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Life Cycle Assessment of unconventional hydrocarbons deposits of shale and tight gas production in Poland

Ocena cyklu życia procesów poszukiwania i eksploatacji węglowodorów ze złóż niekonwencjonalnych typu *shale* i *tight gas* w Polsce

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Keywords: *life cycle assessment; shale gas; tight gas; environment pollution; carbon footprint, global warming potential*

Abstract

Shale and tight gas production create a potential threat to the environment. In Poland, no comprehensive guidelines for Life Cycle Assessment (LCA) have been prepared so far. The paper presents a proposal for Life Cycle Assessment (LCA) which can be used to assess the impact of production of unconventional hydrocarbons processes in Polish circumstances. It can be also a complement to environmental risk assessment. We used the methodology of Life Cycle Assessment (LCA) and estimated the environmental impact of shale and tight gas exploration and operation for several elements like: global warming, water consumption, human carcinogenic toxicity, terrestrial acidification, and others.

Słowa kluczowe: *life cycle assessment; shale gas; tight gas; environment pollution; carbon footprint, global warming potential*

Streszczenie

Procesy poszukiwania i wydobycia gazu ze złóż niekonwencjonalnych typu *shale* (gaz z łupków) oraz *tight* (gaz zamknięty) stwarzają potencjalne zagrożenie dla środowiska. W Polsce nie zostały dotychczas opracowane kompleksowe wytyczne dotyczące oceny ryzyka środowiskowego oraz oceny cyklu życia (LCA) dla produktów takich jak *shale* i *tight gas*. W niniejszym artykule zaprezentowano analizę procesów poszukiwania i eksploatacji *shale* i *tight gas* przy użyciu metodyki oceny cyklu życia (LCA) dla warunków polskich. Może ona stanowić uzupełnienie analizy ryzyka środowiskowego. Metodyka oceny cyklu życia (LCA) została wykorzystana do szacowania wpływu procesów poszukiwania i eksploatacji *shale* i *tight gas* na elementy takie jak: globalne ocieplenie, zużycie wody, oddziaływanie rakotwórcze na człowieka, zakwaszenie gleb i inne.

1. Introduction

Every industry has an impact on the environment, and its comprehensive evaluation is possible by the Life Cycle Assessment (LCA) approach, addressing the stages of construction, operation and decomissioning of any technical system. It is also necessary for making judgments and comprehending the interconnections between human activities and their effects on nature. In the studied case of oil and gas industry, LCA gives a chance to detect and to reduce negative consequences connected with unconventional exploration of hydrocarbons and development, hence enhancing the sector's condition.

Shale and tight gas are two important unconventional gas resources. Shale gas refers to natural gas that is trapped within shale formations of fine-grained sedimentary rocks. Shale and tight gas have a composition similar to that of natural gas from conventional deposits. It contains methane (75-95%) and nitrogen, with some minor share of ethane, propane, helium, oxygen and carbon dioxide [1]. Unconventional natural gases are at the depth of 2500 m (tight gas) and 500 m (shale gas) which is difficult to access because of the nature ofthe rock and sand surrounding the deposits. Hydraulic fracturing and directional drilling is necessary to produce the well. Tight gas is the dominant type of unconventional gas produced in the world.

Global conventional resources of natural gas are estimated at nearly 432 x 1012 m^3. In addition to that, technically recoverable shale gas resources are 233 x 10^{12} m^3 and tight gas 82 x 10^{12} m^3 [2]. North America leads the unconventional gas production, followed by China, Argentina and Australia with increasing production quantities.

Conventional gas resources in Poland are estimated at 95.81 x 109 m^3. Technically recoverable shale gas and tight gas resources amount to 75.3–622.2 10^9 m^3 and 153-200 x 10^9 m^3, respectively [3].

To understand the plain environmental impact of unconventional gas production it is necessary to apply the Life Cycle Assessment (LCA) methodology. The idea of LCA was first introduced at the World Energy Conference in 1963 by Haraold Smith, a nuclear power station manager. In 1990, the foundations of the LCA approach were laid [4], followed by the development of the standardization process, comprising the following key documents: PN-EN ISO 14040: 2009 *Environmental management. Principles and framework of Life Cycle Assessment* [5] and PN-EN ISO 14044: 2009 *Require-*

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ments and recommendations for environmental management. Life Cycle Assessment [6].

The European Commission's Product Environmental Footprint Category Rules (PEFCRs) and Organization Environmental Footprint Sector Rules (OEFSRs) recommendations [7, 8] on life cycle evaluation of products using the LCA approach currently do not include complete and mandatory solutions for many industries (including, i.a. unconventional hydrocarbons production).

