Grant agreement No. 640979

**ShaleXenvironmentT**

Maximizing the EU shale gas potential by minimizing its environmental footprint

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

D10.1
Comparative environmental footprint of shale gas vs. traditional energy sources and alternative low-carbon renewables

**WP 10 – Life Cycle Assessment**

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History of the changes

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</table>
Table of contents

Definitions and acronyms ............................................................................................................................................ 5
1. Introduction .................................................................................................................................................................. 6
  1.1 General context .................................................................................................................................................... 6
  1.2 Deliverable objectives ....................................................................................................................................... 8
2. Methodological approach ......................................................................................................................................... 9
  2.1 Life cycle assessment methodology .................................................................................................................. 9
  2.2 Modelling assumption and system boundaries ................................................................................................. 11
    2.2.1 Functional unit ............................................................................................................................................. 11
    2.2.2 Shale gas ...................................................................................................................................................... 11
  2.3 Electricity from coal ........................................................................................................................................... 15
  2.4 Electricity from waste via production of gas ...................................................................................................... 17
    2.4.1 Electricity from centrally separated waste via anaerobic digestion ................................................................. 20
    2.4.2 Electricity from Bio-SNG produced via advanced gasification and plasma technology ................................ 21
    2.4.3 Electricity from source-separated waste via anaerobic digestion ................................................................. 22
  2.5 Electricity from nuclear power plants .................................................................................................................. 23
3. Summary of activities and research findings ........................................................................................................ 25
4. Conclusions and future steps .................................................................................................................................. 29
5. Publications based on the work described ........................................................................................................... 30
6. Appendix .................................................................................................................................................................. 31
7. Bibliographical references ...................................................................................................................................... 38

List of Tables

| Table 1. Impact categories and indicators used in this study                        | 10 |
| Table 2. Key assumptions of shale gas model                                       | 13 |
| Table 3. Key inventory data used for the shale gas model                           | 13 |
| Table 4. Emission factors for power plants > 50 MW (Thinkstep, 2015)                | 17 |
| Table 5. Key inventory data for the energy from waste scenarios                    | 19 |
## List of Figures

**Figure 1.** The energy trilemma (WEC, 2017) .......................................................... 6

**Figure 2.** System boundary for all the cases compared here. ........................................ 11

**Figure 3.** System boundary specific for shale gas. Yellow boxes represent the hydraulic fracturing process, grey boxes identify the conventional processes and the blue boxes refer to the activities of the background system ............................................................. 13

**Figure 4.** Supply chain of electricity production from coal ............................................ 17

**Figure 5.** System boundary for the energy from waste scenarios ..................................... 18

**Figure 6.** High level diagram of the anaerobic digestion process of centrally separated organic waste .................................................................................................................. 21

**Figure 7.** High level diagram of the gasification and plasma technology producing Bio-SNG from MSW .......................................................................................................................... 22

**Figure 8.** High-level diagram of the anaerobic digestion process of sourced-separated organic waste ................................................................................................................... 23

**Figure 9.** Supply chain of electricity production from nuclear ........................................... 24

**Figure 10.** Abiotic depletion potential .................................................................................. 25

**Figure 11.** Fresh water aquatic ecotoxicity potential ......................................................... 26

**Figure 12.** Global warming potential ................................................................................. 27

**Figure 13.** Terrestrial ecotoxicity potential ......................................................................... 27

**Figure 14.** Global warming potential. Carbon Capture and storage is considered .......... 28
Key word list

Life cycle assessment, shale gas, renewable energy, electricity from coal, biogas, bio-substitute natural gas

Definitions and acronyms

<table>
<thead>
<tr>
<th>Acronyms</th>
<th>Definitions</th>
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<tr>
<td>AD</td>
<td>Anaerobic digestion</td>
</tr>
<tr>
<td>ADP</td>
<td>Abiotic depletion potential</td>
</tr>
<tr>
<td>Bio-SNG</td>
<td>Bio substitute natural gas</td>
</tr>
<tr>
<td>EUR</td>
<td>Estimated ultimate recovery</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>FAETP</td>
<td>Fresh water aquatic ecotoxicity potential</td>
</tr>
<tr>
<td>GWP</td>
<td>Global warming potential</td>
</tr>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>MBT</td>
<td>Mechanical biological treatment</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal solid waste</td>
</tr>
<tr>
<td>SXT</td>
<td>ShaleXenvironmentT</td>
</tr>
<tr>
<td>TEPT</td>
<td>Terrestrial ecotoxicity potential</td>
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</table>
1. Introduction

1.1 General context

The development of the current energy mix is determined by a complex interconnection of engineered changes, type of energy technologies, energy stability and other factors. Energy policies play a major part towards the modification of the energy mix in order to globally and locally decrease the environmental impact of the energy sector. The complex links between politics, environment and economics are yearly addressed by the World Energy Council that support policy makers as they set climate and development goals and design policies at international and local levels. The support to policymakers is founded on the ‘sustainable energy development system’; this is seen as the base for the energy prosperity and competitiveness of individual countries. Three dimensions (energy trilemma) are considered fundamental for all economies, see Figure 1: i) energy security, ii) energy equity, iii) energy sustainability. A country needs to put in place reliable energy infrastructure able to meet the current and future energy requirements. Energy should be accessible and affordable to the entire population and should be produced with high efficiency and low carbon impact fuels including renewables.

![Energy Trilemma](image)

Figure 1. The energy trilemma (WEC, 2017).

Because the three aspects of the energy trilemma are strongly interconnected, a balanced approach needs to be taken. For example, efforts on reducing greenhouse gases (GHG) emissions may impede energy security and access, while a focus on increasing affordability may impact energy security and environmental sustainability.

The Energy Trilemma Index is used to rank all countries in terms of their potential ability to provide energy policies based on the 3 dimensions of the energy trilemma. In
the recent years, EU countries (Denmark, Switzerland, Sweden, Netherlands, Germany, etc.) consistently ranked among the top positions of the energy trilemma index (WEC, 2017). However, to maintain the delivery of a balanced energy system in line with the trilemma, the EU has still to face a number of substantial challenges for the future.

1. The EU will need to supply affordable energy to a rapidly increasing population (from current 510 million people to 520 million people in 2050)

2. On average, the EU energy infrastructure is rapidly ageing, and many obsolete coal power plants will be forced to close; this will make space to lower carbon-intensive and more efficient energy sources and technologies.

3. The EU still strongly relies on fossil fuels for energy production (44% of the electricity production is still based on fossil fuels (Thinkstep, 2015)) unlike some state members and trilemma index leader countries (Switzerland, Sweden, Norway, etc.) that have extensively developed hydro, nuclear and wind power in their energy mixes.

4. Natural gas is seen as a reliable, flexible and clean fuel as it can reduce greenhouse gas emissions when compared to coal, and provide a competitive energy price for a number of purposes (European Commission, 2014). Therefore, switching to gas will be critical for the transformation of the energy system and it will help meeting short-term emission targets for power generation, heating and transport while restructuring the energy mix towards renewables in the long term. However, this strategy will increase gas demand, which in turn will affect energy prices and imports. Hence, questions have raised about possible new gas exploration to continue delivering secure and affordable energy.

The increased attention to alternative fossil natural gas resources and the aspirations to produce unconventional gas, especially shale gas, to meet short-term emission targets have to be balanced with the challenge to surmount technical and environmental barriers and secure public acceptance. Reported side effects of shale gas exploration include groundwater contamination, methane leakage from new wells and old wells, seismic activity, air and noise pollution and visual changes to the landscape (House of Parliament, 2015). It is also unclear whether shale gas exploitation in Europe could have the same effects on the domestic energy market as those reported for the US.

