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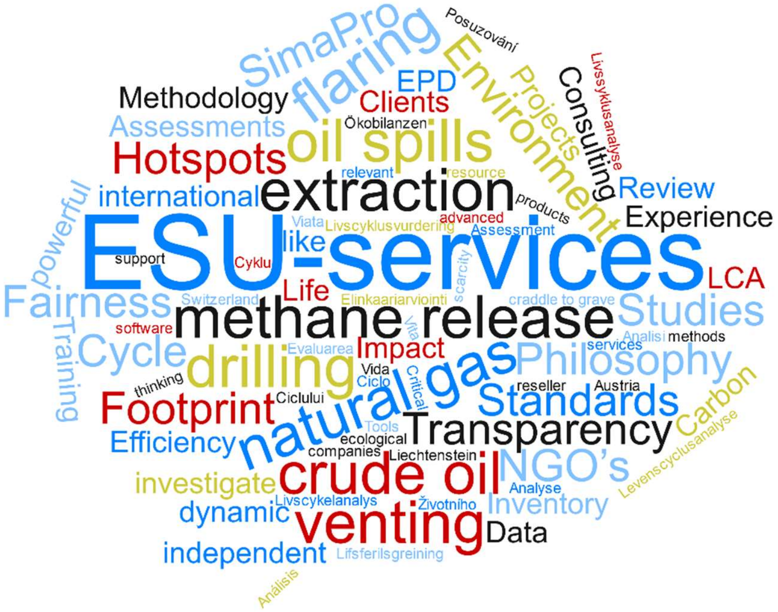
Life cycle inventories of crude oil and natural gas extraction



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Life cycle inventories of crude oil and natural gas extraction

Report

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Abbreviations

a	year (annum)
API	American Petroleum Institute
AZ	Azerbaijan
bbl.	Barrel
bcm	billion cubic meters
bld	below limit of detection
bn	Billion
BOD5	Biochemical oxygen demand for 5 days of microbial degradation
BTU	British Thermal Unit (1 BTU = 1055 J)
BTX	Benzene, Toluene, and Xylenes
Bq	Becquerel
CEL	Central European Pipeline
cf	Cubic Feet
CH4	Methane
CHP	Combined Heat and Power
Ci	Curie
CIS	Commonwealth of Independent States
CMC	Carboxymethyl Cellulose
CO	Carbon monoxide
CO_2	Carbon dioxide
COD	Chemical oxygen demand
Concawe	Conservation of Clean Air and Water in Europe (the oil companies' European organization for environmental and health protection, established in 1963)
d	day
DE	Germany
DeNOx	Denitrification method (general)
DM	Dry matter
DoE	Department of Energy, US
DZ	Algeria
E5/10/15/85•	Petrol with 5%/10%/15%/85% ethanol
EdP	Electricidade de Portugal S.A.
EMPA	Swiss federal material testing institute
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency, US
GB	Great Britain
GGFR	Global Gas Flaring Reduction Partnership
GWP	Global Warming Potential
HC	Hydrocarbons
HEC	Hydroxyethyl cellulose
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	International Panel on Climate Change
IQ	Iraq
J	Joule

KBOB	Koordinationsgremium der Bauorgane des Bundes
KZ	Kazakhstan
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LY	Libyan Arab Jamahiriya
M.	Million
MJ	Megajoule
Mt	Megaton = 1 million tons
MTBE	Methyl tert-butyl ether
MW	Megawatt
MX	Mexico
NCI	Nelson complexity index
NG	Nigeria
NGL	Natural Gas Liquids
NL	Netherlands
Nm^3	Normal-cubic metre (for gases)
NMVOC	Non-Methane-Volatile Organic Compounds
NO	Norway
NOAA	National Oceanic and Atmospheric Administration
NORM	Naturally Occurring Radioactive Materials
NOX	Nitrogen oxides
NR	Not Reported
Ns	not specified
OE	Oil equivalent
OECD	Organisation for Economic Cooperation and Development
PAH	Polycyclic Aromatic Hydrocarbons
PC	Personal Communication
PM	Particulate Matter
QA	Qatar
Rn	Radon
RO	Romania
RU	Russia
SA	Saudi-Arabia
SN	Smoke number
TDS	Total Dissolved Solids
TEL	Tetraethyl lead
toe	Ton Oil Equivalent
TSS	Total Suspended Solids
UCTE	Union for the Co-ordination of Transmission of Electricity
ULCC	Ultra Large Crude Carrier
ULS	Ultra low sulphur
UNEP	United Nations Environment Programme
US (A)	United States of America
VOC	Volatile Organic Compounds

1 Introduction

The goal of this study is to report the data as submitted to ecoinvent for the implementation in their database release version 3.9. Changes made by the commissioner to implement the data in the ecoinvent v3-database are not described in this report but in a separate report (Moreno Ruiz et al. 2022). The content of this document therefore does not fully reflect the LCI data as provided with ecoinvent v3.9.

This document is based on the last update of the life cycle inventory data for crude oil extraction (Meili et al. 2021). This former version has been elaborated in a project for updating and harmonizing the life cycle inventories in the UVEK database (UVEK 2018) for the extraction of crude oil and natural gas (Meili et al. 2021). Also the reports for the transport of crude oil to European refineries (Meili et al. 2022) and the transport of natural gas to the European end user (Bussa et al. 2022) were updated in view of an integration in ecoinvent v3 in the same project.

In general, only subchapters on process steps that are assessed as relevant in former LCIA results (ecological scarcity 2013) were kept or updated in this report (c.f. Meili & Jungbluth 2018).

If the numbers did not change considerably or no new numbers were available, the former text was kept for this report to provide this relevant information (c.f. Meili et al. 2021, Meili & Jungbluth 2018, Jungbluth 2007).

The following chapters analyse crude oil and natural gas extraction from the perspective of production regions relevant for Switzerland, the EU-28 states, North America and the global market.

2 Goal and scope

2.1 Overview

In this report the life cycle inventory (LCI) of crude oil and natural gas extraction in countries with target market Switzerland, the EU-28-states, North America and the global market are described.

Based on the analysis of existing datasets it is known, which LCI components have the highest influence for the life cycle impact assessment (LCIA) method ‘ecological scarcity 2013’. Generic data from previous studies are used to complete the LCIs (Meili & Jungbluth 2019).

The market situation for crude oil and natural gas supplies to Europe, Switzerland, North America, and the global market is updated for the reference year 2019 and new inventories are developed for extraction in some countries. Most relevant for the update are methane emissions (vented, fugitive and flaring), discharge of produced water and the direct energy uses during oil extraction including drilling and flaring. Furthermore, the emissions due to these practices are updated. Other, less important aspects are e.g., construction materials and the use of chemicals for enhanced oil recovery. Such aspects of lesser importance were not updated.

Updates are made mainly according to the following data sources:

- Methane and flaring emissions, consumption of energy, production figures and other key indicators with the latest version of key data sources used in the update of crude oil and natural gas extraction (BP 2020; IOGP 2020; World Bank 2022; IEA 2022). For methane emissions, data are aligned to ensure that the total inventoried methane emissions for crude oil and natural gas do match the global total reported in actual studies.

- Changes documented for ecoinvent v3.4 are included (Faist-Emmenegger et al. 2015)
- Available updates and changes proposed by commissioners or validators at the project start are discussed in this report.
- The reduction for offshore emissions and emissions from transportation for ozone depleting substances is based on assumptions in the study for oil extraction (Meili & Jungbluth 2018)

Besides the data sources mentioned above, no further literature is searched for.

The reporting is based on a former public report commissioned by the Federal Office for the Environment (Meili et al. 2021).

Data are inventoried for 27 countries as shown in Tab. 2.1. These countries cover the most relevant datasets necessary to update the present data for crude oil and natural gas supply mixes (c.f. Bussa et al. 2022, chapter 2 and Meili et al. 2022, chapter 2)). Transport and distribution are discussed in the related reports on “Life cycle inventories for long-distance transport and distribution of natural gas” (Bussa et al. 2022) and “Life cycle inventories for long-distance transport of crude oil” (Meili et al. 2022).

Tab. 2.1 Countries for which oil and gas production is updated or newly modelled in this study. Production data for these countries according to BP 2020 for the reference year 2019. Energy production and oil equivalents are calculated based on energy contents mentioned in chapter 2.2. Crude oil production in mega-tons per year, natural gas production in billion cubic meters per year, energy production in mega-joules per year

Origin	short	Global region	crude oil production	natural gas production	energy production	oil equivalent
Unit			Mt/a	bcm/a	MJ/a	kgOE/a
United Arab Emirates	AE	Middle East	1.8E+2	6.3E+1	1.0E+13	2.3E+11
Azerbaijan	AZ	Independent States of the Former Soviet Union	3.8E+1	2.4E+1	2.5E+12	5.8E+10
Brazil	BR	Latin America & the Caribbean	1.5E+2	2.6E+1	7.5E+12	1.7E+11
Canada	CA	North America	2.7E+2	1.7E+2	1.8E+13	4.2E+11
China	CN	Asia and the Pacific	1.9E+2	1.8E+2	1.5E+13	3.4E+11
Colombia	CO	Latin America & the Caribbean	4.7E+1	1.3E+1	2.5E+12	5.8E+10
Germany	DE	Europe	3.2E+0	5.3E+0	3.3E+11	7.6E+9
Algeria	DZ	Africa	6.4E+1	8.6E+1	5.9E+12	1.4E+11
Ecuador	EC	Latin America & the Caribbean	2.8E+1	3.5E-1	1.2E+12	2.9E+10
United Kingdom	GB	Europe	5.2E+1	4.0E+1	3.7E+12	8.5E+10
Indonesia	ID	Asia and the Pacific	3.8E+1	6.8E+1	4.1E+12	9.4E+10
Iraq	IQ	Middle East	2.3E+2	1.1E+1	1.1E+13	2.4E+11
Iran	IR	Middle East	1.6E+2	2.4E+2	1.6E+13	3.6E+11
Kuwait	KW	Middle East	1.4E+2	1.8E+1	6.9E+12	1.6E+11
Kazakhstan	KZ	Independent States of the Former Soviet Union	9.1E+1	2.3E+1	4.8E+12	1.1E+11
Libyan Arab Jamahiriya	LY	Africa	5.8E+1	9.4E+0	2.8E+12	6.6E+10
Mexico	MX	North America	9.5E+1	3.4E+1	5.3E+12	1.2E+11
Malaysia	MY	Asia and the Pacific	3.0E+1	7.9E+1	4.1E+12	9.5E+10
Nigeria	NG	Africa	1.0E+2	4.9E+1	6.2E+12	1.4E+11
Netherlands	NL	Europe	1.1E+0	2.8E+1	1.1E+12	2.4E+10
Norway	NO	Europe	7.8E+1	1.1E+2	7.5E+12	1.7E+11
Qatar	QA	Middle East	7.9E+1	1.8E+2	9.8E+12	2.3E+11
Romania	RO	Europe	3.6E+0	9.7E+0	5.0E+11	1.2E+10
Russian Federation	RU	Independent States of the Former Soviet Union	5.7E+2	6.8E+2	4.9E+13	1.1E+12
Saudi Arabia	SA	Middle East	5.6E+2	1.1E+2	2.8E+13	6.5E+11
United States	US	North America	7.5E+2	9.2E+2	6.6E+13	1.5E+12
Venezuela	VE	Latin America & the Caribbean	4.7E+1	2.6E+1	3.0E+12	6.9E+10
Global	**GLO**	**Global**	**4.5E+3**	**4.0E+3**	**3.4E+14**	**7.8E+12**

For each of these countries, the 9 datasets, as shown in Tab. 2.2, are updated or newly investigated. The first 3 datasets are multi-output processes for the combined delivery of crude oil and natural gas. They show the LCI before allocation and cannot be directly imported to SimaPro. However, they are needed for an import to the ecoinvent v3 database. Thus, in total 243 datasets are provided for crude oil and natural gas extraction in different countries.

Tab. 2.2 List of provided datasets for crude oil and natural gas extraction, per country (exemplary for Libya)

Name	Location	Category	SubCategory	unit	StartDate	EndDate
combined gas and oil production	LY	oil	production	a	2019	2022
combined gas and oil production offshore	LY	oil	production	a	2019	2022
combined gas and oil production onshore	LY	oil	production	a	2019	2022
crude oil, at production offshore	LY	oil	production	kg	2019	2022
crude oil, at production onshore	LY	oil	production	kg	2000	2022
natural gas, at production offshore	LY	natural gas	production	Nm3	2019	2022
natural gas, at production onshore	LY	natural gas	production	Nm3	2019	2022
crude oil, at production	LY	oil	production	kg	2019	2022
natural gas, at production	LY	natural gas	production	Nm3	2019	2022

2.2 Allocation for combined gas and oil production

Crude oil and natural gas production are often linked, and data are provided for combined production[1]. Therefore, multioutput processes are generated for several regions under investigation. This study presents data on oil and gas production per kg oil equivalent (kg OE). A net calorific value of 43.4 MJ/kg is used for crude oil and related products like condensates and liquefied natural gas liquids. For natural gas an average value of 36 MJ/Sm^3 (standard cubic meters, measured at 15°C and 1013 mbar, according to BP 2020, c.f. chapters 5.1.2 and 5.2.1 in this study).

The life cycle impacts from combined crude oil and natural gas production are mainly allocated based on these net calorific values. These values are used for newly created and updated data sets together with the annual production data for 2019 (cf. Tab. 2.1). Deviating from this general rule, impacts of freshwater use and discharge of produced water are allocated to crude oil only. For venting the share of natural gas and crude oil for the total emissions is known and allocation is based on these known shares.

3 Methods for oil and natural gas extraction

This section gives a basic overview on the technologies in use, mainly based on the description of the first database version (Frischknecht et al. 1996; Jungbluth 2007). Information on production methods in this report has not been updated for current developments.

3.1 Conventional crude oil production

Depending on the variety of crude oils and their properties, the production processes to be used and further treatments are different. While thick, viscous oil must be pumped to the surface, condensate erupts under the high storage site pressure without any additives. The reservoir energy can last for a few days, weeks, months or, as with the oil fields of the Middle East, for years. If the total energy is no longer enough to overcome gravity and friction losses, additional energy must be supplied from outside. Two fundamentally different methods are used:

- The gas lift process and

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[1] https://www.britannica.com/science/sedimentary-rock/Oil-and-natural-gas, online 19.10.2017

- Deep-pump pumping

In the gas lift process, the energy is supplied in the form of compressed gas (natural gas or exhaust gas). This foams the oil column and makes it correspondingly lighter. Piston pumps with external drive or, more recently, electric centrifugal pumps are used for deep-pump pumping.

The crude oil produced is separated from any gas and water produced. Gas separation plants are usually built in several stages to separate the valuable fractions, such as butane and pentane, from the less economically interesting ones. The pressure in the individual separators is reduced in stages (up to seven stages).

If the oil contains saltwater (formation water) after separation of the gas, it must be reduced to a value compatible with the transport system and the refinery (corrosion problems).

3.2 Secondary and tertiary crude oil production

If the pressure in the oil field is not enough to transport the oil to the bottom of the borehole, secondary techniques such as water flooding or gas injection must be used. During water flooding, large quantities of water are pressed into the oil field. Water drives oil towards the bottom of the borehole. It compensates for the required but insufficient deposition energy.

For gas injection, in-situ produced oil-associated gases are pressed into the deposits, which requires a compressor with a capacity of several MW - gas turbines (operated with the produced gases) and electric compressors (operated with diesel-electric generators).

Deposits with highly viscous crude oil and in rocks with low permeability are only conditionally suitable for conventional secondary processes. Tertiary recovery methods must be used at an early stage. Three categories can be roughly distinguished (Speight 1991).

- chemical methods,
- thermal methods and
- mixing methods

Within the chemical methods, three methods can be distinguished. Flooding with polymers is a conceptually simple and cost-effective method, but the additional yield is low. Surfactant flooding is complex, expensive and requires extensive preliminary investigations. It has excellent improvement properties for low and medium viscosity oils. Alkaline flooding processes are only used in deposits with strongly acidic crude oils.

Thermal processes are mainly used in America and Indonesia. There heat is used to reduce the viscosity of the oil or to evaporate the oil. In this way, however, the pressure and thus the energy in the deposit is also increased. A distinction is made between cyclic steam injection, steam flooding and in-situ combustion. Steam processes are often carried out in containers with highly viscous or tarred oils instead of (or after) primary or secondary recovery. Only a few projects were realised in the field of in-situ combustion.

3.3 Natural gas production

Most information mentioned in this chapter is taken from a former study (Schori et al. 2012).

As mentioned in chapter 2.2, crude oil and natural gas production are often very closely linked, and data are often provided for combined production. Like for crude oil, the production of natural gas is preceded by the exploration of reservoirs. Electromagnetic and seismic studies are followed by exploratory drillings. If the size of the reservoir and the quality of the gas is satisfactory, production drillings are carried out for the extraction of the natural gas. Exploration drillings are included in the production of natural gas (stated as meter drilled per m^3 produced gas, see chapter 6).

Onshore and offshore drilling takes place in unique drilling environments, which require special techniques and equipment. The most frequently used technology for onshore exploratory and production drillings is rotary drilling with a drilling tower. For offshore production drilling platforms need to be constructed with concrete and steel.

Usually, a first cleansing of the natural gas takes place immediately after the production (processing in the field). This is especially necessary for natural gas containing hydrogen sulphides and/or water. Free liquids are separated with cyclone cutters, expansion vessels and cooling equipment. In some cases, further unwanted gases (H_2S) are separated before the gas is fed into the pipeline for further transport.

Such by-products are not addressed in the model for this study. It is assumed that they would be allocated based on the energy content as described in chapter 2.2.

To reach the required final quality the natural gas sometimes needs to be processed in a further treatment plant before it is fed into the transport pipelines and the supply network.

The following processing stages are distinguished:

- Separation of free water and oil
- Separation of higher hydrocarbons
- Natural gas drying
- Desulphurisation and recovery of elementary sulphur by means of a Claus plant.
- (possibly) additional drying of higher hydrocarbons

The choice of the treatments and their sequence depends mainly on the composition of the raw gas, which can vary considerably.

The amount of processing needed depends on the quality of the produced gas. In general, sour gas is more complex to process because of the additional desulphurisation step. Energy use and direct emissions related to these processing steps are accounted for in chapter 8 and 9.

3.3.1 Gas drying

Water and water vapour contained in raw gas must be eliminated, because otherwise, at certain pressures and temperatures they would form crystalline, snow-like compounds – so-called gas hydrates – that can lead to a clogging of pipelines and equipment. Gas hydrates can further cause corrosion. Water vapour can be separated by one of the following tested methods:

- Deep freezing by expansion cooling (Joule-Thomson effect) or external cooling
- Drying with liquid organic absorption agents
- Drying with solid absorption agents

For the separation of water by external cooling large amounts of heat are necessary. Therefore, the preferred way is to profit from the Joule-Thomson-Effect, where the natural gas has a sufficiently high pressure at the drill hole.

3.3.2 Desulphurisation

Raw gas is classified as “sour gas” (also called lean gas), or “sweet gas” based on the sulphur content. Natural gas with more than 1 vol. % H_2S-content is sour, sweet gas has a lower H_2S content (see also chapters 9.1.4 and 9.5).

The most used desulphurisation process is the chemical gas scrubbing. The used suds contain very reactive compounds such as Purisol, Sulfinol, Rectisol (trademarks) and ethanolamine. After decompression and pre-heating, the suds are regenerated by adding steam. The separated H_2S is directed to a sulphur production plant (Claus plant). In the Claus plant the H_2S is transformed to SO_2 with partial combustion and in the following catalytic reaction of H_2S/SO_2 transformed to elementary sulphur. It is assumed that the retained sulphur is a by-product that comes burden free and is neither an emission nor a waste which needs further treatment (modelled according to the allocation-approach “Cut-off”).[2]

Various flue gases are burned in a production flare, often with the addition of natural gas or vapour. Hereby the SO_2 emissions are of special interest.

4 Production and market data

Information on market data is given in a more comprehensive way in the reports “Life cycle inventories for long-distance transport and distribution of natural gas” and “Life cycle inventory for long distance transport of crude oil” (Bussa et al. 2022; Meili et al. 2022).

For this study, LCI datasets for crude oil and natural gas production in the 27 countries shown in Tab. 2.1 are either updated or newly modelled.

These selected countries have either a share higher than 1.5% of total imports of crude oil or natural gas either to Switzerland, the EU-28-states, the region North America or the global situation in 2019, or they were historically relevant for datasets available in ecoinvent (e.g. Germany, Netherlands), or they are assumed to be relevant for future analysis, e.g for modelling an import mix for Latin America or Asia.

The import of refined products to Europe and Switzerland is not analysed for this study.

It must be emphasized that the above-mentioned market model does not represent the real supply situation in Switzerland. It is a simplification assuming only one average European refinery. The real supply situation is more complex. In 2016, e.g., more products were imported from refineries in the North Sea region (mainly light crude oil) than from Eastern European refineries (mainly heavy crude oil). It would be necessary to investigate more different refinery regions in Europe to better reflect the real situation for supplies to Switzerland. This is outside of the scope of this project.

The countries selected for this study also play an important role on the global market. Together, these 27 countries cover about 84% of global crude oil and natural gas production in 2019 (BP 2020).

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[2] Allocation cut-off by classification: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html, online 08.03.2021

4.1 Proportion of offshore oil and natural gas production

Global offshore crude oil production (including lease condensate and hydrocarbon gas liquids) accounted for nearly 30% of total global crude oil production in e.g., 2015. [3]

More than 27 million barrels of oil were produced offshore in 2015 in more than 50 different countries. In 2015, five countries provided 43% of total offshore oil production: Saudi Arabia, Brazil, Mexico, Norway, and the United States.[3] On the other side countries like Russia and Iraq[4] only produce onshore (EIA 2016). This means, the proportion of offshore production varies largely between different producing regions.

Independent of the share of onshore and offshore production, also the amount of natural gas extracted in the joint production varies largely between different producing regions.

As no comprehensive data collection is available in the analysed sources, the country- and fuel-type-specific shares for offshore and onshore production are estimated for the reference year 2019 based on different literatures sources (cf. Tab. 4.1).

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[3] U.S. EIA 2016, https://www.eia.gov/todayinenergy/detail.php?id=28492, online: 10.10.17

[4] http://www.opec.org/opec_web/en/about_us/164.htm, online, 09.10.2017

Tab. 4.1 Estimates for share of offshore and onshore-production crude oil and natural gas production in 2019.

Origin	oil offshore	oil onshore	gas offshore	gas onshore	source for share on- vs. offshore
Unit	%	%	%	%	
United Arab Emirates	44%	56%	44%	56%	Assumption based on https://iclg.com/practice-areas/oil-and-gas-laws-and-regulations/united-arab-emirates
Azerbaijan	90%	10%	90%	10%	https://www.eia.gov/beta/international/analysis.php?iso=AZE
Brazil	97%	3%	97%	3%	https://www.trade.gov/energy-resource-guide-brazil-oil-and-gas
Canada	7%	93%	7%	93%	Calculation based on onshore-share of Alberta and Saskatchewan. Data from https://www.cer-rec.gc.ca/en/data-analysis/energy-commodities/crude-oil-petroleum-products/statistics/estimated-production-canadian-crude-oil-equivalent.html, cited on https://en.wikipedia.org/wiki/Petroleum_industry_in_Canada#cite_note-NEB_2015-11
China	5%	95%	5%	95%	Assessed based on share of gas production: https://www.eia.gov/international/content/analysis/countries_long/China/china.pdf
Colombia	13%	88%	13%	88%	Share assessed based on https://www.cccarto.com/oil/colombiaoil/#5/17.015/-95.493
Germany	54%	46%	54%	46%	2Mm3/a: https://www.bmwi.de/Redaktion/EN/Artikel/Energy/petroleum-oil-imports-and-crude-oil-productions-in-germany.html
Algeria	0%	100%	0%	100%	https://www.trade.gov/country-commercial-guides/algeria-oil-and-gas-hydrocarbons
Ecuador	1%	99%	70%	30%	Mainly gas produced offshore: https://www.offshore-technology.com/comment/ecuador-exploration-and-production-outlook/
United Kingdom	98%	2%	98%	2%	https://en.wikipedia.org/wiki/Oil_and_gas_industry_in_the_United_Kingdom#cite_note-3
Indonesia	36%	64%	36%	64%	Estimate based on number of blocks according to https://pwypindonesia.org/en/understanding-the-onshore-and-offshore-schemes-in-the-upstream-oil-and-gas-industry/
Iraq	0%	100%	0%	100%	https://www.eurasiareview.com/28042016-iraq-energy-profile-opecs-second-largest-crude-oil-producer-analysis/
Iran	16%	84%	16%	84%	Calculation based on largest oil fields according to https://en.wikipedia.org/wiki/Oil_reserves_in_Iran
Kuwait	1%	99%	1%	99%	Nearly all onshore: https://www.eia.gov/international/analysis/country/KWT
Kazakhstan	13%	87%	13%	87%	https://www.eia.gov/international/analysis/country/KAZ
Libyan Arab Jamahiriya	20%	80%	20%	80%	Assumption based on proven reserves according to https://www.eia.gov/beta/international/analysis.php?iso=LBY
Mexico	97%	3%	97%	3%	Calculation based on graph on https://www.eia.gov/todayinenergy/detail.php?id=28492
Malaysia	99%	1%	99%	1%	"Nearly" all offshore according to https://www.eia.gov/international/content/analysis/countries_long/Malaysia/malaysia.pdf
Nigeria	90%	10%	90%	10%	https://www.eia.gov/beta/international/analysis_includes/countries_long/Nigeria/nigeria.pdf
Netherlands	90%	10%	90%	10%	https://www.eia.gov/international/overview/country/NLD
Norway	100%	0%	100%	0%	https://www.eia.gov/international/analysis/country/NOR
Qatar	69%	31%	69%	31%	Calculation based on https://www.eia.gov/international/analysis/country/QAT
Romania	30%	70%	30%	70%	Assuming global share
Russian Federation	18%	82%	18%	82%	100 MT of 563.3MT in 2018 from Sakhalin-1 and North Chaivo: https://www.mordorintelligence.com/industry-reports/russian-federation-oil-and-gas-market
Saudi Arabia	33%	67%	33%	67%	Calculation based on graph on https://www.eia.gov/todayinenergy/detail.php?id=28492
United States	15%	85%	3%	97%	https://www.eia.gov/energyexplained/oil-and-petroleum-products/where-our-oil-comes-from.php & https://www.eia.gov/energyexplained/natural-gas/where-our-natural-gas-comes-from.php
Venezuela	30%	70%	30%	70%	No data found - assuming global average
Global	**30%**	**70%**	**30%**	**70%**	**global share: https://www.eia.gov/todayinenergy/detail.php?id=28492**

4.2 Proportion of enhanced oil recovery (EOR)

Enhanced oil recovery is used to enhance the recovery factor of oil fields. The tendency to EOR methods is increasing because aging wells are running dry and new discoveries are often only of smaller sizes.