A number of studies have been dedicated to the Life Cycle Assessment in the oil and gas industry. Costa et al. [9] performed the LCA for shale gas exploration and exploitation project in Spain. They found that the key environmental impact is related to the consumption of diesel fuel and water used for hydraulic fracturing. The global warming potential was estimated at 0.004 kg CO_2 eq/MJ. Recently, Tagliaferri et al. [10] studied a detailed impact of shale gas on the watershed in the UK. They assumed that the extraction of shale gas involves exactly the same processes as the extraction of conventional gas except the hydraulic fracturing. LCA methodology was used to analyze the impact of shale gas on water consumption and degradation. Moreover, there is a large number of studies which reviewed information about carbon footprint for conventional and unconventional gas. Stamford and Azapagic [11] estimated the environmental impacts of electricity from UK shale gas and compared them to electricity derived from other sources (coal, nuclear and solar). Westaway et al. [12] reassessed the conclusions of Stamford and Azapagic who claimed that shale gas was worse than coal for such impact categories like: depletion of the stratospheric ozone layer and terrestrial ecotoxicity. Weber et al. [13] estimated the carbon footprint for shale gas at 14.6 g CO_2eq/MJ and they found it similar to that of conventional gas (16.0 g CO_2eq/MJ). Opposite to this, Howarth et al. [14] stated that the greenhouse gas footprint of shale gas is larger than that from conventional gas, due to methane emissions from flow-back fluids. It may be concluded that for both conventional and shale gas, the total impact is a sum of the direct CO_2 emissions and methane emissions.

In the case of Poland, the environmental effect of unconventional gas production has yet to be fully studied. Niemczewska [15] provided a preliminary introduction to the evaluation of the environmental footprint for oil and natural gas, demonstrating that the LCA methodology in this sector is not well developed and the details have to be elaborated.

The objective of this paper is to demonstrate the applicability and to provide the key results of Life Cycle Assessment for gas production from unconventional hydrocarbon deposits of shale gas and tight gas under Polish specific data and circumstances.

2. Methods

Life Cycle Assessment (LCA) is an environmental management methodology that examines environmental features and possible environmental repercussions across the course of a product's life cycle, or 'from cradle to grave'. Its goal is to examine the environmental hazards connected with the manufacturing process, and it comprises a quantitative summary of the materials used, energy consumed, emissions to the environment, and an evaluation of their environmental effect [16]. The methodology is summarized by the standard PN-EN ISO 14040: 2009 [5], which includes the following: Goal and Scope of the Analysis, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretations of Results.

In the studied case of shale and tight gas production, the LCA approach may be used to estimate the environmental effect of the process, as well as provide advice on how to reduce that impact. The analysis was performed based on: 1) archival 2012-2013 data for shale gas wells S1-S3, 2) recent data (2019-2020) for tight gas wells T1-T3 [17], and the SimaPro 9.1.0.11 PhD database for flows of energy and materials exchanged with nature and the technosphere.

The goal of the Life Cycle Impact Assessment was to estimate the environmental impact and carbon footprint of shale and tight gas production in Poland. The results were also compared to those obtained for conventional natural gas extraction in Poland and Europe.

The goals are reached by using the 'from cradle to grave' methodology, starting from the exploration of shale and tight gas to the end of life which is well and mining plant decommissioning. The system boundaries indicated in Figure 1 were established to identify the number of activities included and to compare different aspects of the shale and tight gas production.

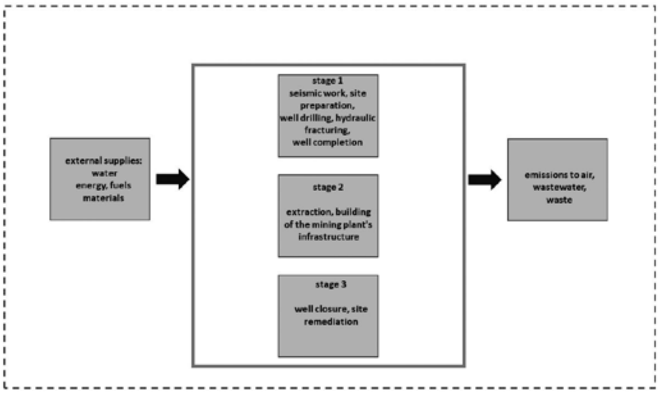
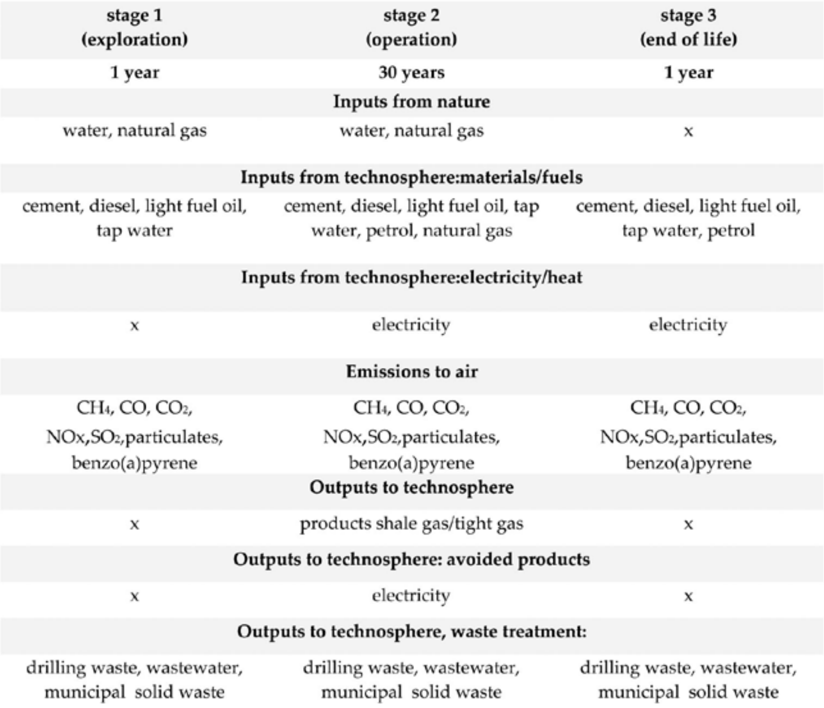