It has been argued that fossil gas development of indigenous EU shale and imports could help meeting the energy requirements and the carbon emissions reduction at short and medium term. However, to achieve the long-term increased reduction in emissions, cuts in fossil gas use and the development of renewable gas are deemed necessary.
Wind and solar energies, among other renewable energies, are expected to become the dominating renewable sources thanks to technological progress and political support. As a matter of fact, the cost of wind energy is rapidly becoming competitive. However, these systems are characterized by a variable and uncertain generation pattern, which is directly connected to meteorological conditions. This is a key difference with other sources, such as conventional power plants or energy from waste, that could instead dispatch energy in a controlled manner. In addition, the development of wind and solar technologies is reported to impose additional costs as the balance between demand and supply has to be ensured by additional breakthroughs, perhaps in energy storage (Abrell and Kunz, 2014; Strbac et al., 2007). Particular emphasis in the EU is put on development of energy production from waste to deliver low carbon footprint.

This deliverable contributes to the general objective of the ShaleXenvironmenT (SXT) project to understand and quantify whether shale gas has the potential of contributing to a clean and efficient energy market, necessary to continue to improve our standards of living and sustain our economy, without compromising the environment. In particular, along with the project’s objectives, this deliverable quantifies the environmental impacts of shale gas production during its lifespan and compares electricity production from shale gas with alternative fossil and renewable energy technologies, including waste, coal and nuclear. The results can help quantifying the sustainability of shale gas, therefore providing useful information for policy formulations.

1.2 Deliverable objectives

The key objective of deliverable 10.1 is to compare the environmental burdens of electricity production from shale gas vs. electricity production from a few selected conventional and renewable sources. For the comparative scenarios the electricity is produced from:

- coal
- bio-methane obtained from centrally separated waste
- bio-substitute natural gas (Bio-SNG) obtained from advanced gasification and plasma technology
- bio-methane obtained from source separated waste
- nuclear power plants
2. Methodological approach

2.1 Life cycle assessment methodology

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

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

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

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

i) what political or technical decision will depend on the results of the study;
ii) what processes are to be investigated (i.e. the system boundaries);
iii) the basis for comparison between different alternatives is (i.e. the functional unit).

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

For the impact assessment phase, this study adopts the CML method version 4.6 (January 2016), which is based on the ISO standards (ISO 14040, 2006). The focus is on the impact categories shown in Table 1.
The **Global Warming Potential (GWP)** characterizes and calculates the impact of greenhouse gases based on the extent to which these gases enhance the radiative forcing. GWP values for specific gases, developed by the Intergovernmental Panel on Climate Change, express the cumulative radiative forcing of an emission over a given time period in terms of the quantity of carbon dioxide giving the same effect (Forster et al., 2007; IPCC, 2006).

The **Abiotic Depletion (ADP)** addresses the problem of the diminishing pool of resources, focusing on the depletion of non-living resources such as iron ore, crude oil, etc. The abiotic depletion is usually measured in MJ when the deployment of energy sources is assessed.

The **Toxicity** impacts include many types of indicators causing damages to different environments based on both the inherent toxicity of a compound and potential exposure. Toxicity categories indicate the toxicological impacts of pollutants emitted to the environment, such as neurological damage, carcinogenic, mutagenic, etc. The *fresh water (FAETP)* assesses the toxic effects of polluting compounds to water life, while the *terrestrial eco-toxicity potential (TETP)* is related to land-based ecosystems.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Impact Indicator</th>
<th>Acronym</th>
<th>Characterisation model</th>
<th>Units</th>
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</thead>
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<tr>
<td>Climate change</td>
<td>Global warming potential</td>
<td>GWP</td>
<td>CML 2001 baseline (IPCC, 2007) (Apr. 2015)</td>
<td>kg CO₂eq</td>
</tr>
<tr>
<td>Resources depletion (fossil)</td>
<td>Abiotic depletion</td>
<td>ADP</td>
<td>CML 2001 baseline (Guinée, 2001) (Apr. 2015)</td>
<td>MJ</td>
</tr>
<tr>
<td>Ecotoxicity (freshwater)</td>
<td>Fresh water aquatic ecotoxicity potential</td>
<td>FAETP</td>
<td>USEtox model (Rosenbaum et al., 2008) (Apr. 2015)</td>
<td>kg DCB eq</td>
</tr>
<tr>
<td>Ecotoxicity (terrestrial)</td>
<td>Terrestrial ecotoxicity potential</td>
<td>TETP</td>
<td>USEtox model (Rosenbaum et al., 2008)</td>
<td>kg DCB eq</td>
</tr>
</tbody>
</table>

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

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

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

2.2 Modelling assumption and system boundaries

2.2.1 Functional unit

The functional unit of this work is the production of 1 kWh of electricity using the sources described in the deliverable objectives (shale gas, bio-methane from source and centrally separated waste, coal, Bio-SNG and nuclear). Although the majority of data used in the LCA model are specific to the UK, the LCA results are considered to be representative of EU conditions. The overall system boundary of the deliverable is shown in Figure 2.

First the environmental burdens of gas production from shale, Bio-SNG and bio-methane were computed and then the electricity production from the produced gas in power plants was considered. According to the Ecoinvent database (Wernet et al., 2016), 8.28 MJ of gas are required to produce 1 kWh of electricity.

2.2.2 Shale gas

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

1. **Well site exploration and investigation.**
2. **Well pad and road preparation and construction.**
3. **Well vertical drilling.** Production of materials needed for drilling; transport of materials; energy required during drilling and emissions from machinery; emissions during drilling; casing and cementing; disposal of drilling wastes.
4. **Hydraulic fracturing of the well.** Horizontal drilling; production and transport of water, chemicals and sand needed for fracturing; energy used during the hydraulic fracturing and emissions from machinery; disposal of wastes.
5. **Well Completion.** Energy and materials required; disposal of flowback fluids and produced water from the well; emissions of natural gas during well completion, workovers, unloadings; and re-fracturing.
6. **Production.** Processing and cleaning.
7. **Pipe construction and transmission.**
8. **Post production phase.** Decommissioning, plugging and removing of equipment.
9. **Distribution at high pressure for electricity production.** Long distance distribution.

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

Horizontal drilling, fracturing of the shale rocks, flowback water disposal and handling of emissions associated with hydraulic fracturing (operations specifically required for shale gas production) were also considered and added to the aforementioned conventional process operations. The main inventory parameters for these are reported in Table 3. More information is available in Tagliaferri et al. (2016).
Figure 3. System boundary specific for shale gas. Yellow boxes represent the hydraulic fracturing process, grey boxes identify the conventional processes and the blue boxes refer to the activities of the background system.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water used during hydraulic fracturing total</td>
<td>1.92E-04 m3/m3 of raw gas produced</td>
</tr>
<tr>
<td>Sand used during fracturing (silica, quartz sand)</td>
<td>2.55E-02 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Additives</td>
<td></td>
</tr>
<tr>
<td>Acid: Hydrochloric acid or muriatic acid</td>
<td>5.65E-04 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Friction reducer: petroleum distillate</td>
<td>1.41E-04 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Surfactant: isopropanol</td>
<td>1.41E-04 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Cly stabilizer/controler: Potassium chloride</td>
<td>9.41E-05 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Geling agent; Guar gum or hydroxyethyl cellulose</td>
<td>9.41E-05 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Scale inhibitor: Ethylene glycol</td>
<td>7.06E-05 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>PH Adjusting agent: Sodium bicarbonate and sodium potassium hydroxide</td>
<td>1.88E-05 kg/m3 of raw gas produced</td>
</tr>
<tr>
<td>Breaker: Ammonium persulfate</td>
<td>1.88E-05 kg/m³ of raw gas produced</td>
</tr>
<tr>
<td>Crosslinker: borate salts</td>
<td>1.88E-05 kg/m³ of raw gas produced</td>
</tr>
<tr>
<td>Iron control: citric acid</td>
<td>7.06E-06 kg/m³ of raw gas produced</td>
</tr>
<tr>
<td>Bactericide/biocide: glutaraldehyde</td>
<td>1.88E-06 kg/m³ of raw gas produced</td>
</tr>
<tr>
<td>Corrosion Inhibitor: Formamide</td>
<td>1.88E-06 kg/m³ of raw gas produced</td>
</tr>
</tbody>
</table>

