026
RESIDENCE_TIME	0.000	-0.003	-0.136	-0.007	0.019	-0.011
BURGOS	0.030	0.051	0.001	-0.223	-0.160	-0.133
ENERGY_EMPLOYMENT	-0.136	-0.182	-0.008	0.178	0.184	0.246
Q01_Preservation	-0.033	0.015	0.128	0.060	0.026	0.022
Q02_Foreigner_Energy	0.031	0.063	-0.012	0.069	-0.010	0.019
Q03_Energy_G_P	0.710	0.745	-0.281	-0.333	-0.287	-0.238
Q04_Energy_Shale	0.586	0.589	-0.397	-0.451	-0.408	-0.289
Q05_Energy_P	0.556	0.545	-0.328	-0.426	-0.394	-0.314
Q06_Energy_Carbon	0.736	0.781	-0.259	-0.314	-0.229	-0.174
Q07_Energy_Nuclear	1.000	0.781	-0.338	-0.277	-0.245	-0.208
Q08_Energy_Renewable	0.781	1.000	-0.315	-0.302	-0.240	-0.164
Q09_Gas_Explotation	-0.338	-0.315	1.000	0.507	0.478	0.360
Q10_Permission	-0.277	-0.302	0.507	1.000	0.707	0.522
Q11_Risks	-0.245	-0.240	0.478	0.707	1.000	0.712
Q12_Benefits	-0.208	-0.164	0.360	0.522	0.712	1.000
Q13_Frack	-0.269	-0.272	0.352	0.322	0.252	0.200
Q14_Studies	0.073	0.066	-0.116	0.000	0.062	0.001
Q15_Changes	0.032	0.043	-0.048	0.119	0.168	0.191
Q16_Water	0.372	0.339	-0.270	-0.093	-0.074	-0.008
Q17_Gases	0.232	0.209	-0.189	0.022	0.037	0.060
Q18_Earthquakes	0.256	0.238	-0.249	-0.072	-0.029	-0.039
Q19_Laws	0.078	0.041	-0.257	0.040	0.001	0.032
Q20_Shale_Clean_Energy	-0.033	-0.034	0.362	0.054	0.071	0.019
Q21_Shale_Reliable	0.015	0.037	0.347	0.098	0.019	-0.005
Q22_Shale_Cheap	0.005	0.027	0.260	0.015	0.021	0.054
Q23_Dependence	0.080	0.100	0.190	-0.093	-0.053	-0.052

Table II-14: Spearman's rank correlation coefficient – Burgos (continuation).

	Q13_Frack	Q14_Studies	Q15_Changes	Q16_Water	Q17_Gases	Q18_Earthquakes
AGE	-0.135	0.110	0.087	-0.101	-0.039	0.003
GENDER	0.113	-0.071	0.094	0.026	0.118	0.176
EDUCATION	-0.026	0.082	0.103	0.051	0.042	-0.006
RESIDENCE	0.241	-0.077	-0.162	-0.118	-0.041	-0.136
RESIDENCE_TIME	-0.049	-0.011	0.076	0.044	0.013	0.046
BURGOS	-0.073	-0.086	-0.100	-0.072	-0.080	0.012
ENERGY_EMPLOYMENT	0.089	-0.008	0.113	0.132	0.136	0.102
Q01_Preservation	0.065	0.135	-0.045	-0.214	-0.146	-0.153
Q02_Foreigner_Energy	-0.047	0.161	0.103	-0.006	0.026	-0.001

Q03_Energy_G_P	-0.286	0.042	-0.021	0.248	0.212	0.230
Q04_Energy_Shale	-0.399	0.125	0.046	0.264	0.161	0.206
Q05_Energy_P	-0.359	0.140	0.014	0.168	0.136	0.150
Q06_Energy_Carbon	-0.264	0.096	0.021	0.266	0.193	0.244
Q07_Energy_Nuclear	-0.269	0.073	0.032	0.372	0.232	0.256
Q08_Energy_Renewable	-0.272	0.066	0.043	0.339	0.209	0.238
Q09_Gas_Explotation	0.352	-0.116	-0.048	-0.270	-0.189	-0.249
Q10_Permission	0.322	0.000	0.119	-0.093	0.022	-0.072
Q11_Risks	0.252	0.062	0.168	-0.074	0.037	-0.029
Q12_Benefits	0.200	0.001	0.191	-0.008	0.060	-0.039
Q13_Frack	1.000	-0.223	-0.173	-0.121	-0.068	-0.137
Q14_Studies	-0.223	1.000	0.180	0.023	0.069	0.067
Q15_Changes	-0.173	0.180	1.000	0.052	0.065	0.107
Q16_Water	-0.121	0.023	0.052	1.000	0.773	0.731
Q17_Gases	-0.068	0.069	0.065	0.773	1.000	0.760
Q18_Earthquakes	-0.137	0.067	0.107	0.731	0.760	1.000
Q19_Laws	-0.124	0.096	0.210	0.157	0.059	0.132
Q20_Shale_Clean_Energy	0.173	-0.062	-0.264	-0.166	-0.114	-0.135
Q21_Shale_Reliable	0.210	-0.153	-0.284	-0.153	-0.087	-0.161
Q22_Shale_Cheap	0.235	-0.184	-0.341	-0.092	-0.053	-0.134
Q23_Dependence	0.163	-0.198	-0.335	-0.028	-0.056	-0.087

Table II-14: Spearman's rank correlation coefficient - Burgos (continuation).

	Q19_Laws	Q20_Shale_Clean_Energy	Q21_Shale_Reliable	Q22_Shale_Cheap	Q23_Dependence
AGE	0.052	-0.191	-0.185	-0.267	-0.224
GENDER	0.095	-0.075	-0.174	-0.110	-0.219
EDUCATION	0.055	0.068	0.047	0.067	0.068
RESIDENCE	-0.130	0.109	0.134	0.181	0.116
RESIDENCE_TIME	0.132	-0.158	-0.139	-0.096	-0.073
BURGOS	-0.148	0.127	0.109	0.044	0.102
ENERGY_EMPLOYMENT	0.188	-0.070	-0.147	-0.088	-0.179
Q01_Preservation	-0.150	0.163	0.145	0.104	0.041
Q02_Foreigner_Energy	0.002	-0.028	-0.009	-0.021	-0.051
Q03_Energy_G_P	-0.079	0.055	0.086	0.039	0.110
Q04_Energy_Shale	0.096	-0.133	-0.124	-0.172	-0.068
Q05_Energy_P	0.046	-0.091	-0.073	-0.144	-0.030
Q06_Energy_Carbon	0.011	0.039	0.066	0.065	0.167
Q07_Energy_Nuclear	0.078	-0.033	0.015	0.005	0.080
Q08_Energy_Renewable	0.041	-0.034	0.037	0.027	0.100
Q09_Gas_Explotation	-0.257	0.362	0.347	0.260	0.190
Q10_Permission	0.040	0.054	0.098	0.015	-0.093
Q11_Risks	0.001	0.071	0.019	0.021	-0.053
Q12_Benefits	0.032	0.019	-0.005	0.054	-0.052
Q13_Frack	-0.124	0.173	0.210	0.235	0.163

Q14_Studies	0.096	-0.062	-0.153	-0.184	-0.198
Q15_Changes	0.210	-0.264	-0.284	-0.341	-0.335
Q16_Water	0.157	-0.166	-0.153	-0.092	-0.028
Q17_Gases	0.059	-0.114	-0.087	-0.053	-0.056
Q18_Earthquakes	0.132	-0.135	-0.161	-0.134	-0.087
Q19_Laws	1.000	-0.402	-0.438	-0.369	-0.356
Q20_Shale_Clean_Energy	-0.402	1.000	0.790	0.689	0.636
Q21_Shale_Reliable	-0.438	0.790	1.000	0.753	0.669
Q22_Shale_Cheap	-0.369	0.689	0.753	1.000	0.734
Q23_Dependence	-0.356	0.636	0.669	0.734	1.000

Table II-15: Spearman's rank correlation coefficient - Spain.

	AGE	GENDER	EDUCATION	RESIDENCE	RESIDENCE_TIME	Communities	ENERGY_EMPLOYMENT
AGE	1.000	-0.122	-0.100	0.014	0.110	-0.042	-0.030
GENDER	-0.122	1.000	0.133	0.042	-0.085	-0.059	0.005
EDUCATION	-0.100	0.133	1.000	0.078	-0.067	0.002	-0.104
RESIDENCE	0.014	0.042	0.078	1.000	-0.054	0.076	-0.080
RESIDENCE_TIME	0.110	-0.085	-0.067	-0.054	1.000	-0.053	0.046
Communities	-0.042	-0.059	0.002	0.076	-0.053	1.000	-0.012
ENERGY_EMPLOYMENT	-0.030	0.005	-0.104	-0.080	0.046	-0.012	1.000
Q01_Preservation	0.087	0.014	0.002	0.067	0.049	0.007	0.033
Q02_Foreigner_Energy	0.012	0.030	0.056	-0.045	0.004	-0.120	-0.015
Q03_Energy_G_P	-0.003	-0.074	0.123	0.082	-0.012	-0.017	-0.175
Q04_Energy_Shale	0.058	-0.173	0.037	-0.005	-0.019	-0.060	-0.163
Q05_Energy_P	0.074	-0.131	0.034	-0.040	-0.005	-0.040	-0.112
Q06_Energy_Carbon	0.034	-0.125	0.032	0.055	-0.026	0.009	-0.080
Q07_Energy_Nuclear	0.041	-0.120	0.058	0.014	0.062	-0.011	-0.046
Q08_Energy_Renewable	-0.024	-0.093	0.062	0.012	0.056	-0.078	-0.145
Q09_Gas_Explotation	-0.117	0.116	0.003	0.047	-0.066	-0.054	0.053
Q10_Permission	-0.038	0.090	-0.013	-0.010	-0.001	0.002	0.081
Q11_Risks	-0.054	0.108	-0.065	-0.006	0.026	-0.072	0.135
Q12_Benefits	-0.007	0.117	-0.016	-0.026	0.033	-0.025	0.162
Q13_Frack	-0.138	0.153	0.034	0.037	-0.096	0.083	0.057
Q14_Studies	0.113	-0.008	0.026	-0.004	0.117	-0.049	0.019
Q15_Changes	0.043	-0.033	-0.041	-0.076	0.146	-0.030	-0.035
Q16_Water	-0.026	-0.066	0.061	-0.027	-0.058	0.038	-0.059
Q17_Gases	-0.081	0.053	0.035	-0.029	-0.010	0.014	0.013
Q18_Earthquakes	-0.015	0.020	0.055	-0.084	0.013	0.002	-0.015
Q19_Laws	0.099	-0.056	-0.010	-0.125	0.118	-0.080	0.066
Q20_Shale_Clean_Energy	-0.159	0.028	-0.045	0.088	-0.087	-0.038	-0.093
Q21_Shale_Reliable	-0.164	-0.040	-0.023	0.142	-0.081	-0.025	-0.191
Q22_Shale_Cheap	-0.158	-0.080	-0.093	0.122	-0.100	-0.034	-0.145
Q23_Dependence	-0.129	-0.063	-0.015	0.114	-0.095	0.004	-0.161

Table II-15: Spearman's rank correlation coefficient - Spain (continuation).