Figure 1. System boundaries
Rysunek 1. Granice systemu

Figure 2 summarizes the gathered input and output data, principal products, waste, and emissions. Due to the relatively small quantity of chemicals using as components of fracturing fluids and proppants (which consist of 99% water with sand, and less than 1 % substances to help efficiently perform fracturing e.g. alcohol, hydrochloric acid, isopropanol, glicol), these substances were not included.



stage 1 (exploration)	stage 2 (operation)	stage 3 (end of life)
1 year	30 years	1 year
Inputs from nature		
water, natural gas	water, natural gas	x
Inputs from technosphere:materials/fuels		
cement, diesel, light fuel oil, tap water	cement, diesel, light fuel oil, tap water, petrol, natural gas	cement, diesel, light fuel oil, tap water, petrol
Inputs from technosphere:electricity/heat		
x	electricity	electricity
Emissions to air		
CH_4, CO, CO_2, NOx,SO_2,particulates, benzo(a)pyrene	CH_4, CO, CO_2, NOx,SO_2,particulates, benzo(a)pyrene	CH_4, CO, CO_2, NOx,SO_2,particulates, benzo(a)pyrene
Outputs to technosphere		
x	products shale gas/tight gas	x
Outputs to technosphere: avoided products		
x	electricity	x
Outputs to technosphere, waste treatment:		
drilling waste, wastewater, municipal solid waste	drilling waste, wastewater, municipal solid waste	drilling waste, wastewater, municipal solid waste

Figure 2. Inputs and outputs data from system boundaries/
Rysunek 2. Wejścia i wyjścia danych do systemu

As shown in Figure 1 and Figure 2, the base production model for shale and tight gas comprises the following stages: exploration, operation (with gas processing) and end of life:

- Stage 1 – exploration: seismic work, exploratory drilling, hydraulic fracturing in a single borehole, well trial operation, and pad preparation for full-scale gas production,
- Stage 2 – operation: gas production (extraction), building mine infrastructure,
- Stage 3 – end of life: gradual reduction of gas production, well decommissioning, complete decommissioning of the mining plant, land reclamation, plate removal, humus deposition from the shafts surrounding the drilling rig, cementing and securing the well, site remediation.

To track and simulate the material and energy fluxes in and out of the system, Life Cycle Inventory (LCI) data for the specific scope was collected. SimaPro 9.1.0.11 PhD software was used to perform the calculations. The system boundaries indicated in Figure 1 were established to identify the number of activities included and to compare different aspects of shale and tight gas production. Modeling was done with real data from in-house sources of the Polish Oil and Gas Company (PGNiG). The maximum period of operation of shale and tight gas deposits was estimated at the level of 30 years based on American experience. Data selection was done in compliance with the rules of the PN – EN ISO 14044: 2009 standard [5]. In the lack of data, researchers turned to the literature. Individual data for S1-S3 shale gas wells and T1-T3 tight gas wells is averaged yearly values. 1 MJ shale gas and 1 MJ tight gas at low pressure (7 bar and > 0.75 mbar) as a functional unit (the same which used Tagliaferri et al. [10]).

To calculate the environmental implications of all inputs and outputs related with the shale and tight gas production (Figure 2), three distinct methods were chosen in accordance with the recommendations of the PN-EN ISO 14040: 2009 standard, enabling presentation of results and analyses in terms of various elements of the impact:

- The ReCiPe Midpoint H approach was used for displaying overall findings. To estimate possible repercussions, ReCiPe employs cause-and-effect pathways [18]. Each environmental impact during 3 stages of shale and tight gas production is converted into an environmental category, such as global warming, water consumption, human carcinogenic toxicity, and terrestrial acidification and the results are expressed in kg CO_2 eq/MJ.
- IPCC 2013 GWP 100a was created by the Intergovernmental Panel on Climate Change and it contains IPCC climate change variables over a 100-year period. The global warming potential of air emissions is depicted by IPCC characterization factors [19]. The functional unit of this method is kg CO_2 eq, same as in the ReCiPe approach.
- Cumulative Energy Demand (LHV) in MJ/MJ to determine total energy consumption (Lower Heating Values) using data from the Ecoinvent 3.0 version database for raw materials in the SimaPro database. Functional unit: MJ/MJ

3. Results

Results of Life Cycle Impact Assessment obtained using the ReCiPe Midpoint H method are shown in Table 1.