**Amount of flowback water**

- **Flowback water disposal**
  - **Fractions**
    - Recycled: 2.73E-02 kg/m³ of raw gas produced
    - Disposal in proper industrial treatment plants: 2.73E-02 kg/m³ of raw gas produced
  - **Energy consumption**
    - Industrial treatment: 3.43E-04 KWh/m³ of raw gas produced

**Difference of materials used between conventional drilling and horizontal drilling**

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<th>Amount</th>
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<tbody>
<tr>
<td>Steel</td>
<td>1.29E-03 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Portland cement</td>
<td>1.96E-03 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Gilsonite (asphaltite)</td>
<td>-7.39E-05 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>1.51E-03 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Bentonite</td>
<td>3.63E-04 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Soda Ash</td>
<td>6.04E-06 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Gelex</td>
<td>4.39E-08 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Polypac</td>
<td>1.14E-05 kg/m³ of raw gas</td>
</tr>
<tr>
<td>Xanthum Gum</td>
<td>5.77E-06 kg/m³ of raw gas</td>
</tr>
</tbody>
</table>

**Water throughput (Water volumes do not account for water associated with hydraulic fracturing activities)**

- 6.31E-03 kg/m³ of raw gas

**Surplus of emission due to wells horizontal drilling**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>4.78E-03 kg/m³ of raw gas</td>
</tr>
<tr>
<td>SO2</td>
<td>4.85E-06 kg/m³ of raw gas</td>
</tr>
<tr>
<td>NOx</td>
<td>6.69E-05 kg/m³ of raw gas</td>
</tr>
<tr>
<td>PM</td>
<td>5.58E-06 kg/m³ of raw gas</td>
</tr>
<tr>
<td>CO</td>
<td>1.45E-05 kg/m³ of raw gas</td>
</tr>
<tr>
<td>NMVOC</td>
<td>2.11E-07 kg/m³ of raw gas</td>
</tr>
</tbody>
</table>

**WELL COMPLETION- Potential emissions due to well completion without flaring or REC conventional wells**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4</td>
<td>1.91E+00 g CH4/m³ of raw gas</td>
</tr>
<tr>
<td>CO2</td>
<td>1.83E-01 g CO2/m³ of raw gas</td>
</tr>
<tr>
<td>C2H6</td>
<td>1.25E-01 g C2H6/m³ of raw gas</td>
</tr>
<tr>
<td>C3H8</td>
<td>6.12E-02 g C3H8/m³ of raw gas</td>
</tr>
<tr>
<td>N2</td>
<td>2.72E-01 g N2/m³ of raw gas</td>
</tr>
</tbody>
</table>

**WELL WORKOVERS- Potential emissions due to well completion without flaring or REC conventional wells**

<table>
<thead>
<tr>
<th>Emission</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4</td>
<td>3.81E-01 g CH4/m³ of raw gas</td>
</tr>
<tr>
<td>CO2</td>
<td>3.65E-02 g CO2/m³ of raw gas</td>
</tr>
<tr>
<td>C2H6</td>
<td>2.50E-02 g C2H6/m³ of raw gas</td>
</tr>
<tr>
<td>C3H8</td>
<td>1.22E-02 g C3H8/m³ of raw gas</td>
</tr>
<tr>
<td>N2</td>
<td>5.42E-02 g N2/m³ of raw gas</td>
</tr>
</tbody>
</table>

**WELL COMPLETION- Emission due to well completion including flaring or REC**
2.3 Electricity from coal

The electricity production from coal was modelled according to the data reported in the GaBi database (Thinkstep, 2015). The supply chain and key inventory data are reported in Figure 4 and in Table 4, respectively.

The national and regional specific technology standards of the power plants in regard to efficiency, firing technology, flue-gas desulphurisation, NOx removal and de-dusting are considered. The fossil power plant models combine emission data from literature with calculated values for non-measured emissions e.g. organics or heavy metals. For the emissions CO2, SO2, NOx, CO, CH4, N2O, NMVOC and particulate matter (PM) data are taken from national inventory reports, emission inventory databases, utility companies and other sources. The calculation of other emissions within the models is based on energy carrier properties, transfer coefficients and power plant thermodynamics representing the applied flue gas treatment technologies and standards (flue gas desulphurisation, dust filter etc.). Combustion residues from solid fuels, such as gypsum, bottom ash or fly ash are assumed to be reused e.g. in construction work. Waste treatment for these substances is therefore not considered. Radioactive emissions from ashes are not considered in the coal power plant model.

The hard coal supply considers the whole supply chain of the energy carrier from exploration, production, processing and transport of the fuels to the power plants. The supply chain is modelled in a specific EU hard coal consumption mix (i.e. domestic production and imports), and considers average hard coal properties (e.g. elemental composition and energy content).

The data set includes the own use of electricity by energy producers (own consumption of power plants). Imported electricity from neighbouring countries,
transmission / distribution losses and other own consumption, e.g. due to pumped storage hydropower etc., are not included.

Electricity requirements are modelled according to the individual regional situations. The regional modelling is achieved on multiple levels. Firstly, individual energy carrier specific power plants and plants for renewable energy sources are modelled according to the current electricity grid mix. Modelling the electricity consumption mix includes transmission/distribution losses and the own use by energy producers (own consumption of power plants and "other" own consumption e.g. due to pumped storage hydro power etc.), as well as imported electricity. Secondly, the emission and efficiency standards of the power plants are modelled as well as the share of electricity plants and combined heat and power plants (CHP). Thirdly, the energy carrier supply (share of imports and / or domestic supply) including the regional-specific energy carrier properties (e.g. element and energy content) is accounted for. Fourthly, the exploration, mining/production, processing and transport processes of the energy carrier supply chains are modelled according to the specific situation of each electricity producing country. The different production and processing techniques (emissions and efficiencies) in the different energy producing countries are considered, e.g. different crude oil production technologies or different flaring rates at the oil platforms.

The thermal energy and process steam supply is also modelled according to the individual regional situation with regard to emission standards and considered energy carriers. The thermal energy and process steam are produced at heat plants. Efficiencies for thermal energy production are by definition 100% in relation to the corresponding energy carrier input. For process steam the efficiency ranges from 85%, 90% to 95%. The energy carriers used for the generation of thermal energy and process steam are modelled according to the specific import situation (see electricity above).

Product transport processes are included. Ocean-going and inland ship transport as well as rail, truck and pipeline transport of bulk commodities are considered.