The maturity of production is an important driver of emissions through time. Simply said, this means, an aged oil field is harder to exploit than a young one and therefore, resource and energy needs are higher and lead to higher emissions. Emissions from the same field 20 years after first production can increase by as much as a factor of 10 to 20 over emissions at the start of production (Energy-Redefined 2010). This increase is driven by several factors, including but not limited to:

- Gas and water injection for secondary and tertiary recovery
- Oil flow rates
- Water cut/water production

Using EOR, 30 to 60%, or more, of the reservoir's original oil can be extracted, compared with 20 to 40% using primary and secondary recovery (Abubaker 2015).[5] This means, by using EOR up to 30% more crude oil can be yielded from a certain oil field. Depending on the market price of crude oil and the availability of easily accessible oil fields, EOR is used intensively.

As current data is not available publicly on a country or global level, it is assumed for the new and updated regional datasets, that 15% of crude oil production is done with EOR. In a former assessment, EOR accounted for 3.2% of total production, assuming to be done mainly with chemical methods (Jungbluth 2007). The estimated increase leads to a factor of 4.7 (15% divided by 3.2%) for chemical use per kg of crude oil and therefore to an amount of 0.55g inorganic and 0.42g organic chemicals per kg oil equivalent.

5 Characteristics and properties

5.1 Crude oil

This section describes the main properties of crude oil.

5.1.1 Classification

Within natural resources, oil belongs to the subgroup of naturally occurring hydrocarbons. In contrast to coal, whose elemental composition is very well investigated and documented, the classification of oil is much more difficult because of the lower number of extensive analyses. The ratios of the elements C and H in oil fluctuate only slightly within rather tight limits – despite the big variation in physical characteristics between light mobile hydrocarbons and oils and bitumen (Speight 1991).

Classifying crude oil can be done from different perspectives (Speight 1991):

- Based on proportion of paraffin, naphthenic, aromatic, wax and asphalt components.
- By a correlation index. It describes the correlation of density and boiling temperature on the one hand, and the chemical composition on the other hand.
- By carbon distribution. The distribution of fractions as a function of their volatility is an important parameter. Furthermore, the fractions of aromatic, naphthenic and paraffinic hydrocarbons are determined, whereby paraffinic is subdivided into normal and iso-paraffin.

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[5] https://energy.gov/fe/science-innovation/oil-gas-research/enhanced-oil-recovery, online 12.10.17

Another measure to classify crude oil is the American Petroleum Institute gravity, or API gravity. It measures how heavy or light a petroleum liquid is compared to water: If the API gravity of crude oil or an oil product is greater than 10, it is lighter and floats on water; if less than 10, it is heavier and sinks.

For API and sulphur content, country-specific values shown in Tab. 5.1, derived from European import statistics are found (EC 2020).

Tab. 5.1 Sulphur content and API for crude oil imports from selected countries to Europe (EC 2020). Weighted global average calculated using production according to Tab. 2.1 (BP 2020)

Origin	Sulphur content	American Petroleum Institute gravity	source/comment
Unit	(%vol)	(API)	
United Arab Emirates	6.69	15.50	Other Middle East Crude according to EC 2020 (reference year 2018)
Azerbaijan	0.17	36.92	Azerbaijan Crude according to EC 2020 (reference year 2019)
Brazil	0.99	22.30	Brazil Crude according to EC 2020 (reference year 2019)
Canada	1.28	27.78	Weighted average Canadian Heavy and Light Sweet according to EC 2020 (reference year 2019)
China	0.05	54.57	Other Asia countries according to EC 2020 (reference year 2014)
Colombia	1.53	19.51	Other Colombia Crude according to EC 2020 (reference year 2019)
Germany	2.15	28.22	Other European Crude according to EC 2020 (reference year 2019)
Algeria	0.09	44.75	Weighted average Other Algeria Crude and Saharan Blend according to EC 2020 (reference year 2019)
Ecuador	1.61	21.35	Weighted average Oriente and Other Ecuador Crude according to EC 2020 (reference year 2014)
United Kingdom	0.55	31.50	Weighted average of different GB-blends according to EC 2020 (reference year 2019)
Indonesia	0.05	54.57	Other Asia countries according to EC 2020 (reference year 2014)
Iraq	2.84	29.42	Weighted average of different IQ-blends according to EC 2020 (reference year 2019)
Iran	1.96	30.74	Weighted average of different Iranian blends according to EC 2020 (reference year 2018)
Kuwait	2.51	30.83	Kuwait Blend according to EC 2020 (reference year 2019)
Kazakhstan	0.62	45.15	Kazakhstan Crude according to EC 2020 (reference year 2019)
Libyan Arab Jamahiriya	0.39	38.43	Weighted average of different Libyan blends according to EC 2020 (reference year 2019)
Mexico	3.62	21.36	Oil field Maya according to EC 2020 (reference year 2019)
Malaysia	1.24	32.23	Other Malaysia Crude according to EC 2020 (reference year 2014)
Nigeria	0.18	33.53	Weighted average of different Nigerian blends according to EC 2020 (reference year 2019)
Netherlands	2.15	28.22	Other European Crude according to EC 2020 (reference year 2019)
Norway	0.28	37.15	Weighted average of different Norwegian blends according to EC 2020 (reference year 2019)
Qatar	1.17	36.03	Qatar Marine according to EC 2020 (reference year 2014)
Romania	2.15	28.22	Other European Crude according to EC 2020 (reference year 2019)
Russian Federation	1.27	32.24	Weighted average of different Russian blends according to EC 2020 (reference year 2019)
Saudi Arabia	1.90	32.97	Weighted average of different Saudi Arabian blends according to EC 2020 (reference year 2019)
United States	0.25	42.42	Weighted average of different US blends according to EC 2020 (reference year 2019)
Venezuela	2.87	14.85	Weighted average of different Venezuelan blends according to EC 2020 (reference year 2019)
Global	**1.46**	**42.85**	**Weighted average based on overall production (BP 2020, reference year 2019)**

5.1.2 Net calorific value and density

The calorific value, as well as the density of crude oil and natural gas products varies, depending on its composition and external conditions. In former studies, a net calorific value of 43.2 MJ/kg for crude oil is used for modelling (Meili & Jungbluth 2018;Jungbluth 2007; Schori et al. 2012). This value is used in the Swiss energy statistics (BFE 2017).

Global consumption data shows net calorific values for crude oil consumed in different countries ranging from 41.9 to 45.5 MJ/kg with a weighted average of 43.4 MJ/kg (BP 2020). This figure also includes condensates and natural gas liquids. In the same source the average density of crude oil is defined as 858.1 kg/m^3. These global average values are used for modelling in this study. If the LCI data provided in this study shall be used for an analysis of the cumulative energy demand, the characterisation factor for "oil, crude" should be adjusted to a new gross calorific value of 46 MJ/kg.

5.1.3 Hydrocarbons

Hydrocarbons (HC), which are the main component of crude oil and which only consist of carbon and hydrogen, can be divided into three groups according to their chemical characteristics:

- **Saturated HC (paraffines and alkanes):**
  They form the main components of crude oil.
  Chemical formula: C_nH_{2n+2}
  Examples:
  $CH_4 – C_5H_{12}$, methane, ethane, propane etc. (gaseous),
  C_6H_{14}- $C_{21}H_{44}$, hexane, heptane, octane etc. (liquid)
  >= $C_{22}H_{46}$, pentacosane, triacontane etc. (solid).
  Cyclic saturated (alicyclic) HC (naphthene, cyclo-paraffines, and cyclo-alkanes).

- **Unsaturated HC (alkenes or olefins or alkines).**
  Chemical formula: C_nH_{2n}, or C_nH_n
  Examples:
  C_2H_4 (IUPAC: ethene, ecoinvent: ethylene),
  C_3H_6 (IUPAC: propene, ecoinvent: propylene),
  C_2H_2 (ethyne, etc.)

  Unsaturated HC are of subordinate importance for natural crude oils. They form in the refineries during cracking processes as valuable by-products, which improve fuel characteristics and partially attained high importance as starting material for many syntheses. Because of their reactivity they have a high significance for the formation of tropospheric ozone.

- **Aromatic HC as aromatics is called unsaturated, ring-shaped HC.**
  Examples:
  C_6H_6 (benzene),
  C_7H_9 (toluene),
  C_8H_{12} (ortho-, meta- and para-xylene)

The share of different components of HCs varies among different crude oils. Generally, it can be said that heavier crude oils (Latin America, Middle East) show higher proportions of polycyclic naphthenic and poly-nuclear aromatics, but lower shares of paraffins and monocyclic naphthene (Speight 1991). Among other things, this also leads to higher metal contents (Ni, V).

5.1.4 Components other than hydrocarbons

Next to the high number of pure hydrocarbons, crude oil contains a variety of organic components other than hydrocarbons. Mainly they are sulphur-, nitrogen-, or oxygen compounds. In smaller amounts, also dissolved organo-metallic components and inorganic salts in different colloidal suspension are present. These components occur within the entire boiling range of crude oil, but mainly they are concentrated in the heavier fraction and the non-volatile residues (Speight 1991).

These components can have a major impact in technical processes, despite the relatively low quantity. This entails thermal decomposition of inorganic chlorides to free hydrochloric acid and thus to corrosion problems in distillation. Also, the presence of organic acidic components such as mercaptans and acids can cause metal corrosion. In catalytic processes, e.g., by nickel and vanadium deposits or by chemisorption of compounds containing nitrogen, a passivation or poisoning of the catalyst can occur, which leads to frequent regeneration or premature replacement of the catalyst.

5.1.5 Sulphur components

Sulphur content correlates, as first approximation, with the density of crude oil. It fluctuates between 0.04% for light paraffin oil and 5% and more for heavy crude oil. Sulphur in oil products can lead to corrosion in many applications. For instance, mercaptan in hydrocarbon solutions leads to corrosion of copper and brass if oxygen is present. The sulphur compounds vary from simple thiols (mercaptans) via sulphides, poly-cyclic sulphates and thiophenes to derivates of benzo-thiophenes (Speight 1991). For the main production areas, the sulphur contents as shown in chapter 5.1.1, Tab. 5.1 can be reported (EC 2020). Sulphur contents of final products depends on processing in the refinery (Jungbluth et al. 2018).

5.1.6 Oxygen compounds

The oxygen compounds are alcohols (phenols), ethers, carboxylic acids, ketones and furans. Thereby, ketones, esters, ethers and anhydrides can rather be found in heavy, non-volatile residues. They can originate from residues and do not need to be original components of crude oil (cf. Jungbluth 2007, chapter 9).

5.1.7 Nitrogen compounds

Nitrogen compounds can be divided into alkaline or non-alkaline. Nitrogen content tends to increase with asphalt content of crude oil. Therefore, nitrogen is more likely to be found in those fractions and remains which are higher boiling. Increasing refinement of residues to lighter fractions ("whitening of the Barrel") can lead to harmful effects of nitrogen on crack-catalysts in refineries (Speight 1991).

5.1.8 Porphyrins

Porphyrins are cyclic, conjugated components, which occur usually in the non-alkaline part of the nitrogen-containing concentrate. Nearly all crude oils contain vanadyl and nickel porphyrins (metal chelates). Other metals were hardly found in such compounds, probably for geochemical reasons. However, by far not all vanadium and nickel is incorporated in porphyrins. They can also occur as non-porphyrin, metallic chelates (Speight 1990). Porphyrins are concentrated in the asphalt fraction. Therefore, deasphalted crude oils do have smaller concentrations of porphyrins and usually also very small concentrations of non-porphyrin metals.

5.1.9 Further trace elements

For processing but also for emission inventories of oil-energy systems, next to calorific value and sulphur content, also information on concentrations of other trace elements of crude oil and its products are of interest.

From the point of view of the oil processor and oil customer, trace elements in the oil are not desired. On the one hand, because they impair the effect of the catalyst in the refinery; on the other hand, for example they can lead to ash formation and corrosion in turbines. The trace elements which occur in significant concentrations in oil can be divided into two groups. Zinc, titanium, calcium and magnesium and others are present as organometallic soaps; while e.g., vanadium, copper, nickel and iron occur as components soluble by oil.

By distillation processes, trace elements are generally concentrated in the residues. Thus, the content of trace elements tends to increase from light to heavy products and is higher in heavy fuel oils and bitumen than in processed crude oil.

Various publications contain results and analyses on trace elements or their emission factors in crude oils and products. The extent to which element contents in crude oil can fluctuate is shown in a former study (Jungbluth 2007, Table A.1). The high concentration of zinc and iron in the composition of oil indicate an enrichment during oil processing (separation of water and gases) and transport (Pacyna 1982, Jungbluth 2007, appendix Tab A.1).

5.1.10 Mercury

Amount of mercury in this study is assessed as 0.030 mg/kg of crude oil (Jungbluth 2007).

5.1.11 Summary of properties used in this study

The LCI data for extraction processes modelled in this study is calculated for crude oil with the physical and chemical properties as defined in Tab. 5.2 (BP 2020).

Tab. 5.2 Physical and chemical properties of crude oil as assessed for this study according to lower heating value and density used in global statistics (BP 2020)

	unit	This study
Lower heating value (LHV)	MJ	43.4
Higher heating value (HHV)	MJ	46.0
Density at 20°C	kg/m^3	858.1
	% by weight	
C-content	83 - 87	84.0%
H-content	10 - 14	10.0%
O-content	0.05 - 1.5	1.5%
N-content	0.1 - 2.0	2.0%
S-content	0.05 - 6	2.5%
Total		100.0%

5.2 Natural Gas

5.2.1 Net calorific value and density

Net calorific value, density and other physical properties of natural gas vary depending on the origin / specific source, mixture, state of processing, etc.

In former studies an average net calorific value of 36.3 MJ/Nm^3 (45.7 MJ/kg) for natural gas is used (Meili & Jungbluth 2018 Jungbluth 2007; Schori et al. 2012). This value was then consistent with a former version of the Swiss energy statistics (BFE 2017).

According to confidential/internal calculation of SGWA, between 1990 and 2018, the net calorific value of natural gas imported to Switzerland fluctuates between 45.7 and 47.6 MJ/kg (BAFU 2020, Tab. 3-11). In a current factsheet, for the Swiss greenhouse gas inventory, the value calculated for 2017, 47.3 MJ/kg, for natural gas with density of 0.783kg/m3 is used (=37.0 MJ/Nm^3). As another example, in ecoinvent v3 a gross calorific value of 39 MJ/Nm^3 is used as default for all calculations related to raw gas (c.f. Faist-Emmenegger et al. 2015).

However, in global statistics used for the current study, for all countries, a generic gross calorific value (GCV) of 40MJ/Nm^3, respectively the net calorific value of 36.0 MJ/Nm^3 is used (BP 2020). Therefore, this value and the related density of 0.735kg/Nm^3 is used for all calculations related to raw natural gas in this study. These values are valid for standard conditions of 15°C and 1013 mbar. As ecoinvent and widely used LCA software use the unit Nm^3 to represent gas, the name of this unit is kept but values represent in fact the conditions for Sm^3. If the LCI data provided in this study shall be used for an analysis of the cumulative energy demand, the characterisation factor for “gas, natural/m3” should be adjusted to a new gross calorific value of 39.9 MJ/Nm^3.

5.2.2 Classification of fuel gases

This chapter is not updated and kept the same as in a former study (Schori et al. 2012). Various fuel gases are available on the market, some of which are natural gas, coke-oven gas and blast furnace gas. The following chapters describe the natural gas system. The production of coke-oven gas is described in Röder et al. (2007). Blast furnace gas is recovered as a by-product of blast furnaces and is described in Classen et al. 2007.

In the first half of the 20th century gas won through gasification of hard coal was commonly used. After the introduction of natural gas, coal gas - also known as city gas or illumination gas - lost its importance. The exploration of the Dutch natural gas field in the vicinity of Groningen led to a boom in the demand of natural gas in Europe from 1965 onwards. Today natural gas makes up 25% of the primary energy consumption in Europe (BP 2011).

The relevance of coke oven gas and blast furnace gas is decreasing. In Germany for example the share of coke oven gas of the total gas supply has dropped below 3% (Cerbe et al. 1999). Blast furnace gas provides about 4.6% of the fuel gases used in Germany.

Biogas is a fuel gas gaining importance. Processed biogas with sufficiently high methane content can be fed into the natural gas distribution network.

Natural gas, coke oven gas, furnace gas and biogas differ substantially with regard to their chemical composition. Tab. 5.3 shows typical values of the composition of the five fuel gases. Additional country-specific properties and newer composition data might also be found in Juhrich 2016. Please note, these data, as well as the old ones, might not be consistent with the natural gas volumes extracted for the reference year and the related numbers (c.f. chapter 4)

Tab. 5.3 Composition of fuel gases (reference values) (Cerbe et al. 1999; Bruijstens et al. 2008); 1) The composition of biogas can vary depending on the feedstock. The data shown here is for upgraded biogas (biomethane) from a plant in Stockholm, Sweden.

	H_2	CO	CH_4	C_2H_6	C_3H_8	C_4H_{10}	Other C_XH_Y	CO_2	N_2	O_2
	vol. %	vol. %	vol. %	vol. %	vol. %	vol. %	vol. %	vol. %	vol. %	vol. %
Blast furnace gas	4.1	21.40						22.0	52.5	
Coke oven gas	54.5	5.50	25.3				2.3	2.3	9.6	0.5
Natural gas L			81.8	2.8	0.4	0.2		0.8	14.0	
Natural gas H			93.0	3.0	1.3	0.6		1.0	1.1	
Biomethane$^{1)}$			>97					< 2	< 0.8	0.2

Natural gas is rich in methane. The high content of nitrogen and carbon monoxide is typical for blast furnace gas. Coke-oven gas on the other hand shows high levels of hydrogen. Natural gas is classified as high-calorific (H-gas or High-gas) and low-calorific gas (L-gas or Low gas) based on the methane content. H-gas contains between 87 and 99 vol. % and L-gas between 80 and 87 vol. % methane.

In Germany the properties and composition of commercial fuel gases are regulated according to the DIN and DVGW directives, in Switzerland according to the SVGW directives. A number of secondary gas substances are limited by threshold values. “Common business practices” for non-odorized high-calorific gas in transboundary traffic in Europe are stated as follows: the total sulphur content must not exceed 30 mg/Nm^3, hydrogen sulphide content needs to be below 5 mg/Nm^3. Further threshold values exist for different hydrocarbons, water, dust, liquids, mercaptans, nitrogen oxides, ammoniac and hydrogen cyanide.

5.2.3 Fuel data of raw natural gas

This chapter is not updated and kept the same as in a former study, original sources might be retrieved there (Schori et al. 2012). This section shows the composition of natural gas after the extraction and before processing, for the so-called raw gases. These compositions are used to calculate emissions at the extraction and processing of natural gas. The resource use is quantified as “Gas, natural, in ground”. This covers both natural gas from carbonification and natural gas formed in association with crude oil (also known as associated petrol gas, APG). The natural gas is processed to ensure the purity and quality needed for end-use. During the transport and distribution, the composition of the natural gas changes only slightly.

The composition of raw gases from different origins varies considerably. The main component is methane; other important components are ethane, propane, nitrogen, carbon dioxide, helium, sulphurous substances and higher hydrocarbons (higher C/H). The sulphurous compounds are mainly hydrogen sulphide, as well as carbonyl sulphide (COS), carbon disulphide (CS_2) other organic sulphites, disulphides, mercaptaines and thiopenes. Among the higher hydrocarbon’s benzene, toluene and xylene are of importance because of their toxicity <Nerger et al. 1987>.

Tab. 5.4 shows the chemical composition of various raw gases prior to processing. A differentiation is made between so-called "sour" gases (with high sulphur content) and "sweet" gases.

Tab. 5.4 Chemical composition of raw gases prior to processing

Substances	**Range of fluctuation**	**Raw gas from Groningen (NL)**	**Raw gas from Süd Oldenburg**	**Raw gas from Bentheim (DE)**	**Mean raw gas (NO)***	**Raw gas from Urengoy „C“, West-Siberia**
	vol. %	vol. %	vol. %	vol. %	vol. %	vol. %
Methane	>80	81.50	79.10	93.20	88.80	99.00
Ethane C_2H_6	up to 8	2.80	0.30	0.60	4.80	0.10
Propane C_3H_8	up to 3	0.40			1.70	0.01
Butane C_4H_{10}		0.14	<0.01		0.70	0.02
Higher C/H	up to 4	0.14			0.70	0.00
H_2S	0-24		6.90			8.5 E-06
CO_2	up to 18	0.92	9.10		1.60	0.09
N_2	up to 15	14.10	4.60	6.20	1.40	0.79
Source	Infras 1981	Infras 1981	Infras 1981	Landolt Börnstein 1972	Statoil, 2001	Müller, 1997

*) Weighted mean value for natural gases processed in the plants Kollsnes and Kårsto.

In addition to the substances mentioned above natural gas may contain further substances that are of importance from an environmental point of view. Raw gas can be enriched with other substances in trace concentrations up to 10^{-3} bis 10^{-6} g/Nm^3 <Nerger et al. 1987>. In the United States and Europe, natural gas is tested for mercury since the 1930'ies. Steinfatt & Hoffmann 1996 reports mercury concentrations of natural gas from Algeria, the Netherlands and Germany. The mercury contents are shown in Tab. 5.5.

Tab. 5.5 Mercury contents of natural gas from Algeria, the Netherlands and Germany (Steinfatt & Hoffmann 1996)

Region	**Elemental mercury (µg/Nm^3)**
Algeria	58-193
The Netherlands (North Sea)	180
Germany	Up to 11'000*)
Russia (Dnjepr-Donetzk)	53

*) The mercury content of German deposits is in the range of the Dutch ones, however in rare cases it can reach up to 11'000 µg/Nm^3.

The investigation of pipeline gases revealed a rapid decrease in the Hg-content in pipelines <Tunn 1973>. The study examined gas transported from the Netherlands to Germany. A large share of the mercury contained in the Groningen-gas was removed on the way to the Dutch-German border due to processing and condensate separation. From an initial concentration of 180 µg/Nm^3, the mercury concentration dropped down to 20 µg/Nm^3. In the German pipeline system, the concentration is further reduced to 2 to 3 µg/Nm^3. Only when natural gas from German production is fed into the pipeline the concentration remains as high as 19 µg/Nm^3. However, by the time the natural gas reaches the end consumer, the mercury concentration is reduced to very low levels, often below the detection limit (1 to 2 µg/Nm^3).

The raw gas of certain deposits shows traces of Radon-222, a radioactive gaseous decomposition product of uranium. <Gray 1990> summarised the results of various studies. Radon concentrations in natural gases at the production site range from 1 to 10 pCi/l[6] in Germany, from 1

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[6] 1 Ci = 3.7*10^{-7} KBq

to 45 pCi/l in the Netherlands and from 1 to 3 pCi/l in offshore production in the North Sea. In this study the radon emissions are reported in kilobecquerel (kBq) units.

A more precise declaration of the various natural gases is not possible due to local and temporal variations, as well as a lack of data. For this study plausible standard gas compositions are defined, based on the data in Tab. 5.4 and the information mentioned above. The composition is given for important countries of origin for the Swiss and European natural gas supply: The standard composition is applied e.g., for the leakages in the exploration and processing of the natural gas. For the raw gas prior to processing plausible mean values from Tab. 5.4 are used: a mercury concentration of 200 µg/Nm^3 and a radon-222 concentration of 10 pCi/l or roughly 0.4 kBq/Nm^3. The calorific values and CO_2 emission factors were calculated assuming complete combustion.

Tab. 5.6 shows the chemical composition and the fuel data of the auxiliary modules “leakage raw gas sweet” and “leakage raw gas sour” which are used to calculate the composition of raw natural gases from different countries and regions (see Tab. 5.7). The latter composition data are used to model the leakage emissions of produced natural gas.