	Q01_Preservation	Q02_Foreigner_Energy	Q03_Energy_G_P	Q04_Energy_Shale	Q05_Energy_P	Q06_Energy_Carbon
AGE	0.087	0.012	-0.003	0.058	0.074	0.034
GENDER	0.014	0.030	-0.074	-0.173	-0.131	-0.125
EDUCATION	0.002	0.056	0.123	0.037	0.034	0.032
RESIDENCE	0.067	-0.045	0.082	-0.005	-0.040	0.055
RESIDENCE_TIME	0.049	0.004	-0.012	-0.019	-0.005	-0.026
Communities	0.007	-0.120	-0.017	-0.060	-0.040	0.009
ENERGY_EMPLOYMENT	0.033	-0.015	-0.175	-0.163	-0.112	-0.080
Q01_Preservation	1.000	0.080	-0.051	-0.055	-0.070	-0.063
Q02_Foreigner_Energy	0.080	1.000	0.034	0.119	0.129	0.013
Q03_Energy_G_P	-0.051	0.034	1.000	0.554	0.508	0.685
Q04_Energy_Shale	-0.055	0.119	0.554	1.000	0.804	0.501
Q05_Energy_P	-0.070	0.129	0.508	0.804	1.000	0.453
Q06_Energy_Carbon	-0.063	0.013	0.685	0.501	0.453	1.000
Q07_Energy_Nuclear	-0.062	0.028	0.663	0.532	0.462	0.745
Q08_Energy_Renewable	-0.027	0.025	0.665	0.488	0.425	0.636
Q09_Gas_Explotation	0.013	-0.024	-0.275	-0.469	-0.416	-0.175
Q10_Permission	0.056	-0.030	-0.145	-0.380	-0.315	-0.096
Q11_Risks	0.023	-0.007	-0.190	-0.402	-0.321	-0.117
Q12_Benefits	0.002	0.008	-0.159	-0.310	-0.260	-0.066
Q13_Frack	-0.009	-0.064	-0.170	-0.376	-0.314	-0.113
Q14_Studies	0.062	0.095	-0.037	0.042	0.026	0.011
Q15_Changes	0.074	0.034	-0.052	0.120	0.110	-0.030
Q16_Water	-0.132	0.026	0.328	0.294	0.225	0.320
Q17_Gases	-0.127	-0.010	0.239	0.180	0.198	0.216
Q18_Earthquakes	-0.111	-0.022	0.238	0.173	0.184	0.190
Q19_Laws	-0.083	0.021	0.064	0.152	0.108	0.112
Q20_Shale_Clean_Energy	-0.029	-0.045	-0.014	-0.228	-0.204	-0.042
Q21_Shale_Reliable	-0.043	-0.118	0.031	-0.178	-0.169	0.009
Q22_Shale_Cheap	-0.055	-0.060	0.026	-0.139	-0.146	0.017
Q23_Dependence	-0.036	-0.067	0.162	-0.049	-0.065	0.124

Table II-15: Spearman's rank correlation coefficient - Spain (continuation).

	Q07_Energy_Nuclear	Q08_Energy_Renewable	Q09_Gas_Explotation	Q10_Permission	Q11_Risks	Q12_Benefits
AGE	0.041	-0.024	-0.117	-0.038	-0.054	-0.007
GENDER	-0.120	-0.093	0.116	0.090	0.108	0.117
EDUCATION	0.058	0.062	0.003	-0.013	-0.065	-0.016
RESIDENCE	0.014	0.012	0.047	-0.010	-0.006	-0.026
RESIDENCE_TIME	0.062	0.056	-0.066	-0.001	0.026	0.033
Communities	-0.011	-0.078	-0.054	0.002	-0.072	-0.025
ENERGY_EMPLOYMENT	-0.046	-0.145	0.053	0.081	0.135	0.162
Q01_Preservation	-0.062	-0.027	0.013	0.056	0.023	0.002
Q02_Foreigner_Energy	0.028	0.025	-0.024	-0.030	-0.007	0.008

Q03_Energy_G_P	0.663	0.665	-0.275	-0.145	-0.190	-0.159
Q04_Energy_Shale	0.532	0.488	-0.469	-0.380	-0.402	-0.310
Q05_Energy_P	0.462	0.425	-0.416	-0.315	-0.321	-0.260
Q06_Energy_Carbon	0.745	0.636	-0.175	-0.096	-0.117	-0.066
Q07_Energy_Nuclear	1.000	0.737	-0.250	-0.145	-0.179	-0.084
Q08_Energy_Renewable	0.737	1.000	-0.212	-0.152	-0.186	-0.088
Q09_Gas_Explotation	-0.250	-0.212	1.000	0.654	0.635	0.552
Q10_Permission	-0.145	-0.152	0.654	1.000	0.804	0.685
Q11_Risks	-0.179	-0.186	0.635	0.804	1.000	0.728
Q12_Benefits	-0.084	-0.088	0.552	0.685	0.728	1.000
Q13_Frack	-0.153	-0.117	0.476	0.445	0.394	0.316
Q14_Studies	0.039	0.015	0.072	0.045	0.121	0.181
Q15_Changes	0.059	0.008	-0.079	0.051	0.053	0.114
Q16_Water	0.377	0.325	-0.290	-0.058	-0.148	-0.091
Q17_Gases	0.236	0.286	-0.173	0.015	-0.043	-0.007
Q18_Earthquakes	0.240	0.227	-0.253	-0.041	-0.074	0.023
Q19_Laws	0.180	0.156	-0.334	-0.136	-0.163	-0.081
Q20_Shale_Clean_Energy	-0.130	-0.108	0.464	0.327	0.303	0.163
Q21_Shale_Reliable	-0.102	-0.055	0.432	0.261	0.224	0.068
Q22_Shale_Cheap	-0.092	-0.025	0.338	0.166	0.151	0.019
Q23_Dependence	0.035	0.032	0.206	0.088	0.044	-0.137

Table II-15: Spearman's rank correlation coefficient - Spain (continuation).

	Q13_Frack	Q14_Studies	Q15_Changes	Q16_Water	Q17_Gases	Q18_Earthquakes
AGE	-0.138	0.113	0.043	-0.026	-0.081	-0.015
GENDER	0.153	-0.008	-0.033	-0.066	0.053	0.020
EDUCATION	0.034	0.026	-0.041	0.061	0.035	0.055
RESIDENCE	0.037	-0.004	-0.076	-0.027	-0.029	-0.084
RESIDENCE_TIME	-0.096	0.117	0.146	-0.058	-0.010	0.013
Communities	0.083	-0.049	-0.030	0.038	0.014	0.002
ENERGY_EMPLOYMENT	0.057	0.019	-0.035	-0.059	0.013	-0.015
Q01_Preservation	-0.009	0.062	0.074	-0.132	-0.127	-0.111
Q02_Foreigner_Energy	-0.064	0.095	0.034	0.026	-0.010	-0.022
Q03_Energy_G_P	-0.170	-0.037	-0.052	0.328	0.239	0.238
Q04_Energy_Shale	-0.376	0.042	0.120	0.294	0.180	0.173
Q05_Energy_P	-0.314	0.026	0.110	0.225	0.198	0.184
Q06_Energy_Carbon	-0.113	0.011	-0.030	0.320	0.216	0.190
Q07_Energy_Nuclear	-0.153	0.039	0.059	0.377	0.236	0.240
Q08_Energy_Renewable	-0.117	0.015	0.008	0.325	0.286	0.227
Q09_Gas_Explotation	0.476	0.072	-0.079	-0.290	-0.173	-0.253
Q10_Permission	0.445	0.045	0.051	-0.058	0.015	-0.041
Q11_Risks	0.394	0.121	0.053	-0.148	-0.043	-0.074
Q12_Benefits	0.316	0.181	0.114	-0.091	-0.007	0.023
Q13_Frack	1.000	-0.009	-0.034	-0.135	-0.064	-0.087

Q14_Studies	-0.009	1.000	0.344	-0.037	0.000	-0.048
Q15_Changes	-0.034	0.344	1.000	0.113	0.118	0.132
Q16_Water	-0.135	-0.037	0.113	1.000	0.751	0.567
Q17_Gases	-0.064	0.000	0.118	0.751	1.000	0.631
Q18_Earthquakes	-0.087	-0.048	0.132	0.567	0.631	1.000
Q19_Laws	-0.243	-0.044	0.148	0.230	0.165	0.155
Q20_Shale_Clean_Energy	0.308	-0.033	-0.177	-0.187	-0.130	-0.090
Q21_Shale_Reliable	0.254	-0.060	-0.199	-0.146	-0.113	-0.134
Q22_Shale_Cheap	0.212	-0.097	-0.209	-0.094	-0.114	-0.117
Q23_Dependence	0.164	-0.119	-0.214	-0.039	-0.096	-0.072

Table II-15: Spearman's rank correlation coefficient - Spain (continuation).