The energy carriers are modelled according to the specific supply situation. Diesel fuel, gasoline, technical gases, fuel oils, lubricants and residues such as bitumen are modelled with a parameterised regional refinery model. The refinery model represents the current region standard in refining techniques (e.g. emission level, internal energy consumption, etc.) as well as the individual region-specific product output spectrum. The supply of crude oil is modelled, again, according to the region-specific situation with the respective properties of the resources.
Figure 4. Supply chain of electricity production from coal.

Table 4. Emission factors for power plants > 50 MW (Thinkstep, 2015).

<table>
<thead>
<tr>
<th>Energy carrier specific power plants [data are specific for UK]</th>
<th>Hard coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 [kg/TJ fuel input]</td>
<td>87.9</td>
</tr>
<tr>
<td>CO [kg/TJ fuel input]</td>
<td>24.6</td>
</tr>
<tr>
<td>SO2 [kg/TJ fuel input]</td>
<td>166.9</td>
</tr>
<tr>
<td>NOx [kg/TJ fuel input]</td>
<td>172.8</td>
</tr>
<tr>
<td>Efficiency electricity plant [%]</td>
<td>39</td>
</tr>
</tbody>
</table>

2.4 Electricity from waste via production of gas

Figure 5 shows the system boundary of biomethane/Bio-SNG production from waste, circles identify flows whereas squares identify processes. Indirect activities of the supply chains and waste disposal processes constitute the background, whereas the scenarios investigated are the foreground. Avoided burdens are allocated to valuable substances production/recovery and emissions and residual waste material disposal are included in the assessment. The analysis starts from the waste stream (referred to as MSW) exiting a material recovery facility, through to the production of methane suitable for electricity production. Key inventory data are reported in Table 5.

In the centrally separated waste scenario with production of gas from anaerobic digestion and in the advanced gasification and plasma technology scenario, the metals (ferrous and non-ferrous) are mechanically separated from MSW and recovered for future reprocessing and final sale as recycled metals. Therefore, avoided burdens are allocated to those processes according to the models already reported in Evangelisti et al. (2015).
Avoided burdens are allocated to the production of electricity recovered from the waste (later described in details) on the base of an average mix of technology (Thinkstep, 2015).

Figure 5. System boundary for the energy from waste scenarios.
**Table 5. Key inventory data for the energy from waste scenarios**

<table>
<thead>
<tr>
<th>Modelled parameter</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anaerobic digestio of centrally separated waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-treatment and digester</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous, single-stage, mixed tank mesophilic reactor operating at a temperature of 35 °C</td>
<td>-</td>
<td>(Berglund and Börjesson, 2006; Sara Evangelisti et al., 2014; Monnet, 2003; Severn Wye Energy Agency, 2009)</td>
</tr>
<tr>
<td>Biogas yield</td>
<td>0.079 Nm$^3$/kg of centrally separated organic fraction</td>
<td>(Monson et al., 2007)</td>
</tr>
<tr>
<td>Digester methane losses</td>
<td>3%</td>
<td>(Berglund and Börjesson, 2006; Boldrin et al., 2011; Dalemo et al., 1997; Fruegaard and Astrup, 2011)</td>
</tr>
<tr>
<td><strong>Water and acids removal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reaction of H$_2$S with a catalytic bed of ZnO</td>
<td>-</td>
<td>(Hagen and Polman, 2001; Persson, 2003)</td>
</tr>
<tr>
<td>Water adsorbed on silica gel</td>
<td>-</td>
<td>(Hagen and Polman, 2001; Persson et al., 2006)</td>
</tr>
<tr>
<td><strong>Biogas upgrading by PSA</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>0.8-0.88 kWh/Nm$^3$</td>
<td>(Persson, 2003; Persson et al., 2006)</td>
</tr>
<tr>
<td>Methane losses</td>
<td>3%</td>
<td>(Patterson et al., 2011; Persson et al., 2006; Petersson, A. Wellinger, 2009)</td>
</tr>
<tr>
<td><strong>Digestate disposal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>To incineration</td>
<td>-</td>
<td>(Swiss Centre for Life Cycle Inventories, 2014)</td>
</tr>
<tr>
<td><strong>Anaerobic digestio of source separated waste</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-treatment and digester</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biogas yield</td>
<td>0.14 Nm$^3$/kg of source separated organic fraction</td>
<td>(Banks et al., 2011; Sara Evangelisti et al., 2014; Møller et al., 2009; Robertson et al., 2010)</td>
</tr>
<tr>
<td>Fibres in the digestate</td>
<td>20%</td>
<td>(Wrap, 2012)</td>
</tr>
<tr>
<td>Liquor in the digestate</td>
<td>80%</td>
<td>(Wrap, 2012)</td>
</tr>
<tr>
<td>N of the liquor readily available to crops</td>
<td>80%</td>
<td>(Wrap, 2011)</td>
</tr>
<tr>
<td>P$_2$O$_5$ of the liquor readily available to crops</td>
<td>100%</td>
<td>(Wrap, 2011)</td>
</tr>
<tr>
<td>K$_2$O of the liquor readily available to crops</td>
<td>100%</td>
<td>(Wrap, 2011)</td>
</tr>
<tr>
<td>Chemical fertilizer substituted by N</td>
<td>ammonium sulphate</td>
<td>(Defra, 2010)</td>
</tr>
<tr>
<td>Chemical fertilizer substituted by P$_2$O$_5$</td>
<td>superphosphate</td>
<td>(Defra, 2010)</td>
</tr>
<tr>
<td>Chemical fertilizer substituted by K$_2$O</td>
<td>potassium chloride</td>
<td>(Defra, 2010)</td>
</tr>
<tr>
<td>Nutrients dispersed to environment</td>
<td>-</td>
<td>(Boldrin et al., 2011; Bruun et al., 2006; S. Evangelisti et al., 2014; Møller et al., 2009)</td>
</tr>
<tr>
<td><strong>Advanced gasification and plasma technology</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen requirements</td>
<td>Average EU cryogenic oxygen production</td>
<td>(Thinkstep, 2015)</td>
</tr>
<tr>
<td>Vitrified slag: system expansion</td>
<td>Primary aggregates crushed rock</td>
<td>(Korre and Durucan, 2009; Mankelow et al., 2011)</td>
</tr>
<tr>
<td>APC residue treatment</td>
<td>-</td>
<td>(Swiss Centre for Life Cycle Inventories, 2014; Thinkstep, 2015)</td>
</tr>
<tr>
<td>Water disposal</td>
<td>-</td>
<td>(Thinkstep, 2015)</td>
</tr>
<tr>
<td>Chemical requirements</td>
<td>-</td>
<td>(Swiss Centre for Life Cycle Inventories, 2014; Thinkstep, 2015)</td>
</tr>
<tr>
<td>Direct and avoided burdens</td>
<td>-</td>
<td>Supplied by industrial developers</td>
</tr>
</tbody>
</table>
2.4.1 Electricity from centrally separated waste via anaerobic digestion

The residual waste is assumed to be mechanically sorted in a material recovery facility and then the centrally separated organic fraction is biologically treated in an anaerobic digestion plant at the same site. The separated non-biodegradable waste is partially recycled and partially sent to incineration. Literature data have been used to build the models for bio-methane production from centrally separated waste as referred in Table 5; the high level diagram of this scenario is reported in Figure 6.