Tab. 5.6 Fuel data for raw gases prior to processing. Sources: Tab. 5.4 and notes in the text.

Gas type	Unit	Raw gas "sour" prior to processing	Raw gas "sweet" prior to processing	Raw gas "sour" prior to processing	Raw gas "sweet" prior to processing
Country of origin		Germany, Russian Federation	Norway, Netherlands, Germany, Russian Federation, Algeria	Germany, Russian Federation	Norway, Netherlands, Germany, Russian Federation, Algeria
Unit		vol. %	vol. %	kg/Nm^3	kg/Nm^3
Methane		70	85	0.50	0.61
Ethane		8	3	0.11	0.04
Propane		5		0.10	
Butane			1		
C5+		1	1	0.04	0.04
Carbon dioxide		5	10	0.10	0.02
Nitrogen		5		0.06	0.13
H_2S		6		0.09	
Mercury	µg/Nm^3			200	200
Radon-222	kBq/Nm^3			0.4	0.4
Gross calorific value GCV	MJ/Nm^3			41	38
Net calorific value NCV	MJ/Nm^3			37	34
Density	kg/Nm^3			1.00	0.84
EF-CO_2 Hu *)	kg/GJ			89.2	88.7

*) Assumption: complete combustion

Tab. 5.7 Average composition of raw natural gas from DE, NAC, NL, NO and RU prior to processing based on their share of sour gas. Source: Tab. 5.6.

		Raw gas DE	**Raw gas RU**	**Raw gas NO**	**Raw gas NL**	**Raw gas NAC**	**Raw gas NG**
	Unit	Nm^3	Nm^3	Nm^3	Nm^3	Nm^3	Nm^3
Sour gas	%	50	20	5	0	0	0
CH_4 Methane	kg	0.555	0.588	0.6045	0.61	0.61	0.61
CO_2 Carbon dioxide	kg	0.06	0.036	0.024	0.02	0.02	0.02
Ethane	kg	0.075	0.054	0.0435	0.04	0.04	0.04
H_2S Hydrogen sulphide	kg	0.045	0.018	0.0045	0	0	0
Hg Mercury	kg	2.00E-07	2.00E-07	2.00E-07	2.00E-07	2.00E-07	2.00E-07
N_2 Nitrogen	kg	0.0365	0.0224	0.01535	0.013	0.013	0.013
NMVOC	kg	0.04	0.04	0.04	0.04	0.04	0.04
Propane	kg	0.05	0.02	0.005	0	0	0
Radioactive Rn 222	kBq	0.4	0.4	0.4	0.4	0.4	0.4

6 Material use and land occupation for infrastructure

The LCI modules “well for exploration and production, onshore", “well for exploration and production, offshore", “production plant crude oil, onshore", "platform, crude oil, offshore", “plant offshore, natural gas, production” and “plant onshore, natural gas, production” are used to model infrastructure expenses. Details about data collection are provided in a former study (Jungbluth 2007). The infrastructure is allocated to natural gas and crude oil production based on the quantity produced (in calorific value).

It is assumed that these inventories are still accurate for this model and no major updates were commissioned for the infrastructure. However, as described in chapters 3.2 and 4.2 oil fields get more depleted globally, which means, that wells need to get deeper, the number of wells increases, and new/ enhanced oil recovery methods must be used. Data for these factors are investigated and updated in this study.

6.1 Number and length of wells

In a former study only, estimates based on crude oil extraction were used to calculate the well length for combined production. In this study, if available, newer, as well as values from gas extraction were considered.

The number of wells needed to maintain a steady flow of crude oil and natural gas highly depends on regional aspects. E.g., in the Rumaila oil field in Iraq, 350 wells are sufficient to extract 1.5 million barrels per day (b/d), leading to a productivity of 4’300 b/d and well (2b1stconsulting[7]) On the other hand, in the U.S., in 2018, the average oil well produced 24.4 barrel/d, and the average natural gas well produced about 156,000 cubic feet per day. The distribution is generally skewed. Many wells produce smaller volumes per day and fewer wells produce very large volumes per day. In 2018, about 79% of the more than 980,000 U.S. wells produced 15 or fewer barrels oil equivalent per day (BOE/day), and about 5% of the wells produced more than 100 BOE/day (EIA 2019).

The national average length of the wells has a smaller variability with 1524m for US (EIA[8]) and 2400 m in Iraq (FAS[9]).

For offshore production typically, well lifetime lies between 5 to 10 years and for onshore production it lies between 15 to 30 years.[10]

The share of on- and offshore wells is unknown. However, it is assumed that offshore wells are only drilled if they grant a relatively high production volume.

To balance this out, for calculation of the well length per kg OE, an average lifetime of wells of 15 years is assumed.

Where other country specific values were easily found in literature they were considered as well (Schori et al. 2012; Jungbluth 2007). For other countries, a globally weighted average is estimated based on the before mentioned specific values from literature as shown in Tab. 6.1. If for a specific country only either an estimate for well length for off- or onshore wells is available, this value is also applied to the other country-specific extraction method.

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[7] 2b1stconsulting: https://www.2b1stconsulting.com/bp-and-cnpc-tender-iraq-rumaila-produced-water-re-injection-prwi/, online 19.10.17

[8] EIA: https://www.eia.gov/dnav/pet/pet_crd_welldep_s1_a.htm, online 19.10.17

[9] FAS: https://fas.org/sgp/crs/mideast/RS21626.pdf, online 19.10.17

[10] https://www.planete-energies.com/en/medias/close/life-cycle-oil-and-gas-fields

Tab. 6.1 Well length in meters per kilogram of oil equivalent estimated for countries under study, for onshore and offshore production. Values not highlighted are used to estimate a weighted average which is used for countries where no estimate was possible (highlighted in blue).

Origin	well length (m) per kg OE, onshore	well length (m) per kg OE, offshore	Comment and source for estimate or calculation
Unit	m/kg OE	m/kg OE	
Azerbaijan	4.35E-06	4.35E-06	Calculated based on Schori 2012, assuming same length for offshore production
Germany	4.49E-06	4.49E-06	Calculated based on Schori 2012, assuming same length for offshore production
Algeria	4.35E-06	4.35E-06	Calculated based on Schori 2012, assuming same length for onshore production
United Kingdom	1.75E-05	1.25E-05	Global weighted average based on cited literature for other countries
Iraq	1.54E-07	1.54E-07	calculation based on 2b1stconsulting: https://www.2b1stconsulting.com/bp-and-cnpc-tender-iraq-rumaila-produced-water-re-injection-prwi/, online 19.10.17 and FAS: https://fas.org/sgp/crs/mideast/RS21626.pdf, online 19.10.17, assuming a well lifetime of 22.5 years
Kazakhstan	4.35E-06	4.35E-06	Calculated based on Schori 2012, assuming same length for offshore production
Libyan Arab Jamahiriya	4.35E-06	4.35E-06	Calculated based on Schori 2012, assuming same length for onshore production
Mexico	1.75E-05	1.25E-05	Global weighted average based on cited literature for other countries
Nigeria	1.75E-05	1.25E-05	Global weighted average based on cited literature for other countries
Netherlands	1.63E-06	9.52E-06	Calculated based on Schori 2012
Norway	3.26E-06	3.26E-06	Calculated based on Schori 2012, assuming same length for onshore production
Qatar	1.54E-07	1.54E-07	Assuming same productivity of wells as in Iraq (shared oil fields)
Romania	1.75E-05	1.25E-05	Global weighted average based on cited literature for other countries
Russian Federation	2.55E-05	2.55E-05	Calculated based on Jungbluth 2007, assuming same length for offshore production
Saudi Arabia	1.54E-07	1.54E-07	Assuming same productivity of wells as in Iraq (shared oil fields)
United States	4.39E-05	4.39E-05	Calculation based on EIA 2020 and EIA: https://www.eia.gov/dnav/pet/pet_crd_welldep_s1_a.htm, online 19.10.17, assuming a well lifetime of 22.5 years
Global	1.75E-05	1.25E-05	**Weighted average of specifically cited literature values**

6.2 Well drilling

No update of the LCI for wells is foreseen for this study. Tab. 6.2 and Tab. 6.3 show the life cycle inventory for the drilling of one meter of well for exploration and production of crude oil and natural gas onshore and offshore, respectively. Data in general is kept similar to the former study (Jungbluth 2007). For onshore production land must be transformed to drill the well and access it. For this model it is estimated that a smaller area of 50m times 50m is needed for a well with depth 2000m[11]. This estimation is applied in all the datasets in this study.

Compared to the former study emissions due to venting and flaring are excluded from this inventory as they are covered with the new overall data for venting and flaring applied to oil and gas extraction. Also, the energy use for well drilling is covered in the general data on energy consumption and not recorded here anymore.

An error in the calculation of Zinc emissions to oceans is now corrected in the dataset for offshore production (OLF 2001).

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[11] http://www.ecoinvent.org/support/ecoinvent-forum/topic.html?&tid=410, online 11.01.2018

Tab. 6.2 Life cycle inventory data for the drilling of wells for exploration and production of crude oil, onshore

	Name	Location	InfrastructureProce	Unit	well for exploration and production, onshore	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				GLO			
	InfrastructureProcess				1			
	Unit				m			
product	well for exploration and production, onshore	GLO	1	m	1.00E+0			
resource, land	Occupation, mineral extraction site	-	-	m2a	1.88E+1	1	1.80	(3,4,5,3,1,BU:1.5); ; Lifetime of well 15a
	Transformation, from forest, unspecified	-	-	m2	1.25E+0	1	2.03	(3,4,1,3,1,BU:2); ; Estimation 50*50 metre area for a 2000 m well
	Transformation, to mineral extraction site	-	-	m2	1.25E+0	1	2.03	(3,4,1,3,1,BU:2); ; Calculation
resource, in water	Water, well, GLO	-	-	m3	3.34E+0	1	1.51	(2,3,5,3,1,BU:1.05); ; Literature, basic uncertainty estimated with 2
technosphere	lignite, at mine	RER	0	kg	2.00E-1	1	1.51	(2,3,5,1,1,BU:1.05); ; Literature
	barite, at plant	RER	0	kg	2.70E+2	1	1.51	(2,3,5,1,1,BU:1.05); ; Literature
	bentonite, at processing	DE	0	kg	2.00E+1	1	1.51	(2,3,5,1,1,BU:1.05); ; Literature
	chemicals inorganic, at plant	GLO	0	kg	4.22E+1	1	1.51	(2,3,5,1,1,BU:1.05); ; Literature
	chemicals organic, at plant	GLO	0	kg	9.05E+0	1	1.51	(2,3,5,1,1,BU:1.05); ; Literature
	lubricating oil, at plant	RER	0	kg	6.00E+1	1	1.51	(2,3,5,1,1,BU:1.05); ; Literature
	reinforcing steel, at plant	RER	0	kg	2.10E+2	1	1.54	(3,4,5,3,1,BU:1.05); ; Literature
	portland cement, strength class Z 52.5, at plant	CH	0	kg	2.00E+2	1	1.54	(3,4,5,3,1,BU:1.05); ; Literature
	transport, freight, lorry 16-32 metric ton, fleet average	RER	0	tkm	8.11E+1	1	2.99	(4,5,5,5,5,BU:2); ; Standard distance 100km
	transport, freight, rail	RER	0	tkm	4.87E+2	1	2.99	(4,5,5,5,5,BU:2); ; Standard distance 600km
	crude oil, used in drilling tests	GLO	0	kg	3.16E+1	1	1.60	(3,4,5,3,3,BU:1.05); ; Estimation with data for offshore, basic uncertainty estimated with 2
	diesel, burned in diesel-electric generating set	GLO	0	MJ	0	1	1.64	(3,5,5,3,3,BU:1.05); ; Excluded as part of production data
	natural gas, vented	GLO	0	Nm3	0	1	1.58	(4,4,5,3,1,BU:1.05); ; Excluded as part of production data
	disposal, drilling waste, 71.5% water, to landfarming	CH	0	kg	2.37E+2	1	1.51	(2,3,5,3,1,BU:1.05); ; Environmental reports and literature
	disposal, drilling waste, 71.5% water, to residual material landfill	CH	0	kg	1.58E+2	1	1.51	(2,3,5,3,1,BU:1.05); ; Environmental reports and literature
	disposal, hazardous waste, 25% water, to hazardous waste incineration	CH	0	kg	5.00E+0	1	1.53	(2,4,5,3,1,BU:1.05); ; Environmental reports and literature
emission air, low population density	Particulates, > 10 um	-	-	kg	1.49E-2	1	1.84	(3,5,5,3,1,BU:1.5); ; Literature, use of barite
emission water, river	Aluminium	-	-	kg	6.00E-2	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	4.78E-7	1	1.79	(3,3,5,1,1,BU:1.5); ; Environmental report
	Arsenic	-	-	kg	4.20E-4	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Barium	-	-	kg	6.00E-3	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	BOD5, Biological Oxygen Demand	-	-	kg	3.00E-1	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	Boron	-	-	kg	9.00E-3	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Calcium	-	-	kg	6.00E-1	1	3.31	(3,4,5,5,3,BU:3); ; Literature, effluent sludge pond
	Chloride	-	-	kg	6.00E+0	1	3.31	(3,4,5,5,3,BU:3); ; Literature, effluent sludge pond, basic uncertainty estimated with 3
	Chromium	-	-	kg	6.00E-4	1	3.31	(3,4,5,5,3,BU:3); ; Literature, effluent sludge pond
	COD, Chemical Oxygen Demand	-	-	kg	3.00E+0	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	Fluoride	-	-	kg	3.00E-3	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	Hydrocarbons, aromatic	-	-	kg	3.00E-3	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	Iron	-	-	kg	1.80E-1	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Magnesium	-	-	kg	1.20E-1	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Manganese	-	-	kg	3.00E-3	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Methane, dichloro-, HCC-30	-	-	kg	6.00E-2	1	3.31	(3,4,5,5,3,BU:3); ; Literature, effluent sludge pond
	Phosphorus	-	-	kg	1.20E-3	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	Potassium	-	-	kg	9.00E-1	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond, basic uncertainty estimated with 3
	Silicon	-	-	kg	3.00E-2	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Sodium	-	-	kg	6.00E+0	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond, basic uncertainty estimated with 3
	Strontium	-	-	kg	1.80E-2	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond
	Sulfur	-	-	kg	1.20E-1	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	DOC, Dissolved Organic Carbon	-	-	kg	3.00E-1	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	TOC, Total Organic Carbon	-	-	kg	3.00E-1	1	1.87	(3,4,5,5,3,BU:1.5); ; Literature, effluent sludge pond
	Zinc	-	-	kg	1.20E-3	1	5.35	(3,4,5,5,3,BU:5); ; Literature, effluent sludge pond

Tab. 6.3 Life cycle inventory data for the drilling of wells for exploration and production of crude oil, offshore

	Name	Location	InfrastructureProcess	Unit	well for exploration and production, offshore	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				OCE			
	InfrastructureProcess				1			
	Unit				m			
product	well for exploration and production, offshore	OCE	1	m	1.00E+0			
resource, land	Occupation, dump site, benthos	-	-	m2a	2.60E+2	1	3.33	(4,5,3,1,na,BU:1.5); Estimation 1 year use
	Transformation, from seabed, unspecified	-	-	m2	2.60E+2	1	3.77	(4,5,3,1,na,BU:2); Literature
	Transformation, to dump site, benthos	-	-	m2	2.60E+2	1	3.77	(4,5,3,1,na,BU:2); Literature
resource, in water	Water, salt, ocean	-	-	m3	1.73E+0	1	3.07	(3,5,3,1,na,BU:1.05); Environmental report of Saipem, basic uncertainty estimated with 2
technosphere	lignite, at mine	RER	0	kg	2.00E-1	1	3.06	(3,5,1,1,na,BU:1.05); Literature, drilling chemical
	barite, at plant	RER	0	kg	2.70E+2	1	3.06	(3,5,1,1,na,BU:1.05); Literature, drilling chemical
	bentonite, at processing	DE	0	kg	2.00E+1	1	3.06	(3,5,1,1,na,BU:1.05); Literature, drilling chemical
	chemicals inorganic, at plant	GLO	0	kg	4.22E+1	1	3.06	(3,5,1,1,na,BU:1.05); Literature, drilling chemical
	chemicals organic, at plant	GLO	0	kg	9.05E+0	1	3.06	(3,5,1,1,na,BU:1.05); Literature, drilling chemical
	lubricating oil, at plant	RER	0	kg	6.00E+1	1	3.06	(3,5,1,1,na,BU:1.05); Literature
	reinforcing steel, at plant	RER	0	kg	2.10E+2	1	3.11	(4,5,3,1,na,BU:1.05);
	portland cement, strength class Z 52.5, at plant	CH	0	kg	2.00E+2	1	3.11	(4,5,3,1,na,BU:1.05); Literature, used in bore hole
	transport, freight, lorry 16-32 metric ton, fleet average	RER	0	tkm	8.11E+1	1	3.90	(5,na,na,na,na,BU:2); Standard distance 100km
	transport, freight, rail	RER	0	tkm	4.87E+2	1	3.90	(5,na,na,na,na,BU:2); Standard distance 600km
	crude oil, used in drilling tests	GLO	0	kg	3.16E+1	1	3.11	(4,5,3,1,na,BU:1.05); Environmental report NO, basic uncertainty estimated with 2
	diesel, burned in diesel-electric generating set	GLO	0	MJ	0	1	4.84	(4,5,3,3,na,BU:3); Excluded as part of production data
	natural gas, vented	GLO	0	Nm3	0	1	3.11	(4,5,3,1,na,BU:1.05); Excluded as part of production data
	natural gas, sour, burned in production flare	GLO	0	MJ	0	1	3.11	(4,5,3,1,na,BU:1.05); Excluded as part of production data
	disposal, drilling waste, 71.5% water, to residual material landfill	CH	0	kg	3.00E+1	1	3.07	(3,5,3,1,na,BU:1.05); Environmental reports and literature
	disposal, hazardous waste, 25% water, to hazardous waste incineration	CH	0	kg	4.00E+0	1	3.11	(4,5,3,1,na,BU:1.05); Literature
emission air, low population density	Particulates, > 10 um	-	-	kg	1.49E-2	1	3.96	(5,5,3,1,na,BU:2); Literature, use of barite
emission water, ocean	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	4.78E-7	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Arsenic	-	-	kg	3.78E-3	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Barite	-	-	kg	1.62E+2	1	7.16	(4,5,3,3,na,BU:5); Literature (Barite and Bentonite) from mud
	Cadmium	-	-	kg	3.02E-4	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Carboxylic acids, unspecified	-	-	kg	1.70E+0	1	7.16	(4,5,3,3,na,BU:5); Literature, emulgator
	Chloride	-	-	kg	1.30E+0	1	3.33	(4,5,3,1,na,BU:1.5); Literature, anorg. salt, basic uncertainty estimated with 3
	Chromium	-	-	kg	1.72E-3	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Copper	-	-	kg	9.15E-3	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Glutaraldehyde	-	-	kg	2.00E-2	1	7.16	(4,5,3,3,na,BU:5); Literature
	Hydrocarbons, aromatic	-	-	kg	2.31E-1	1	4.84	(4,5,3,1,na,BU:3); Literature, 5% of oil emission
	Hydrocarbons, unspecified	-	-	kg	3.00E+0	1	4.84	(4,5,3,1,na,BU:3); Literature, polymers
	Lead	-	-	kg	1.32E-2	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Mercury	-	-	kg	2.79E-4	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Nickel	-	-	kg	3.44E-4	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Oils, unspecified	-	-	kg	4.39E+0	1	4.81	(3,5,3,1,na,BU:3); Literature
	Phenol	-	-	kg	4.02E-7	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Potassium	-	-	kg	1.60E-1	1	3.33	(4,5,3,1,na,BU:1.5); Literature, anorg. salt, basic uncertainty estimated with 3
	Silicon	-	-	kg	3.06E-5	1	7.10	(3,5,1,1,na,BU:5); Environmental report
	Sulfate	-	-	kg	6.00E-1	1	3.33	(4,5,3,1,na,BU:1.5); Literature, lignosuphonate
	BOD5, Biological Oxygen Demand	-	-	kg	1.39E+1	1	3.28	(na,5,3,1,na,BU:1.5); Extrapolation for sum parameter
	COD, Chemical Oxygen Demand	-	-	kg	1.39E+1	1	3.28	(na,5,3,1,na,BU:1.5); Extrapolation for sum parameter
	DOC, Dissolved Organic Carbon	-	-	kg	3.80E+0	1	3.28	(na,5,3,1,na,BU:1.5); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	3.80E+0	1	3.33	(4,5,3,1,na,BU:1.5); Literature, lignite
	Nitrogen	-	-	kg	3.39E-3	1	3.33	(4,5,3,1,na,BU:1.5); Literature
	Suspended solids, unspecified	-	-	kg	5.70E+2	1	3.30	(3,5,3,1,na,BU:1.5); Literature, drillings, wastes subtracted
	Zinc	-	-	kg	2.86E-2	1	7.10	(3,5,1,1,na,BU:5); Environmental report OLF 2001, corrected in 2020

6.3 Offshore platform

Material costs for production drillings are inventoried in the process step “exploration” and must be requested under the respective life cycle inventory. For offshore production, at this place, material requirements for the platforms and further production installations are assessed and described in more detail in former studies (Jungbluth 2007; Schori et al. 2012). The inventory is created for an average platform with a total weight of 2500 t.

Tab. 6.4 and Tab. 6.5 show the life cycle inventory for the construction and disposal of production platforms for crude oil and natural gas production offshore. Construction occurs onshore. Thereafter the platform is transferred to its destination. Transports of the mentioned materials are estimated using standard distances. Transport of platforms to the destination could not be considered here (Jungbluth 2007).

Tab. 6.4 Material input and construction costs for drilling platforms for crude oil, used in this study (Jungbluth 2007).

	Name	Location	InfrastructureProcess	Unit	platform, crude oil, offshore	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				OCE			
	InfrastructureProcess				1			
	Unit				unit			
product	platform, crude oil, offshore	OCE	1	unit	1.00E+0			
resource, land	Occupation, industrial area, benthos	-	-	m2a	4.50E+4	1	2.03	(5,4,5,3,1,BU:1.5); Life time 15a
	Transformation, from seabed, unspecified	-	-	m2	3.00E+3	1	2.47	(5,4,5,3,1,BU:2); Literature
	Transformation, to industrial area, benthos	-	-	m2	3.00E+3	1	2.47	(5,4,5,3,1,BU:2); Literature
	Occupation, industrial area	-	-	m2a	1.50E+4	1	2.03	(5,4,5,3,1,BU:1.5); Life time 15a
	Transformation, from unknown	-	-	m2	1.00E+3	1	2.47	(5,4,5,3,1,BU:2); Literature
	Transformation, to industrial area	-	-	m2	1.00E+3	1	2.47	(5,4,5,3,1,BU:2); Literature
resource, in water	Water, unspecified natural origin, GLO	-	-	m3	1.11E+2	1	1.51	(1,3,5,3,1,BU:1.05); Environmental report
technosphere	electricity, medium voltage, production ENTSO, at grid	ENTSO	0	kWh	9.18E+6	1	1.83	(5,5,5,3,1,BU:1.05); Estimation, plus 25% for disposal
	diesel, burned in building machine, average	CH	0	MJ	1.65E+7	1	1.51	(1,3,5,3,1,BU:1.05); Environmental report, plus 25% for disposal
	concrete, exacting, with de-icing salt contact, at plant	CH	0	m3	6.14E+2	1	1.53	(3,3,5,3,1,BU:1.05); Literature
	chromium steel 18/8, at plant	RER	0	kg	7.51E+3	1	1.53	(3,3,5,3,1,BU:1.05); Literature
	steel, low-alloyed, at plant	RER	0	kg	1.14E+6	1	1.53	(3,3,5,3,1,BU:1.05); Literature
	aluminium, production mix, cast alloy, at plant	RER	0	kg	1.36E+5	1	10.80	(5,5,5,1,1,BU:10); Estimation for aluminium anode, basic uncertainity estimated = 10
	cast iron, at plant	RER	0	kg	1.73E+2	1	10.80	(5,5,5,1,1,BU:10); Estimation for aluminium anode, basic uncertainity estimated = 10
	MG-silicon, at plant	NO	0	kg	2.16E+2	1	10.80	(5,5,5,1,1,BU:10); Estimation for aluminium anode, basic uncertainity estimated = 10
	copper, at regional storage	RER	0	kg	8.64E+0	1	10.80	(5,5,5,1,1,BU:10); Estimation for aluminium anode, basic uncertainity estimated = 10
	zinc, primary, at regional storage	RER	0	kg	7.20E+3	1	10.80	(5,5,5,1,1,BU:10); Estimation for aluminium anode, basic uncertainity estimated = 10
	transport, freight, lorry 16-32 metric ton, fleet average	RER	0	tkm	2.64E+5	1	2.09	(4,5,na,na,na,BU:2); Standard distance 100km
	transport, freight, rail	RER	0	tkm	7.76E+5	1	2.09	(4,5,na,na,na,BU:2); Standard distance 600km
	disposal, concrete, 5% water, to inert material landfill	CH	0	kg	1.35E+6	1	1.53	(3,3,5,3,1,BU:1.05); Estimation
	disposal, hazardous waste, 25% water, to hazardous waste incineration	CH	0	kg	4.75E+4	1	1.51	(1,3,5,3,1,BU:1.05); Environmental report
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	5.25E+4	1	1.51	(1,3,5,3,1,BU:1.05); Environmental report
emission air, low population density	Heat, waste	-	-	MJ	3.30E+7	1	1.83	(5,5,5,3,1,BU:1.05); Calculation
emission water, ocean	Aluminium	-	-	kg	1.16E+5	1	5.57	(5,5,5,1,1,BU:5); Estimation 85% utilisation of anode
	Iron	-	-	kg	1.47E+2	1	5.57	(5,5,5,1,1,BU:5); Estimation 85% utilisation of anode
	Silicon	-	-	kg	1.84E+2	1	5.57	(5,5,5,1,1,BU:5); Estimation 85% utilisation of anode
	Copper	-	-	kg	7.34E+0	1	3.50	(5,5,5,1,1,BU:3); Estimation 85% utilisation of anode
	Zinc	-	-	kg	6.12E+3	1	5.57	(5,5,5,1,1,BU:5); Estimation 85% utilisation of anode
	Titanium	-	-	kg	3.06E+1	1	5.57	(5,5,5,1,1,BU:5); Estimation 85% utilisation of anode

Tab. 6.5 Material input and construction costs for drilling platforms for natural gas production, used in this study (Schori et al. 2012).