	Q19_Laws	Q20_Shale_Clean_Energy	Q21_Shale_Reliable	Q22_Shale_Cheap	Q23_Dependence
AGE	0.099	-0.159	-0.164	-0.158	-0.129
GENDER	-0.056	0.028	-0.040	-0.080	-0.063
EDUCATION	-0.010	-0.045	-0.023	-0.093	-0.015
RESIDENCE	-0.125	0.088	0.142	0.122	0.114
RESIDENCE_TIME	0.118	-0.087	-0.081	-0.100	-0.095
Communities	-0.080	-0.038	-0.025	-0.034	0.004
ENERGY_EMPLOYMENT	0.066	-0.093	-0.191	-0.145	-0.161
Q01_Preservation	-0.083	-0.029	-0.043	-0.055	-0.036
Q02_Foreigner_Energy	0.021	-0.045	-0.118	-0.060	-0.067
Q03_Energy_G_P	0.064	-0.014	0.031	0.026	0.162
Q04_Energy_Shale	0.152	-0.228	-0.178	-0.139	-0.049
Q05_Energy_P	0.108	-0.204	-0.169	-0.146	-0.065
Q06_Energy_Carbon	0.112	-0.042	0.009	0.017	0.124
Q07_Energy_Nuclear	0.180	-0.130	-0.102	-0.092	0.035
Q08_Energy_Renewable	0.156	-0.108	-0.055	-0.025	0.032
Q09_Gas_Explotation	-0.334	0.464	0.432	0.338	0.206
Q10_Permission	-0.136	0.327	0.261	0.166	0.088
Q11_Risks	-0.163	0.303	0.224	0.151	0.044
Q12_Benefits	-0.081	0.163	0.068	0.019	-0.137
Q13_Frack	-0.243	0.308	0.254	0.212	0.164
Q14_Studies	-0.044	-0.033	-0.060	-0.097	-0.119
Q15_Changes	0.148	-0.177	-0.199	-0.209	-0.214
Q16_Water	0.230	-0.187	-0.146	-0.094	-0.039
Q17_Gases	0.165	-0.130	-0.113	-0.114	-0.096
Q18_Earthquakes	0.155	-0.090	-0.134	-0.117	-0.072
Q19_Laws	1.000	-0.451	-0.460	-0.374	-0.329
Q20_Shale_Clean_Energy	-0.451	1.000	0.820	0.705	0.595
Q21_Shale_Reliable	-0.460	0.820	1.000	0.771	0.701
Q22_Shale_Cheap	-0.374	0.705	0.771	1.000	0.711
Q23_Dependence	-0.329	0.595	0.701	0.711	1.000

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Appendix III

Supplementary Material of "Life cycle assessment of a shale gas exploration and exploitation project in the province of Burgos, Spain"

1. Life Cycle Inventory

1.1. Site utilities

Site utilities refers to the basic fluxes for living activities: water consumption, energy requirements, as well as waste and wastewater generation. This calculation is performed considering the total number of workers in each life cycle stage as well as the total time for its execution.

Workforce requirements to calculate onsite living impacts in Urraca 1 are considered as 2.41 Full Time Work Equivalent (FTE) in pre-drilling activities (site preparation), 10.49 FTE during drilling, hydraulic fracturing and completion operations, 0.19 FTE in production and 0.20 FTE in gas processing (MSETC, 2011; Witter et al., 2014). For well abandonment it is assumed that the same FTE is used as in pre-drilling activities. A FTE correspond to one full time worker per year or 260 eight-hour working days (MSETC, 2011).

The duration each life cycle stage according to the project is: 45 days for exploration and site preparation, 85 days for vertical and horizontal drilling (including mobilization and demobilization), 25 days for hydraulic fracturing and well completion and 15 days for well abandonment (BNK, 2014). For the natural production phase, we assume 30 years of operation.

For energy requirements, it is estimated the use of 2 set of computers (estimated as 320 W each) in the control room (BNK, 2014; Chang et al., 2014b). Illumination the in control room is assumed as 5 W/m^2 (20 m^2, illuminance level of 500 lux) (ISO 8995:2002/CIE S 008/E:2001). Site lighting is considered as 0.2 W/m^2 to maintain a minimum illuminance level of 10 lux in the main working areas (12,322 m^2) (ISO 8995-3:2006/CIE S 016/E:2005).

Non-hazardous waste is assessed by considering one third of the daily waste generation per capita during the whole life cycle. Total waste rate in Spain is 1.25 kg per capita/day of non-hazardous household waste with a recycle fraction of 10.7% (Eurostat, 2016e; INE, 2016b) – 43% of paper, 25% packaging waste and 32% glass (INE, 2016b). Hazardous waste generated is less than 0.3% of waste generated per capita/day and is considered negligible (Eurostat, 2016e).

Daily water consumption indicators is based on one third of the Castile and León region domestic consumption per capita (157 liters/inhabitant/day) and the volume of treated wastewater (0.435 m^3/inhabitant/day) (INE, 2016c). It is considered that the site is connected to the public services for wastewater treatment.

1.2. Site identification and preparation

Site identification and preparation includes the preparation of the well pad area, preparation of site accesses, followed by the construction of a water impoundment, a water abstraction network and of the gathering line. Material requirements for this life cycle stage include construction material, geotextile, cement, and diesel. Process in this stage corresponds to soil excavation.

As for site identification, the total occupied area was calculated in ArcGIS as 24.368 m^2. Based on the forest map of Spain, this area is classified as agriculture land (MAGRAMA, 2010).

Three major sections in the site can be highlighted: an auxiliary platform (6922 m^2), a main platform (5400 m^2) and a water impoundment (10230 m^3).

For estimates of materials required in site preparation, it is considered in the Urraca 1 project. The main and the auxiliary platform (where the drilling rig will be positioned) will be covered with a 1.5 mm thickness-geotextile layer followed by a compacted 30 cm layer of gravel (BNK, 2014). In the main platform, two layers of a polyethylene cover are considered.

Geotextile is modeled as plastic film extrusion (Hischier, 2007) of high density polyethylene (density is equivalent to 0.94 kg/cm^3) (BPF, 2016). Total estimates for high density polyethylene is 25 ton considering both areas. A 2% waste rate is adopted (Chang et al., 2014b). These assumptions led to a total requirement of 25.5 ton of geotextile, and 5.6 ton of gravel.

Also in this phase, a 14 m^3 excavation is considered for the positioning of the well cellar (BNK, 2014). Excavated materials are assumed to be reused on site for levelling or other purposes. Therefore, materials for disposal and treatment are not generated. Total concrete requirements for the well cellar construction is 4,5 m^3, which is estimated based on its dimensions (2,50 x 2,50 x 2,25). A concrete waste rate of 2% was used.

Site accesses is done through existing roads which require repairs in some sections (BNK, 2014). These sections correspond to a total length of 1.5 km and a width of 11 m (calculated by Google Earth). Repairing is simplified by grading and creation of base *stone* for *roads (*which includes the hauling, placing, and compacting of roadway base material) *operations*.

A creation of a 25 cm base layer of aggregate material (assumed as a mix of sand, gravel and stone) and a 5 cm crushed limestone layer (BNK, 2014) is considered. The adopted waste rate for sand and limestone is 4% (Chang et al., 2014b). Therefore, total material requirements are 7700 ton for the aggregate material and 1400 ton for limestone.

Diesel consumption in the building machinery to perform such operations follows Skolnik et al. (2013). Waste mineral oil in generated was adjusted following European recommendations in the corresponding Ecoinvent 3.1 process (EC, 2016; Wernet et al., 2016).

For the construction of the water impoundment, its geometry was approximated by a truncated rectangular pyramid (dimensions: L=98 m, W = 35 m, a = 22 m, b = 80 m and h = 4 m). For its construction soil excavation corresponding to its total volume was considered. Total required materials correspond to 3680 m^2 of geotextile (modelled as above), which is equivalent to 5.3 ton of geotextile.

The length of the water abstraction network is calculated in ArcGIS as 2068 m, which is the minimum distance to the Nela river (MAGRAMA, 2017). Its construction is based on extrusion of polyvinyl chloride (PVC) pipelines. This process is modelled considering the extrusion of plastic pipes (Hischier, 2007) and production of PVC made from suspension polymerization (PVC, 2017).

Due to the lack of specification in the project, it is assumed that Schedule 80 PVC is used, with a linear mass of 0.32 kg/m (NRCS, 2005) and a 2% waste rate. Therefore, a total mass of PVC of 675 kg is considered. Diesel consumption in building machine required to install this line follows Skolnik et al. (2013). Waste mineral oil generated was always adjusted as mentioned above.

The total length of gathering lines required to connect the site to the existing natural gas transmission network was calculated as 20230 m using ArcGIS. Existing pipelines considered follows the exiting Spanish network (ENAGAS, 2017b). Construction of gathering lines follows are modeling considering a similar Ecoinvent 3.1 process (low-pressure natural gas construction) (Wernet et al., 2016).

1.3. Well design, drilling, casing and cementing

Materials in well drilling, casing and cementing includes diesel to be consumed in the drilling rig and in the drilling mud circulating system, chemicals and other materials for drilling mud and cement production, steel for casing manufacturing and cement. Assumptions and requirements for such materials are discussed in the following sections. The well specification follows Table III-1.

Table III-1: Urraca well specification.

Section	Section diameter (inches)	Section diameter (m)	Casing Size[1] (inches)	Casing Size[1] (m)	Total length (m)
1	36	0.91	30	0.76	40
2	26	0.66	20	0.51	510
3	17 1/2	0.44	13 3/8	0.34	1450
4	12 1/4	0.31	9 5/8	0.24	395
5	8 1/2	0.22	5 1/2	0.14	2635[2]

1: Outside diameter

2: From which, 635 m is vertical and 2000 m horizontal.

It assumed that two portable diesel fueled water pumps of 37-kW (5 m^3/minute) are used to withdrawal surface water to the water impoundment (Chang et al., 2014b) to supply water for the preparation of cement and drilling fluids. The diesel consumption for water pumps and emissions follows definitions for stage IV engines in EMEP/EEA (2006).