As can be seen, shale gas has a global warming potential of 0.003 kg CO_2eq/MJ and tight gas has of 0.004 kg CO_2eq/MJ estimated using the ReCiPe Midpoint H method. Stage 2 shale and tight gas have a big impact on it (Figure 3 and Figure 4).

Table 1. ReCiPe Midpoint H method – main impact categories and units of *shale* and *tight* gas production

Tablica 1. Metoda ReCiPe Midpoint H – główne kategorie oddziaływania oraz jednostki dla *shale* i *tight* gas

			shale gas	tight gas
Impact category	**Unit**	**Total**	**Unit**	**Total**
Global warming	kg CO2 eq	0.003	kg CO2 eq	**0.004**
Stratospheric ozone depletion	kg CFC11 eq	$-1.05*10^{-10}$	kg CFC11 eq	$-9.44*10^{-11}$
Freshwater eutrophication	kg P eq	$-8.87*10^{-7}$	kg P eq	$-8.60*10^{-7}$
Terrestrial ecotoxicity	kg 1.4-DCB	-0.00087	kg 1.4-DCB	-0.00084
Freshwater ecotoxicity	kg 1.4-DCB	$-4.54*10^{-5}$	kg 1.4-DCB	$-4.43*10^{-5}$
Human carcinogenic toxicity	kg 1.4-DCB	-5.09*10-5	kg 1.4-DCB	$-4.94*10^{-5}$
Human non-carcinogenic toxicity	kg 1.4-DCB	-0.00113	kg 1.4-DCB	-0.00111
Mineral resource scarcity	kg Cu eq	$-4.71*10^{-7}$	kg Cu eq	$-4.45*10^{-7}$
Fossil resource scarcity	kg oil eq	0.025	kg oil eq	0.026
Water consumption	m^3	$-1.58*10^{-5}$	m^3	$-1.37*10^{-5}$

Global warming potential values are lower than those estimated using the GWP 100a method for hard coal [20] (i.e. 0.042 kg CO_2eq/MJ), comparable to those calculated for shale gas in Spain (i.e. 0.004 kg CO_2eq/MJ [9], and comparable to those calculated for conventional natural gas in Poland (i.e. 0.003 kg CO_2eq/MJ) [20].

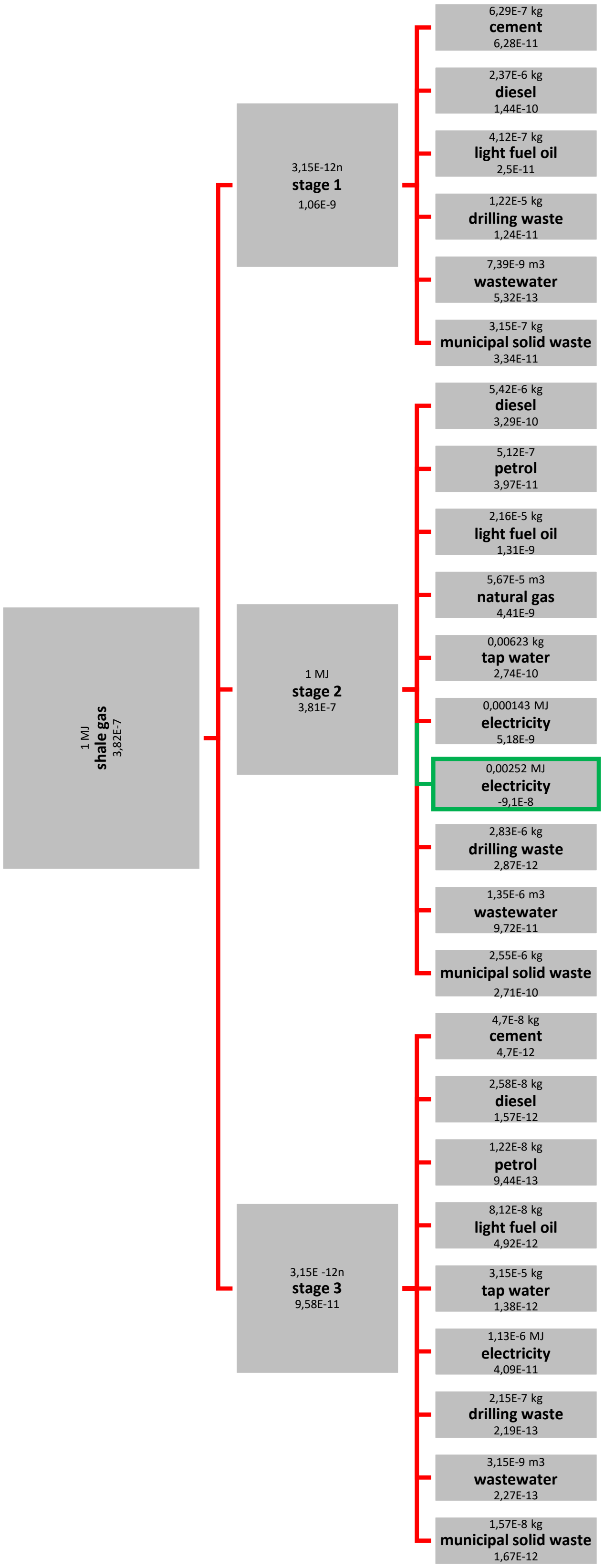
As shown in Figures 7 and 8, the cumulative energy demand for shale and tight gas amounts to 1.05 and 1.08 MJ/MJ, respectively. Therefore, to obtain 1 MJ of chemical energy of shale and tight gas we need to use 0.05 and 0.08 MJ of additional energy carirers in the whole process lifetime. In addition, the mine equipped with a combined heat and power plant, which enables the production of electricity for own needs and the transfer of surplus energy to the grid.