Explanations	Name	Location	InfrastructureProcess	Unit	plant offshore, natural gas, production	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				OCE			
	InfrastructureProcess				1			
	Unit				unit			
Resources, land	Transformation, from sea and ocean	-	0	m2	1.60E+3	1	2.03	(2,4,2,1,1,4); Greenpeace report, one platform
	Transformation, to sea and ocean	-	0	m2	1.60E+3	1	2.03	(2,4,2,1,1,4); Greenpeace report, one platform
	Transformation, from industrial area, benthos	-	0	m2	1.60E+3	1	2.03	(2,4,2,1,1,4); Greenpeace report, one platform
	Transformation, to industrial area, benthos	-	0	m2	1.60E+3	1	2.03	(2,4,2,1,1,4); Greenpeace report, one platform
	Occupation, industrial area, benthos	-	0	m2a	1.76E+4	1	1.54	(2,4,2,1,1,4); Greenpeace report, one platform
Technosphere	diesel, burned in building machine	GLO	0	MJ	1.16E+8	1	1.28	(3,4,4,1,1,4); calculated based on data from 1980
	tap water, at user	RER	0	kg	2.83E+6	1	1.28	(3,4,4,1,1,4); calculated based on data from 1980
	electricity, medium voltage, production UCTE, at grid	UCTE	0	kWh	2.12E+7	1	1.28	(3,4,4,1,1,4); calculated based on data from 1980
	steel, low-alloyed, at plant	RER	0	kg	1.31E+7	1	1.27	(2,4,2,1,3,4); Greenpeace report, one platform, standard module
	epoxy resin, liquid, at plant	RER	0	kg	7.30E+4	1	1.61	(3,4,3,2,4,5); Data for wind turbines
	polyvinylchloride, bulk polymerised, at plant	RER	0	kg	3.00E+4	1	1.27	(2,4,2,1,3,4); Greenpeace report, one platform, standard module
	aluminium, production mix, at plant	RER	0	kg	2.53E+5	1	1.27	(2,4,2,1,3,4); Greenpeace report, one platform, standard module
	cast iron, at plant	RER	0	kg	3.03E+2	1	10.43	(5,5,1,1,1,na); Estimation for aluminium anode, basic uncertainity estimated = 10
	MG-silicon, at plant	NO	0	kg	3.79E+2	1	10.43	(5,5,1,1,1,na); Estimation for aluminium anode, basic uncertainity estimated = 10
	copper, at regional storage	RER	0	kg	1.52E+1	1	10.43	(5,5,1,1,1,na); Estimation for aluminium anode, basic uncertainity estimated = 10
	zinc for coating, at regional storage	RER	0	kg	7.82E+3	1	1.27	(2,4,2,1,3,4); Greenpeace report, one platform, standard module
	concrete, normal, at plant	CH	0	m3	4.09E+3	1	1.27	(2,4,2,1,3,4); Greenpeace report, one platform, standard module
	transport, lorry 32t	RER	0	tkm	1.80E+6	1	2.09	(4,5,na,na,na,na); standard distance
	transport, freight, rail	RER	0	tkm	2.70E+6	1	2.09	(4,5,na,na,na,na); standard distance 600km
	transport, transoceanic freight ship	OCE	0	tkm	2.81E+6	1	2.09	(4,5,na,na,na,na); standard distance
	Heat, waste	-		MJ	7.62E+7	1	1.17	(2,4,2,1,1,4); Greenpeace report, one platform, standard module
emission water, ocean	Aluminum	-	-	kg	2.15E+5	1	10.43	(5,5,1,1,1,na); Estimation 85% utilisation of anode
	Iron, ion	-	-	kg	2.58E+2	1	10.43	(5,5,1,1,1,na); Estimation 85% utilisation of anode
	Silicon	-	-	kg	3.22E+2	1	10.43	(5,5,1,1,1,na); Estimation 85% utilisation of anode
	Copper, ion	-	-	kg	1.29E+1	1	10.43	(5,5,1,1,1,na); Estimation 85% utilisation of anode
	Zinc, ion	-	-	kg	6.65E+3	1	10.43	(5,5,1,1,1,na); Estimation 85% utilisation of anode
	Titanium, ion	-	-	kg	5.37E+1	1	10.43	(5,5,1,1,1,na); Estimation 85% utilisation of anode
Outputs	plant offshore, natural gas, production	OCE	1	unit	1.00E+0			
	weigth				2.25E+7			

6.4 Onshore production plant

For onshore production, several hundred production sites are summarized to one production field. The inventory is estimated for a field with 100 drilling sites and described in more detail in former studies (Schori et al. 2012; Jungbluth 2007). Oil and gas refining are done centrally, which requires pipes and pumps.

Onshore production requires space for pumps, separators, tanks, pipes, energy generation (for internal electricity production) as well as cleaning processes (particularly wastewater cleaning). In this study a value of 1000 m^2/drilling is used. Like this, the production sites which are mostly situated in a remote area, are transforming a virtually unaffected area into a developed area. Therefore, for all production sites, transformation of forest to industrial area is assumed. There is no information on recultivation after production ceased, for the regions investigated here.

Tab. 6.6 and Tab. 6.7 show the life cycle inventories for production plants for crude oil and natural gas, based on former studies (Schori et al. 2012; Jungbluth 2007). It is assumed that the lifetime of the land use change is only 20 instead of the formerly estimated 30 (oil) or 50 (gas) years. This assumption is based on analysis done for horizontal wells in Oklahoma US. In the

US, more than half of the production of oil and gas, which is projected for the total lifetime occurs during its first three years.[12] As an estimate, 20 years of lifetime might be too low for exceptionally large oil fields as Rumaila in Iraq. Therefore, by using this estimate, the impact of land use might be slightly underestimated for the dataset for Iraq. However, for most of the globally accessible, smaller oil fields, this estimate seems appropriate.

Tab. 6.6	Material input and construction costs for onshore crude oil production.

	Name	Location	Unit	*production plant crude oil, onshore*	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			*GLO*			
	InfrastructureProcess			*1*			
	Unit			*unit*			
resource, land	Occupation, industrial area	-	m2a	2.00E+6	1	1.53	(3,4,1,3,1,na); Life time 20a
	Transformation, from forest, unspecified	-	m2	1.00E+5	1	2.26	(3,4,5,3,1,na); Literature
	Transformation, to mineral extraction site	-	m2	1.00E+5	1	2.26	(3,4,5,3,1,na); Literature
resource, in water	Water, unspecified natural origin, GLO	-	m3	8.28E+1	1	1.13	(1,3,3,3,1,na); Environmental report
technosphere	electricity, medium voltage, production ENTSO, at grid	ENTSO	kWh	3.67E+6	1	1.84	(5,4,5,3,3,na); Literature
	diesel, burned in building machine	GLO	MJ	6.75E+5	1	1.14	(2,3,3,3,1,na); Environmental report
	reinforcing steel, at plant	RER	kg	7.20E+5	1	1.54	(3,4,5,3,1,na); Literature
	transport, lorry >16t, fleet average	RER	tkm	3.60E+5	1	2.38	(4,5,5,5,3,na); Estimation 500km
	transport, freight, rail	RER	tkm	1.44E+5	1	2.38	(4,5,5,5,3,na); Standard distance 600km
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	kg	7.20E+2	1	1.51	(1,3,5,3,1,na); Environmental report
emission air, low population density	Heat, waste	-	MJ	1.32E+7	1	1.83	(5,5,5,3,1,na); Literature

Tab. 6.7	Material input and construction costs for onshore natural gas production.

	Name	Location	Unit	plant onshore, natural gas, production	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			GLO			
	InfrastructureProcess			1			
	Unit			unit			
product	plant onshore, natural gas, production	GLO	unit	1.00E+0			
resource, land	Transformation, from forest, unspecified	-	m2	7.50E+3	1	2.09	(3,4,3,3,3,BU:2); Area according to Schori
	Transformation, to mineral extraction site	-	m2	7.50E+3	1	2.09	(3,4,3,3,3,BU:2); Area according to Schori
	Occupation, industrial area	-	m2a	1.50E+5	1	1.59	(3,4,1,3,3,BU:1.5); Adjusted life time 20a according to Oklahoma Watch 2018
technosphere	diesel, burned in building machine, with particle filter	GLO	MJ	1.50E+6	1	1.34	(4,4,3,3,3,BU:1.05); Schori 2012
	electricity, medium voltage, production GLO, at	GLO	kWh	8.25E+5	1	1.34	(4,4,3,3,3,BU:1.05); Schori 2012
	reinforcing steel, at plant	RER	kg	1.50E+6	1	1.34	(4,4,3,3,3,BU:1.05); Schori 2012
	transport, freight, lorry 16-32 metric ton, fleet average	RER	tkm	1.50E+5	1	2.78	(4,5,3,5,5,BU:2); Estimation 500km
	transport, freight, rail	RER	tkm	3.00E+5	1	2.78	(4,5,3,5,5,BU:2); Standard distance 600km
emission air, low population density	Heat, waste	-	MJ	2.97E+6	1	1.29	(3,4,3,3,3,BU:1.05); Schori 2012

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[12] Oklahoma Watch: https://nondoc.com/2017/07/12/horizontal-wells-first-three-years/, online 03.01.2018

6.5 Gas treatment plants

The inventory is not updated and kept the same as in a former study (Schori et al. 2012). Data for material use and construction expenditures as well as the land use is shown in Tab. 6.8.

Tab. 6.8 Material input and construction costs for natural gas treatment plants (Schori et al. 2012)

Explanations	Name	Location	Category	SubCategory	InfrastructureProcess	Unit	*production plant, natural gas*	UncertaintyType	Standard Deviation 95%	GeneralComment
	Location						*GLO*			
	InfrastructureProcess						*1*			
	Unit						*unit*			
Resources, land	Transformation, from pasture and meadow	-	resou	land	0	m2	2.86E+06	1	2.06	(2,3,1,3,1,5); personal communication, Statoil
	Transformation, to pasture and meadow	-	resou	land	0	m2	2.86E+06	1	2.06	(2,3,1,3,1,5); personal communication, Statoil
	Transformation, from industrial area	-	resou	land	0	m2	2.86E+06	1	2.06	(2,3,1,3,1,5); personal communication, Statoil
	Transformation, to industrial area	-	resou	land	0	m2	2.86E+06	1	2.06	(2,3,1,3,1,5); personal communication, Statoil
	Occupation, industrial area	-	resou	land	0	m2a	1.71E+08	1	1.57	(2,3,1,3,1,5); personal communication, Statoil
Technosphere	diesel, burned in building machine	GLO	-	-	0	MJ	5.07E+09	1	1.64	(3,3,5,3,3,5); extrapolation from German data
	electricity, medium voltage, production UCTE, at grid	UCTE	-	-	0	kWh	2.82E+09	1	1.64	(3,3,5,3,3,5); extrapolation from German data
	reinforcing steel, at plant	RER	-	-	0	kg	5.07E+09	1	1.64	(3,3,5,3,3,5); extrapolation from German data
	concrete, normal, at plant	CH	-	-	0	m3	9.82E+05	1	1.64	(3,3,5,3,3,5); extrapolation from German data
	transport, lorry 32t	RER	-	-	0	tkm	6.15E+08	1	2.09	(4,5,na,na,na,na); standard distance
	transport, freight, rail	RER	-	-	0	tkm	1.01E+09	1	2.09	(4,5,na,na,na,na); standard distance
	Heat, waste	-	air	low popul		MJ	1.01E+10	1	1.64	(3,3,5,3,3,5); extrapolation from German data
Outputs	production plant, natural gas	GLO	-	-	1	unit	1.00E+00			

7 Operating materials

7.1 Chemicals

As operating materials, those production chemicals are considered which fulfil different functions. Generally, in oil production, three process steps are distinguished that require chemicals:

- Production and separation
- Water flooding
- Stimulation and workover

For gas production, to treat the gas chemicals are used too. The production can be disturbed by depositions and corrosion. An overview over troubles and chemicals used to fight them, can be found in the appendix of the former report (Jungbluth 2007).

As chemicals for stimulation and workover, acids and corrosion inhibitors are used. Investigations for the former report led to 90g of organic chemicals and 118g of inorganic chemicals per ton of crude oil extracted (Jungbluth 2007). As described in chapter 4.2, a factor of 4.7 is applied on these values to model the increased demand due to more depleted oil fields.

Transport of these chemicals is assumed with 100 km by lorry and 600 km by rail.

7.2 Fresh water

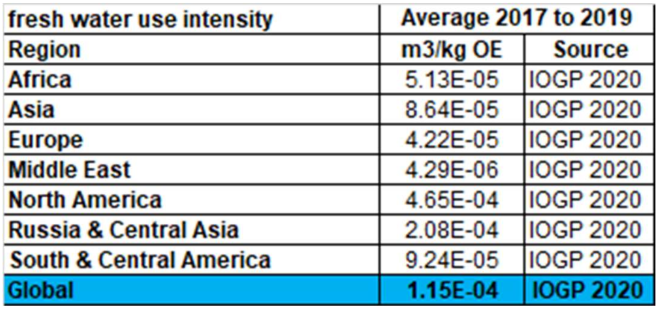
Water consumption in oil production varies substantially by geography, geology, and recovery-technique and reservoir depletion. Water in oil extraction is mainly used for enhanced oil recovery (EOR), where a reservoir is flooded with water or steam to displace or increase the flow of oil to the surface. Oil extraction also generates large volumes of produced water (cf. chapter

10.1). After treatment, the produced water can be used for reinjection as part of EOR activities. Consumed water is thus total water injected less produced water used for injection (Mielke et al. 2010; Wu et al. 2009). As EOR activities are increasing globally, this parameter was considered relevant for the update and therefore new data was collected.

7.2.1 Amount

For this study, average values reported for the latest 3 years are used, as shown in Tab. 7.1. The data source applied is the environmental report for different oil producing regions (IOGP 2020). Depending on regional aspects other country and company data show an even larger variation as presented in a former report (Meili & Jungbluth 2018). In order to stay consistent and to simplify updates the newer values from one single source are chosen.

Tab. 7.1 Fresh water use intensity in cubic meter per kg of extracted crude oil per region, average of 3 latest years reported.



fresh water use intensity	**Average 2017 to 2019**	
Region	**m3/kg OE**	**Source**
Africa	5.13E-05	IOGP 2020
Asia	8.64E-05	IOGP 2020
Europe	4.22E-05	IOGP 2020
Middle East	4.29E-06	IOGP 2020
North America	4.65E-04	IOGP 2020
Russia & Central Asia	2.08E-04	IOGP 2020
South & Central America	9.24E-05	IOGP 2020
Global	**1.15E-04**	**IOGP 2020**

While the water consumption estimates vary, it is possible to summarize the data, e.g., for the U.S., into two data sets: primary/secondary and tertiary recovery using common EOR techniques (Mielke et al. 2010). An example of this variety is shown in Tab. 7.2.

Tab. 7.2 Water consumption for different oil production techniques in the US (conversion factor for this table: 58MMBtu per barrel according to EIA). Own calculation of average based on literature (Mielke et al. 2010)

	gal/MMBtu	**% of US output**	**m3 water / kg crude oil**
Primary	1.4	0.2%	1.53E-04
Secondary	62	79.7%	6.79E-03
Tertiary			
Steam injection	39	5.5%	4.27E-03
CO2 injection	94	11.0%	1.03E-02
Caustic injection	28	0.0%	3.07E-03
Forward combustion/air injection	14	0.1%	1.53E-03
Other	63	3.5%	6.90E-03
Micellar polymer injection	2485	0.0%	2.72E-01
Weighted Average	**64**	**100.0%**	**7.02E-03**

7.2.2 Allocation

Impacts of freshwater use are allocated to crude oil only, as for natural gas extraction alone, no water injection would be necessary, and the water is used for and released due to EOR.

7.2.3 Origin of water

Depending on the availability, diverse types of water are used for crude oil production.

For offshore, typically saltwater from the ocean is used. Surface water from lakes or rivers is used onshore, if the availability is high.

In arid regions like Saudi Arabia mostly desalinated seawater and brackish water is used for oil recovery (Wu et al. 2009).

7.2.4 Return of water

A full water balance is not demanded by ecoinvent v2 guidelines. In view of ecoinvent v3 data the return of water to rivers (amount taken from the surface water plus discharged produced water) is inventoried as an emission to water in the same country. Further research seems to be necessary how to fully balance the water flows in case of crude oil extraction considering the environmental relevance of water flows through the well (production and injection water). Such research goes beyond the scope of this update study.

A correction was made in the calculation of the water balance for arid countries to avoid erroneous negative impacts.[13] If, due to inconsistent data, a surplus of water would result in the model, this is assumed to go into ocean.

8 Energy demand

For the direct energy uses of fuel oil, gas and electricity, region specific data for the reference year 2019 are applied (IOGP 2020).

8.1 Data sources

Operations which are to be **included** in data IOGP reporting are E&P (exploration and production) activities for which the reporting company has operational control. Examples include (IOGP 2019, page 6 explanations):

- Oil and gas extraction and separation (primary production)
- Primary oil processing (water separation, stabilisation)
- Crude oil transportation by pipeline to storage facilities
- Offshore crude oil ship loading from primary production
- Onshore crude oil storage connected by pipeline to primary production facilities
- Gas transportation to processing plant (offshore/onshore)
- Primary gas processing (dehydration, liquids separation, sweetening, CO2 removal) performed with the intent of making the produced gas meet sales specifications
- Floating Storage Units (FSUs)
- Offshore support and standby vessels
- Exploration (including seismic) activities
- Activities related to geologic storage of CO2 from natural gas processing
- Mining activities related to the extraction of hydrocarbons

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[13] Countries with water use factor lower than 1m3 depriv./m3 for water, river according to method EF 3.0 are considered as humid. All others are considered arid.

Operations which are to be **excluded** in IOGP reporting are non-E&P activities and those that fall outside the operational control of the reporting company. Examples include:

- Gas processing activities with the primary intent of producing gas liquids for sale (unless data cannot be separated out)
- Secondary liquid separation (i.e., Natural Gas Liquids extraction using refrigeration processing)
- Ethane, Propane, Butane, Condensate (EPBC) fractionation
- Liquefied Natural Gas (LNG) and Gas to Liquids (GTL) operations (LNG data are being compiled separately from the E&P data using this same process)
- Transportation of personnel
- Transportation of oil and gas, after sales metering devices (LACT units) or after ship loading at the primary production site
- Storage of refined products
- Partners' operations
- Non-operated joint ventures, except when the operator is not an IOGP member, and the joint venture has agreed that one company should take the lead on data reporting
- Upgrading activities related to the extraction of hydrocarbons. All other non-E&P activities

Most of these mentioned, excluded operations are assessed separately in the current or former studies. Outside of the scope of the life-cycle inventory are only the transportation of personnel.

8.2 Regional energy demand by type

Tab. 8.1 to Tab. 8.5 give an overview of the values for energy demand per kg crude oil extracted which are used for this study. It must be noted that the value for the total energy demand include also energy uses for well drilling, flaring, and venting. This was considered when estimates for the energy use were made to prevent double counting.

In the data sources listed in Tab. 8.1, it is not stated, if energy losses due to oil spills are considered (IOGP 2020). For this study it is assumed that they are not included in these figures published for the total energy demand. Modelling assumptions for oil spills are described in chapter 10.3. It must be noted that in this study, the oil loss is also accounted for in the calculation of the cumulative energy demand (see chapter 14.2).

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[14] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4687841/

[15] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4687841/figure/pone.0144141.g002/, online 15.01.2018

[16] http://carnegieendowment.org/2015/03/11/know-your-oil-creating-global-oil-climate-index-pub-59285, online 15.01.2018

[17] http://carnegieendowment.org/files/Brief-OCI.pdf, online 15.01.2018

Tab. 8.1 Total fossil energy use per kg crude oil extracted (Included in "total fossil energy use" but not listed here: drilling and energy losses due to flaring and venting)

Total fossil energy use	**2019**	
Region	**MJ/kg OE**	**Source**
Africa	1.41E+00	IOGP 2020
Asia/Australia	1.85E+00	IOGP 2020
Europe	1.32E+00	IOGP 2020
Middle East	6.20E-01	IOGP 2020
North America	2.81E+00	IOGP 2020
Russia & Central Asia	1.46E+00	IOGP 2020
South & Central America	1.41E+00	IOGP 2020
Global	**1.49E+00**	**calculation**

Electricity demand is assumed to be represented by the share of energy which is purchased from elsewhere (IOGP 2020). It is calculated by multiplying the total energy consumption by the percentage that does not come from onsite combustion and converted from MJ to kWh (see Tab. 8.2).

Tab. 8.2 Electricity demand, per kg oil equivalent

Electricity at grid		**2019**	
Region		**kWh/kg OE**	**Source**
Africa	kWh/kg OE	3.92E-03	Calculation based on data from IOGP 2020
Asia/Australia	kWh/kg OE	2.57E-02	Calculation based on data from IOGP 2020
Europe	kWh/kg OE	3.30E-02	Calculation based on data from IOGP 2020
Middle East	kWh/kg OE	5.34E-02	Calculation based on data from IOGP 2020
North America	kWh/kg OE	5.46E-02	Calculation based on data from IOGP 2020
Russia & Central Asia	kWh/kg OE	1.62E-02	Calculation based on data from IOGP 2020
South & Central America	kWh/kg OE	7.83E-03	Calculation based on data from IOGP 2020
Global		**3.10E-02**	**weighted average**

The amount of diesel, burned onsite, shown in Tab. 8.3, is calculated based on the overall energy consumption multiplied by the percentage of onsite combustion and multiplied by a rough estimate of 2%, assuming that a bit of diesel is needed on all extraction sites (IOGP 2020).

Tab. 8.3 Energy demand of diesel, burned in equipment, per kg oil equivalent.

Diesel, burned in equipment		**2019**	
Region		**MJ/kg OE**	**Source**
Africa	MJ/kg OE	2.79E-02	Calculation based on data from IOGP 2020 and estimated share of 2%.
Asia/Australia	MJ/kg OE	3.52E-02	Calculation based on data from IOGP 2020 and estimated share of 2%.
Europe	MJ/kg OE	2.40E-02	Calculation based on data from IOGP 2020 and estimated share of 2%.
Middle East	MJ/kg OE	8.56E-03	Calculation based on data from IOGP 2020 and estimated share of 2%.
North America	MJ/kg OE	5.23E-02	Calculation based on data from IOGP 2020 and estimated share of 2%.
Russia & Central Asia	MJ/kg OE	2.80E-02	Calculation based on data from IOGP 2020 and estimated share of 2%.
South & Central America	MJ/kg OE	2.76E-02	Calculation based on data from IOGP 2020 and estimated share of 2%.
Global		**2.76E-02**	**weighted average**

The amount of heavy fuel oil burnt in this region is assessed as shown in Tab. 8.4. It is calculated based on the overall energy consumption multiplied by half of the percentage of onsite combustion minus the share for diesel combustion as defined above (IOGP 2020).

Tab. 8.4 Energy demand of heavy fuel oil, burned in equipment, per kg oil equivalent.

Heavy fuel oil, burned in equipment	**2019**	
Region	**MJ/kg OE**	**Source**
Africa	0.00E+00	IOGP 2020
Asia/Australia	0.00E+00	IOGP 2020
Europe	0.00E+00	IOGP 2020
Middle East	0.00E+00	IOGP 2020
North America	0.00E+00	IOGP 2020
Russia & Central Asia	0.00E+00	IOGP 2020
South & Central America	6.63E-01	IOGP 2020
Global	**7.71E-02**	**calculation**

For the current study, SO_2 emissions from the combustion of sour gas are directly implemented in an overall figure shown in chapter 9.5. Nevertheless, it might be interesting to have a rough estimate of the share of sweet and sour gas extracted by region. Such an estimate is provided in Tab. 8.5, based on share of overall gas burned in gas turbines and regional shares of sweet and sour gas reserves (IOGP 2020; IEA 2008).