Anaerobic digestion cannot be directly applied to the entire fraction of MSW, therefore a mechanical treatment is needed to separate waste and apply anaerobic digestion only to the organic fraction of the centrally separated MSW. In this case, extensive physical/mechanical separation and pre-treatment is always necessary prior to digestion (Monson et al., 2007). The outputs of the mechanical separation are assumed to be i) organic fraction suitable for biological treatment in an AD plant; ii) recovered metals suitable for reprocessing and sales in the market; iii) inert material used as landfill cover; and iv) residual waste containing the remaining not separated MSW fractions sent to incineration. The unsorted remaining fractions are not transformed into refused derived fuel but are directly sent to the disposal facilities; no pelletizing is assumed as also reported in Consonni et al. (2005b). Defra (2013) reports that recyclables (such as plastic and card) derived from the various mechanical biological treatment (MBT) processes are typically of a lower quality than those derived from a separate household recyclate collection system and have a lower potential for high value markets. Therefore, for many mechanical separation systems, metals (ferrous and non-ferrous) are the only recyclates always extracted (as assumed in this study). The energy consumption for the mechanical separation of waste is based on literature data (Consonni et al., 2005; Defra, 2013; Montejo et al., 2013).

Six operations are identified in the AD process: i) pre-treatment; ii) anaerobic digestion; iii) water and acids removal; iv) upgrading of the biogas in a pressure swing adsorber system; v) disposal of digestate to incineration. The characteristics of each part and the assumptions used in the LCA models based on literature data are specified in the Table 5 and in Tagliaferri et al. (2016).
2.4.2 Electricity from Bio-SNG produced via advanced gasification and plasma technology

The dual stage gasification and plasma technology for Bio-SNG production from MSW is a novel advanced thermal conversion technology currently under development (Advanced Plasma Power, 2015; Chapman et al., 2014; Ray et al., 2012; Taylor et al., 2013; Taylor and Chapman, 2012). It is a highly flexible two-stage thermal process, capable of treating a wide range of organic and inorganic wastes including Municipal Solid Waste.

The high level diagram of this process is shown in Figure 6. Reference source not found.

Pre-treatment of the received waste includes shredding, drying and mechanical metals recovery, sold as recyclates. The fluidised bed gasifier using oxy-steam converts the prepared non-pelletized shredding waste to a raw syngas containing significant levels of char, ash, tars and other liquid organic contaminants. This gas stream, together with the char and ash product from the gasifier, is then treated in a high temperature plasma converter unit. It efficiently cracks problematic tars in the raw syngas to produce a reformed quality synthetic gas. The inorganic ash fraction from the gasifier is vitrified in the plasma converter unit to produce a dense, stable vitrified product, which can be used as aggregate in road construction. The syngas, after cooling, air pollution control removal, tertiary cleaning of the acid gases and further polishing in a guard bed, is suitable for catalytic conversion to Bio Substitute Natural Gas (Bio-SNG). A high temperature water-gas shift adjusts the stoichiometric ratio $\text{H}_2/\text{CO}$ in the syngas to around 3:1, as required at the methanator stage. After the final polishing in a $\text{ZnO}$ guard bed, the compressed gas is injected into the methanator reactor where the raw Bio-SNG is produced. This is upgraded in a pressure swing adsorber system and injected into the grid. The low quality combustible gas (mainly mix of $\text{CH}_4$, $\text{H}_2$ and inert) recovered in the pressure swing adsorber system is used to produce electricity and the off gas is flared and emitted to the environment. The heat produced through the process which is not used for serving the internal requirement, is assumed to be used.
for electricity production in a steam turbine. The solid fuel preparation, syngas generator and syngas refining are modelled as reported in Evangelisti et al. (2015).

Figure 7. High level diagram of the gasification and plasma technology producing Bio-SNG from MSW.

Further inventory data for the LCA model of this process are based on experimental and modelling data provided by industrial developers and are reported in Table 5 and in Tagliaferri et al. (2016).

2.4.3 Electricity from source-separated waste via anaerobic digestion

For this scenario, we assumed that the organic fraction of municipal solid waste is source separated at the household and treated in an aerobic digestion plant. The residual waste is assumed incinerated. The high level diagram is reported in Figure 8.

The substrate of the anaerobic digestion is kitchen source separated waste and its composition is reported in Banks et al. (2011); this is the substrate that determines the highest yield in biogas production. No cardboard and paper are assumed to be anaerobically digested. As the waste is separated at source, the amount of mechanical separation and pre-treatment required (and thus the complexity and cost of the system) is reduced, although some mechanical separation is always necessary.

The model for the production of gas via anaerobic digestion of source separated waste is the same as the model for the production of gas via anaerobic digestion of centrally separated waste except for the assumptions regarding the biogas yield and the digestate use. The raw biogas production has been assumed to be 0.14 Nm$^3$ per kg of bio-degradable fraction of MSW (wt%), based on literature data (Banks et al., 2011; Sara Evangelisti et al., 2014; Moller et al., 2007; Robertson et al., 2010). The whole
digestate is physically separated in liquor and fibre as standard practice (Wrap, 2012, 2010). The liquor separated from the whole digestate in the dewatering process is used as fertilizer, whereas the fibres are sent to incineration as inert material (Wrap, 2012). The system boundaries are expanded to include the avoided burdens allocated to the substitution of chemical fertilisers, and to the amount of carbon sequestered in the soil when the digestate is used as chemical fertilizer (Moller et al., 2007). The emissions due to the organic fertilizers when those are on the soil are also included in the inventory. Further assumptions regarding the model are specified in Table 5 and in Tagliaferri et al. (2016).

Figure 8. High-level diagram of the anaerobic digestion process of sourced-separated organic waste.

### 2.5 Electricity from nuclear power plants

A mix of pressure and boiling water reactors is used in the model according to Ecoinvent database version 3.1 (Swiss Centre for Life Cycle Inventories, 2014), shown in Figure 9.

For the pressure water technology, the average burnup 48 MWd/kg heavy metal has been assumed representative for the lifetime of the modelled plant. The average burnup corresponds to an average enrichment of 4.0% U235 for fresh uranium fuel elements. The utilisation factor for the infrastructure is the inverse of the total net electricity delivered in 40 years lifetime; the production of the Swiss pressure water reactors has been adjusted by the average country specific capacity factors. Material and transport requirements have been extrapolated from the Swiss pressure water reactors by the ratio of the capacity factors weighted by the energy production. Radioactive emission data are weighted averages of the emissions of the boiling water reactors in Germany, Spain, and Switzerland. The radioactive water emissions have
been inputted to the most detailed available emission species; the difference between the "total beta-gamma (excluding H-3)" calculated from the country-specific values given by the reference and the sum of the detailed species has been inputted as "Radioactive species, Nuclides, unspecified". The radioactive waste streams are modelled according to the Swiss scheme: spent fuel to reprocessing (50%) and conditioning (50%) (assumption for lack of information); operational low active waste for conditioning in the intermediate repository; and, contaminated waste from dismantling. The latter stream has been recalculated by the ratio of the utilisation factors for infrastructure.