4.Discussions

In ReCiPe Midpoint H method production of unconventional hydrocarbons, such as shale and tight gas, the impact on climate change category was of the greatest importance. The reason is the emissions of greenhouse gasses, especially CO_2 and CH_4 due to direct gas flares, as well as emissions from car engines and booster generators. In addition, the processes of exploration and production of unconventional hydrocarbons require the use of non-renewable energy sources, which causes significant emissions of nitrogen compounds, thus affecting the freshwater eutrophication process, and damage the ozone formation.

Also in GWP 100a method mineral resources and fossil fuels category is affected by the use of diesel fuel and light fuel to transport and power aggregates.The usage of electricity is linked to the development of unconventional fuels like shale and tight gas. Electricity usage has the largest impact on climate change, and fuel combustion emits greenhouse gasses that contribute to the greenhouse effect worsening. Electricity in Poland has a significant carbon footprint due to the fact that it is mostly derived from fossil sources. The highest consumption of electricity occurs in stage 2, but it is compensated due to the production of electricity by the combined heat and power plant located in the mine. Electricity and heat constitute the basic source of energy for technological processes. Due to hydraulic fracturing, there is a lot of water used. According to actual statistics and literature, around 25% of the water is reused [10], including for scrubber preparation. Using tap water also has the largest impact on stage 2 (0,0719% for shale gas and 0,0553 % for tight gas).

Finally in Cumulative Energy Demand (LHV) method to obtain 1 MJ of chemical energy from shale gas must be used 0.08 MJ from shale gas and 0.05 MJ from tight gas energy and energy source over the entire period. There is only 10% of the energy it needs to