Tab. 8.5 Energy demand of sweet and sour gas burned in gas turbines, in MJ per kg oil equivalent. Share of sweet and sour gas based on information from IEA 2008.

gas, burned in gas turbine, production	**share sweet gas**	**share sour gas**	**sweet gas**	**sour gas**	**Source**
Region	%	%	MJ/kg OE	MJ/kg OE	
Africa	57%	43%	0.78	0.59	IOGP 2020 for total amount burned, multiplied by share global share according to IEA 2008
Asia/Australia	57%	43%	0.98	0.74	IOGP 2020 for total amount burned, multiplied by share global share according to IEA 2008
Europe	57%	43%	0.67	0.51	IOGP 2020 for total amount burned, multiplied by share global share according to IEA 2008
Middle East	40%	60%	0.17	0.25	IOGP 2020 for total amount burned, multiplied by share IEA 2008
North America	57%	43%	1.46	1.10	IOGP 2020 for total amount burned, multiplied by share global share according to IEA 2008
Russia & Central Asia	66%	34%	0.91	0.47	IOGP 2020 for total amount burned, multiplied by share IEA 2008
South & Central America	57%	43%	0.39	0.30	IOGP 2020 for total amount burned, multiplied by share global share according to IEA 2008
Global	**57%**	**43%**	**0.72**	**0.56**	**weighted average for total amount burned, multiplied by share IEA 2008**

9 Emissions to air

9.1 Flared natural gas

9.1.1 Definition

Flaring is the controlled and intentional burning of natural gas as part of production and processing of crude oil and natural gas.

Flaring is mainly done for the following reasons[18]:

- **Flaring for safety**
  By burning excess natural gas, flaring protects against the dangers of over-pressuring industrial equipment. Natural gas can be stored and transported instead of flared, but it is highly flammable. Transporting natural gas from a rig to homes and businesses is high risk and many companies choose flaring as the alternative.
- **Flaring for disposal**
  One of the main reasons for gas flaring is the disposal and burning of natural gas as waste. Typically, when there are large volumes of hydrogen sulphide in natural gas, it cannot be safely extracted. To dispose of this gas, it is burned off. It is common to flare natural gas that contains hydrogen sulphide (i.e., sour gas), to convert the highly toxic hydrogen sulphide gas into less toxic compounds.
- **Flaring for remote locations**
  When petroleum crude oil is extracted and produced from onshore or offshore oil wells, natural gas associated with the oil is also brought to the surface. If companies do not have the infrastructure in place to capture natural gas and safely transport it – such as when oil rigs are in deep waters – natural gas is often flared.
- **Flaring for economics**
  There is a significant gap between oil and natural gas prices. Natural gas costs more than oil to produce on an energy-equivalent basis. For this reason, drillers are searching for oil, not gas, and companies are reluctant to invest in costly projects to capture and transport natural gas from oil wells to the market.

9.1.2 Allocation

Much of the flaring is done for maximizing profits in crude oil extraction and pure natural gas extraction facilities strive to keep flaring to a minimum and sell as much natural gas as possible. Therefore, it could be argued that all the emissions related to flaring should be allocated to the oil extraction.

However, many extraction sites sell oil and gas at the same time (e.g. 50% of APG in Russia in 2010) and the remaining gas must be flared as well (Carbon Limits 2013). Also, initially the dataset for flaring was created for the natural gas extraction (Faist Emmenegger et al. 2007, chapter 6.3.13).

Therefore, in this study, emissions from flaring (and venting) are allocated to crude oil and natural gas extraction as explained in chapter 2.2.

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[18] https://www.earthworks.org/issues/flaring_and_venting 05.05.2021

9.1.3 Amount of flared gas

Estimates for flaring are available in different sources as shown in a former study (Meili & Jungbluth 2018). For the current study only estimates based on three different sources are compared as shown in Tab. 9.1 (World Bank 2022; IOGP 2020)[19]. For the countries under investigation, data is taken from the Global Gas Flaring Reduction Partnership (GGFR), which estimated the country specific amounts of flared gas based on satellite measurements done according to a methodology provided by the National Oceanic and Atmospheric Administration (NOAA), a part of the US department of Defence[20]. These measured flaring data is provided publicly for the reference year 2019 (World Bank 2022). Another study provides flaring intensities for 2019 based on company data which cover about 10% of the world oil and gas production (IOGP 2020). The global average intensity derived from these company data is on average about 25% lower than the one reported according to satellite data and therefore are neglected. In the evaluation done for Worldbank, no flaring intensities are shown for Germany. However, such data was found in estimates from the earth observation group at the Colorado school of mines which also bases the assessments on satellite data.[19] Downside of this data is that it is only published for the reference year 2018 yet. Therefore, this data source is only considered where no newer data is available in the primary source of information.

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[19] Flare gas volume: https://viirs.skytruth.org/apps/heatmap/flarevolume.html#, 25.11.2020

[20] Flare gas volume: http://pubdocs.worldbank.org/en/251461483541510567/ACS.pdf, 25.11.2020

Tab. 9.1 Total amount of natural gas flared (million norm cubic meters per year) and intensities of flaring (norm cubic meters per kg oil equivalent) from considered sources (World Bank 2022; IOGP 2020)[19]. Marks: Red =high values, Green= low values, Bold = used for calculation in this study.

Origin	**annual flaring**	**annual flaring**	**flaring per kg oil equivalent**	**flaring per kg oil equivalent**	**flaring per kg oil equivalent**
Source	Worldbank	Skytruth	Worldbank	Skytruth	IOGP
Reference year	2019	2018	2019	2018	2019
Unit	mcm/a	mcm/a	Nm3/kgOE	Nm3/kgOE	Nm3/kgOE
United Arab Emirates	900	1’298	**3.88E-03**	5.59E-03	4.60E-03
Azerbaijan	223	248	**3.82E-03**	4.26E-03	6.09E-03
Brazil	1’136	1’216	**6.59E-03**	7.06E-03	1.01E-02
Canada	1’052	1’455	**2.51E-03**	3.48E-03	1.82E-02
China	2’025	2’053	**5.98E-03**	6.07E-03	1.76E-02
Colombia	534	531	**9.27E-03**	9.22E-03	1.01E-02
Germany	-	28	0.00E+00	**3.63E-03**	7.44E-03
Algeria	9’343	9’645	**6.88E-02**	7.10E-02	3.41E-02
Ecuador	919	938	**3.20E-02**	3.26E-02	1.01E-02
United Kingdom	1’111	1’264	**1.31E-02**	1.49E-02	7.44E-03
Indonesia	2’004	2’189	**2.13E-02**	2.32E-02	1.76E-02
Iraq	17’914	18’006	**7.37E-02**	7.41E-02	4.60E-03
Iran	13’781	18’549	**3.79E-02**	5.10E-02	4.60E-03
Kuwait	731	982	**4.59E-03**	6.16E-03	4.60E-03
Kazakhstan	1’567	2’069	**1.41E-02**	1.87E-02	6.09E-03
Libyan Arab Jamahiriya	5’124	4’776	**7.81E-02**	7.28E-02	3.41E-02
Mexico	4’484	4’648	**3.64E-02**	3.78E-02	1.82E-02
Malaysia	2’368	2’576	**2.49E-02**	2.71E-02	1.76E-02
Nigeria	7’825	7’490	**5.50E-02**	5.26E-02	3.41E-02
Netherlands	3	19	**1.27E-04**	7.89E-04	7.44E-03
Norway	129	204	**7.46E-04**	1.18E-03	7.44E-03
Qatar	1’344	1’335	**5.94E-03**	5.90E-03	4.60E-03
Romania	12	19	**1.04E-03**	1.65E-03	7.44E-03
Russian Federation	23’212	21’863	**2.05E-02**	1.93E-02	6.09E-03
Saudi Arabia	2’100	2’949	**3.23E-03**	4.53E-03	4.60E-03
Ukraine	115	164	**6.08E-03**	8.66E-03	7.44E-03
United States	17’294	14’501	**1.14E-02**	9.60E-03	1.82E-02
Venezuela	9’541	9’502	**1.39E-01**	1.39E-01	1.01E-02
Global	142’501	153’328	**1.83E-02**	1.97E-02	1.44E-02

9.1.4 Composition and emissions

Flaring losses of natural gas are modelled including the resource extraction from ground (which is not included in figures about natural gas production) and the emissions to air.

Flaring releases greenhouse gases like CO_2, CH_4, NO_x and other gases like SO_2 into the atmosphere. In this study, region specific emission data for the overall production of crude oil and natural gas are considered for CH_4, NO_x and SO_2(c.f. chapters 9.2 and 9.5). Therefore, for the composition of flared gas, only the remaining gases are estimated in a separate LCI for sweet gas burned in production flare, per Nm^3 as presented in Tab. 9.2.

Tab. 9.2 LCI data for natural gas, sweet, burned in production flare per Nm^3.

	Name	Unit	natural gas, sweet, burned in production flare	UncertaintyType	StandardDeviation95%	GeneralComment
	Location		GLO			
	InfrastructureProcess		0			
	Unit		Nm3			
resource, in ground	Gas, natural/m3	Nm3	1.00E+0	1	1.05	(1,1,1,1,1,BU:1.05);
emission air, low population density	Methane, fossil	kg	0	1	2.74	(5,5,5,5,5,BU:1.5); Excluded. Country-specific overall-emissions need to be assessed separately
	Carbon dioxide, fossil	kg	2.45E+0	1	1.24	(2,2,3,3,3,BU:1.05); Faist 2007, in ecoinvent v3.6, Allocation, cut-off (2019)
	Carbon monoxide, fossil	kg	1.00E-3	1	5.07	(2,2,3,3,3,BU:5); Standard emission factor (EFDB 2011)
	NMVOC, non-methane volatile organic compounds, unspecified origin	kg	2.98E-5	1	1.62	(2,2,4,3,3,BU:1.5); Faist 2007, in ecoinvent v3.6, Allocation, cut-off (2019)
	Nitrogen oxides	kg	0	1	2.74	(5,5,5,5,5,BU:1.5); Excluded. Country-specific overall-emissions need to be assessed separately
	Dinitrogen monoxide	kg	2.00E-5	1	1.62	(2,2,4,3,3,BU:1.5); Standard emission factor (EFDB 2011)
	Particulates, < 2.5 um	kg	5.40E-4	1	3.28	(2,2,5,3,3,BU:3); Estimation for refinery flare from (Jungbluth 2003)
	Sulfur dioxide	kg	0	1	2.52	(5,5,5,5,5,BU:1.05); Excluded. Country-specific overall-emissions need to be assessed separately
	Mercury	kg	2.00E-7	1	5.11	(2,2,4,3,3,BU:5); Estimation, average value (Schori 2012)
	Radon-222	kBq	4.00E-1	1	3.10	(2,2,4,3,3,BU:3); Estimation, average value (Schori 2012)
	Heat, waste	MJ	3.60E+1	1	1.05	(1,2,1,1,1,BU:1.05); Lower heating value according to BP 2020

9.2 Vented and fugitive natural gas emissions

9.2.1 Definition

Venting is the word used to describe the release of unburned natural gas to the atmosphere during the production and processing of crude oil and natural gas.

Venting is defined by the industry as intended release of natural gas in the technical process chain. Venting occurs at several points in the oil and gas development process (well completion; well maintenance; pipeline maintenance; tank maintenance; etc.). However, unintended natural gas emissions may also occur due to incomplete flaring and fugitive emissions e.g., due to leakages or forced changes in geological structures during fracking)[21;22]. For this study intended and unintended releases of methane from all known sources are considered.

9.2.2 Allocation

Emissions from venting and fugitive natural gas emissions are directly available specifically for on- and offshore oil and gas extraction in all countries under study. The factors for oil and gas extraction are used directly for the allocation of total emissions between natural gas and crude oil. However, it was not possible to differentiate between on- and offshore production as consistent production amounts were not available (c.f. chapter 2.2).

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[21] https://www.nrdc.org/sites/default/files/fracking-air-pollution-IB.pdf, online 27.09.2018

[22] https://earthworks.org/issues/flaring_and_venting/, online 27.09.2018

9.2.3 Technical scope

In some studies, consulted and described below, values on methane release are given for the whole product chain of crude oil products. Therefore, these figures would need to be adjusted by subtracting emissions occurring in transportation, storage, and handling. According to the LCA methodology used for this and a former project they are reported at distinct stages of the life cycle (Jungbluth & Meili 2018; Meili et al. 2018). However, as will be explained in the following chapters, the values chosen for this study are related to upstream emissions only. Therefore, no adjustment must be made for downstream estimates for methane emissions.

The assumed percentage of methane in emitted natural gas is shown in chapter 9.2.5.

To simplify comparison of values in the following chapter, values given in e.g., billion cubic meters (bcm) of methane are recalculated to kg per kg oil-equivalent using the properties defined in chapter 5.

Emission values estimated in the different literature sources presented below are summarized in Tab. 9.3. Where values are given for another year besides the reference year, the related crude oil and natural gas production data were either directly taken from that study or from the same data source as used in Tab. 2.1 (BP 2020).

9.2.4 Amount of emissions

Robust and consistent data is provided by different research institutes as described in the following subchapter 9.2.4.1. Therefore, it is possible to use country-specific methane emissions in the model (c.f. Tab. 9.3).

Net calorific values and densities are used consistently with extraction data provided in BP 2020 (c.f. chapter 5.1.2 and 5.2.1).

To assess the overall release of natural gas, the methane emissions rates are divided by a share of 0.585kg of methane per Nm^3 of natural gas (c.f. chapter 9.2.5).

9.2.4.1 Consulted studies

One study, published in 2020, uses the temporal profiles from the Emissions Database for Global Atmospheric Research (EDGAR) for the development of country/region- and sector-specific yearly profiles for fugitive emissions from oil and gas (Crippa et al. 2019). From this study methane emission data are available on a country level for the years 1970 to 2012. It is not mentioned specifically if these numbers also include emissions due to intended venting and incomplete flaring. Also, it is not explicitly mentioned if the numbers include upstream and downstream emissions. Based on the setup of the study and the naming of the category, it is assumed, that the numbers include all upstream and downstream emissions related to oil and gas extraction. In Tab. 9.3, the fugitive emission values for the year 2012 are shown for the countries investigated in the current study. Based on these values a global average emission of 10 g of methane/kg oil equivalent is calculated for up- & downstream processes combined.

The IOGP environmental reporting, published in 2020, uses data from members of the international organization of oil and gas producing companies, reported for 2019 (IOGP 2020). The reporting companies together produced about 28% of the global total annual production as reported in the BP statistical review of world energy 2020 (BP 2020). Based on these figures region-specific methane emissions for oil and gas extraction (upstream) are calculated. Besides emissions due to process vents, gas-driven pneumatic devices and tank vents, also fugitive emissions from process components (valves, flanges, etc.) and emissions due to incomplete flaring are reported (c.f. page 13, IOGP 2020). Based on the sample and its production, a global average emission of 0.6 g of methane/kg oil equivalent is calculated for upstream processes only. This figure is much lower than the figures found in independent studies considering all possible methane releases from fossil fuel and natural gas extraction.

Countries reported their greenhouse gas emissions in 2020 to the United Nations Framework Convention on Climate Change (UNFCCC)[23]. In table 1.B.2 of each country specific report (in the common reporting format, CRF), figures for methane emissions due to oil and natural gas production (up- and downstream, i.e., extraction, transport, refining and distribution), for the reference year 2018, are provided. These values are set in relation to the oil and gas production reported in the same tables to UNFCCC. The values for oil or natural gas production for Kazakhstan and the United States are much lower than reported by BP. Therefore, in a second column, the emission rates are calculated again by using the oil-equivalent production of BP. The weighted average of the reported data in relation to BP-production is 4.4 g of methane/kg oil equivalent for up- and downstream processes.

The international energy agency (IEA) analyses emissions sources along the full oil and natural gas value chains for the reference year 2019 (IEA 2022).

Their estimates are cross-checked with other studies and constantly improved to show a highly comprehensive picture of methane emissions per country, sector (oil/gas, down/upstream), subsectors (onshore/offshore, conventional/unconventional) and type of emission (fugitive/vented/incomplete flaring). By adding up all the upstream emissions, multiplying and setting them in relation with production data according to BP 2020, a global average emission of 10.6 g of methane/kg oil equivalent is calculated for up- and downstream processes combined. For upstream processes only, an average emission of 8.9 g of methane/kg oil equivalent is calculated.

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[23] https://unfccc.int/ghg-inventories-annex-i-parties/2020,.online 07.12.2020

Tab. 9.3 Country specific methane emissions factors based on emission data from different reports (Crippa et al. 2019; UNFCCC 2020; IEA 2022). Year in brackets is the reference year used in that study. For emission data found in UNFCCC 2020 and IEA 2022 the methane emission factor is calculated using crude oil and natural gas production data from BP 2020. White background: no data available, red background: high emission factors, green background: low emission factors, **in bold: source used in the last study (Meili et al. 2021).**

Origin	**Methane emission factors**						
Source	Crippa et al. 2019, data from EDGAR, up- & downstream (2012)	IOGP 2020, upstream only (2019)	UNFCCC 2020, up- & downstream (2018)	UNFCCC 2020, up- & downstream (2018); Production: BP (2018)	IEA 2022, up- & downstream (2019); Production: BP (2019)	**IEA 2022, upstream (2019); Production: BP (2019)**	IEA 2022, downstream (2019); Production: BP (2019)
Unit	kg/kgOE	kg/kgOE	kg/kgOE	kg/kgOE	kg/kgOE	kg/kgOE	kg/kgOE
United Arab Emirates	5.78E-03	1.00E-04	n.a.	n.a.	5.81E-03	5.26E-03	5.51E-04
Azerbaijan	6.64E-03	1.12E-03	n.a.	n.a.	5.68E-03	5.09E-03	5.83E-04
Brazil	6.10E-03	6.20E-04	na	na	7.19E-03	6.42E-03	7.67E-04
Canada	7.52E-03	1.25E-03	na	na	5.43E-03	4.94E-03	4.97E-04
China	9.04E-03	4.70E-04	na	na	7.98E-03	5.84E-03	2.14E-03
Colombia	6.69E-03	6.20E-04	2.69E-02	2.43E-02	5.35E-03	4.81E-03	5.38E-04
Germany	1.80E-02	3.20E-04	2.69E-02	2.43E-02	2.05E-02	3.55E-03	1.70E-02
Algeria	1.69E-02	8.30E-04	n.a.	n.a.	1.90E-02	1.76E-02	1.35E-03
Ecuador	1.17E-02	6.20E-04	2.31E-03	2.32E-03	9.18E-03	9.11E-03	6.96E-05
United Kingdom	3.09E-03	3.20E-04	2.31E-03	2.32E-03	2.52E-03	1.74E-03	7.80E-04
Indonesia	1.46E-02	4.70E-04	n.a.	n.a.	1.04E-02	8.74E-03	1.70E-03
Iraq	1.22E-02	1.00E-04	n.a.	n.a.	1.15E-02	1.14E-02	1.07E-04
Iran	1.42E-02	1.00E-04	na	na	1.50E-02	1.31E-02	1.84E-03
Kuwait	5.22E-03	1.00E-04	2.00E-02	1.96E-03	5.08E-03	4.74E-03	3.39E-04
Kazakhstan	2.00E-02	1.12E-03	2.00E-02	1.96E-03	1.56E-02	1.49E-02	6.77E-04
Libyan Arab Jamahiriya	1.06E-02	8.30E-04	n.a.	n.a.	3.66E-02	3.60E-02	6.25E-04
Mexico	7.69E-03	1.25E-03	n.a.	n.a.	1.04E-02	8.57E-03	1.80E-03
Malaysia	1.30E-02	4.70E-04	n.a.	n.a.	4.67E-03	3.97E-03	7.04E-04
Nigeria	2.10E-02	8.30E-04	n.a.	n.a.	1.34E-02	1.28E-02	6.32E-04
Netherlands	3.71E-03	3.20E-04	2.23E-05	6.58E-04	2.05E-04	8.19E-05	1.23E-04
Norway	3.28E-03	3.20E-04	9.99E-05	1.04E-04	1.62E-04	1.62E-04	0.00E+00
Qatar	1.18E-02	1.00E-04	n.a.	n.a.	5.06E-03	4.71E-03	3.54E-04
Romania	1.15E-02	3.20E-04	1.22E-02	1.21E-02	7.50E-03	5.35E-03	2.16E-03
Russian Federation	8.76E-03	1.12E-03	6.37E-03	6.16E-03	1.26E-02	1.11E-02	1.50E-03
Saudi Arabia	4.45E-03	1.00E-04	n.a.	n.a.	4.33E-03	4.03E-03	2.95E-04
Ukraine	4.49E-02	3.20E-04	5.96E-02	6.40E-02	1.50E-02	9.47E-03	5.50E-03
United States	8.26E-03	1.25E-03	1.37E-02	5.58E-03	9.13E-03	7.40E-03	1.73E-03
Venezuela	9.61E-03	6.20E-04	1.37E-02	5.58E-03	3.78E-02	3.63E-02	1.56E-03
Global	1.01E-02	6.01E-04	7.93E-03	4.15E-03	1.06E-02	8.86E-03	1.41E-03

9.2.4.2 *Discussion*

According to an expert opinion[24], values derived in Crippa et al. 2019, based on EDGAR data are recommended as "state-of-the-art". However, as the latest data is representative for the year 2012, they do not meet the requirement regarding the reference year.

Estimates in IOGP 2020 seem to heavily underestimate fugitive emissions and are therefore neglected.

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[24] Communication by E-Mail with Prof. Dr. André Butz from Institute of Environmental Physics at Heidelberg University, 17.09.2020

Reported data to UNFCCC[25] reflect the emissions officially confirmed by state authorities for the reference year 2018. However, this data does only cover reports from about half of the countries under study (8 of 16).

Estimates in IEA 2022 seem to be the most comprehensive and consistent source of information for the reference year 2019. They are in the same order of magnitude as the figures reported by Crippa et al. 2019 (and about twice as high as reported to UNFCCC[25]). The IEA 2022 data are applied in this study.

9.2.4.3 Estimate used in this study

Country-specific upstream methane emissions according to IEA 2022 are available for on- and offshore crude oil and natural gas production for the reference year 2019. Additionally, emissions from satellite-detected large leaks are available. These emission values are added proportionally to the values for on- and offshore production of crude oil and natural gas.

The shares for on- and offshore production are estimated from different sources and therefore might be inconsistent with the reported emissions (c.f. chapter 4.1). To avoid such inconsistencies, values for on- and offshore emissions are added for oil and gas and set in relation to production data according to BP 2020 (reference year 2019).

The values for the methane emissions related to oil and gas production are used to estimate the total upstream natural gas emissions. To do so, the numbers are divided by a volumetric share of 0.585 kg methane per Nm^3 of natural gas according to the composition presented in chapter 9.2.5.

To reflect the high uncertainty behind these estimates, a basic uncertainty of 2 is applied on this value in the EcoSpold format.

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[25] https://unfccc.int/ghg-inventories-annex-i-parties/2020, online 07.12.2020

Tab. 9.4 Country specific upstream methane emissions factors for onshore and offshore crude oil and natural gas production according to IEA 2022 (reference year 2019) related to production data from BP 2020 (reference year 2019) and shares off-/onshore according to chapter 4.1. Per column: Red background: high emission factors, green background: low emission factors (or no on-/offshore production)

Origin	**Methane emissions, Crude oil, Offshore, Total**	**Methane emissions, Crude oil, Onshore, Total**	**Methane emissions, Natural gas, Offshore, Total**	**Methane emissions, Natural gas, Onshore, Total**
Unit	kg/kg crude oil offshore	kg/kg crude oil onshore	kg/Nm^3 natural gas	kg/Nm^3 natural gas
United Arab Emirates	5.03E-03	5.28E-03	3.45E-03	5.51E-03
Azerbaijan	5.65E-03	2.36E-03	4.25E-03	4.11E-04
Brazil	6.10E-03	1.35E-02	5.13E-03	2.58E-02
Canada	0.00E+00	3.74E-03	0.00E+00	6.93E-03
China	2.10E-02	4.69E-03	6.85E-03	5.04E-03
Colombia	0.00E+00	5.73E-03	2.43E-03	3.38E-03
Germany	2.33E-03	2.04E-03	0.00E+00	8.14E-03
Algeria	0.00E+00	2.58E-02	0.00E+00	7.94E-03
Ecuador	4.83E-03	9.16E-03	1.23E-02	0.00E+00
United Kingdom	1.81E-03	1.93E-03	1.36E-03	0.00E+00
Indonesia	5.53E-03	1.29E-02	1.09E-02	3.86E-03
Iraq	0.00E+00	1.14E-02	0.00E+00	6.31E-03
Iran	2.91E-02	1.74E-02	3.00E-02	2.23E-03
Kuwait	1.39E-02	4.63E-03	0.00E+00	3.73E-03
Kazakhstan	1.88E-02	1.18E-02	1.61E-02	1.63E-02
Libyan Arab Jamahiriya	1.13E-02	4.41E-02	3.39E-02	1.64E-02
Mexico	7.77E-03	6.40E-02	1.97E-03	7.82E-02
Malaysia	6.06E-03	2.68E-02	2.45E-03	0.00E+00
Nigeria	9.96E-03	5.49E-02	1.89E-03	5.40E-02
Netherlands	0.00E+00	0.00E+00	3.96E-05	3.56E-04
Norway	1.66E-04	0.00E+00	1.31E-04	0.00E+00
Qatar	5.05E-03	3.32E-03	5.69E-03	1.64E-04
Romania	1.87E-03	7.61E-03	1.72E-03	5.31E-03
Russian Federation	2.68E-03	1.18E-02	9.71E-04	9.02E-03
Saudi Arabia	3.72E-03	4.24E-03	4.34E-03	2.52E-03
United States	3.12E-03	6.47E-03	3.36E-03	7.10E-03
Venezuela	3.50E-02	5.62E-02	3.78E-03	7.18E-03
Global	**6.85E-03**	**9.72E-03**	**4.15E-03**	**7.51E-03**

9.2.5 Composition of emitted natural gas

Direct emissions of natural gas are modelled including the resource extraction from ground (which is not included in figures about natural gas production) and the emissions to air.