1.3.1. Diesel consumption in the drilling rig

The consumption of diesel in the drilling rig is related to the total time requirement and total power of the system. Time requirements are based on the drilling efficiency. Even though there are different measures to evaluate drilling efficiency (BH, 2017; Cochener, 2010), the Rate of Penetration (ROP) is adopted. ROP values were estimated based on a triangular distribution developed from literature data with a=3.54 m/h, b=19.38 m/h and c=13.13 m/h (Chang et al., 2014b; EIA, 2016d; Jiang et al., 2011a).

The total power of the drilling rig is related to the number of generator sets, which depends on total drilling rig capacity. Considering the true vertical depth of the well, it is assumed that capacities of 1500hp or 2000hp would be suitable for the depth to be drilled Urraca 1 (BENTEC, 2012; Chuan and Chenghai, 2006). Considering existing suppliers in Europe, the powering system of the drilling rig may use a minimum of 3 and a maximum of 5 drilling generators of 1200 kW, and is assumed to operate at 66% efficiency (Chang et al., 2014b; Drillmec, 2017a, b).

Fuel consumption of diesel generators varies in the literature and in equipment specification (CAT, 2013; Chang et al., 2014b; Clark et al., 2011a; EMEP/EEA, 2006, 2016a; Stephenson et al., 2011b). Therefore, an average diesel consumption of 250 g per kWh is defined as a reference. Diesel generators in the drilling rig operate at a real power equivalent of 66% of their rated power due to load variations during drilling operations (Chang et al., 2014b; Pavković et al., 2016).

1.3.2. Drilling fluids

In Urraca 1, water based fluids (WBF) and synthetic-base mud (SBM) are expected to be used (BNK, 2014). WBF is expect to be used in Sections 17 ½", 12 ¼" and in the vertical phase of Section 8 ½". SBM is going to be used in the horizontal phase of the Section 8 ½".

Composition of WBF to be used in Section 36" and 26" is 1026 kg/m^3 of water, 2 kg/m^3 of sodium hydroxide, 70 kg/m^3 of bentonite and 2 kg/m^3 of carboxymethyl cellulose (BNK, 2014). Table III-2 presents the composition of WBF for sections 17 ½", 12 ¼" and 8 ½".

Table III-2: Material and water requirements for 17 ½", 12 ¼" and 8 ½" sections.

Substance	Concentration (kg/m3)
Barite (Barium Sulfate)	250
Sodium Hydroxide	0.4
Starch, soluble[1]	2
Glutaraldehyde[2,3]	1
Carboxymethyl cellulose[1]	10
Sodium Carbonate	4
Calcium Carbonate	70
Ether amine acetate[3]	30
Aliphatic thermopolimer[3]	5
Xanthan gum[3]	5

1: Assumed as natural starch from potato (Schulumberger, 2017).

1: Following material specification in EPA (2015b).

2: Following frequencies presented in Kahrilas et al. (2015).

3: A proxy for these constituents was production of organic chemical.

The composition of SBM to be used is not presented in the project specification. Therefore, its composition is assumed to be composed of 400.86 kg/m^3 of base fluid (diesel), 14.24 kg/m^3 of viscosifier, 18.20 kg/m^3 of primary emulsifier, 9.39 kg/m^3 of secondary emulsifier, 14.24 kg/m^3 of lime, 296.99 kg/m^3 of water, 86.29 kg/m^3 of $CaCl2$ and 479.65 kg/m^3 of barite (HSE, 2000). The product 'unspecified inorganic chemicals' in Ecoinvent 3.1 database (Wernet et al., 2016) was considered as a proxy to replace the emulsifier and viscosifiers.

1.3.2.1. Drilling fluid requirements

Theoretically, total circulating system volume is the sum of the drilling fluid in the wellbore, the mud volume in surface system and mud in auxiliary tank systems (M-I SWACO, 1998; Morgan, 2005). Surface system is composed of surface tanks, piping, solid control equipment, among others. Drilling fluids in the wellbore are calculated not considering the drill string in the hole as the volume of the excavated section plus the volume of previous cased section ($V_{wellbore}$).

The Urraca 1 project describes the existence of two mud pits (3m x 10m x 4m) operating at 60% of total capacity (M-I SWACO, 1998), totaling 144m^3 ($V_{circulation\ tank}$). Volume in piping and other equipment (V_{pe}) is considered negligible and volume of reserve tank (V_{tank}) is 80m^3 (Chang et al., 2014b). Total volumes for each section are presented in Table III-3. Variations to the total drilling mud are assumed to be equivalent to the usage of two times the expected volumes to deal with pressure losses or other operational issues (Chang et al., 2014b).

Table III-3: Drilling fluid consumption per section.

Section	$V_{wellbore}$ (m^3)	$V_{circulation\ tank}$ (m^3)	V_{pe} (m^3)	V_{tank} (m^3)	Total volume (m^3)	Total mass (ton)
Section 30" and 20"	217.69	144.00	0.00	80	441.69	530.03
Sections 13 ½", 12 ¼" and 8 ½"	608.82	144.00	0.00	80	832.82	1290.87
Section 8 ½"	151.50	144.00	0.00	80	375.50	481.44

1.3.2.2. Equipment for drilling fluid circulation

It is assumed that mud treatment will follow the minimum equipment requirements described in M-I SWACO (1998), the usage of shale shakers and 2 mud cleaning units (BNK, 2014). Equipment data, were obtained from a company operating in the European market (GN, 2016).

Equipment considered corresponded to 2 shale shakers >65 µm (3.44 kW each), a vacuum degasser (22 kW), two mud cleaners (3.44 kw each), a centrifuge (37 kw) and a shear pump (45 kW) (GN, 2016). Energy requirement of these equipment are assumed to be provided by diesel generators with a minimum capacity of 500kw considering a power factor of 0.8.

1.3.2.3. Drill cuttings and drilling waste

Drilling waste is composed by waste drilling fluid, drilled cuttings with associated drilling fluid, and miscellaneous fluids such as excess cement, spacers, and a variety of other fluids (Piper et al., 2005). To estimate final drilling fluids to disposal, a mass balance was performed considering the volume of the wellbore plus the total drilling fluid returning to the surface. For the total drill cuttings mass, the average density of the formation is assumed as 2384.65 kg/m^3 (Ahmad and Rezaee, 2015; Chang et al., 2014b).

Downhole losses rates vary according to the formation and are a direct result of fluid and well characteristics, but an average of 8% of fluid is lost downhole (Lindland, 2006; Pettersen, 2007). Recycling rates of drilling muds generates a triangular distribution characterized by a=

54%, b=85% and c=76.3% (Jiang et al., 2011a; Jiang et al., 2014a; Lindland, 2006; Maloney and Yoxtheimer, 2012a; Pettersen, 2007).

1.3.3. Well casing and tubing

The weight of well tubing was calculated considering the density of the material and was considered as seamless steel. For each casing size, a range of casing weights are available. Dimensions and masses for standard casing for the project followed the API Specification 5CT for casing and tubing (ISO 11960:2004) assuming the median of wall thickness and are shown in Table III-4. For simplicity, the conductor pipe, that provide the initial stable structural foundation is assumed to be the same thickness and plain weight of the 30" section.

Table III-4: Dimensions and masses for standard casing used in Urraca 1.

Section	Hole size (inches)	Casing Size (inches)	Outside diameter (mm)	Wall thickness (mm)	Depth (m)	Nominal linear mass (kg/m)
1	36	30	762.00	12.7	40	158.49
2	26	20	508.00	12.7	550	158.49
3	17 1/2	13 3/8	339.73	10.92	2000	90.78
4	12 1/4	9 5/8	244.48	13.84	2395	13.84
5	8 1/2	5 1/2	139.70	13.485	5030	42.04

1.3.4. Cementing

Modelling cement used in drilling presents a great limitation related to the large number of commercial constituents of which the composition is not disclosed. This proportion of usage of such additives generate the main differences of cement characteristics to be used in each well sections and are not available in Ecoinvent 3.1 (Wernet et al., 2016).

Therefore, it is considered to be of the same composition for all phases of the well. The composition adopted corresponds to: 1,252 kg/m^3 of cement, 25 kg/m^3 of bentonite, 12 kg/m^3 of cement retarder (density data obtained from Halliburton (2016), 58.5 kg/m^3 of liquid silicate (considered as liquid sodium silicate), 1.8 kg/m^3 of defoamer and 551 kg/m^3 of water (BNK, 2014).

The specific gravity for class G cement is 1.91 at 44 wt% water-cement ratio (ISO 10426-1:2009). The waste rate for cement is 2% (Chang et al., 2014b). Cement retarder and defoamer are modelled generically as production of inorganic chemicals.

In order to determine the energy use and air pollutant emissions estimates for the equipment, the cementation time was estimated by following Equations 1 to 3 (Lyons et al., 2005). Mixing rate is 25 sacks of cement per minute (one sack is equivalent to 33.56kg) (Lyons et al., 2005). These estimates result in a total of 24.5 hours for cement slurry batching and pumping. It is considered the usage of one cementation truck with a diesel engine of 387kW for such operations (Chang et al., 2014b; Halliburton, 2013, 2016).

$$T_O = T_m + T_d + T_p + T_s \quad (1)$$

$$T_m = \frac{volume\ of\ dry\ cement}{mixing\ rate} \quad (2)$$

$$T_d = \frac{Internal\ capacity\ of\ the\ casing}{\mathrm{Vp-out}} \tag{3}$$

Where:

- T_O (h): Total operation time.
- T_m (h): time required to mix the dry cement (and additives) with water.
- T_d (h): the time required to displace the cement slurry (that was pumped to the well as mixing took place) by mud or water from inside the casing.
- T_p (h): plug release time, assumed as 0.25h (Lyons et al., 2005).
- Ts (h): the safety factor, assumed as 2h (Lyons et al., 2005).
- Vp-out (m^3/s): Volume capacity of the mud pump per stroke, 0.027 m^3/s.