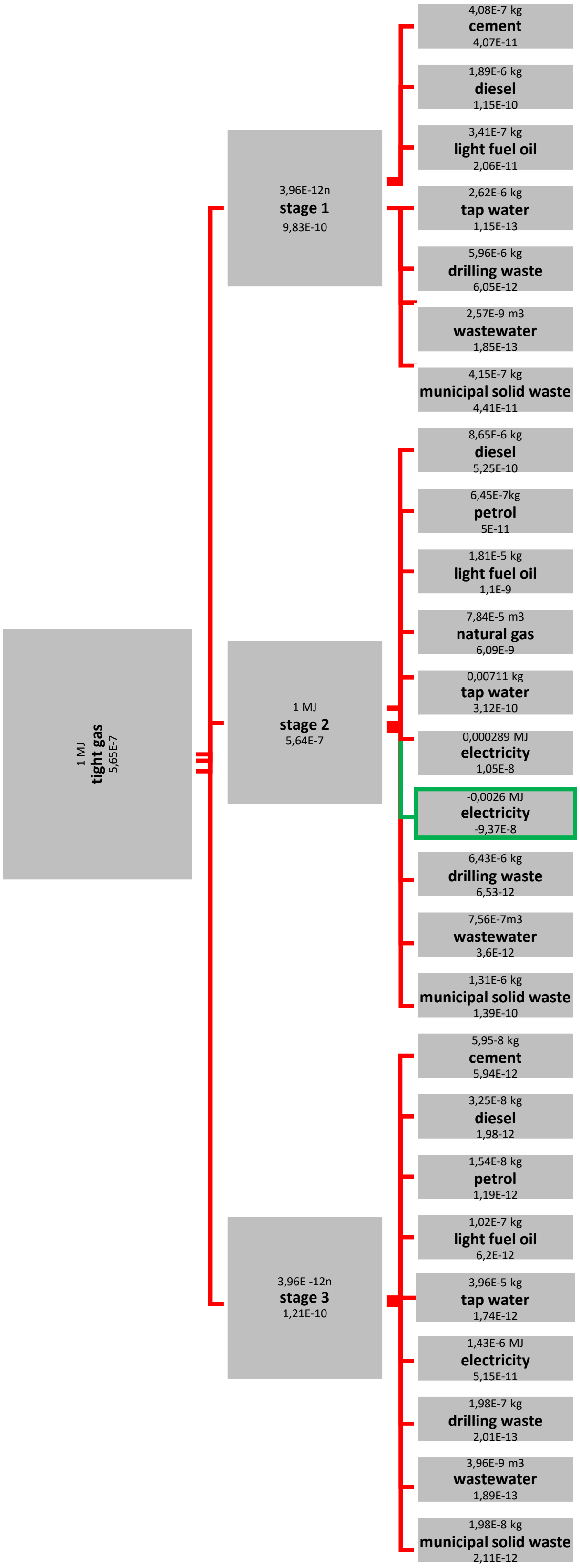
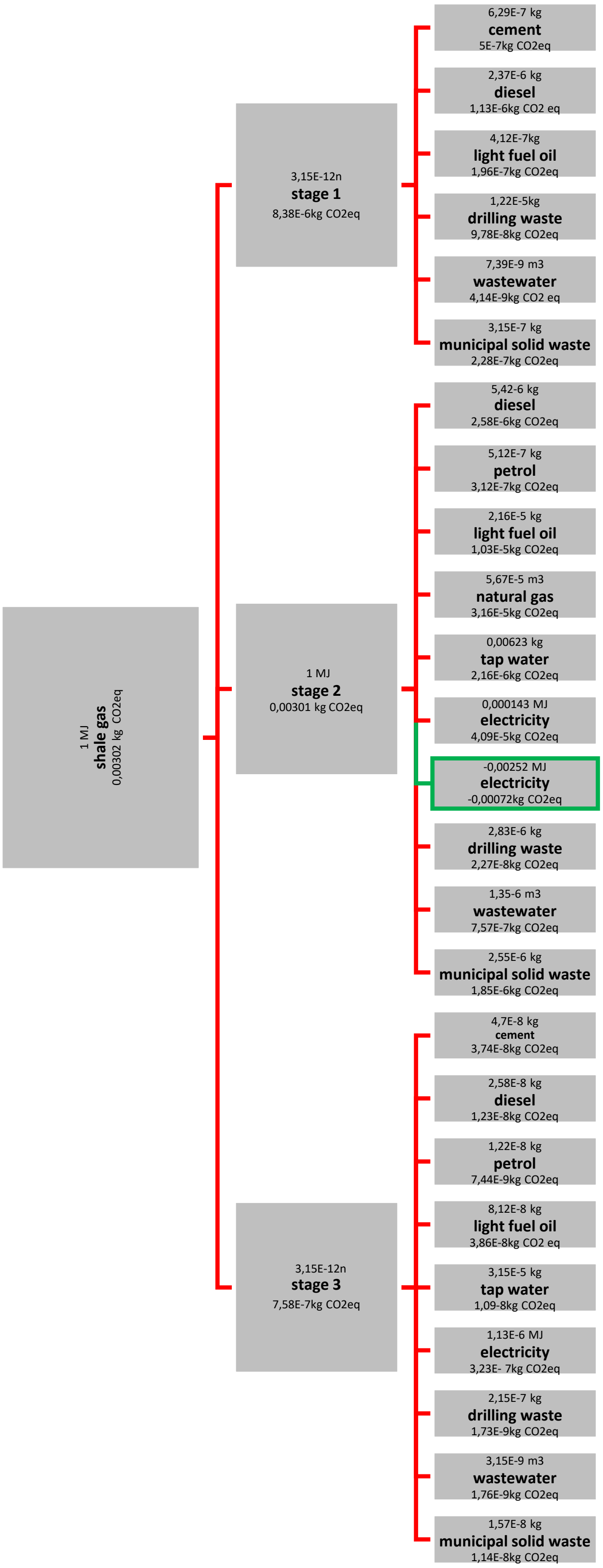


Figure 3. a Contribution to Recipe Midpoint H index for shale gas, by stage and by flows
Rysunek 3.a. Recipe Midpoint H dla shale gas według etapów i przepływów

Figure 3. b Contribution to Recipe Midpoint H index for tight gas, by stage and by flows/
Rysunek 3.b. Recipe Midpoint H dla tight gas według etapów i przepływów