For the boiling water technology, the average burnup 48 MWd/kg heavy metal around year 2000 has been assumed representative for the lifetime of the modelled plant. The average burnup corresponds to an average enrichment of 4.0% U235 for fresh uranium fuel elements. The utilisation factor for the infrastructure is the inverse of the total net electricity delivered in 40 years lifetime; the production of the Swiss boiling water reactor has been adjusted by the average country specific capacity. Material and transport requirements have been extrapolated from the Swiss boiling water reactor by the ratio of the capacity factors weighted by the energy production. Radioactive emission data are weighted averages of the emissions of the boiling water reactors in Germany, Spain, and Switzerland. The radioactive water emissions have been inputted to the most detailed available emission species; the difference between the "total beta-gamma (excluding H-3)" calculated from the country-specific values given by the reference and the sum of the detailed species has been inputted as "Radioactive species, Nuclides, unspecified". The radioactive waste streams are modelled according to the Swiss scheme: spent fuel to reprocessing (50%) and conditioning (50%) (assumption for lack of information); operational low active waste for conditioning in the intermediate repository; and, contaminated waste from dismantling. The latter stream has been recalculated by the ratio of the utilisation factors for infrastructure.

![Figure 9. Supply chain of electricity production from nuclear.](image-url)
3. Summary of activities and research findings

The Figures below show the environmental impacts of the technologies introduced in Section 2 for the production of 1 kWh of electricity (the functional unit).

As expected, results for the abiotic depletion potential category (of fossil reserves - Figure 10) show that the renewable and alternative technologies have lower environmental impact than the fossil-based ones. No significant difference is found between electricity production from shale gas or coal. The very similar abiotic depletion score of shale gas and coal is due to their calorific value; notably, about 10 MJ of coal and 8.5 MJ of gas are needed to generate 1kWh of electricity. The production of electricity using the gas obtained via anaerobic digestion of centrally and source separated waste results in being the best option for the abiotic depletion category; this is because the system is credited for the avoided burdens associated to the waste disposal. Finally, the low impact score of the nuclear energy is related to the fact that nuclear does not use fossil resources for the production of electricity.

Figure 11 reports the LCA results for contamination of water bodies due to toxic pollutants. Coal features the highest burden (2.88*10^-1 kg of DCB equivalent, compared to 2.59*10^-3 kg of DCB equivalent for anaerobic digestion of source separated waste). The freshwater aquatic ecotoxicity of coal is almost entirely caused by the emissions associated with cleaning of the flue gas after combustion, and the disposal of the residue from cooling towers.
Figure 11. Fresh water aquatic ecotoxicity potential.

Figure 12 shows that the global warming potential (estimated as equivalent amounts of CO₂ emitted) of all the technologies producing electricity from renewable sources is higher than that of fossil-based energies. This is due to the lower energy efficiency of these technologies compared with the high energy density of fossil fuels (i.e. coal and shale gas). Nuclear energy shows a negligible GWP score because the production of electricity in nuclear plants does not involve any discharge of CO₂ or other greenhouse gases.

Figure 13 reports the toxic impacts associated with terrestrial discharges. Coal and shale gas show the highest impact due to the emissions associated with coal mining and well exploration and production, respectively. Nuclear energy results in having scores in the same order of magnitude as shale gas.
It has to be highlighted that the LCA models that correlates the environmental impacts of emissions and waste from the production of nuclear energy is not yet fully developed in the scientific literature. For example, the CML impact method does not fully account for the emissions and effects of storage of nuclear waste. The quantification of the environmental impacts of nuclear energy in LCA is still under development, especially with respect to radiological impacts on ecosystems and humans (Paulillo et al., 2018).
Finally, Figure 14 shows the results for the global warming impact category in the case the CO2 contained in the flue gas generated from the production of electricity from shale gas and coal is captured and stored - rather than being emitted into the atmosphere. The GWP of these two energy sources significantly decrease as a result of reduced CO2 emissions to atmosphere, but is still higher than that of nuclear energy.

![Figure 14. Global warming potential. Carbon Capture and storage is considered.](image-url)
4. Conclusions and future steps

The environmental impacts related to the production of electricity from shale gas have been quantified and compared with conventional energy production systems, i.e. coal and nuclear, and renewable energy technologies, including renewable gas obtained from i) anaerobic digestion of centrally separated waste, ii) gasification and plasma technology, iii) anaerobic digestion of source separated waste. The environmental results have been calculated on the basis of the production of 1 kWh of electricity sent to the national grid.

The production of electricity from shale gas features environmental impacts consistently lower than coal. However, the results with respect to the other technologies depend on the impact category analysed. For the global warming category, all renewable technologies perform worse than shale gas. This is primarily attributable to the higher efficiency of the electricity generation process of fossil fuels compared to renewable sources. On the other hand, both coal and shale gas result in having greater terrestrial toxicological impacts, which are associated with emissions from mining and well construction. Notably, both processes are not required in case of production of electricity from waste. As expected, shale gas has the second highest score in the abiotic depletion category (this is because alternative and renewable technologies feature very low consumption of fossil fuels). For the terrestrial toxicity category, shale gas shows environmental impacts comparable with nuclear and Bio-SNG, but considerably lower than coal and bio-methane. It must be noted that the significant toxic impacts associated with nuclear energy are primarily associated with the mining of uranium.

The process of shale gas extraction using hydraulic fracturing is still in the development stage in terms of both technology and regulations in the EU. Industry data are therefore rarely publicly disclosed and available field measurements are lacking so that the limited inventory data available are widely contested. This aspect will be addressed in future research (deliverable 10.2) where the effect of changing key inventory parameters in the life cycle model of shale gas production will be explored.

Besides deliverable 10.2, future efforts should focus on three main aspects: i) the use of shale gas to produce heat (rather than electricity), ii) a distance-based comparison between natural gas produced offshore and shale gas produced in-house, and iii) the analysis of “good” and “bad” practices (besides the best practice that has been analysed in this deliverable) to highlight the most detrimental procedures for the environment that shall be avoided under all circumstances.
5. **Publications based on the work described**


6. Appendix

Operations common between shale and conventional gas extraction

In the common operations model it was not possible to differentiate between exploration, production (drilling and extraction) and purification. Hence, aggregate data for those processes are used (Swiss Centre for Life Cycle Inventories, 2014) according to indirect, direct and avoided burdens UK site specific.

The gas distribution systems included in the analysis (long distance distribution at high pressure, regional distribution at high pressure and local distribution at low pressure) reflect the three gas pressure levels that can be found in the UK distribution system: i) national transmission system; ii) distribution network; iii) local distribution (National-grid, 2006).

Operations specific for shale gas production

Horizontal drilling

Part of the drilling process (the vertical drilling) can generally be considered the same whether a conventional or an unconventional well are drilled. Therefore, the vertical drilling is included in the common operations model. However, the LCI model also accounts for the materials used during the directional drilling that is typical of shale gas recovery (conventional wells rarely require horizontal drilling).

The energy and materials usually required for both shale gas extraction and conventional gas extraction are reported in literature (Burnham et al., 2013, 2011; Clark et al., 2011). The difference between the two represents the material and energy required for horizontal drilling that is included in the LCI model built for this study. The drilling emissions from machineries are modelled according to Table S14, as also done for the emissions due to the fracturing machineries.

The amount of materials (steel, water, bentonite, cement etc.) included in this analysis for both vertical and horizontal drilling reflect the dimensions of a typical UK shale plays borehole as reported in Stamford et al. (Stamford and Azapagic, 2014).

Fracturing the shale formation

The amount of water needed for the rocks fracturing process (~15000 m³) is calculated as the average of the values found in literature (Burnham et al., 2011; Dale et al., 2013; DECC, 2013; Jiang et al., 2011; Laurenzi and Jersey, 2013; Stamford and Azapagic, 2014; Stephenson et al., 2011; Weber and Clavin, 2012). The values
reviewed did not change significantly; the amount of water used for the hydraulic fracturing fluids is the same order of magnitude in all the articles reviewed. Half of the fresh water used for the fracturing process is assumed to be sourced from surface water and the other half from municipal water plants (as in (Jiang et al., 2011)). The fracturing water is not assumed to be coming from other well as recycled water because the methodology of the system expansion allows the consideration of the recovery and recycling of flowback water directly in the process of flowback water disposal.