It is assumed, that the composition of the gas did not change compared to the former studies (Faist Emmenegger et al. 2007; Jungbluth 2007). No distinction is made between sweet and sour gas as SO_2-emissions are assessed separately according to chapter 9.5. The respective emissions are presented in Tab. 9.5.

Tab. 9.5 Unit process raw data for the direct release of natural gas (Jungbluth 2007)

	Name	Location	InfrastructureProcess	Unit	*natural gas, vented*	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				*GLO*			
	Unit				*Nm3*			
resource, in ground	Gas, natural/m3	-	-	Nm3	1.00E+0	1	1.53	(3,3,5,3,1,na); Calculation
emission air, low population density	Carbon dioxide, fossil	-	-	kg	1.40E-2	1	1.53	(3,3,5,3,1,na); Literature
	Helium	-	-	kg	1.00E-3	1	1.79	(3,3,5,3,1,na); Literature
	Mercury	-	-	kg	1.50E-8	1	5.28	(3,3,5,3,1,na); Literature
	Methane, fossil	-	-	kg	5.85E-1	1	1.79	(3,3,5,3,1,na); Literature
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.71E-1	1	1.79	(3,3,5,3,1,na); Literature
	Radon-222	-	-	kBq	1.00E-1	1	3.24	(3,3,5,3,1,na); Literature

9.2.6 Future emissions of abandoned oil and gas fields

A study published in in Environmental Science and Technology finds that annual methane emissions from abandoned oil and gas (AOG) wells in Canada and the US have been greatly underestimated - by as much as 150% in Canada, and by 20% in the US compared to what national environmental protection agencies are reporting (Williams et al. 2021). Extraction from Canada is not analysed in the current study and for the US, the values based on IEA 2020 data are already higher than what is reported to UNFCCC (c.f. Tab. 9.3). Therefore, it is assumed, that current emissions from abandoned oil and gas fields are appropriately represented in this study.

However, without proper maintenance of AOG, such emissions would continue for a long time after the extraction took place. Such prospective emissions are not yet included/allocated to the current production.

9.3 Energy supply with diesel aggregates

To produce electricity in oil and gas exploration and production, diesel generators with more than 9'000 cm3 cubic capacity are used. In groups of 3 to 5 machines they supply the required electrical energy. They are powered by diesel or in dual mode with 5% diesel and 95% gas (Jungbluth 2007).

9.3.1 Efficiency, energy, and material requirements

Inventory data to produce a diesel electric generating set is shown in Tab. 9.7.The efficiency of the aggregates used in this study is given as 36% (Jungbluth 2007).

The diesel requirement is 23.36 t/TJ_{In}. The steel requirement is estimated on the basis of data from the ship engine building industry (Jungbluth 2007). The specific weight of about 12 t/MW in the power range of engines from 9 to 13 MW (balance sheet size 10 MW) is assumed to be steel only (other materials neglected). The running time (service life) is assumed to be 150'000 h. To take the generator into account, the demand is increased by 50%. Furthermore, a share of 5% of high alloy steel and 10% copper is assumed.

Tab. 9.6 Life cycle inventory data for a 10MW diesel-electric generating set

	Name	Location	Unit	*diesel-electric generating set production 10MW*	UncertaintyType	StandardDeviation95%	GeneralComment
	Location			*RER*			
	InfrastructureProcess			*1*			
	Unit			*unit*			
product	diesel-electric generating set production 10MW	RER	unit	1.00E+0			
technosphere	copper, at regional storage	RER	kg	1.80E+4	1	3.05	(na,5,na,1,na,BU:1.05); Estimation
	chromium steel 18/8, at plant	RER	kg	9.00E+3	1	3.05	(na,5,na,1,na,BU:1.05); Estimation
	steel, low-alloyed, at plant	RER	kg	1.80E+5	1	3.05	(na,5,na,1,na,BU:1.05); Estimation
	transport, freight, lorry 16-32 metric ton, fleet average	RER	tkm	2.07E+4	1	3.95	(5,5,na,na,na,BU:2); Standard distance 100km
	transport, freight, rail	RER	tkm	1.24E+5	1	3.95	(5,5,na,na,na,BU:2); Standard distance 600km

9.3.2 Direct emissions

Direct emissions are estimated as shown in Tab. 9.7 and mainly explained in a former study (Jungbluth 2007). To avoid double counting, emissions of CH_4, SO_2 and NO_x were removed as they are assessed separately for overall extraction of crude oil and natural gas according to chapter 9.5. Other emissions are assessed in analogy to the engines of trucks. Benzene is assumed to be emitted with 0.02 kg/TJ_{In} and Benzo(a)pyrene with 0.1E-3 kg/TJ_{In} and heavy metal emissions corresponding to the content in diesel. For chromium VI, a share of 0.2% of overall chromium is assumed.

Tab. 9.7 Life cycle inventory for diesel, burned in diesel-electric generating set, without CH_4, SO_2 and NO_x-emissions

	Name	Location	InfrastructureProce	Unit	*Diesel, burned in diesel-electric generating set, without SO2, Nox and CH4-emissions*	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				*GLO*			
	InfrastructureProcess				*0*			
	Unit				*MJ*			
product	Diesel, burned in diesel-electric generating set, without SO2, Nox and CH4-emissions	GLO	0	MJ	1.00E+0			
technosphere	diesel, at regional storage	RER	0	kg	2.34E-2	1	1.24	(3,3,3,3,1,BU:1.05); Calculation
	lubricating oil, at plant	RER	0	kg	6.70E-5	1	2.06	(3,5,1,3,5,BU:1.05); Rough estimation with data for cogen 200kWe
	diesel-electric generating set production 10MW	RER	1	unit	1.85E-10	1	3.12	(3,5,3,3,3,BU:3); Estimation
Disposal	disposal, used mineral oil, 10% water, to hazardous waste incineration	CH	0	kg	6.70E-5	1	2.06	(3,5,1,3,5,BU:1.05); Rough estimation
emission air, low population density	Benzene	-	-	kg	2.00E-8	1	3.03	(3,3,3,3,1,BU:3); Extrapolation
	Benzo(a)pyrene	-	-	kg	1.00E-10	1	3.03	(3,3,3,3,1,BU:3); Extrapolation
	Carbon dioxide, fossil	-	-	kg	7.30E-2	1	1.10	(2,3,2,3,1,BU:1.05); Literature
	Carbon monoxide, fossil	-	-	kg	6.80E-4	1	5.03	(3,3,3,3,1,BU:5); Literature
	Dinitrogen monoxide	-	-	kg	6.00E-6	1	1.54	(3,3,3,3,1,BU:1.5); Literature
	Mercury	-	-	kg	4.67E-10	1	5.08	(3,3,3,3,3,BU:5); Literature on content in diesel
	Methane, fossil	-	-	kg	0	1	1.51	(2,3,1,3,1,BU:1.5); Set 0 as assessed in overall emissions for extraction
	Nitrogen oxides	-	-	kg	0	1	1.51	(2,3,1,3,1,BU:1.5); Set 0 as assessed in overall emissions for extraction
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	9.24E-5	1	1.51	(2,3,1,3,1,BU:1.5); Environmental report
	Particulates, < 2.5 um	-	-	kg	1.70E-4	1	3.03	(3,3,3,3,1,BU:3); Literature
	Sulfur dioxide	-	-	kg	0	1	1.09	(2,3,1,3,1,BU:1.05); Set 0 as assessed in overall emissions for extraction
	Cadmium	-	-	kg	2.34E-10	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions
	Copper	-	-	kg	3.97E-8	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions
	Chromium	-	-	kg	1.17E-9	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions
	Chromium VI	-	-	kg	2.34E-12	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions, 0.2% share of Cr is Cr VI
	Nickel	-	-	kg	1.64E-9	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions
	Selenium	-	-	kg	2.34E-10	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions
	Zinc	-	-	kg	2.34E-8	1	5.06	(2,3,1,1,3,BU:5); Literature for automobile emissions

9.4 Natural gas burned in gas turbine

In this study, only the existing dataset for the combustion of sweet gas is adjusted as presented in Tab. 9.8. Emissions of methane, SO_2 and NO_x were removed as they are assessed separately for overall extraction of crude oil and natural gas according to chapter 9.5.

Tab. 9.8 Unit process raw data for burning of sour natural gas in gas turbine

	Name	Location	InfrastructureProce	Unit	*sweet gas, burned in gas turbine, production*	UncertaintyType	StandardDeviation 95%	GeneralComment
	Location				*GLO*			
	InfrastructureProcess				*0*			
	Unit				*MJ*			
product	sweet gas, burned in gas turbine, production	GLO	0	MJ	1.00E+0			
Input from nature	Gas, natural/m3	-	-	Nm3	2.78E-2	1	1.92	(3,3,5,3,3,BU:1.05); environmental report for Norway
technosphere	gas turbine, 10MWe, at production plant	RER	1	unit	3.37E-10	1	3.29	(3,3,5,3,3,BU:3); environmental report for Norway
emission air, low population density	Methane, fossil	-	-	kg	0	1	1.84	(3,3,5,3,3,BU:1.5); Set 0 as assessed in overall emissions for extraction
	Carbon dioxide, fossil	-	-	kg	6.69E-2		1.58	(3,3,5,3,3,BU:1.05); environmental report for Norway
	Carbon monoxide, fossil	-	-	kg	1.39E-4	1	5.33	(3,3,5,3,3,BU:5); environmental report for Norway
	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	3.07E-6	1	1.84	(3,3,5,3,3,BU:1.5); environmental report for Norway
	Nitrogen oxides	-	-	kg	0	1	1.84	(3,3,5,3,3,BU:1.5); Set 0 as assessed in overall emissions for extraction
	Dinitrogen monoxide	-	-	kg	2.50E-7	1	1.84	(3,3,5,3,3,BU:1.5); Assumption Faist-Emmenegger 2007
	Sulfur dioxide	-	-	kg	0	1	1.58	(3,3,5,3,3,BU:1.05); Set 0 as assessed in overall emissions for extraction
	Mercury	-	-	kg	2.78E-9	1	5.33	(3,3,5,3,3,BU:5); Assumption Faist-Emmenegger 2007
	Radon-222	-	-	kBq	5.56E-3	1	3.29	(3,3,5,3,3,BU:3); Assumption Faist-Emmenegger 2007

9.5 SO_2 and NO_x

Sulphur oxide (SO_2) emissions arise through oxidation during combustion of sulphur naturally contained within fuel gas or flared gas (H S content) and within diesel and other liquid fuels (sulphur content). Emissions of nitrogen oxides, (principally nitric oxide and nitrogen dioxide, expressed as NO_x), occur almost exclusively from the combustion of natural gas or other fuels. These emissions are heavily influenced by energy use and are also a function of the combustion equipment, loading and technology.

Regional emission data reported to the international organization of oil and gas producing companies are listed in Tab. 9.9 and Tab. 9.10 (IOGP 2020). These data are directly considered in the inventories for oil and gas extraction. The emissions are not accounted for in the combustion processes applied within these inventories (c.f. chapters9.1.4, 9.3.2 and 9.4).

Tab. 9.9 Sulphur dioxide (SO_2) emissions in kg per kg oil equivalent

Sulphur dioxide released	**Average 2017 to 2019**	
Region	**kg/kg OE**	**Source**
Africa	5.00E-05	IOGP 2020
Asia	5.00E-05	IOGP 2020
Europe	2.33E-05	IOGP 2020
Middle East	6.67E-04	IOGP 2020
North America	1.03E-04	IOGP 2020
Russia & Central Asia	2.03E-04	IOGP 2020
South & Central America	6.00E-05	IOGP 2020
Global	**2.03E-04**	**weighted average**

Tab. 9.10 Nitrogen oxide (NO_x) emissions in kg per kg oil equivalent

NOx released	**Average 2017 to 2019**	
Region	**kg/kg OE**	**Source**
Africa	3.83E-04	IOGP 2020
Asia	3.73E-04	IOGP 2020
Europe	2.90E-04	IOGP 2020
Middle East	1.63E-04	IOGP 2020
North America	5.27E-04	IOGP 2020
Russia & Central Asia	2.10E-04	IOGP 2020
South & Central America	5.23E-04	IOGP 2020
Global	**3.44E-04**	**weighted average**

9.6 Use and emissions of Halon and other chemicals in firefighting equipment

No updates are made in this chapter compared to Meili & Jungbluth 2018.

This means, a generic amount 1.16e-8 kg of “Methane, Bromo trifluoro-, Halon 1301” is emitted per kg oil equivalent and a generic amount of 4.66e-8kg of “Methane, trifluoro-, HFC-23” is emitted per kg oil equivalent. Both emissions are only allocated to offshore production.

Halon 1301 was used in stationery firefighting equipment for offshore operations. Because of its ozone depletion potential, industrial states stopped the production of halon in 1994, in line with the requirements of the Montreal Protocol.[26] The use, however, continues to be permitted for certain critical uses as set out in Annex VI to Regulation (EC) No 1005/2009. These critical uses also include the protection of spaces where flammable liquid or gas could be released in oil, gas and petrochemicals facilities.[27]

- Halon is only required to support legacy facilities; all new facilities are halon - free.
- Legacy facilities in the far north (i.e., Alaskan North Slope in the United States and parts of the former Soviet Union) will continue to require the use of halons in occupied spaces owing to severe ambient (very low temperature) conditions.

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[26] http://www.ecoinvent.org/support/ecoinvent-forum/topic.html?&tid=279, online 18.10.2017

[27] http://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32010R0744&from=EN, online 01.11.2017

- Facility owners neither own nor control the quantities of halons needed to support operations over the continually extended time horizons. This situation will continue to place demands on the level of available halon stocks. However, owing to the adoption of alternatives in new facilities, this sector has reduced its future demand for the diminishing supplies of halon (UNEP 2014)

In most cases, existing facilities with halon 1301 fixed systems were designed and constructed as an integral part of the safety system design as well as the physical layout of the facility. After extensive research, it has been determined that in some cases the retrofit of such facilities with currently available alternative systems is not economically feasible, and that current research is unlikely to lead to an economic solution. Thus, these facilities will likely rely on existing halon banks for their operating lifetimes (UNEP 2014).

For new facilities, companies are adopting an inherently safe design approach to the protection of their facilities. This means preventing the release of hydrocarbons and eliminating the availability of flammable or explosive materials. Only when all such measures have been considered, and a residual risk of the hazard remains, are other risk reducing measures considered. In most cases, new technology detection systems are employed to shut-down and blow-down processes and turn on high-rate ventilation systems rather than closing the space and trying to inert it with an extinguishing agent. However, where an inerting agent is still required in occupied spaces, halon 1301 has been replaced by Trifluoromethane (HFC-23) or FK-5-1-12, if temperatures permit. Currently, HFC-23 is the only alternative that can be used in very cold climatic conditions. Halon 1301 is also used for fire and explosion suppression systems that protect offshore oil exploration platforms in the tropical climatic zone in Asia (UNEP 2014).

Parties in the Asia pacific region, including India, use halon 1301 systems in refineries, gas pumping stations and offshore oil platforms. Refineries and oil pumping stations have/are gradually switching over to dry powders in pumping stations, HFC-227ea, FK-5 -1-12, and inert gases in refineries where it is technically feasible given space and weight concerns. For offshore oil platforms, space and weight are still a big concern and thus the replacement of old legacy systems and those systems on new platforms have been delayed. Thus, for such applications halon requirements still exist. Oil companies are obtaining this halon from local sources of recovered halon, which they use to refill existing cylinders.

However, there is no halon recycling, banking, or quality testing facility for such recovered halon in this part of Asia. Therefore, the quality and effectiveness of such recovered halon is currently a major concern. In onshore halon 1301 systems, where a clean agent is important, some oil companies are hesitating to switch over to HFCs because of their high GWP as they do not want to switch over twice. HFC-23 has never been used in this region by the oil industry (UNEP 2014).

It is assumed that for European offshore plants 0.7 $mg_{halon}/t_{crude\ oil}$ is emitted, for the remaining areas 58 $mg_{halon}/t_{crude\ oil}$. Because test flooding, false alarms, losses from filling and leakage cause 70-90% of the total emissions, halon demand to extinguish fires in case of accidents is not assigned (Jungbluth 2007).

Based on the above information it is assumed, that 20% of the oil platforms still use Halon 1301. As there is no ecoinvent data available for the production of FK-5-1-12, the remaining share of flame retardants (80%) is modelled with Trifluoromethane (HFC-23).

HFC-23 has a high global warming potential compared to the other flame retardants while FK-5-1-12 has a GWP of 1[28]. Therefore, this replacement will overestimate the impacts on climate change.

No such emissions are modelled for onshore operations.

The same amounts that are emitted are considered as an input for the products. As there is no dataset for the production of such flame retardants available in the current ecoinvent database, it is approximated with the general dataset for organic chemicals.

10 Emissions to water & soil

10.1 Produced water

No updates are made in this chapter compared to Meili & Jungbluth 2018. Where no country specific values were available in the former study, generic estimates were used in the current model.

10.1.1 Overview

Produced water may originate as natural water in the formations holding oil and gas or can be water that was previously injected into those formations through activities designed to increase oil production from the formations such as water flooding or steam flooding operations. In some situations, additional water from other formations adjacent to the hydrocarbon-bearing layers may become part of the produced water that comes to the surface.

When the oil and gas flows to the surface, the produced water is brought to the surface with the hydrocarbons. Produced water contains some of the chemical characteristics of the formation from which it was produced and from the associated hydrocarbons.

Most wells in unconventional oil and gas formations are stimulated using hydraulic fracturing, through which water is injected under pressure into the formation to create pathways allowing the oil or gas to be recovered in a cost-effective manner. Immediately following hydraulic fracturing in the well (a frack job), some of the injected water returns to the surface and is known as flowback water. Flowback water is often managed in a similar manner to produced water and some engineers in the industry consider it as part of the produced water flow stream.[29]

At the beginning of production of a new field this fraction of co-produced water is usually small. If water content exceeds the maximal content tolerable for transport in the pipeline, water is separated with a separator. From ca. 10-20% watering, the drilling usually stops conveying automatically. Then, e.g., subsurface pumps need to be installed. In total, the entire load of produced water can exceed the amount of produced oil in an oil field by ten times during the economic lifetime. If watering is 90 to 95% (i.e., 10-20 times more water than oil), production usually ceases for economic reasons (Jungbluth 2007).

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[28] Product documentation of special hazard fire protection fluid: https://web.archive.org/web/20110927030243/http://solutions.3m.com/wps/portal/3M/en_US/Novec/Home/Product_Information/Product_Navigator/?PC_7_RJH9U5230GE5D02J33P04L38E5_univid=1180599171161, online 14.12.2017

[29] http://www.producedwatersociety.com/produced-water-101/, online 19.10.2017

10.1.2 Disposal

Produced water receives various types of treatment before it is disposed, reused, or otherwise managed. Many types of processes and technologies can be used to treat produced water depending on how clean the water must be before it moves on to its destination. Produced water must be treated to remove oil and grease and toxic chemicals before discharging it to the ocean from an offshore platform.

Produced water that is discharged to onshore freshwater rivers must be further treated to reduce salt content. Water that is injected for either enhanced recovery or for disposal is treated in a different way from water that is discharged. The treatment processes used prior to injection are designed to remove free oil, solids, and bacteria. Chemicals are often used to enhance treatment processes and to protect underground formations and equipment.

As oil, gas, and water are produced from a well, the fluids need to be separated into separate streams. This is typically done using some type of gravity separation, such as API separators, free water knockout tanks, or gun barrel separators. In addition to separating the fluids, these devices allow for large solid particles to settle out. When the oil and water are emulsified, they can be separated by applying heat or appropriate chemical treatments.

In most instances, several technologies are used as stages in a pre-treatment/treatment system.

Most U.S. produced water was re-injected. About 91% of the produced water was re-injected underground (this included water injected for enhanced recovery, water injected for disposal, and water sent to offsite commercial disposal).[29] About 80% of the produced water from offshore wells was treated on the platform and discharged to the ocean. Only about 3% of onshore produced water was discharged. The percentage discharged from all wells (onshore and offshore combined) was about 5.6%.[29] From this it can be concluded that most of the water is injected again and only a small part of the extracted produced water therefore causes emissions into the environment.

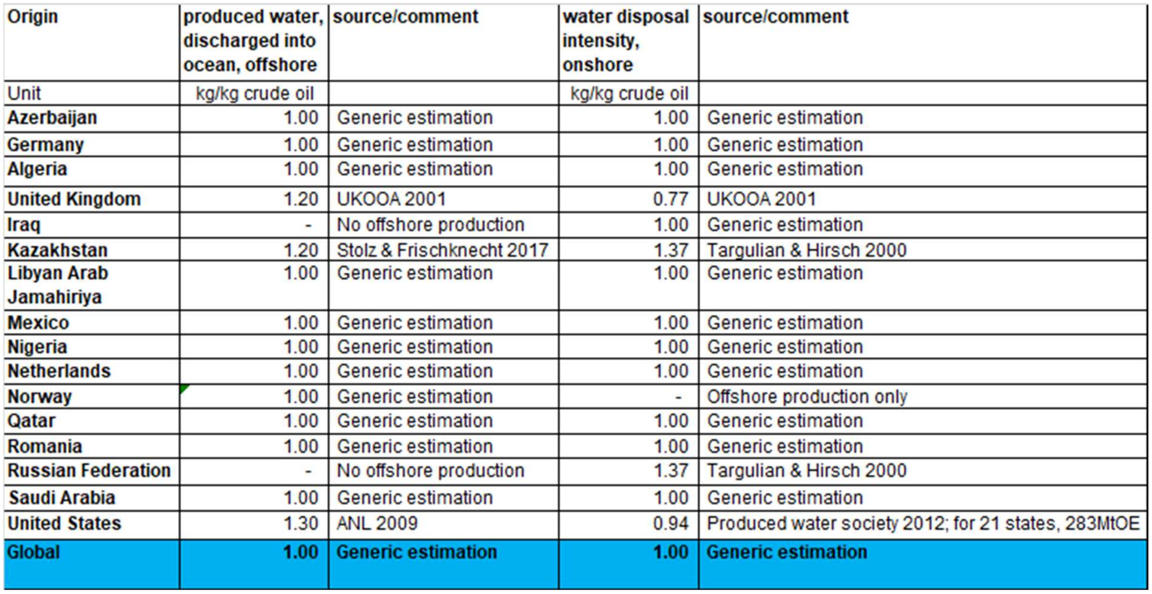
10.1.3 Allocation

For combined oil and gas production, 100% of the produced water is allocated to oil production as the water is used for and released due to EOR.

10.1.4 Amount

On- and offshore, the amount of water disposed to surface water like river and ocean seems to stay rather constant, as shown in Tab. 10.1. This might be the case as most of the produced water is reinjected to the ground[29] (Agip Division 2001; ANL 2009; Tiedeman et al. 2012; UKOOA 2001). Only for a few countries, specific values are available (ANL 2009; Stolz & Frischknecht 2017; Targulian & Hirsch 2000; UKOOA 2001)[29]. Where no specific amount was available for a country average, a generic value of 1kg produced water per kg of crude oil was used in the model for on- and offshore production.

Tab. 10.1 Amount of produced water from off- and onshore production, disposed to surface water in different regions



Origin	produced water, discharged into ocean, offshore	source/comment	water disposal intensity, onshore	source/comment
Unit	kg/kg crude oil		kg/kg crude oil	
Azerbaijan	1.00	Generic estimation	1.00	Generic estimation
Germany	1.00	Generic estimation	1.00	Generic estimation
Algeria	1.00	Generic estimation	1.00	Generic estimation
United Kingdom	1.20	UKOOA 2001	0.77	UKOOA 2001
Iraq	-	No offshore production	1.00	Generic estimation
Kazakhstan	1.20	Stolz & Frischknecht 2017	1.37	Targulian & Hirsch 2000
Libyan Arab Jamahiriya	1.00	Generic estimation	1.00	Generic estimation
Mexico	1.00	Generic estimation	1.00	Generic estimation
Nigeria	1.00	Generic estimation	1.00	Generic estimation
Netherlands	1.00	Generic estimation	1.00	Generic estimation
Norway	1.00	Generic estimation	-	Offshore production only
Qatar	1.00	Generic estimation	1.00	Generic estimation
Romania	1.00	Generic estimation	1.00	Generic estimation
Russian Federation	-	No offshore production	1.37	Targulian & Hirsch 2000
Saudi Arabia	1.00	Generic estimation	1.00	Generic estimation
United States	1.30	ANL 2009	0.94	Produced water society 2012; for 21 states, 283MtOE
Global	**1.00**	**Generic estimation**	**1.00**	**Generic estimation**

10.1.5 Composition and pollutants

No updates are made in this chapter compared to Meili & Jungbluth 2018.