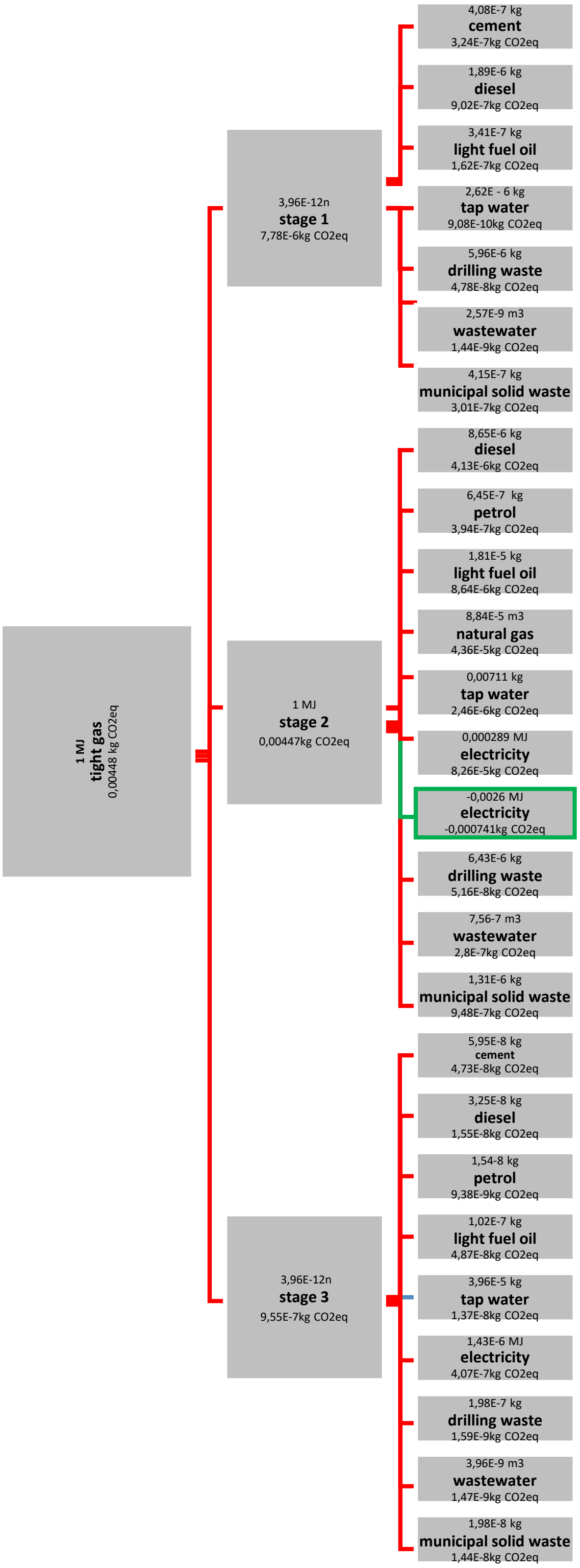
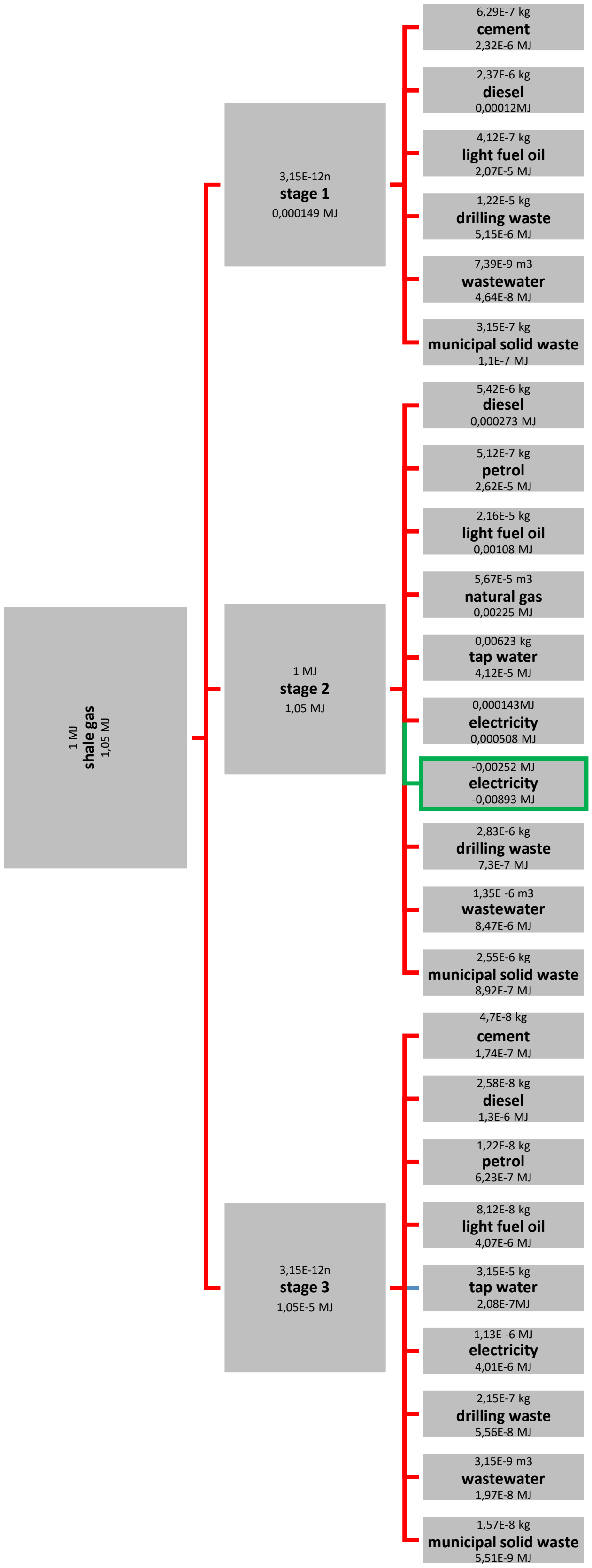