The amount of sand used in the hydraulic fracturing fluids is calculated again as the average of the values found in the literature ((Burnham et al., 2011; Dale et al., 2013; DECC, 2013; Jiang et al., 2011; Laurenzi and Jersey, 2013; Stamford and Azapagic, 2014)). In this case Trouba et al. (Trouba and Abeldt, 2014) reports a value more than one order of magnitude lower than the values found in the other publications and, therefore, it is not included in the average.

The amount of additives contained in the fracturing fluid is taken from Jiang et al. (Jiang et al., 2011). This represents a good assumption also for the UK situation where the chemicals are reported to be ~0.05% of the fracturing fluid; however, the production of the fracturing chemical is not expected to strongly influence the results.

The energy required to mix the water, sand and chemicals on the well site to produce the fracking fluid is considered negligible.

Few articles report on the energy requirements to pump the hydraulic fracturing liquids in the well. Some of them (Jiang et al., 2014, 2011; Stephenson et al., 2011; Trouba and Abeldt, 2014) report the power delivered by the pump system and the time of pumping but do not specify the amount of diesel required to deliver the power. Stephenson et al. (Stephenson et al., 2011) are alone in specifying the amount of diesel consumed for each watt delivered by the diesel pumps (250 g of diesel/kWh). The amount of diesel consumed by the pumps is calculated based on the hydraulic horsepower delivered (12250), number of fracturing operations (15), hours of fracturing for each operation (2h) and the consumption of diesel per hydraulic horsepower delivered (250 g of diesel/kWh) (Stephenson et al., 2011).

The emissions due to the use of diesel during hydraulic fracturing and horizontal drilling are included in the model and these are based on the amount of diesel consumed. The machines used for drilling and fracturing, such as diesel engines are probably the same, as well as the air pollutants emitted by these machines (Lechtenbohmer et al., 2011). The emission of air pollutants from stationary diesel engines used for drilling and hydraulic fracturing are reported in Table S14 according to literature (Howarth et al., 2011; Lechtenbohmer et al., 2011). For CO₂ emissions the
calculations are based on the carbon content of diesel fuel. A constant relation of 3.175 kg CO$_2$ emitted/kg fuel consumed is assumed according to the diesel carbon content of 0.866 kg of C/ kg of fuel (Thinkstep, 2015). A medium density of 0.832 kg/l (diesel) results in 2.642 kg CO$_2$ emitted per l of diesel consumed.

**Flowback disposal**

The problem of fresh water course contamination due to shale gas production was firstly raised in the film documentary “Gasland” of Josh Fox; it reported on the phenomena of burning water and also critical aspects about direct disposal of flowback water to fresh water course or in evaporation pits. Heavy environmental harnesses are due to the contamination of fresh water with the chemicals used in hydraulic fracturing (Waxman et al., 2011) and the chemicals and radioactive elements found in flow back water. The major problems are associated with improper operational practice of waste water disposal and well casing (Mair et al., 2012). Hence, wide spread literature is available about the threat of shale gas extraction on water scarcity and contamination (Jiang et al., 2014; John, 2010). Since the beginning of shale exploration in the US, new policy rules about the disposal of flowback water have been introduced in some US states to ban direct flowback disposal to fresh water and impose more environmentally friendly disposal methods. Critics were also raised in the US because the composition of fracturing water and waste water, at the beginning of the shale extraction spreading, was not disclosed by industries on the basis of commercial confidentiality. If shale gas spreads in Europe, direct disposal to water will be banned and full details about the chemicals using in fracking fluids will have to be publicly available (DECC, 2014).

A sensitivity analysis on the fraction of flowback water produced (that is quite variable from well to well) and different disposal methods is performed. Four flowback disposal options have been identified: i) flow back recycling (as reported in (Jiang et al., 2014)); ii) flowback injection in deep well of Class II (as reported in (Clark et al., 2013; Jiang et al., 2011)); iii) direct disposal to fresh water (as reported in (Jiang et al., 2014)); iv) disposal to appropriate industrial waste treatment plant (as reported in (Stephenson et al., 2011)).

The base scenario represents the best practice. Therefore, the flowback is assumed to be disposed to a specific industrial plant. The scenarios where the flowback is directly released to the environment should represent an unreal situation according to the UK policy. Direct disposal of flowback to environment is not allowed in UK, but this scenario allows the identification of the environmental threats of water spills to the environment or improper waste water management (as already happened in the US). The other two disposal options are based on possible methods of flowback water disposal already tested in the US. According to the four flowback disposal methods
identified, four different energy requirements have been calculated and used in the model.

In the case of flowback recycling the amount of energy required to reprocess flowback water is assumed to be negligible compared to the total energy requirement of the extraction process (as also reported in (Jiang et al., 2014)). The allocation of avoided burdens to the recycling of flowback water is taken into account in the model as a decrease of materials required for the fracking fluids of another well.

The electricity requirement to run an electric pump for the injection of one kg of water in Class II wells has been calculated as the average of the values (between the different shale plays) reported in Clark et al. (Clark et al., 2011).

The electricity requirements for the treatment of flowback water in industrial plants are reported in Stephenson et al. (Stephenson et al., 2011). The treatment involves reverse osmosis and evaporation or freeze-thaw evaporation, as described in Thomas (Thomas, 2009). The burden due to the production of the electricity required for the freeze-thaw evaporation process is added to the burden of an industrial waste water treatment plant as reported in GaBi database (Thinkstep, 2015).

The direct disposal of flowback water to surface water is assumed not to require any further energy. In this case, the composition of flowback water (as reported in (Jiang et al., 2014)) is considered for fresh water discharges.

**Completion and workover emissions**

The emissions of natural gas associated with well completion, workover, well unloadings, re-fracturing, well equipment, transmission and storage and distribution are considered in the LCI model. The emissions due to unloading, well equipment, transmission, storage and distribution are considered to be the same for conventional and unconventional extraction (Burnham et al., 2013; Stephenson et al., 2011) and hence those are included in the common operations model according to the Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2014). On the contrast, the potential emissions (the volume of natural gas that may leak, i.e. the potential emissions, not the actual emissions) due to well completion and workover are higher in the case of shale gas extraction because of the hydraulic fracturing phase and well maintenance.

The surplus of emissions due to the hydraulic fracturing process is included in the hydraulic fracturing model according to the values reported in literature (Allen et al., 2015b, 2015a; Burnham et al., 2013; Claire Satellite, 2017; Kang et al., 2014); re-fracturing of wells is also included in the assessment. The emissions reported in some literature work (Burnham et al., 2013) includes the use of flaring and green technologies but at first instance those are ignored in our model in order to be able to
calculate the amount of potential emission associated with shale gas extraction. Then, in the sensitivity analysis different possibilities to reduce these potential emissions are explored.

As previously reported, completion of shale wells and workovers usually involves the hydraulic fracturing process and this can result in significant releases of natural gas and emission to the atmosphere. The handling method of the potential emission during completion and workovers is reported to have a dramatic impact on the carbon footprint of the shale gas production process (O’Sullivan and Paltsev, 2012). Venting of natural gas emissions would significantly increase the carbon footprint of the process; alternative more challenging handling methods such as flaring or capture and injection in the grid decreases the potential warming of the process.