1.4. Hydraulic fracturing

1.4.1. Fracturing fluid

Choice of fluids consisted of data presented in the Ecoinvent 3 database that reflect common field practices (GWPC, 2009; Wernet et al., 2016). However, due to the early stage of the exploration, it is not clear how fluid composition is going to change in a commercial production scenario. Modelling or developing an average fluid from literature data based on a comparison of the reported constituents with data presented by the EPA is difficult considering that all chemicals are not fully disclosed and it is not possible to identify a significant average composition per well (EPA, 2015a; FracFocus, 2015).

Total water usage is another parameter that varies significantly in the literature. Data compiled from the literature have generate a triangular distribution with parameters a=3096 m^3, b=46140 m^3 and c=1121 m^3 (Chang et al., 2014b; Clark et al., 2013a; Stamford and Azapagic, 2014; Vengosh et al., 2017; Yang et al., 2015a).

It assumed that two portable diesel fueled water pumps of 37-kW (5m^3/minute) are used to withdrawal surface water to the water impoundment (Chang et al., 2014b) to supply water for the preparation of cement and drilling fluids. Diesel consumption and emissions from the water pumps follows definitions for stage IV engines in EMEP/EEA (2006).

1.4.2. Hydraulic fracturing operations

Equipment power used were obtained from a company catalogue (Stewart&Stevenson, 2016), considering similar equipment to be used in Urraca 1 as a reference. Total fleet for hydraulic fracturing in Urraca 1 is equivalent to 24287 kW and consists of 14 pumper trucks (1678 kw each), 1 blender truck (783 kW) and one monitoring van (20kw), following project specification for equipment (BNK, 2014). Fracturing water heating is an equipment reported in some plays, but it is not going to be considered due to the ambient temperatures in Burgos.

Total power requirements per hydraulic fracturing treatment has increased in recent the years due to the rapid development of shale gas plays (Smith and Montgomery, 2015). Across the shale gas literature, it is reported the usage of a total fleet power ranging of 9134 kW or 12250hp (Stephenson et al., 2011b), 25353 kW or 34000 hp (Chang et al., 2014b) and 25465 kW or 34150 hp (Jiang et al., 2011b). Therefore, we assume that total fleet power can range between 9134 kW to 25465 kW, based on different combinations of the aforementioned equipment.

Energy consumption during the hydraulic fracturing is related to the total operational time. Literature data led to a triangular distribution with a=10, b= 48 and c =31 for total hydraulic fracturing hours (Chang et al., 2014b; EERC, 2015; Jiang et al., 2011b; Stephenson et al., 2011b). However, it is worth mentioning that total time can be calculated considering the number of fracturing stages or the spacing among fractures (Stephenson et al., 2011b).

1.4.3. Flowback water

Fluid returning to the surface (injected hydraulic fracturing and native formation fluids) can be referred to as either "flowback" or "produced water," and may contain both hydraulic fracturing fluid and natural formation water (EPA, 2011b). The volume of the returned (flowback) water varies significantly across literature, ranging from 10% to 80% of the injected hydraulic fracturing volume and result in a triangular distribution with a=10%, b=80% and c=11.5% (CSUR, 2013; Groat and Grimshaw, 2012; GWPC, 2009; Haluszczak et al., 2013; Jiang et al., 2014a; Liu et al., 2015; Maloney and Yoxtheimer, 2012a; Stamford and Azapagic, 2014).

Chemical disclosure of the composition for hydraulic fracturing flowback is the subject of several studies in literature. Understanding the composition of the flowback water is essential for assessing its reuse potential. In the absence of average data, the full disclosure of flowback water in Urraca 1 and its impacts cannot be performed. As a proxy, the composition of the flowback fluid emitted to soil is modeled after the results of Lester et al. (2015a).

We assume the Ecoinvent 3 process water discharge from onshore petroleum/natural gas extraction as a proxy, and is performed at an industrial treatment facility located 73-km away. The total amount of flowback for treatment and in soil is determined by a mass balance of flowback rate and recycle rates in literature, describing a triangular distribution with a=30%, b=95% and c=78% (Jiang et al., 2014a; Jiang et al., 2011b; Maloney and Yoxtheimer, 2012a).

1.5. Well completion

Natural gas consumption by Reduced Emissions Completion (REC) equipment is modelled after literature data (EPA, 2011d). Estimate of total time required to completion was done in order to calculate such consumption. However, this parameter varies significantly in the literature (Allen et al., 2013; Chang et al., 2014b; EPA, 2011d; Jiang et al., 2011b; NYDEC, 2009; Sandlin, 2012), generating a triangular distribution with a=5, b= 360, c =107.23.

Flaring efficiency is considered to be 98%, as extensively reported in literature (Caulton et al., 2014a; O'Sullivan and Paltsev, 2012; Stephenson et al., 2011b). The other 2% is assumed to not be combusted (API, 2009; ICF, 2009a; NETL, 2014). Emissions of vented emissions to the atmosphere are based in Equation 4 which was applied to each constituent of the NG produced.

$$m_{substance\ i,\ si}^{OUT} = m_{si}^{IN} - m_{si}^{IN} F F_e - m_{si}^{IN} C \quad (4)$$

Where: m_{si}: mass of substance i, F: flaring rate, F_e: flaring efficiency and C: capture rate.

Despite the existence of different emission factors for natural gas flaring (API, 2009; EMEP/CORINAIR, 2007; EMEP/EEA, 2016b), in order to obtain greater sensibility to the composition of NG considered, flaring emissions are estimated considering the complete emissions of natural gas constituent substances. This assumption leads to emission factors equivalent to 2.75 $kgCO_2/kgCH_4$, 2.93 $kgCO_2/C_2H_6$, 3.00 $kgCO_2/kgC_3H_8$, 3.03 $kgCO_2/kg\ C_4H_{10}$, 1.88 $kgSO_2/kgH_2S$ and 3.29 $kgNO_2/kgN_2$. Total flared emissions are equivalent to 1.98E+04 kg of CO_2, 8.10E+02 kg of NO_2 and 9.42E+08 kg of SO_2.

1.6. Natural gas production

Produced water and recycle rate are poorly reported in literature and the existing information differ significantly. It can be reported as a range during the well lifecycle (Jiang et al., 2011a; Jiang et al., 2014a) or as a function of the total gas produced (Stephenson et al., 2011b). Since produced water literature values are, the values presented by the EPA are considered, which vary between 15.04 to 80.21 million of produced water to millions of millions of NG produced (EPA, 2011c).

1.7. Gathering

Fugitive emissions from gathering are calculated considering an emission factor presented in the EPA (2017). This factor is expressed in terms of $kgCH_4$ per year and gathering line length. From this value the fugitive natural gas volume is estimated to base emissions in terms of raw natural gas.

1.8. Processing

The most typical NG processing includes acid gas removal (or NG sweetening) and dehydration. Both process are modelled as described in description in NETL (2014). Dehydration considers natural gas consumption and process emission are CO_2, CH_4 and N_2O (NETL, 2011, 2014). Sweetening also includes natural gas consumption and amine solution (estimated by averaging the molar mass of monoethanolamide and diethanolamine) (NETL, 2010, 2014). Process emissions from this stage are CO_2, CH_4, N_2O, CO, VOC, PM, Pb and NOx (NETL, 2010, 2014).

1.9. Transmission and distribution

Fugitive emissions and NG losses from transmission, distribution and storage are also calculated considering emission factor from the 2015 Spanish National Inventory Report (MAPABA, 2017). Other parameters in transmission modelling (water, fuels and waste generation) are based on a three-years average of environmental indicators reported by the main transmission company for primary NG in Spain *(*Enagas, 2017a*;* Sedigas, 2017*)*.

1.10. Well closure

Once a well has been abandoned, the site will be restored, and a period of aftercare conducted to ensure the land returns to a state that is the same or better than it was prior to operations. Restoration involves the removal of all equipment that was not originally at the site and which had been brought in to conduct the operations and plugging the well.

Well plugging is expected to occur considering three concrete sections. Total cement requirements in Urraca 1 were calculated considering as 4.77 m^3 (BNK, 2014). A concrete waste rate of 2% was used.

2. Inventory tables

Inventory data per life cycle stage is presented in Table III-5 to Table III-13. In these tables, inputs and inputs for each life cycle stage. All values are reported to the functional unit (1MJ of natural gas delivered). Site utilities are included for each life cycle stage.

Table III-5: Inventory table for site identification and preparation. All units are reported to the functional unit.

Site identification					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Transformation, from agriculture	1.48E-05	m^2	Waste concrete {RoW}| treatment of, inert material landfill | Alloc Def, U	1.26E-07	kg
Transformation, to mineral extraction site	1.48E-05	m^2	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Alloc Def, U	6.85E-08	kg
Site preparation					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Gravel	3.48E-06	ton	Waste polyethylene {CH}| treatment of, sanitary landfill | Alloc Rec, U	3.03E-07	kg
Diesel, burned in building machine {GLO}| processing | Alloc Def, U	6.40E-05	MJ			
Polyethylene, high density, granulate {RER}| production | Alloc Def, U	9.39E-06	kg			
Extrusion, plastic film {RER}| production | Alloc Def, U	9.39E-06	kg			
Polyethylene, high density, granulate {RER}| production | Alloc Def, U	6.04E-06	kg			
Extrusion, plastic film {RER}| production | Alloc Def, U	6.04E-06	kg			
Excavation, hydraulic digger {RoW}| processing | Alloc Def, U	8.52E-09	m^3			
Concrete, normal {RoW}| production | Alloc Def, U	2.71E-09	m^3			
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	2.74E-05	kgkm			
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | Alloc Rec, U	1.55E-06	kgkm			
Access construction and road repair					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Sand, gravel and stone, extracted for use	4.68E-06	ton	Limestone residue {RoW}| treatment of, inert material landfill | Alloc Def, U	3.32E-08	ton
Limestone	8.61E-07	ton	Inert waste, for final disposal {RoW}| treatment of inert waste, inert material landfill | Alloc Def, U	1.48E-07	ton