The physical and chemical properties of produced water vary considerably depending on the geographic location of the field, the geologic formation from which the water was produced, and the type of hydrocarbon product being produced. The major constituents of concern according to the produced water society[29] are:

- *Salt content (often expressed as salinity, conductivity, or total dissolved solids (TDS).* Although some produced water is nearly fresh (<3,000 mg/L TDS), most produced water is saltier than seawater (~35,000 mg/L) and can be >300,000 mg/L). Removing salt is not difficult, but it is usually costly.
- *Oil and grease.* This is not a single chemical compound; the analytical method for oil and grease measures various organic compounds associated with hydrocarbons in the formation). Oil and grease can be found in different physical forms:
  - Free oil: large droplets - readily removable by gravity separation methods
  - Dispersed oil: small droplets - somewhat difficult to remove; and
  - Dissolved oil: hydrocarbons and other similar materials dissolved in the water stream - very challenging to eliminate.
- *Inorganic and organic toxic compounds.* The toxics may be introduced as chemical additives to improve drilling and production operations or they may leach into the produced water from the formation rock or the hydrocarbon.
- *Naturally occurring radioactive material (NORM).* Some hydrocarbon-bearing formations contain natural radiation that leaches into the produced water. The presence and concentration of NORM varies between formations.

Because data on oil emissions is available for different production areas, this value is not used directly at discharge of produced water but is assessed in the inventory of crude oil production directly (see chapter 10.3).

Formation water contains radionuclides from natural decay processes. The contents strongly depend on the geologic situation. A correlation between content of dissolved solids and content of nuclides does not exist. In fact, the content of ^{238}U and ^{232}Th in the adjacent rock is decisive. For scale formation, however, contents of solid matter in the formation water are relevant due to the chemical relationship of radium with strontium and barium (c.f. chapter 11.1)

The data basis in the former study was narrow and therefore extended with new data to have more complete background-data (Neff et al. 2011). An additional discussion and compilation of information can be found in the appendix, in table A.12 and A.13 of a former study (Jungbluth 2007).

Tab. 10.2 shows the life cycle inventory for the chemical composition of discharged produced water in offshore production. For the discharge onshore, the same data is used, but as subcategory for water emissions “to river” is indicated instead of “to ocean”. Uncertainties of this estimation are relatively high because different values are expected for different regions and there are only values for a random sample of the various regions. Considered literature is shown in Tab. 10.3.

The water balance for type of freshwater input and reinjection and discharge of (treated) produced water is modelled at country level as different countries and compartments are involved (see chapter 12).

Tab. 10.2 Life cycle inventory for the chemical composition of discharged produced water in offshore production. Data for onshore emissions are recorded with the same numbers and with subcategory river instead of ocean

Name	Location	Category	SubCategory	InfrastructureProcess	Unit	*discharge, produced water, offshore*	UncertaintyType	StandardDeviation95%	GeneralComment
Location						*OCE*			
InfrastructureProcess						*0*			
Unit						*kg*			
Acenaphthene	-	water	ocean	-	kg	2.36E-9	1	3.08	(2,3,3,3,3,na); Literature, specific PAH
Acenaphthylene	-	water	ocean	-	kg	1.17E-9	1	3.07	(2,2,3,3,3,na); Literature, specific PAH
Ammonium, ion	-	water	ocean	-	kg	1.62E-4	1	5.09	(2,2,3,3,3,na); Literature
Arsenic	-	water	ocean	-	kg	2.78E-8	1	5.09	(2,2,3,3,3,na); Literature
Barium	-	water	ocean	-	kg	1.29E-4	1	5.09	(2,2,3,3,3,na); Literature
Benzene	-	water	ocean	-	kg	3.72E-6	1	3.07	(2,2,3,3,3,na); Literature
Benzene, ethyl-	-	water	ocean	-	kg	1.34E-6	1	3.08	(3,2,3,3,3,na); Literature
Boron	-	water	ocean	-	kg	1.20E-5	1	5.09	(2,2,3,3,3,na); Literature
Bromine	-	water	ocean	-	kg	3.50E-5	1	3.30	(3,3,5,3,3,na); Literature
BOD5, Biological Oxygen Demand	-	water	ocean	-	kg	5.25E-4	1	1.65	(4,2,3,3,3,na); Threshold limit for IN
Cadmium	-	water	ocean	-	kg	3.51E-9	1	5.09	(2,2,3,3,3,na); Literature
Calcium	-	water	ocean	-	kg	8.58E-3	1	1.61	(3,2,3,3,3,na); Literature
Carbonate	-	water	ocean	-	kg	2.79E-4	1	5.09	(2,2,3,3,3,na); Literature
Carboxylic acids, unspecified	-	water	ocean	-	kg	1.84E-4	1	3.29	(2,3,5,3,3,na); Environmental report for NO
Cesium	-	water	ocean	-	kg	5.00E-8	1	5.34	(3,3,5,3,3,na); Literature
Chloride	-	water	ocean	-	kg	7.18E-2	1	1.61	(3,2,3,3,3,na); Literature
Chromium	-	water	ocean	-	kg	1.09E-8	1	5.09	(2,2,3,3,3,na); Literature
COD, Chemical Oxygen Demand	-	water	ocean	-	kg	3.50E-5	1	1.89	(4,3,5,3,3,na); Threshold limit for IN
Copper	-	water	ocean	-	kg	3.93E-8	1	5.09	(2,2,3,3,3,na); Literature
Fluoride	-	water	ocean	-	kg	5.00E-7	1	1.86	(3,3,5,3,3,na); Literature
Hydrocarbons, aliphatic, alkanes, unspecified	-	water	ocean	-	kg	6.50E-6	1	3.30	(3,3,5,3,3,na); Literature
Hydrocarbons, aliphatic, unsaturated	-	water	ocean	-	kg	6.00E-7	1	3.30	(3,3,5,3,3,na); Literature
Hydrocarbons, aromatic	-	water	ocean	-	kg	2.60E-5	1	3.30	(3,3,5,3,3,na); Literature
Iodide	-	water	ocean	-	kg	5.83E-5	1	1.61	(3,2,3,3,3,na); Literature
Iron	-	water	ocean	-	kg	1.19E-5	1	5.09	(2,2,3,3,3,na); Literature
Lead	-	water	ocean	-	kg	1.13E-8	1	5.09	(2,2,3,3,3,na); Literature
Lead-210	-	water	ocean	-	kBq	4.75E-2	1	5.09	(2,2,3,3,3,na); Literature
Lithium	-	water	ocean	-	kg	1.33E-5	1	5.09	(2,2,3,3,3,na); Literature
Manganese	-	water	ocean	-	kg	3.77E-6	1	5.10	(3,2,3,3,3,na); Literature
Magnesium	-	water	ocean	-	kg	1.46E-3	1	5.10	(3,2,3,3,3,na); Literature
Mercury	-	water	ocean	-	kg	2.50E-9	1	5.09	(2,2,3,3,3,na); Literature
Molybdenum	-	water	ocean	-	kg	6.25E-10	1	5.09	(2,2,3,3,3,na); Literature
Nickel	-	water	ocean	-	kg	1.09E-7	1	5.09	(2,2,3,3,3,na); Literature
Oils, unspecified	-	water	ocean	-	kg	-	1	3.07	(2,2,3,3,3,na); Directly reported for the single country
PAH, polycyclic aromatic hydrocarbons	-	water	ocean	-	kg	1.09E-6	1	3.07	(2,2,3,3,3,na); Literature
Phenol	-	water	ocean	-	kg	4.00E-6	1	3.29	(2,3,5,3,3,na); Environmental report for NO
Polonium-210	-	water	ocean	-	kBq	1.62E-6	1	5.09	(2,2,3,3,3,na); Literature
Potassium	-	water	ocean	-	kg	1.01E-3	1	1.61	(3,2,3,3,3,na); Literature
Radium-224	-	water	ocean	-	kBq	1.26E-2	1	3.08	(3,2,3,3,3,na); Literature
Radium-226	-	water	ocean	-	kBq	3.04E-1	1	3.07	(2,2,3,3,3,na); Literature
Radium-228	-	water	ocean	-	kBq	5.00E-2	1	3.08	(3,2,3,3,3,na); Literature
Rubidium	-	water	ocean	-	kg	5.00E-7	1	2.31	(3,3,5,3,3,na); Literature
Silver	-	water	ocean	-	kg	3.00E-8	1	5.34	(3,3,5,3,3,na); Literature
Sodium	-	water	ocean	-	kg	3.51E-2	1	2.09	(3,2,3,3,3,na); Literature
Strontium	-	water	ocean	-	kg	3.42E-4	1	5.10	(3,2,3,3,3,na); Literature
Sulfate	-	water	ocean	-	kg	3.45E-4	1	5.09	(2,2,3,3,3,na); Literature
Suspended solids, unspecified	-	water	ocean	-	kg	4.50E-5	1	1.89	(4,3,5,3,3,na); Threshold limit for IN
Thorium-228	-	water	ocean	-	kBq	1.00E-2	1	3.30	(3,3,5,3,3,na); Literature
Thorium-232	-	water	ocean	-	kBq	3.24E-7	1	5.09	(2,2,3,3,3,na); Literature
DOC, Dissolved Organic Carbon	-	water	ocean	-	kg	2.95E-4	1	1.86	(3,3,5,3,3,na); Literature
TOC, Total Organic Carbon	-	water	ocean	-	kg	3.05E-3	1	1.61	(3,2,3,3,3,na); Literature
Toluene	-	water	ocean	-	kg	5.85E-6	1	3.08	(3,2,3,3,3,na); Literature
Vanadium	-	water	ocean	-	kg	3.25E-10	1	5.09	(2,2,3,3,3,na); Literature
VOC, volatile organic compounds, unspecified origin	-	water	ocean	-	kg	1.75E-5	1	3.30	(3,3,5,3,3,na); Literature
Uranium-238	-	water	ocean	-	kBq	2.50E-5	1	5.09	(2,2,3,3,3,na); Literature
Xylene	-	water	ocean	-	kg	4.88E-6	1	3.08	(3,2,3,3,3,na); Literature
Zinc	-	water	ocean	-	kg	1.00E-5	1	5.09	(2,2,3,3,3,na); Literature

Tab. 10.3 Literature values considered for chemical composition of discharged produced water in offshore and onshore production (cf. Tab. 10.2).

	Name	Unit	*discharge, produced water, offshore*	*Neff 2011, average*	*Neff 2011, average*	*Neff 2011, min*	*Neff 2011, max*	*Neff 2011, average*	*Jungbluth 2007*
	Location		*OCE*	*MX*	*IN*	*OCE*	*OCE*	*OCE*	*OCE*
	InfrastructureProcess		*0*						
	Unit		*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*
emission water, ocean	Acenaphthene	kg	2.36E-9	-	-	-	4.10E-9	2.05E-9	6.22E-10
	Acenaphthylene	kg	1.17E-9	-	-	-	2.30E-9	1.15E-9	3.89E-11
	Ammonium, ion	kg	1.62E-4	-	-	2.30E-5	3.00E-4	1.62E-4	
	Arsenic	kg	2.78E-8	1.58E-8	-	5.00E-10	9.00E-8	4.53E-8	1.03E-8
	Barium	kg	1.29E-4	-	-	3.01E-7	3.42E-4	1.71E-4	8.70E-5
	Benzene	kg	3.72E-6	1.62E-6	1.19E-6	8.40E-08	2.80E-06	1.44E-6	6.00E-06
	Benzene, ethyl-	kg	1.34E-6	2.84E-7	1.88E-7	3.80E-8	5.30E-7	2.84E-7	2.40E-6
	Boron	kg	1.20E-5	-	-	8.00E-6	4.00E-5	2.40E-5	-
	Bromine	kg	3.50E-5	-	-			-	7.00E-5
	BOD5, Biological Oxygen Demand	kg	5.25E-4	-	-	5.95E-4	1.44E-3	1.02E-3	3.00E-5
	Cadmium	kg	3.51E-9	5.25E-10	-	2.00E-11	1.00E-8	5.01E-9	2.00E-9
	Calcium	kg	8.58E-3	-	-	2.53E-3	2.58E-2	1.42E-2	3.00E-3
	Carbonate	kg	2.79E-4	-	-	1.07E-4	1.01E-3	5.59E-4	-
	Carboxylic acids, unspecified	kg	1.84E-4	-	-			-	3.68E-4
	Cesium	kg	5.00E-8	-	-			-	1.00E-7
	Chloride	kg	7.18E-2	-	-	4.61E-2	1.41E-1	9.36E-2	5.00E-2
	Chromium	kg	1.09E-8	7.50E-10	-	1.00E-10	3.40E-8	1.71E-8	4.65E-9
	COD, Chemical Oxygen Demand	kg	3.50E-5	-	-			-	7.00E-5
	Copper	kg	3.93E-8	2.00E-10	-	2.00E-10	1.37E-7	6.86E-8	1.00E-8
	Fluoride	kg	5.00E-7	-	-			-	1.00E-6
	Hydrocarbons, aliphatic, alkanes, unspecified	kg	6.50E-6	-	-			-	1.30E-5
	Hydrocarbons, aliphatic, unsaturated	kg	6.00E-7	-	-			-	1.20E-6
	Hydrocarbons, aromatic	kg	2.60E-5	-	-			-	5.20E-5
	Iodide	kg	5.83E-5	-	-	3.00E-6	2.10E-4	1.07E-4	1.00E-5
	Iron	kg	1.19E-5	-	-	1.91E-6	3.70E-5	1.95E-5	4.30E-6
	Lead	kg	1.13E-8	1.41E-8	-	9.00E-11	4.50E-8	2.25E-8	7.00E-13
	Lead-210	kBq	4.75E-2	-	-	5.00E-5	1.90E-1	9.49E-2	-
	Lithium	kg	1.33E-5	-	-	3.00E-6	5.00E-5	2.65E-5	-
	Manganese	kg	3.77E-6	4.00E-6	-	8.10E-8	7.00E-6	3.54E-6	4.00E-6
	Magnesium	kg	1.46E-3	-	-	5.30E-4	4.30E-3	2.42E-3	5.00E-4
	Mercury	kg	2.50E-9	1.05E-10	-	1.00E-11	1.00E-8	5.01E-9	1.90E-12
	Molybdenum	kg	6.25E-10	-	-	3.00E-10	2.20E-9	1.25E-9	-
	Nickel	kg	1.09E-7	4.00E-9	-	1.00E-10	4.20E-7	2.10E-7	6.99E-9
	Oils, unspecified	kg	-	-	-	2.90E-5	4.00E-5	3.45E-5	-
	PAH, polycyclic aromatic hydrocarbons	kg	1.09E-6	-	-	4.00E-8	2.15E-6	1.09E-6	4.68E-7
	Phenol	kg	4.00E-6	-	-			-	8.00E-6
	Polonium-210	kBq	1.62E-6	-	-	1.85E-7	6.29E-6	3.24E-6	-
	Potassium	kg	1.01E-3	-	-	1.30E-4	3.10E-3	1.62E-3	4.00E-4
	Radium-224	kBq	1.26E-2	-	-	5.00E-4	4.00E-2	2.02E-2	5.00E-3
	Radium-226	kBq	3.04E-1	-	-	1.85E-6	1.20E+0	5.99E-1	8.00E-3
	Radium-228	kBq	5.00E-2	-	-	3.00E-4	1.80E-1	9.01E-2	1.00E-2
	Rubidium	kg	5.00E-7	-	-			-	1.00E-6
	Silver	kg	3.00E-8	-	-			-	6.00E-8
	Sodium	kg	3.51E-2	-	-	2.30E-2	5.73E-2	4.02E-2	3.00E-2
	Strontium	kg	3.42E-4	-	-	7.00E-6	1.00E-3	5.04E-4	1.80E-4
	Sulfate	kg	3.45E-4	-	-	2.10E-4	1.17E-3	6.90E-4	-
	Suspended solids, unspecified	kg	4.50E-5	-	-			-	9.00E-5
	Thorium-228	kBq	1.00E-2	-	-			-	2.00E-2
	Thorium-232	kBq	3.24E-7	-	-	2.96E-7	9.99E-7	6.48E-7	-
	DOC, Dissolved Organic Carbon	kg	2.95E-4	-	-			-	5.90E-4
	TOC, Total Organic Carbon	kg	3.05E-3	-	-	1.00E-7	1.10E-2	5.50E-3	5.90E-4
	Toluene	kg	5.85E-6	1.02E-6	4.45E-7	8.90E-8	1.70E-6	8.95E-7	1.08E-5
	Vanadium	kg	3.25E-10	-	-	1.00E-10	1.20E-9	6.50E-10	-
	VOC, volatile organic compounds, unspecified origin	kg	1.75E-5	-	-			-	3.50E-5
	Uranium-238	kBq	2.50E-5	-	-	2.96E-7	9.99E-5	5.01E-5	-
	Xylene	kg	4.88E-6	4.40E-7	2.47E-7	1.30E-8	7.20E-7	3.67E-7	9.40E-6
	Zinc	kg	1.00E-5	1.81E-6	-	1.00E-9	2.60E-5	1.30E-5	7.00E-6

10.2 Production chemicals

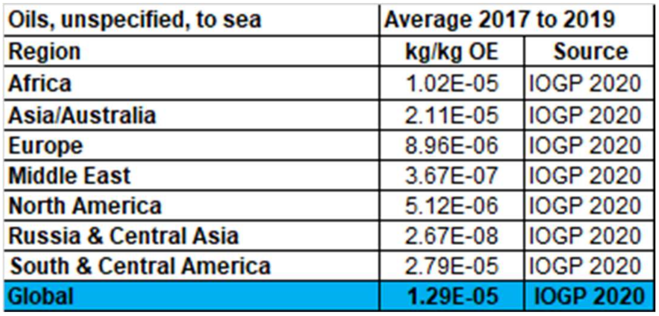
It can be assumed that the emissions of production chemicals were already recorded with the composition of production water. The amount of chemicals that are injected depends on the possibility to force produced water into abandoned oil and gas fields or aquifers (Jungbluth 2007).

10.3 Oil spills to water

Operational oil spills include all types of spills that might occur during drilling and pumping and exclude spills related to transportation and refining.

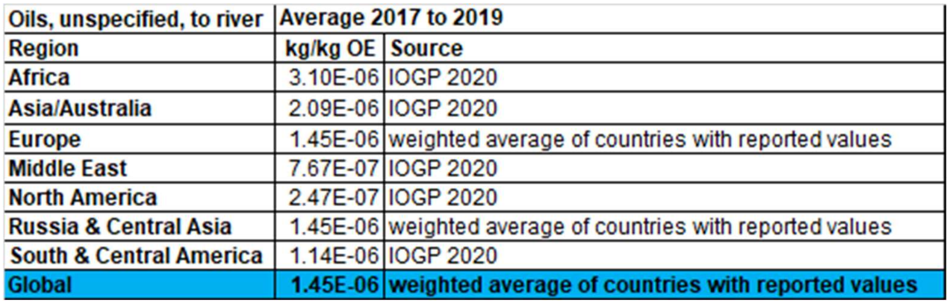
In a former study, the values vary widely with 0.019kg oil/kg oil-eq. extracted offshore spilled to water in Russia and 0.00007 kg/kg oil-eq. offshore in Nigeria (Jungbluth 2007). According to IOGP this variation in the ratio of kg oil spilled per kg oil equivalent extracted is visible (see Tab. 10.4). The share of offshore production in Nigeria is around 90% and in Russia close to 0% (c.f. chapter 4.1). As the values reported by IOGP are in relation to the total amount of oil equivalents extracted on- and offshore, it seems plausible that the values for Nigeria and the whole region Africa are quite similar and the ones for Russia are by many orders of magnitude smaller (IOGP 2020).

Tab. 10.4 Amount of oil spilled to sea per kg of oil equivalent extracted per region, average of latest 3 years reported (offshore, IOGP 2020)



Oils, unspecified, to sea	Average 2017 to 2019	
Region	**kg/kg OE**	**Source**
Africa	1.02E-05	IOGP 2020
Asia/Australia	2.11E-05	IOGP 2020
Europe	8.96E-06	IOGP 2020
Middle East	3.67E-07	IOGP 2020
North America	5.12E-06	IOGP 2020
Russia & Central Asia	2.67E-08	IOGP 2020
South & Central America	2.79E-05	IOGP 2020
Global	**1.29E-05**	**IOGP 2020**

Tab. 10.5 Amount of oil spilled to rivers per kg of oil equivalent extracted per region, average for 3 latest years (onshore, IOGP 2020). For the regions where no spills were reported, the global, weighted average is assumed.

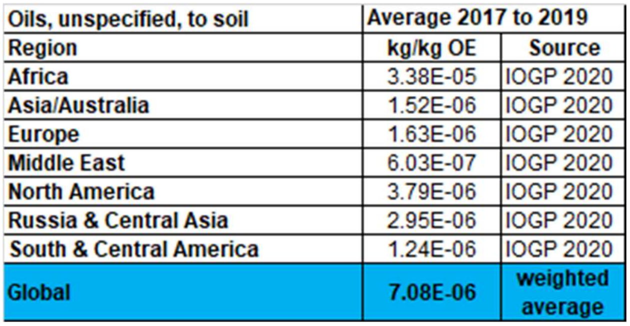


Oils, unspecified, to river	Average 2017 to 2019	
Region	**kg/kg OE**	**Source**
Africa	3.10E-06	IOGP 2020
Asia/Australia	2.09E-06	IOGP 2020
Europe	1.45E-06	weighted average of countries with reported values
Middle East	7.67E-07	IOGP 2020
North America	2.47E-07	IOGP 2020
Russia & Central Asia	1.45E-06	weighted average of countries with reported values
South & Central America	1.14E-06	IOGP 2020
Global	**1.45E-06**	**weighted average of countries with reported values**

10.4 Oil spills to soil

A calculation of regional averages with company data of the latest 3 years has been used for the estimation of oil emissions to soil during onshore operations (IOGP 2020). Values used in the model are shown in Tab. 10.6.

Tab. 10.6 Amount of oil spilled to soil per kg of oil equivalent extracted per region (onshore), average of 3 latest years reported.



Oils, unspecified, to soil	Average 2017 to 2019	
Region	**kg/kg OE**	**Source**
Africa	3.38E-05	IOGP 2020
Asia/Australia	1.52E-06	IOGP 2020
Europe	1.63E-06	IOGP 2020
Middle East	6.03E-07	IOGP 2020
North America	3.79E-06	IOGP 2020
Russia & Central Asia	2.95E-06	IOGP 2020
South & Central America	1.24E-06	IOGP 2020
Global	**7.08E-06**	**weighted average**

11 Waste

No updates are made in this chapter compared to Meili & Jungbluth 2018.

11.1 Deposition

In oil production, the mineral substances dissolved in water precipitate and are deposited in the equipment (pumps, separator, valves etc.). The deposition is estimated with a dataset for hazardous waste in underground deposits. For Norway, a country specific value of 0.16 g/t is available (Schori et al. 2012). For all other countries, a generic value of 0.2 g/t as assessed in (Jungbluth 2007) is considered.

11.2 Other wastes

For disposal of other wastes that form during crude oil production, data from Nigeria: 363 g/t (Shell 2001) and Norway 86.6g/t (Schori et al. 2012) is available. For other countries, 100 g/t are used as generic assumption (c.f. Meili & Jungbluth 2018).

12 Summary of life cycle inventory data

For the updated datasets on crude oil and natural gas extraction, the most relevant changes for the reference year 2019 compared to the former assessment (Meili & Jungbluth 2018; Schori et al. 2012) are:

- Harmonization of general assumptions between crude oil and natural gas production.
- Extension of the list of country-specific inventories from 8 to 27 countries (c.f. Tab. 2.1)
- Change of calorific values used for allocation in combined production (c.f. chapter 2.2)
- Recent country specific data for share of on- and offshore production, well drilling, flaring and methane emissions (fugitive and technical venting combined)
- Regional average data for freshwater use, emission of oil to soil and water

- Replacement of halon in fire extinguishers with less ozone depleting substances
- Harmonized generic estimates for chemical use, oil spills due to accidents, other emissions to soil, water, and air.

Some changes and corrections were also made in the LCIs for well drilling basic infrastructure for platform and production plants.

No changes were made due to lesser relevance in background data for machinery use on these plants.

The life cycle inventories for the newly modelled and updated processes are provided as multi-output or unit process raw data in the EcoSpold v1 format. The electronic data is including full EcoSpold v1 documentation.