Reduced emissions completions (RECs) – also known as reduced flaring completions or green completions – is a term used to describe an alternate practice that captures gas produced during well completions and well workovers following hydraulic fracturing. Portable equipment is brought on site to separate the gas from the solids and liquids produced during the high-rate flowback, and produce gas that can be delivered into the sales pipeline (Natural gas star partners, 2014). Flaring is another option to handle the potential emissions but it only eliminates methane and other hydrocarbons contained in the natural gas; this is not always the preferred option as it does not avoid the emission of other polluting compounds (such as SOx, Nox, PM and CO).

A sensitivity analysis is performed on the fraction of potential emissions captured, flared and vented to assess the influence of the emission handling methods on the total environmental burden. Starting from the potential emissions released during well completion and workovers and the values of the parameters regarding the percent of potential emissions sent to flaring or to green technologies, the following equations are used to calculate the real emissions to the atmosphere:

**Mass balance on methane**

\[ m_{CH_4}^{OUT} = m_{CH_4}^{IN} - m_{CH_4}^{IN}x_F e_F - m_{CH_4}^{IN}x_C e_C \]  

**eq.1**

**Mass balance on ethane**

\[ m_{C_2H_6}^{OUT} = m_{C_2H_6}^{IN} - m_{C_2H_6}^{IN}x_F e_F - m_{C_2H_6}^{IN}x_C e_C \]  

**eq.2**

**Mass balance on propane**

\[ m_{C_3H_8}^{OUT} = m_{C_3H_8}^{IN} - m_{C_3H_8}^{IN}x_F e_F - m_{C_3H_8}^{IN}x_C e_C \]  

**eq.3**

**Mass balance on nitrogen**

\[ m_{N_2}^{OUT} = m_{N_2}^{IN} - m_{N_2}^{IN}x_C e_C \]  

**eq.4**

Mass balance on CO₂
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\[ m_{\text{OUT}}^{CO_2} = m_{\text{IN}}^{CO_2} + \frac{m_{\text{CH}_4}^{IN} \cdot e^{F}}{MW_{\text{CH}_4}} + \frac{m_{\text{H}_2}\text{e}^{F}}{MW_{\text{H}_2}\text{e}} \cdot 2 \cdot MW_{\text{CO}_2} + \frac{m_{\text{C}_2}\text{H}_6\text{e}^{F}}{MW_{\text{C}_2}\text{H}_6\text{e}} \cdot 3 \cdot MW_{\text{CO}_2} \text{ eq.5} \]

Where: \( m \) is the mass, \( x \) is the fraction of gas, \( F \) indicates flaring, \( C \) indicates captured, \( e \) is the efficiency of flaring or capture, \( \text{IN} \) indicates the potential emissions, \( \text{OUT} \) indicates the emissions released to the atmosphere and \( MW \) indicates the molecular weight.

The flaring efficiency is assumed to be 98% (Hultman et al., 2011; Jiang et al., 2011; Laurenzi and Jersey, 2013; O’Sullivan and Paltsev, 2012; Stephenson et al., 2011). In the scenarios where part of the completion and workover emissions are assumed to be captured in green technologies, the capturing efficiency of those devices is assumed to be 90% according to literature (Forster and Perks, 2012; Weber and Clavin, 2012) (90% of emissions from well completion are captured and utilised and the remaining 10% are vented).

**Transport**

Road transport is widely reported to be one of the drawbacks associated with the production of natural gas from shale rocks. Air pollution, traffic and noise, are only few of the main problems associated with massive road transport of fracturing water, sand and other materials. Shale gas has drawn more critics than conventional extraction because the inconveniences associated with massive transport are not reported to be a major problem in conventional extraction.

The transport of materials needed for fracturing the rocks and for disposal of waste water are included in the LCI of the hydraulic fracturing model. A sensitivity analysis is then performed on the transport distances to explore the influence of these parameters on the total environmental impact of shale gas production. Table 1 reports the main transport routes, the distances assumed and the transport mode. Return journeys are also considered.

The transport of material needed for horizontal drilling is considered negligible as this amount of material is small if compared to the amount of materials required for fracking.

Municipal water is assumed to be piped to site and surface fresh water is assumed to be transported by truck prior the fracturing operations. All the other materials needed on the well site are also assumed to be trucked to the well site. The sand quarry is assumed to be close enough that no rail transport is needed (MPA, 2014).
In the case of flow back injection in class II wells, the waste water is assumed to be transported by truck to the Southern North Sea where it is assumed to be injected in gas fields. Recycled flowback water is assumed to be transported only 10 km away as other shale wells are usually close to the well under study.

Transport has been modelled using Gabi datasets (Thinkstep, 2015). The payload of trucks has been chosen following the data reported in literature. For the hydraulic fracturing water the values of 19 t and 16 t of water per truck are reported (Burnham et al., 2011) (Stephenson et al., 2011). Smaller trucks are used for all other materials.

**Estimated ultimate recovery and processed natural gas**

The EUR is a key parameter for the LCA model as a change of its value is reported to determine a significant variation in the results (Laurenzi and Jersey, 2013; O’Sullivan and Paltsev, 2012). This is because the burdens of the production process are calculated according to a defined amount of gas (the functional unit) but primary inventory data of the gas production process are related to the gas extraction per well and do not depend on the productivity of the well. Hence, the inventory data calculated per functional unit are strictly related to the EUR and this makes the results very sensible to this parameter. To contextualize the process of hydraulic fracturing in the UK, the US EUR is not considered suitable for this analysis, and the per well data are divided by the estimated UK amount of processed gas (strictly related to the EUR) that could be commercially produced in UK shale plays (DECC, 2013). The raw and processed shale gas composition is reported in Table S15 (DECC, 2013); the raw gas methane composition is 74%w/w that is an intermediate value between the value reported in literature (Dones et al., 2007; Stamford and Azapagic, 2014). As widely reported (Hultman et al., 2011; Stephenson et al., 2011), shale gas is assumed to have the same composition as conventional gas. The processed gas is assumed to be 100% methane pure with a calorific value of 52 MJ/kg (40MJ/m³) and a density of 0.76 kg/m³ (as already reported in (DECC, 2013)). Those values match the values used in the common operations model ((Swiss Centre for Life Cycle Inventories, 2014)) where the processed gas has a calorific value is 39.5 MJ/Nm³.

The sensitivity of the results on the EUR is assessed by changing the value of this parameter and at the same time keeping fixed the density and composition of the gas produced.
7. Bibliographical references


Deliverable D10.1

Chemistry, London.


Defra, 2013. UK renewable energy road map update [WWW Document].


European Commission, 2014. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions a policy framework for climate and energy in the period from 2020 to 2030.


Panel on Climate Change.
Lechtenbohmer, S., Altamann, M., Capito, S., Matra, Z., Weindorf, W., Zittel, W., 2011. Impacts of shale gas and shale oil extraction on the environment and on human health.
UK: a review of hydraulic fracturing.


Natural gas star partners, 2014. Reduced Emissions Completions for Hydraulically Fractured Natural Gas Wells 1–12.


Robertson, R., Blanco-Madrigal, E., Arnold, R., 2010. Seventh framework programme...
theme energy.2009.3.2.2- Biowaste as feedstock for 2nd generation [WWW Document].
Taylor, R., Chapman, C., 2012. ADVANCED PLASMA POWER LTD CONVERTING WASTE INTO VALUABLE RESOURCES WITH THE GASPLASMA® PROCESS.