Diesel, burned in building machine {GLO}| processing | Alloc Def, U	1.62E-04	MJ			
Diesel, burned in building machine {GLO}| processing | Alloc Def, U	1.86E-04	MJ			
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	1.82E-06	tkm			
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	8.18E-06	kgkm			
Transport, freight, light commercial vehicle {Europe without Switzerland}| processing | Alloc Def, U	8.42E-06	kgkm			
Impoundment construction					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Polyethylene, high density, granulate {RoW}| production | Alloc Def, U	3.21E-06	kg	Waste polyethylene {CH}| treatment of, sanitary landfill | Alloc Rec, U	6.30E-08	kg
Extrusion, plastic film {RoW}| production | Alloc Def, U	3.21E-06	kg			
Excavation, hydraulic digger {RER}| processing | Alloc Def, U	6.20E-06	m^3			
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	1.76E-04	kgkm			
Water abstraction network					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Extrusion, plastic pipes {RER}| production | Alloc Def, U	4.26E-07	kg	Waste polyethylene {CH}| treatment of, sanitary landfill | Alloc Rec, U	8.36E-09	kg
Polyvinylchloride, suspension polymerised {RER}| polyvinylchloride production, suspension polymerisation | Alloc Def, U	4.26E-07	kg			
Diesel, burned in building machine {GLO}| processing | Alloc Def, U	4.87E-04	MJ			
Municipal waste collection service by 21 metric ton lorry {GLO}| market for | Alloc Def, U	4.59E-07	tkm			
Gathering line construction					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Pipeline, natural gas, low pressure distribution network {RoW}| construction | Alloc Def, U	8.85E-10	km			
Raw material transportation					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Transport, truck >20t, EURO3, 100%LF, default/GLO Mass	1.44E-03	kgkm			
Transport, truck <10t, EURO3, 100%LF, empty return/GLO Mass	3.28E-05	kgkm			
Transport, truck >20t, EURO3, 100%LF, empty return/GLO Mass	2.68E-04	tkm			
Transport, truck 10-20t, EURO3, 100%LF, empty return/GLO Mass	4.96E-04	kgkm			
Transport, truck <10t, EURO3, 100%LF, default/GLO Mass	6.67E-05	tkm			
Transport, truck 10-20t, EURO3, 80%LF, empty return/GLO Mass	7.39E-04	kgkm			
Transport, freight, lorry >32 metric ton, EURO3 {RER}| transport, freight, lorry >32 metric ton, EURO3 | Alloc Def, U	3.61E-04	tkm			
Site utilities					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	1.99E-05	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	5.51E-08	kg

Electricity, low voltage {ES}| market for | Alloc Def, U	8.07E-07	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	1.41E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	3.71E-08	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	4.19E-09	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.40E-07	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	7.24E-09	kg
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	8.73E-06	kgkm	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	5.44E-09	kg

Table III-6: Inventory table for well design, drilling, casing and cementing. All units are reported to the functional unit.

Drilling rig					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	1.38E-04	kg	Nitrogen oxides	5.56E-03	g
			Carbon monoxide, fossil	7.70E-04	g
			NMVOC, non-methane volatile organic compounds, unspecified origin	2.19E-04	g
			Sulfur oxides	2.72E-04	g
			TSP	1.66E-04	g
			Particulates, < 10 um	1.32E-04	g
			Particulates, < 2.5 um	1.28E-04	g
			Particulates, diesel soot	1.00E-04	g
			Lead	2.40E-05	mg
			Cadmium	8.00E-06	mg
			Mercury	8.00E-06	mg
			Arsenic	1.07E-05	mg
			Chromium	8.00E-06	mg
			Nickel	8.00E-06	mg
			Selenium	4.01E-05	mg
			Zinc	1.07E-05	mg
			Dioxins (unspec.)	5.84E-06	ng
			Benzene, hexachloro-	1.30E-06	µg
			Polychlorinated biphenyls	7.70E-07	ng
			Benzo(a)pyrene	6.85E-07	mg
			Benzo(b)fluoranthene	2.96E-06	mg
			Benzo(k)fluoranthene	5.82E-07	mg
			Indeno(1,2,3-cd)pyrene	1.10E-06	mg
			Carbon dioxide	4.36E-04	kg
			Sulfur dioxide	1.38E-02	mg
Drilling fluids production and circulating system					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Avoided products			Nitrogen oxides	4.64E-05	g
Drilling fluid - section 26"	2.45E-07	ton	VOC, volatile organic compounds	1.51E-05	g
Drilling fluid - Sections 17 ½”, 12 ¼” and 8 ½”	5.97E-07	ton	Methane	3.48E-07	g
Drilling fluid (synthetic) - Section 8 ½" and 5 ½"	2.22E-07	ton	Carbon monoxide, fossil	1.74E-04	g
Materials/fuels			Nitrogen dioxide	4.06E-06	g
Drilling fluid - Section 26"	3.21E-07	ton	Ammonia	2.32E-07	g
Drilling fluid - Sections 17” ½, 12 ¼” and 8 ½”	7.82E-07	ton	Particulates, unspecified	2.90E-06	g

Drilling fluid (synthetic) - Section 8 1/2" and 5 1/2"	2.92E-07	ton	Particulates, < 10 um	2.90E-06	g
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	2.90E-05	kg	Particulates, < 2.5 um	2.90E-06	g
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	2.14E-04	tkm	Particulates, diesel soot	2.09E-06	g
			Carbon dioxide, fossil	9.15E-02	g
			Sulfur dioxide	2.90E-03	mg
			Cadmium	2.90E-07	mg
			Copper	4.93E-05	mg
			Chromium	1.45E-06	mg
			Nickel	2.03E-06	mg
			Selenium	2.90E-07	mg
			Zinc	2.90E-05	mg
			Outputs (waste to treatment)	Value	Unit
			Drilling waste {CH}| treatment of, residual material landfill | Alloc Def, U	1.02E-06	ton
Drilling fluid production - Section 26"					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Water, river, ES	3.01E-07	m^3			
Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, membrane cell | Alloc Def, U	1.07E-06	kg			
Bentonite {RoW}| quarry operation | Alloc Def, U	1.87E-05	kg			
Carboxymethyl cellulose, powder {RER}| production | Alloc Def, U	5.35E-07	kg			
Drilling fluid production - Sections 17 ½”, 12 ¼” and 8 ½”					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Water, river, ES	6.12E-07	m^3			
Sodium carbonate	2.02E-09	ton			
Calcium carbonate	3.53E-08	ton			
Barite {RER}| production | Alloc Def, U	1.26E-04	kg			
Sodium hydroxide, without water, in 50% solution state {RER}| chlor-alkali electrolysis, membrane cell | Alloc Def, U	4.04E-07	kg			
Potato starch {RoW}| production | Alloc Def, U	1.01E-06	kg			
Carboxymethyl cellulose, powder {RER}| production | Alloc Def, U	5.05E-06	kg			
Chemical, inorganic {GLO}| production | Alloc Def, U	2.07E-05	kg			
Drilling fluid (synthetic) production - Section 8 ½" and 5 ½"					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Water, river, ES	6.55E-08	m^3			
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	8.85E-05	kg			
Chemical, inorganic {GLO}| production | Alloc Def, U	7.15E-06	kg			
Calcium chloride {RER}| soda production, solvay process | Alloc Def, U	1.91E-05	kg			
Lime {RoW}| production, milled, loose | Alloc Def, U	3.15E-06	kg			
Barite {RER}| production | Alloc Def, U	1.06E-04	kg			
Water pump					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	6.85E-08	kg	Nitrogen oxides	9.94E-07	g
			VOC, volatile organic compounds	1.09E-07	g
			Methane	2.61E-09	g
			Carbon monoxide	5.73E-07	g

			Nitrogen dioxide	9.09E-09	g
			Ammonia	5.21E-10	g
			Particulates	3.90E-09	g
			Particulates, < 10 um	3.90E-09	g
			Particulates, < 2.5 um	3.90E-09	g
			Soot	5.21E-10	g
			Carbon dioxide	2.16E-07	kg
			Sulfur dioxide	6.85E-06	mg
			Cadmium	6.85E-10	mg
			Copper	1.16E-07	mg
			Chromium	3.41E-09	mg
			Nickel	4.78E-09	mg
			Selenium	6.85E-10	mg
			Zinc	6.85E-08	mg
Cementing operations					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Cement	1.79E-07	m^3	Nitrogen oxides	1.94E-06	g
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	1.21E-06	kg	VOC, volatile organic compounds	6.30E-07	g
			Methane	1.45E-08	g
			Carbon monoxide, fossil	7.27E-06	g
			Nitrogen dioxide	1.70E-07	g
			Ammonia	9.70E-09	g
			Particulates, unspecified	1.21E-07	g
			Particulates, < 10 um	1.21E-07	g
			Particulates, < 2.5 um	1.21E-07	g
			Particulates, diesel soot	8.73E-08	g
			Carbon dioxide, fossil	3.84E-03	g
			Sulfur dioxide	1.21E-04	mg
			Cadmium	1.21E-08	mg
			Copper	2.06E-06	mg
			Chromium	6.06E-08	mg
			Nickel	8.48E-08	mg
			Selenium	1.21E-08	mg
			Zinc	1.21E-06	mg
			Outputs	Value	Unit
			Inert waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	6.67E-06	kg
Cement production					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Water, unspecified natural origin, ES	9.88E-08	m^3			
Cement, Portland {Europe without Switzerland}| market for | Alloc Def, U	2.24E-04	kg			
Bentonite {GLO}| market for | Alloc Def, U	4.48E-06	kg			
Sodium silicate, without water, in 48% solution state {GLO}| market for | Alloc Def, U	1.05E-05	kg			
Chemical, inorganic {GLO}| production | Alloc Def, U	2.45E-06	kg			
Well casing and tubing					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Steel, unalloyed {RER}| steel production, converter, unalloyed | Alloc Def, U	3.15E-07	ton			
Raw material transportation					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Transport, truck 10-20t, EURO3, 80%LF, default/GLO Mass	7.94E-03	kgkm			

Transport, truck >20t, EURO3, 80%LF, empty return/GLO Mass	2.42E-05	tkm			
Transport, truck 10-20t, EURO3, 80%LF, empty return/GLO Mass	1.06E-02	kgkm			
Transport, truck 10-20t, EURO5, 80%LF, empty return/GLO Mass	1.85E-02	kgkm			
Site Utilities					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	2.23E-05	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	6.17E-08	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.52E-06	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	1.58E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	2.10E-07	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	4.70E-09	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	7.91E-07	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	8.12E-09	kg
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	9.76E-06	kgkm	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	6.10E-09	kg

Table III-7: Inventory table for hydraulic fracturing. All units are reported to the functional unit.