Figure 4. a. GWP 100a method calculation for shale gas

Rysunek 4.a. GWP 100a dla shale gas według etapów i przepływów

Figure 4. b. GWP 100a method calculation for tight

Rysunek 4.b. GWP 100a dla tight gas według etapów i przepływów



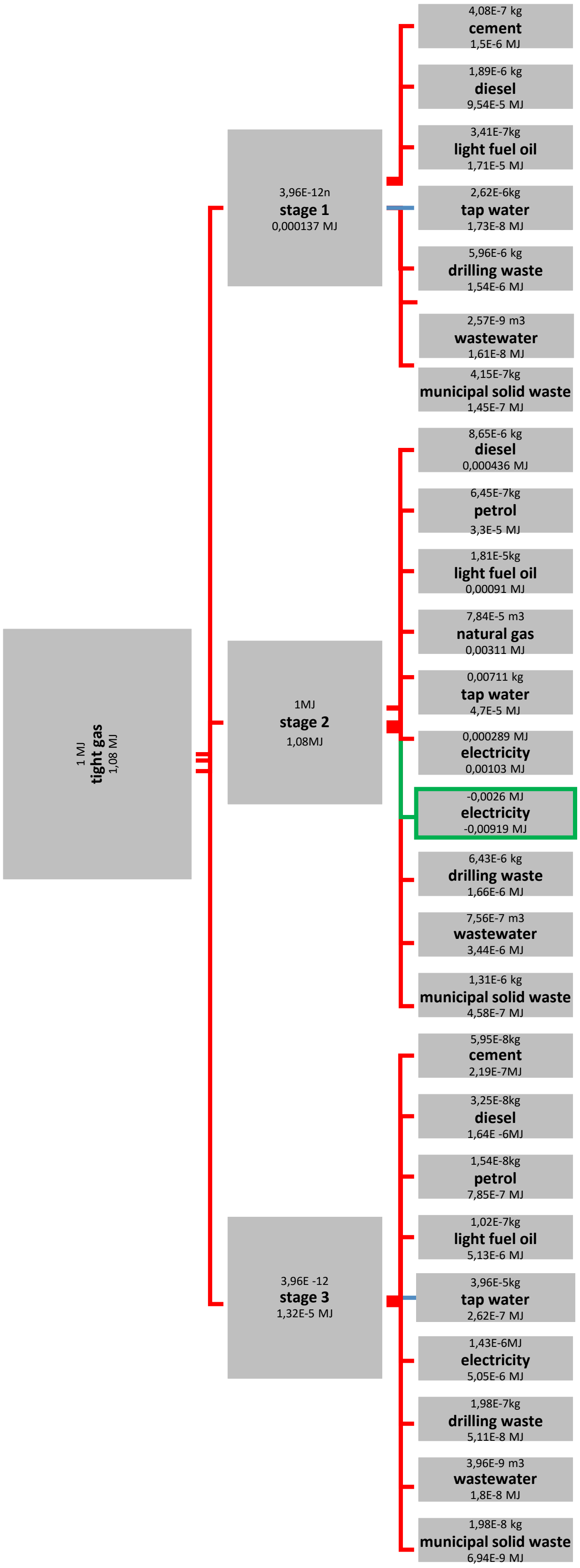


Figure 5. a. Cumulative Energy Demand (LHV) method calculation for shale gas

Rysunek 5. a. Cumulative Energy Demand (LHV) dla shale gas według etapów i przepływów

Figure 5. b. Cumulative Energy Demand (LHV) method calculation for tight gas

Rysunek 5. b.-Cumulative Energy Demand (LHV) dla tight gas według etapów add. This result is guaranteed, inter alia, thanks to the operation of the CHP plant at Stage 2, which enables the generation of surplus energy and its transfer to the grid.

5. Conclusions

The interpretation of the acquired data is the final stage of the LCA study. Its goal is to go over the findings and show how products might be made to have less of an impact on the environment [3, 4].The most significant impacts like emissions to air, wastewater, waste, water intake are generally lower during stage 1 and 3 than in stage 2 for both shale and tight gas. For example cradle to gate studies of Tagliaferri at al. [21] pointed out that the LNG imported to the UK has a higher life cycle GHG emissions compared to domestic natural gas. Processes of LNG liquefaction and shipping transport determine more than 50% global warming potential which equals 0.0174 kg of CO_2 eq GWP (including extraction and drying, liquefaction, shipping transport and evaporation without distribution). This value is consistent with values reported by NETL for 2019 [22]. Global warming potential for shale gas (0.003 kg CO_2eq/MJ) and tight gas (0.004 kg CO_2eq/MJ) in Polish circumstances is slightly lower than LNG due to the emissions saved by avoiding liquefaction, shipping and regasification. However LNG can be used as a fuel for marine which will help to reduce GHG emissions.

Exploration and operation of shale and tight gas in Poland uses well-established technologies. However, in the realms of industrial production, there is little experience. Our research was based on as much genuine data as possible. We provided the results of a study in this publication for shale and tight gas Life Cycle Assessment. Identification of unit processes, as well as all inputs and outputs, it is possible to take measures to reduce the consumption of raw materials and energy, as well as to effectively manage the generated waste.

Sensitivity and uncertainty analysis is the next challenge of Life Cycle Assessment of unconventional hydrocarbons deposits of shale and tight gas production in Poland. ■

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