Tab. 12.1 shows one example for the meta information and Tab. 12.2 shows one example for the modelled life cycle inventory (unit process raw data) for crude oil and natural gas extraction in the united states of America (US). Meta information for other processes updated in this study, as well as country-specific unit process raw data for crude oil and natural gas produced in other countries analysed in this study are available in an additional PDF document, or on request, from ESU-services in the electronic EcoSpold format or in an LCA-database generated in SimaPro 9.1.[30]

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[30] Download is available on http://esu-services.ch/data/public-lci-reports/

Tab. 12.1 Meta information for the investigated life cycle inventories, example for crude oil and natural gas production in the US, part1

ReferenceFunction	Name	combined gas and oil production	combined gas and oil production offshore	combined gas and oil production onshore	crude oil, at production offshore	crude oil, at production onshore
Geography	Location	US	US	US	US	US
ReferenceFunction	InfrastructureProcess	0	0	0	0	0
ReferenceFunction	Unit	a	a	a	kg	kg
	IncludedProcesses	Production of oil and gas including energy use, infrastructure and emissions.	Production of oil and gas including energy use, infrastructure and emissions.	Production of oil and gas including energy use, infrastructure and emissions.	Production of crude oil including energy use, infrastructure and emissions.	Production of crude oil including energy use, infrastructure and emissions.
	GeneralComment	The multioutput-process 'combined offshore gas and oil production' delivers the co-products crude oil and natural gas. Allocation for co-products is based on heating value.	The multioutput-process 'combined offshore gas and oil production' delivers the co-products crude oil and natural gas. Allocation for co-products is based on heating value.	The multioutput-process 'combined offshore gas and oil production' delivers the co-products crude oil and natural gas. Allocation for co-products is based on heating value.	The offshore oil production delivers the product crude oil. The values are derived from a multioutput-process "combined offshore gas and oil production" by allocation based on heating values for crude oil and natural gas	The onshore oil production delivers the product crude oil. The values are derived from a multioutput-process "combined onshore gas and oil production" by allocation based on heating values for crude oil and natural gas
	InfrastructureIncluded	1	1	1	1	1
	Category	oil	oil	oil	oil	oil
	SubCategory	production	production	production	production	production
TimePeriod	StartDate	2019	2019	2019	2019	2019
	EndDate	2022	2022	2022	2022	2022
	DataValidForEntirePeriod	1	1	1	1	1
	OtherPeriodText	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.
Geography	Text	Data valid for US.	Data valid for US.	Data valid for US.	Data valid for US.	Data valid for US.
Technology	Text	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production
	ProductionVolume	747 megatons of crude oil and 921 billion Nm3 natural gas per year in 2019.	109 megatons of crude oil and 134 billion Nm3 natural gas per year in 2019.	638 megatons of crude oil and 786 billion Nm3 natural gas per year in 2019.	109 megatons of crude oil per year in 2019.	638 megatons of crude oil per year in 2019.
	SamplingProcedure	Statistics and use of generic data	Statistics and use of generic data	Statistics and use of generic data	Statistics and use of generic data	Statistics and use of generic data
	Extrapolations	A part of the data has been estimated with generic assumptions for on- and offshore production.	A part of the data has been estimated with generic assumptions for offshore production.	A part of the data has been estimated with generic assumptions for onshore production.	A part of the data has been estimated with generic assumptions for offshore production.	A part of the data has been estimated with generic assumptions for onshore production.
	UncertaintyAdjustments	none	none	none	none	none
ecoinvent v3	ProductionVolumeNumber	1510.6	1510.6	1510.6	109	637.7
	ProductionVolumeText	Megatons of oil-equivalents produced in 2019	Megatons of oil-equivalents produced in 2019	Megatons of oil-equivalents produced in 2019	Megatons of oil produced in 2019	Megatons of oil produced in 2019

Meta information for the investigated life cycle inventories, example for crude oil and natural gas production in the US, part2

ReferenceFunction	Name	natural gas, at production offshore	natural gas, at production onshore	crude oil, at production	natural gas, at production
Geography	Location	US	US	US	US
ReferenceFunction	InfrastructureProcess	0	0	0	0
ReferenceFunction	Unit	Nm3	Nm3	kg	Nm3
	IncludedProcesses	Production of natural gas including energy use, infrastructure and emissions.	Production of natural gas including energy use, infrastructure and emissions.	Production of crude oil including energy use, infrastructure and emissions.	Production of natural gas including energy use, infrastructure and emissions.
	GeneralComment	The offshore natural gas production delivers the product natural gas. The values are derived from a multioutput-process "combined offshore gas and oil production" by allocation based on heating values for crude oil and natural gas	The onshore oil production delivers the product natural gas. The values are derived from a multioutput-process "combined onshore gas and oil production" by allocation based on heating values for crude oil and natural gas	Oil production delivers the co-product natural gas. The values are derived from a multioutput-process "combined onshore gas and oil production" by allocation based on heating values for crude oil and natural gas	Oil production delivers the co-product natural gas. The values are derived from a multioutput-process "combined onshore gas and oil production" by allocation based on heating values for crude oil and natural gas
	InfrastructureIncluded	1	1	1	1
	Category	natural gas	natural gas	oil	natural gas
	SubCategory	production	production	production	production
TimePeriod	StartDate	2019	2019	2019	2019
	EndDate	2022	2022	2022	2022
	DataValidForEntirePeriod	1	1	1	1
	OtherPeriodText	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.	Time of most relevant publications and statistics. Other generic data, e.g. for infrastructure are based on older publications.
Geography	Text	Data valid for US.	Data valid for US.	Data valid for US.	Data valid for US.
Technology	Text	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production	15 % offshore and 85 % onshore production
	ProductionVolume	134 billion Nm3 natural gas per year in 2019.	786 billion Nm3 natural gas per year in 2019.	747 megatons of crude oil per year in 2019.	921 billion Nm3 natural gas per year in 2019.
	SamplingProcedure	Statistics and use of generic data	Statistics and use of generic data	Statistics and use of generic data	Statistics and use of generic data
	Extrapolations	A part of the data has been estimated with generic assumptions for offshore production.	A part of the data has been estimated with generic assumptions for onshore production.	A part of the data has been estimated with generic assumptions for on- and offshore production.	A part of the data has been estimated with generic assumptions for on- and offshore production.
	UncertaintyAdjustments	none	none	none	none
ecoinvent v3	ProductionVolumeNumber	134.4	786.4	746.7	920.9
	ProductionVolumeText	Billion cubic meters of natural gas produced in 2019	Billion cubic meters of natural gas produced in 2019	Megatons of oil produced in 2019	Billion cubic meters of natural gas produced in 2019

Tab. 12.2 Unit process raw data, example for crude oil and natural gas production in the US, part 1

US	Name	Location	InfrastructureProcess	Unit	*combined gas and oil production offshore*	*crude oil, at production offshore*	*natural gas, at production offshore*	*combined gas and oil production onshore*	*crude oil, at production onshore*	*natural gas, at production onshore*	*combined gas and oil production*	*UncertaintyType*	*StandardDeviation95%*	*GeneralComment*
	Location				*US*	*US*	*US*	*US*	*US*	*US*	*US*			
	InfrastructureProcess				*0*	*0*	*0*	*0*	*0*	*0*	*0*			
	Unit				*a*	*kg*	*Nm3*	*a*	*kg*	*Nm3*	*a*			
products	crude oil, at production offshore	US	0	kg	1.09E+11	100%					1.09E+11	1	1.00	https://www.eia.gov/energyexplained/oil-and-petroleum-products/where-our-oil-comes-from.php
	crude oil, at production onshore	US	0	kg				6.38E+11	100%		6.38E+11	1	1.00	https://www.eia.gov/energyexplained/oil-and-petroleum-products/where-our-oil-comes-from.php
	natural gas, at production offshore	US	0	Nm3	2.83E+10		100%				2.83E+10	1	1.00	https://www.eia.gov/energyexplained/natural-gas/where-our-natural-gas-comes-from.php
	natural gas, at production onshore	US	0	Nm3				8.93E+11		100%	8.93E+11	1	1.00	https://www.eia.gov/energyexplained/natural-gas/where-our-natural-gas-comes-from.php
resources, in ground	Oil, crude	-	-	kg	1.09E+11	100%		6.38E+11	100%		7.47E+11	1	1.05	(1,1,1,1,1,BU:1.05); BP Statistical Review of World Energy 2020
	Oil, crude	-	-	kg	6.03E+6	100%		6.27E+7	100%		6.87E+7	1	1.05	(1,1,1,3,1,BU:1.05); calculated losses due to oil spills
	Gas, natural/m3	-	-	Nm3	2.83E+10		100%	8.93E+11		100%	9.21E+11	1	1.05	(1,1,1,1,1,BU:1.05); BP Statistical Review of World Energy 2020
water resource	Water, unspecified natural origin, US	-	-	m3	0	100%	0%	2.96E+8	100%	0%	2.96E+8	1	1.05	(1,1,1,3,1,BU:1.05); Average 2017 to 2019, IOGP 2020
	Water, salt, ocean	-	-	m3	5.07E+7	100%	0%	0	100%	0%	5.07E+7	1	1.05	(3,3,1,3,1,BU:1.05); salt water use for offshore production assumed to be the same as freshwater use onshore
	Water, fossil	-	-	m3	9.11E+07	100%	0%	3.04E+08	100%	0%	3.95E+08	1	1.05	(3,3,1,3,1,BU:1.05); Balancing of input-output
water emission	Water, US	-	-	m3	0	100%	0%	6.00E+8	100%	0%	6.00E+8	1	1.50	(3,3,1,3,1,BU:1.5); calculation
	Water, US	-	-	m3	1.42E+8	100%	0%	0	100%	0%	1.42E+8	1	1.50	(3,3,1,3,1,BU:1.5); calculation
	Water, US	-	-	m3	0	100%	0%	0	100%	0%	0	1	1.50	(3,3,1,3,1,BU:1.5); calculation
	discharge, produced water, offshore	OCE	0	kg	1.42E+11	100%	0%	0	100%	0%	1.42E+11	1	1.05	(3,4,4,3,3,na); ANL 2009
	discharge, produced water, onshore	GLO	0	kg	0	100%	0%	6.00E+11	100%	0%	6.00E+11	1	1.05	(3,4,3,3,3,na); Produced water society 2012
technosphere	chemicals inorganic, at plant	GLO	0	kg	7.33E+7	82%	18%	7.62E+8	46.3%	53.7%	8.36E+8	1	1.05	(4,4,1,3,3,BU:1.05); Generic estimation
	chemicals organic, at plant	GLO	0	kg	5.59E+7	82%	18%	5.81E+8	46.3%	53.7%	6.37E+8	1	1.05	(4,4,1,3,3,BU:1.05); Generic estimation
	transport, freight, lorry 16-32 metric ton, fleet average	RER	0	tkm	1.29E+7	82%	18%	1.34E+8	46.3%	53.7%	1.47E+8	1	2.00	(3,4,1,3,3,BU:2); Standard distance for chemical transport 100km
	transport, freight, rail	RER	0	tkm	7.75E+7	82%	18%	8.06E+8	46.3%	53.7%	8.84E+8	1	2.00	(3,4,1,3,3,BU:2); Standard distance for chemical transport 600km
Infrastructure	well for exploration and production, offshore	OCE	1	m	5.82E+6	49%	51%	0	0%	0%	5.82E+6	1	3.00	(3,3,3,2,2,na) Calculation based on EIA 2020 and EIA: https://www.eia.gov/dnav/pet/pet_crd_welldep_s1_a.htm, online 19.10.17, assuming a well lifetime of 22.5 years
	well for exploration and production, onshore	GLO	1	m	0	0%	0%	6.06E+7	49%	51%	6.06E+7	1	3.00	(3,3,3,2,2,na) Calculation based on EIA 2020 and EIA: https://www.eia.gov/dnav/pet/pet_crd_welldep_s1_a.htm, online 19.10.17, assuming a well lifetime of 22.5 years

Unit process raw data, example for crude oil and natural gas production in the US, part 2

US	Name	Location	InfrastructureProcess	Unit	combined gas and oil production offshore	crude oil, at production offshore	natural gas, at production offshore	combined gas and oil production onshore	crude oil, at production onshore	natural gas, at production onshore	combined gas and oil production	UncertaintyType	StandardDeviation95 %	GeneralComment
	Location				US	US	US	US	US	US	US			
	InfrastructureProcess				0	0	0	0	0	0	0			
	Unit				a	kg	Nm3	a	kg	Nm3	a			
oil	pipeline, crude oil, offshore	OCE	1	km	6.45E+2	100%	0	0	0	0	6.45E+2	1	3.00	(3,4,1,3,3,BU:3); Generic estimation based on estimate for Nigeria 2018
	pipeline, crude oil, onshore	RER	1	km	0	0	0	4.43E+3	100%	0	4.43E+3	1	3.00	(3,4,1,3,3,BU:3); Generic estimation based on estimate for Kazakhstan 2016
	platform, crude oil, offshore	OCE	1	unit	4.52E+0	100%	0	0	0	0	4.52E+0	1	3.00	(3,4,1,3,3,BU:3); Lodewijkx et al. 2001
	production plant crude oil, onshore	GLO	1	unit	0	0	0	7.92E+1	100%	0	7.92E+1	1	3.00	(3,4,5,3,3,BU:3); Lodewijkx et al. 2001
gas	plant offshore, natural gas, production	OCE	1	unit	6.37E-1	0%	100%	0	0%	0%	6.37E-1	1	3.00	(3,4,1,3,3,BU:3); Generic estimation
	plant onshore, natural gas, production	GLO	1	unit	0	0%	0%	2.55E+2	0%	100%	2.55E+2	1	3.00	(3,4,1,3,3,BU:3); Generic estimation
	pipeline, natural gas, long distance, high capacity, offshore	GLO	1	km	1.80E+2	0	100%	0	0	0%	1.80E+2	1	3.00	(3,4,1,3,3,BU:3); Estimation based on values for crude oil pipeline
	pipeline, natural gas, long distance, high capacity, onshore	GLO	1	km	0	0	0%	9.22E+3	0	100%	9.22E+3	1	3.00	(3,4,1,3,3,BU:3); Estimation based on values for crude oil pipeline
energy	electricity, medium voltage, at grid	US	0	kWh	7.24E+9	82%	18%	7.53E+10	46.3%	53.7%	8.25E+10	1	2.00	(3,2,2,3,3,BU:2); Data for 2019, IOGP 2020
	Diesel, burned in diesel-electric generating set, at extraction site	GLO	0	MJ	6.93E+9	82%	18%	7.20E+10	46.3%	53.7%	7.90E+10	1	2.00	(3,2,2,3,3,BU:2); Data for 2019, IOGP 2020
	heavy fuel oil, burned in industrial furnace 1MW, non-modulating	RER	0	MJ	0	82%	18%	0	46.3%	53.7%	0	1	2.00	(3,2,2,3,3,BU:2); Data for 2019, IOGP 2020
	sweet gas, burned in gas turbine, production	GLO	0	MJ	3.39E+11	82%	18%	3.52E+12	46.3%	53.7%	3.86E+12	1	2.00	(3,2,2,3,3,BU:2); Data for 2019, IOGP 2020, SOx content of sour gas assessed separately in overall emissions.
waste	natural gas, vented	GLO	0	Nm3	1.49E+9	77%	23%	1.76E+10	37.9%	62.1%	1.91E+10	1	2.00	(2,1,1,1,3,BU:2); Country specific methane emissions according to IEA 2022, includes all methane emissions from upstream production, recalculated using a share of 0.88 Nm3 methane per Nm3 natural gas. Allocation based on country specific emissions for oil and gas.
	natural gas, sweet, burned in production flare	GLO	0	Nm3	1.52E+9	82%	18%	1.58E+10	46.3%	53.7%	1.73E+10	1	2.00	(3,2,1,1,3,BU:2); Total amount of flared gas per kg OE according to Worldbank 2022 (reference year 2019), Sox emissions from flared sour gas assessed separately in overall emissions.
	disposal, hazardous waste, 0% water, to underground deposit	DE	0	kg	2.65E+7	82%	18%	2.76E+8	46.3%	53.7%	3.02E+8	1	1.05	(3,4,1,3,3,BU:1.05); Generic estimation
	disposal, municipal solid waste, 22.9% water, to municipal incineration	CH	0	kg	1.33E+7	82%	18%	1.38E+8	46.3%	53.7%	1.51E+8	1	1.05	(3,4,1,3,3,BU:1.05); Generic estimation

Unit process raw data, example for crude oil and natural gas production in the US, part 3

US	Name	Location	InfrastructureProcess	Unit	combined gas and oil production offshore	crude oil, at production offshore	natural gas, at production offshore	combined gas and oil production onshore	crude oil, at production onshore	natural gas, at production onshore	combined gas and oil production	UncertaintyType	StandardDeviation95 %	GeneralComment
	Location				US	US	US	US	US	US	US			
	InfrastructureProcess				0	0	0	0	0	0	0			
	Unit				a	kg	Nm3	a	kg	Nm3	a			
emission to water, river	Oils, unspecified	-	-	kg	0	0%	0%	3.40E+5	49%	51%	3.40E+5	1	1.50	(2,1,1,3,3,BU:1.5); Average 2017 to 2019, IOGP 2020
	BOD5 (Biological Oxygen Demand)	-	-	kg	0	0%	0%	1.07E+6	49%	51%	1.07E+6	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	COD (Chemical Oxygen Demand)	-	-	kg	0	0%	0%	1.07E+6	49%	51%	1.07E+6	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	DOC, Dissolved Organic Carbon	-	-	kg	0	0%	0%	2.94E+5	49%	51%	2.94E+5	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	0	0%	0%	2.94E+5	49%	51%	2.94E+5	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	0	0%	0%	3.50E+0	49%	51%	3.50E+0	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	Nitrogen	-	-	kg	0	0%	0%	2.63E+2	49%	51%	2.63E+2	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	Sulfur	-	-	kg	0	0%	0%	9.10E+2	49%	51%	9.10E+2	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
emission to water, ocean	Oils, unspecified	-	-	kg	5.49E+6	49%	51%	0	0%	0%	5.49E+6	1	1.50	(2,1,1,3,3,BU:1.5); Average 2017 to 2019, IOGP 2020
	BOD5 (Biological Oxygen Demand)	-	-	kg	1.73E+7	49%	51%	0	0%	0%	1.73E+7	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	COD (Chemical Oxygen Demand)	-	-	kg	1.73E+7	49%	51%	0	0%	0%	1.73E+7	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	DOC, Dissolved Organic Carbon	-	-	kg	4.75E+6	49%	51%	0	0%	0%	4.75E+6	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	TOC, Total Organic Carbon	-	-	kg	4.75E+6	49%	51%	0	0%	0%	4.75E+6	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	AOX, Adsorbable Organic Halogen as Cl	-	-	kg	5.66E+1	49%	51%	0	0%	0%	5.66E+1	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	Nitrogen	-	-	kg	4.24E+3	49%	51%	0	0%	0%	4.24E+3	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
	Sulfur	-	-	kg	1.47E+4	49%	51%	0	0%	0%	1.47E+4	1	1.50	(2,1,1,3,3,BU:1.5); Extrapolation for sum parameter
emission to soil	Oils, unspecified	-	-	kg	0	0%	0%	5.22E+6	49%	51%	5.22E+6	1	1.50	(2,1,1,3,3,BU:1.5); Average 2017 to 2019, IOGP 2020
emission to air, low population density	Sulfur dioxide	-	-	kg	1.37E+7	82%	18%	1.42E+8	46.3%	53.7%	1.56E+8	1	1.50	(2,1,1,3,3,BU:1.5); Average 2017 to 2019, IOGP 2020
	Nitrogen oxides	-	-	kg	6.98E+7	82%	18%	7.26E+8	46.3%	53.7%	7.96E+8	1	1.50	(2,1,1,3,3,BU:1.5); Average 2017 to 2019, IOGP 2020
	Methane, bromotrifluoro-, Halon 1301	-	-	kg	1.54E+3	82%	18%	0	0	0	1.54E+3	1	1.50	(3,3,1,3,3,BU:1.5); assuming 20% halon compared to Jungbluth 2007
	Methane, trifluoro-, HFC-23	-	-	kg	6.17E+3	82%	18%	0	0	0	6.17E+3	1	1.50	(3,3,1,3,3,BU:1.5); assuming 80% HFC-23 compared to Jungbluth 2007

13 Data quality

The modules for crude oil and natural gas production are complete in terms of environmental impacts. However, the variation between different oil fields can be extremely high. A part of the data was just available for single oil fields, for regional averages or for globally operating companies. Thus, it is not possible to consider all types of data sources to establish good estimates on a country level.

To model the market situation, top-down data for the reference year 2019 are used (BP 2020). These data, in general, can be considered as reliable. However, also such data might receive updates. For example, a newer version of the datasheets shows about 40% higher natural gas production for Libya and Kazakhstan in the same reference year 2019 (BP 2022). For other countries considered in this study, the seen deviations are much lower (0 to 8%). The global gas production is reported to be 1% lower.

For other relevant inputs and outputs like energy consumption, flaring, fugitive methane release and oil spills, internationally consistent data sources are considered.

The demand for production chemicals is extrapolated based on studies in the North Sea. As enhanced oil recovery is getting more important every day, this value might increase in the future.

The quantities of production water and the proportion of water discharged into surface waters are also partly based on assumptions. The composition of the production waters is estimated based on several measurements and is subject to great fluctuations, which can hardly be estimated. For a potential next update, the focus might be limited to the four most important emissions (zinc, toluene, xylene and oil, unspecified).

For data expected to be of lower relevance according to former evaluations in Meili & Jungbluth 2018, with the ecological scarcity method 2013, generic data and data for regions, investigated in former reports were used as approximations (e.g. Jungbluth 2007; Stolz & Frischknecht 2017). This data includes e.g., LCI for infrastructure, content of trace elements in spilled oil, composition of chemicals used for EOR and disposal routes for several types of wastes.

In summary the data for single countries are a combination of different data sources and it is difficult to establish such inventories for single countries due to e.g., the following difficulties:

- Environmental impacts of oil and gas extraction depend to a substantial extent on local conditions at the single field (e.g., depth of the oil resource, oil per well, age of field, formation water, on- or offshore, etc.) and less on general technical issues such as energy efficiency or type of operation (onshore/offshore). Thus, they can be quite different per oil field or country.
- Environmental reports of single companies are often established for global operation and the system boundaries do not match the stages and regional boundaries investigated in this study. This makes it difficult to use this type of information for establishing a life cycle inventory.
- Summarizing information for flaring and venting was available from country specific estimates.
- Information by companies representing about one quarter of global oil production was available in regional figures for the energy use, emissions of oil and use of water.

The present data is an improvement compared to the former version because:

- Assumptions are harmonized, and cross checked between different countries. Thus, the former bias e.g., due to lack of information is avoided.
- Information for several single aspects was revised and checked again. Therefore, several new data sources were consulted.
- With the increased amount of information used for this study, possible uncertainties and variations of data are now known better.
- Data for additional countries relevant for the global supply situation were newly investigated.
- The background datasets for well production are revised and corrected.
- Estimates for the most important aspects like venting, flaring, energy use, emission of oil and use of water are each based on one consistent source of data.

The current model is a good compromise between consistency and accuracy of data. For the most relevant factors, country or region-specific values are used. For most other factors, generic estimates are considered sufficient.

14 Life cycle impact assessment and interpretation

No detailed impact assessment or impact related interpretation is commissioned for this project.

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[31] The fundament of this database is ecoinvent v2.2. Updates and data published on www.lc-inventories.ch as well as further studies available on www.treeze.ch are incorporated in this database UVEK LCI Data 2018.

15 Outlook

With this study and the related background model, a harmonized way to model country-specific life cycle inventories for combined crude oil and natural gas production is available. For now, this model is built based on the UVEK database (UVEK 2018).

To cover the global production better it would be recommended to investigate the production in Australia.

So far, there is only a weak basis for distinguishing the LCI of onshore and offshore extraction. Therefore, it might be considered for future updates to simplify and reduce the LCI to summarize the two on- and offshore datasets to one overall production dataset per country and thus reduce the number of datasets considerably.

The methane emissions will be a hotspot for future updates. The International Methane Emissions Observatory (IMEO)[32] is a data-driven, action-focused initiative by the UN Environment Programme (UNEP) with support from the European Commission to catalyse dramatic reduction of methane emissions, starting with the energy sector. Data for methane emissions might in future be available also from this initiative.

The water balance for arid regions is not yet fully correct. To make a full balance of water inputs and outputs a collaboration with life cycle impact assessment developers in order to correctly balance the output of fossil water inputs would be necessary. Guidelines water balancing should address the issues specific to the extraction of fossil resources.

A possible extension would be a distinction between conventional and unconventional oil and gas production. This could be helpful for political discussions related to future import policies, e.g., for LNG from countries with a high rate of shale gas extracted through fracking. But such data are not available with the information sources used in this study and thus would need a fully different approach of modelling. In the future the re-injection of CO_2 as a means of carbon capture storage (CCS) and a replacement of injected water might become more important and thus should be included in the analysis as soon as global or country specific data are available.

Considered market share and effective production amounts in combination with reported venting have a high impact on several LCIA-indicators. Depending e.g. on political and economical situation in the countries under study, both values might fluctuate a lot from year to year. Therefore, it might be considered for future updates to either do them in shorter intervals (e.g. each year) or using moving averages for e.g. the last 5 years.

As explained in chapter 9.6, due to lack of LCI data for the flame-retardant FK-5-1-12, the replaced Halon 1301 had to be modelled completely with direct emissions of HFC-23. Like this, the impacts on climate change due to the use of flame retardants might be overestimated. To fix this, the production of FK-5-1-12 should be modelled for ecoinvent and global amounts for each flame retardant should be gathered.

The assessment of methane releases from oil and gas fields shows that abandoned or closed oil and gas fields still can lead to emissions of methane in the future. This is especially relevant in cases where the fields are badly maintained e.g., due to political reasons like war or lack of financial resources. These releases might even occur after the global society has managed to stop the use of fossil resources. So far, such future releases or technical measures to avoid them

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[32] https://www.unep.org/explore-topics/energy/what-we-do/imeo

are not covered in the inventory and they would further increase the burden of the fossil resources extracted and used today.

The present update for natural gas is also quite relevant for LCI related to plastic products and other products made directly from oil and gas products. The data for plastics in the ecoinvent and UVEK database are not yet directly linked to these inventories. It would be recommended to establish new LCI data directly linked to the inventories presented in this report.

The stop of gas deliveries from Russia to Europe due to the war in Ukraine lead to unnecessary flaring of natural gas at the compressor stations. Such emissions should be addressed in the next update of these inventory data.

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