Fracturing fluid injection					
Avoided products	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Fracking fluid	8.55E-07	m^3	Water discharge from petroleum/natural gas extraction, onshore {GLO}| treatment of | Alloc Def, U	2.41E-07	ton
Fracking fluid production					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Hydraulic fracturing fluid {GLO}| hydraulic fluid production, for geological stimulation | Alloc Def, U	9.52E-06	m^3			
Pumper trucks operation					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	1.10E-04	kg	Nitrogen oxides	1.55E-03	g
			VOC, volatile organic compounds	5.75E-05	g
			Methane	1.33E-06	g
			Carbon monoxide	6.61E-04	g
			Nitrogen dioxide	1.55E-05	g
			Ammonia	8.85E-07	g
			Particulates	1.99E-05	g
			Particulates, < 10 um	1.99E-05	g
			Particulates, < 2.5 um	1.99E-05	g
			Soot	8.85E-07	g
			Carbon dioxide	3.49E-04	kg
			Sulfur dioxide	1.10E-05	kg
			Cadmium	1.10E-06	mg
			Copper	1.88E-04	mg
			Chromium	5.53E-06	mg
			Nickel	7.76E-06	mg
			Selenium	1.10E-06	mg
			Zinc	1.10E-04	mg
Blender trucks operation					

Inputs	Value	Unit	Emissions to air	Value	Unit
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	3.68E-06	kg	Nitrogen oxides	5.16E-05	g
			VOC, volatile organic compounds	1.92E-06	g
			Methane	4.42E-08	g
			Carbon monoxide	2.21E-05	g
			Nitrogen dioxide	5.16E-07	g
			Ammonia	2.95E-08	g
			Particulates	6.61E-07	g
			Particulates, < 10 um	6.61E-07	g
			Particulates, < 2.5 um	6.61E-07	g
			Soot	2.95E-08	g
			Carbon dioxide	1.16E-05	kg
			Sulfur dioxide	3.68E-07	kg
			Cadmium	3.68E-08	mg
			Copper	6.24E-06	mg
			Chromium	1.84E-07	mg
			Nickel	2.58E-07	mg
			Selenium	3.68E-08	mg
			Zinc	3.68E-06	mg
Data acquisition center operation					
Inputs	Value	Unit	Emissions to air	Value	Unit
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	9.88E-08	kg	Nitrogen oxides	1.44E-06	g
			VOC, volatile organic compounds	1.58E-07	g
			Methane	3.76E-09	g
			Carbon monoxide	8.30E-07	g
			Nitrogen dioxide	1.32E-08	g
			Ammonia	7.52E-10	g
			Particulates	5.64E-09	g
			Particulates, < 10 um	5.64E-09	g
			Particulates, < 2.5 um	5.64E-09	g
			Soot	7.52E-10	g
			Carbon dioxide	3.12E-07	kg
			Sulfur dioxide	9.88E-08	kg
			Cadmium	9.88E-10	mg
			Copper	1.68E-07	mg
			Chromium	4.93E-09	mg
			Nickel	6.91E-09	mg
			Selenium	9.88E-10	mg
			Zinc	9.88E-08	mg
Water pumps fracking operation					
Inputs	Value	Unit	Emissions to air	Value	Unit
Diesel, low-sulfur {Europe without Switzerland}| production | Alloc Def, U	1.11E-06	kg	Nitrogen oxides	1.61E-05	g
			VOC, volatile organic compounds	1.78E-06	g
			Methane	4.22E-08	g
			Carbon monoxide	9.27E-06	g
			Nitrogen dioxide	1.48E-07	g
			Ammonia	8.42E-09	g
			Particulates	6.30E-08	g
			Particulates, < 10 um	6.30E-08	g
			Particulates, < 2.5 um	6.30E-08	g
			Soot	8.42E-09	g

			Carbon dioxide	3.50E-06	kg
			Sulfur dioxide	1.11E-07	kg
			Cadmium	1.11E-08	mg
			Copper	1.88E-06	mg
			Chromium	5.53E-08	mg
			Nickel	7.76E-08	mg
			Selenium	1.11E-08	mg
			Zinc	1.11E-06	mg
Flowback water in soil					
Inputs	**Value**	**Unit**	**Emissions to soil**	**Value**	**Unit**
Flowback water in soil	8.42E-06	m^3	Ammonia	2.08E-04	mg
			Nitrate	4.38E-05	mg
			Chloride	1.15E+00	mg
			Cyanide compounds	4.63E-07	mg
			Bromide	7.33E-04	mg
			Sulfide	2.61E-06	mg
			Sulfate	1.10E-05	mg
			Phenols, unspecified	1.18E-05	mg
			Acetic acid	1.35E-02	mg
			Butyric acid	1.60E-04	mg
			Propionic acid	2.78E-04	mg
			Aluminium	5.39E-07	mg
			Arsenic	5.64E-07	mg
			Boron	2.61E-05	mg
			Barium	7.21E-05	mg
			Calcium	4.41E-03	mg
			Chromium	4.88E-07	mg
			Cesium-137	6.12E-07	mBq
			Copper	2.42E-06	mg
			Iron	6.85E-04	mg
			Potassium	8.55E-04	mg
			Lithium	2.96E-05	mg
			Magnesium	8.97E-04	mg
			Manganese	1.24E-05	mg
			Sodium	5.84E-02	mg
			Nickel	3.53E-07	mg
			Silicon	1.65E-04	mg
			Strontium	5.07E-04	mg
			Titanium	2.36E-07	mg
			Vanadium	1.01E-06	mg
			Zinc	4.29E-07	mg
			Acetone	1.35E-01	µg
			Methyl ethyl ketone	2.02E-03	µg
			Xylene	2.53E-04	µg
			1,4-Dioxane	5.05E-04	µg
			o-Cresol	1.26E-03	µg
			m-Cresol	7.15E-04	µg
			p-Cresol	7.15E-04	µg
			Naphthalene, 2-methyl-	3.36E-05	µg
			Phthalate, dimethyl-	1.26E-04	µg
			Phenanthrene	2.53E-05	µg
			Pyrene	7.58E-06	µg

			Phthalate, butyl-benzyl-	3.53E-05	µg
			Phthalate, dioctyl-	2.44E-04	kg
			Phenol	6.97E-03	µg
			Phenol, 2,4-dimethyl-	6.67E-03	µg
Raw material and waste transportation					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Transport, truck <10t, EURO3, 80%LF, default/GLO Mass	5.93E-01	kgkm			
Transport, truck <10t, EURO5, 80%LF, default/GLO Mass	1.76E-05	tkm			
Transport, truck 10-20t, EURO3, 80%LF, empty return/GLO Mass	8.91E-03	kgkm			
Site utilities					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	3.28E-06	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	9.09E-09	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	2.24E-07	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	2.33E-08	ton
Electricity, low voltage {ES}| market for | Alloc Def, U	3.09E-08	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	6.91E-10	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.16E-07	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	1.19E-09	kg
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	1.44E-06	kgkm	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	8.97E-10	kg

Table III-8: Inventory table for well completion. All units are reported to the functional unit.

Well Completion					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Gas, natural/m3	1.21E-05	m3			
Materials/fuels					
4.1.2 Venting	6.12E-06	m3			
4.1.1 Flaring	5.91E-06	m3			
Flaring					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
			Carbon dioxide	1.20E-05	kg
			Nitrogen dioxide	4.91E-07	kg
			Sulfur dioxide	5.71E-07	kg
Venting					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
			Methane	3.41E-06	kg
			Carbon dioxide	3.69E-07	kg
			Ethane	4.61E-07	kg
			Hydrogen sulfide	2.77E-07	kg
			Mercury	1.23E-12	kg
			Nitrogen	2.24E-07	kg
			NMVOC, non-methane volatile organic compounds, unspecified origin	2.46E-07	kg
			Propane	3.07E-07	kg
			Radon-222	2.46E-03	Bq
Site utilities					

Inputs	Value	Unit	Outputs	Value	Unit
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	3.28E-06	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	9.09E-09	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	2.24E-07	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	2.33E-08	ton
Electricity, low voltage {ES}| market for | Alloc Def, U	3.09E-08	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	6.91E-10	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.16E-07	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	1.19E-09	kg
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	1.44E-06	kgkm	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	8.97E-10	kg

Table III-9: Inventory table for natural gas production.

Well production					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Resources			Methane	2.20E-05	kg
Gas, natural/m3	2.40E-02	m^3	Carbon dioxide	2.38E-06	kg
Materials/fuels			Ethane	2.98E-06	kg
Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {GLO}| market for | Alloc Def, U	8.33E-05	tkm	Hydrogen sulfide	1.79E-06	kg
			Mercury	7.93E-12	kg
			Nitrogen	1.45E-06	kg
			Propane	1.98E-06	kg
			NMVOC, non-methane volatile organic compounds, unspecified origin	1.59E-06	kg
			Radon-222	1.59E-02	Bq
			Waste to treatment	**Value**	**Unit**
			Water discharge from petroleum/natural gas extraction, onshore {GLO}| treatment of | Alloc Def, U	1.14E-06	ton
Site Utilities					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	4.69E-05	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	1.3E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	2.70E-05	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	3.34E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.96E-04	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	9.95E-09	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.02E-04	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	1.71E-08	kg

Table III-10: Inventory table for natural gas gathering.

Gathering					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
			Methane	9.01E-05	kg
			Carbon dioxide	9.74E-06	kg
			Ethane	1.22E-05	kg
			Hydrogen sulfide	7.30E-06	kg
			Mercury	3.25E-11	kg
			Nitrogen	5.92E-06	kg
			NMVOC, non-methane volatile organic compounds, unspecified origin	6.49E-06	kg
			Propane	8.12E-06	kg
			Radon-222	6.49E-02	Bq
			Carbon dioxide	1.07E-05	kg

Table III-11: Inventory table for natural gas processing.

Processing					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Sweetening	2.39E-02	m3			
Dehydration	2.38E-02	m3			
Natural gas processing plant {GLO}| market for | Alloc Def, U	9.43E-15	p			
Sweetening					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Resources			Carbon dioxide	1.42E-04	kg
Water, process, unspecified natural origin/m3	4.43E-08	m3	Methane	2.74E-06	kg
Materials/fuels			Dinitrogen monoxide	7.63E-07	kg
Monoethanolamine {RoW}| ethanolamine production | Alloc Def, U	1.92E-08	kg	Nitrogen oxides	1.07E-07	kg
Diethanolamine {RoW}| ethanolamine production | Alloc Def, U	1.92E-08	kg	Carbon monoxide	9E-08	kg
Venting	3.27E-05	m3	Lead	5.36E-13	kg
			Particulates	8.14E-09	kg
			Sulfur dioxide	6.43E-10	kg
			VOC, volatile organic compounds	5.89E-09	kg
			Carbon dioxide	3.9E-06	kg
			Emissions to air (vented)	**Value**	**Unit**
			Methane	1.57E-05	kg
			Carbon dioxide	1.69E-06	kg
			Ethane	2.12E-06	kg
			Hydrogen sulfide	1.27E-06	kg
			Mercury	5.64E-12	kg
			Nitrogen	1.03E-06	kg
			NMVOC, non-methane volatile organic compounds, unspecified origin	1.13E-06	kg
			Propane	1.41E-06	kg
			Radon-222	1.13E-02	Bq
Dehydration					
Materials/fuels	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**

4.1.2 Venting	5.86E-06	m3	Carbon dioxide	8.38E-06	kg
			Methane	1.48E-10	kg
			Dinitrogen monoxide	9.31E-09	kg
			Emissions to air (vented)	**Value**	**Unit**
			Methane	3.48E-06	kg
			Carbon dioxide	3.76E-07	kg
			Ethane	4.70E-07	kg
			Hydrogen sulfide	2.82E-07	kg
			Mercury	1.25E-12	kg
			Nitrogen	2.29E-07	kg
			NMVOC, non-methane volatile organic compounds, unspecified origin	2.51E-07	kg
			Propane	3.14E-07	kg
			Radon-222	2.51E-03	Bq
Site utilities					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	4.94E-05	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	1.37E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	2.70E-05	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	3.51E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.96E-04	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	1.05E-08	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	1.02E-04	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	1.80E-08	kg
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	3.93E-07	kgkm	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	1.90E-08	kg

Table III-12: Inventory table for transmission and distribution.

Transmission					
Inputs	**Value**	**Unit**	**Emissions to air**	**Value**	**Unit**
Resources			Methane	1.52E-06	kg
Water, unspecified natural origin, ES	9.99E-09	m3	Carbon dioxide	3.91E-08	kg
Materials/fuels			**Waste to treatment**	**Value**	**Unit**
Electricity, medium voltage {ES}| market for | Alloc Def, U	1.35E-07	MWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	4.37E-15	ton
Diesel {Europe without Switzerland}| market for | Alloc Def, U	5.30E-07	kg	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	4.37E-15	ton
Petrol, low-sulfur {Europe without Switzerland}| market for | Alloc Def, U	6.82E-08	kg	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	4.37E-15	ton
Tap water {Europe without Switzerland}| market for | Alloc Def, U	8.32E-08	ton	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	8.39E-15	ton
			Hazardous waste, for incineration {RoW}| treatment of hazardous waste, hazardous waste incineration | Alloc Rec, U	1.36E-14	ton
Distribution					

			Emissions to air	Value	Unit
			Methane	2.35E-05	kg
			Carbon dioxide	6.06E-07	kg

Table III-13: Inventory table for well abandonment.

Well abandonment					
Inputs	**Value**	**Unit**	**Outputs**	**Value**	**Unit**
Resources			Outputs		
Transformation, from mineral extraction site	1.48E-05	m2	Waste concrete {RoW}| treatment of, inert material landfill | Alloc Def, U	5.78E-11	kg
Transformation, to urban, green areas	1.48E-05	m2			
Materials/fuels					
Concrete, normal {RoW}| production | Alloc Def, U	2.95E-09	m3			
Municipal waste collection service by 21 metric ton lorry {GLO}| market for | Alloc Def, U	4.45E-09	tkm			
Site utilities					
Inputs	**Value**	**Unit**	Outputs	**Value**	**Unit**
Tap water {Europe without Switzerland}| tap water production, conventional treatment | Alloc Def, U	1.99E-05	kg	Waste water treatment, domestic waste water according to the Directive 91/271/EEC concerning urban waste water treatment, at waste water treatment plant EU-27 S	5.51E-08	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	2.69E-07	kWh	Municipal solid waste {RoW}| treatment of, sanitary landfill | Alloc Def, U	1.41E-07	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	4.95E-09	kWh	Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Alloc Def, U	4.19E-09	kg
Electricity, low voltage {ES}| market for | Alloc Def, U	4.65E-08	kWh	Paper (waste treatment) {GLO}| recycling of paper | Alloc Def, U	7.24E-09	kg
Municipal waste collection service by 21 metric ton lorry {RoW}| processing | Alloc Def, U	8.73E-06	kgkm	Packaging glass, white (waste treatment) {GLO}| recycling of packaging glass, white | Alloc Def, U	5.44E-09	kg

3. Results

Results from characterization step are presented in Table III-14. Results are presented for each impact category and discussed in the contribution analysis.

Table III-14: Results from the normalization step presented for each impact category and for all the life cycle stages. Row title legend: IC – Impact category, SS&P – Site selection and preparation, WDDC&C – Well design, drilling, casing and cementing, HF – hydraulic fracturing, WC – well completion, NGP – Natural gas production, GA – Gathering, PC – Processing, T&D – Transmission and distribution and WA – Well abandonment. First column legend: ADP – abiotic depletion potential, ADP-F – abiotic depletion potential (fossil fuels), GWP100a – global warming potential, ODP – Ozone Layer Depletion potential, HT – human toxicity potential, FAETP – freshwater aquatic ecotoxicity potential, MAETP – marine aquatic ecotoxicity potential, TETP – terrestrial ecotoxicity, POP – photochemical oxidation potential, AP – acidification potential and EP – eutrophication potential.

Life cycle stage		Pre-production				Production				
IC	Total	SS&P	WDDC&C	HF	WC	NGP	GA	PC	T&D	WA
ADP (kg Sbeq)	3.82E-09	8.83E-10	1.12E-09	5.54E-10	0.00E+00	4.63E-10	0.00E+00	7.63E-10	3.36E-11	9.01E-13
		23.1%	29.3%	14.5%	0.0%	12.1%	0.0%	20.0%	0.9%	0.0%
ADP-F (MJ)	9.65E-01	4.35E-03	1.85E-02	1.18E-02	4.65E-04	9.25E-01	0.00E+00	3.60E-03	9.51E-04	7.60E-06
		0.5%	1.9%	1.2%	0.0%	95.9%	0.0%	0.4%	0.1%	0.0%
GWP (kg CO2eq)	7.70E-03	2.39E-04	1.62E-03	7.69E-04	9.80E-05	7.61E-04	2.28E-03	1.24E-03	6.92E-04	1.33E-06
		3.1%	21.0%	10.0%	1.3%	9.9%	29.6%	16.1%	9.0%	0.0%
ODP (kg CFC-11eq)	3.92E-10	2.34E-11	1.86E-10	1.08E-10	0.00E+00	3.19E-11	0.00E+00	3.25E-11	1.02E-11	6.98E-14
		6.0%	47.5%	27.5%	0.0%	8.1%	0.0%	8.3%	2.6%	0.0%
HTP (kg 1,4-DBeq)	7.12E-04	6.44E-05	2.74E-04	9.40E-05	7.14E-07	1.10E-04	1.81E-06	1.57E-04	8.76E-06	1.07E-07
		9.1%	38.6%	13.2%	0.1%	15.5%	0.3%	22.1%	1.2%	0.0%
FAETP (kg 1,4-DB eq)	5.39E-05	1.87E-06	8.73E-06	1.18E-05	3.91E-10	2.79E-05	1.03E-08	2.93E-06	6.81E-07	4.87E-09
		3.5%	16.2%	21.8%	0.0%	51.8%	0.0%	5.4%	1.3%	0.0%
MAETP (kg 1,4-DB eq)	8.42E-01	6.64E-02	2.64E-01	1.11E-01	1.48E-06	1.98E-01	3.91E-05	1.59E-01	4.29E-02	2.63E-04
		7.9%	31.3%	13.2%	0.0%	23.5%	0.0%	18.9%	5.1%	0.0%
TETP (kg 1,4-DB eq)	7.91E-06	6.90E-07	1.80E-06	8.42E-07	3.49E-08	1.40E-06	9.23E-07	2.07E-06	1.53E-07	2.49E-09
		8.7%	22.7%	10.6%	0.4%	17.7%	11.7%	26.2%	1.9%	0.0%
POP (kg 1,4-DBeq)	6.90E-06	6.84E-08	5.24E-07	7.28E-07	1.73E-07	9.00E-07	3.48E-06	8.61E-07	1.66E-07	1.73E-10
		1.0%	7.6%	10.5%	2.5%	13.0%	50.5%	12.5%	2.4%	0.0%
AP (kg SO2eq)	3.04E-05	1.34E-06	7.43E-06	1.74E-05	9.33E-07	1.19E-06	0.00E+00	1.69E-06	3.90E-07	3.83E-09
		4.4%	24.4%	57.3%	3.1%	3.9%	0.0%	5.6%	1.3%	0.0%
EP (kg PO4--- eq)	6.41E-06	2.39E-07	1.23E-06	6.20E-07	1.59E-07	7.26E-07	2.50E-06	9.09E-07	2.80E-08	5.24E-10
		3.7%	19.2%	9.7%	2.5%	11.3%	39.0%	14.2%	0.4%	0.0%

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