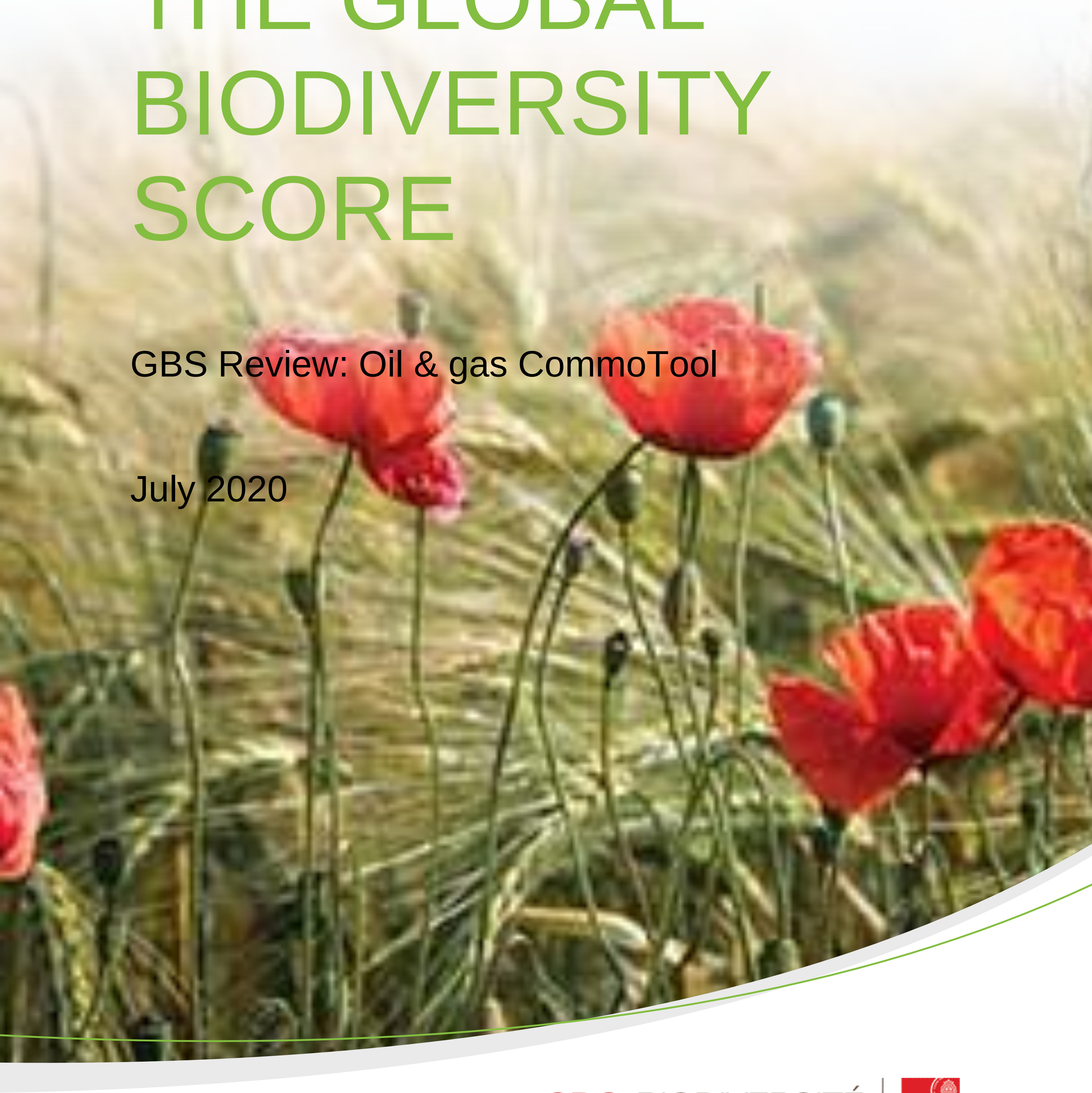
# THE GLOBAL BIODIVERSITY SCORE



GBS Review: Oil & gas CommoTool

July 2020

CDC BIODIVERSITÉ

Caisse des Dépôts GROUPE

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# 1 Context

## 1.1 Why assess the biodiversity impact of oil & gas production?

Global warming caused by oil & gas combustion is certainly the most widely known contribution of oil & gas to biodiversity loss. Yet, oil & gas also generate direct pressures on biodiversity through other major threats identified by the latest IPBES report (Díaz et al. 2019). Exploration processes cause habitat conversion and intense noise pollution in terrestrial and marine ecosystems, also contributing to landscape fragmentation. During fossil fuel exploitation, direct – habitat conversion, degradation, pollution and disturbance – and indirect impacts – increased accessibility and human expansion into previously wild areas, causing additional disturbance, illegal hunting, the introduction of invasive alien species, water pollution… – are intense (Beckmann et al. 2012). These impacts are damaging to nature and costly to human societies due to the reduction of ecosystem services.

Research assessing the indirect biodiversity impacts of oil & gas due to climate change are numerous. A growing body of literature now focuses on the direct impacts of present and future fossil fuel extraction. Indeed, oil and natural gas demands are projected to increase in the near future, causing ever-growing pressures on remote and previously undisturbed areas.(Butt et al. 2013) unveil the existing spatial congruence between fossil fuel reserves and areas presenting both high species richness and high proportion of threatened species, stressing out the very high risks to biodiversity in South America and western Pacific Ocean (Figure 1). According to the authors, the combined political power of the fossil fuel extraction industry and the weak governance and poor implementation of environmental regulations characterizing many countries hosting both areas of high biodiversity and areas under fossil fuel exploration further accentuates the threats to biodiversity.(Harfoot et al. 2018) show that near-future fossil fuel exploitation sites have greater overlap with protected areas than current sites in almost all regions and overlap with more strictly protected areas. Thus, the land use footprint of energy development and other accompanying biodiversity impacts of fossil fuel production will likely increase. (Trainor, McDonald, and Fargione 2016) estimate that direct land use change due to oil, natural gas and coal production could be as high as 6 900 km² per year until 2040 in the United States (US) only, with a higher impact of unconventional extraction techniques.

Therefore, effective implementation of both industry regulations, conservation management and biodiversity monitoring are crucial to limit and, hopefully, reduce the biodiversity impact of fossil fuel production in order to achieve the goal of setting up an economy in which nature preservation and human well-being are compatible and sustained. Including the biodiversity impact of fossil fuel extraction and purchases in biodiversity assessment tools like the GBS is thus key to provide stakeholders with the means to quantify, inform and monitor their actions.

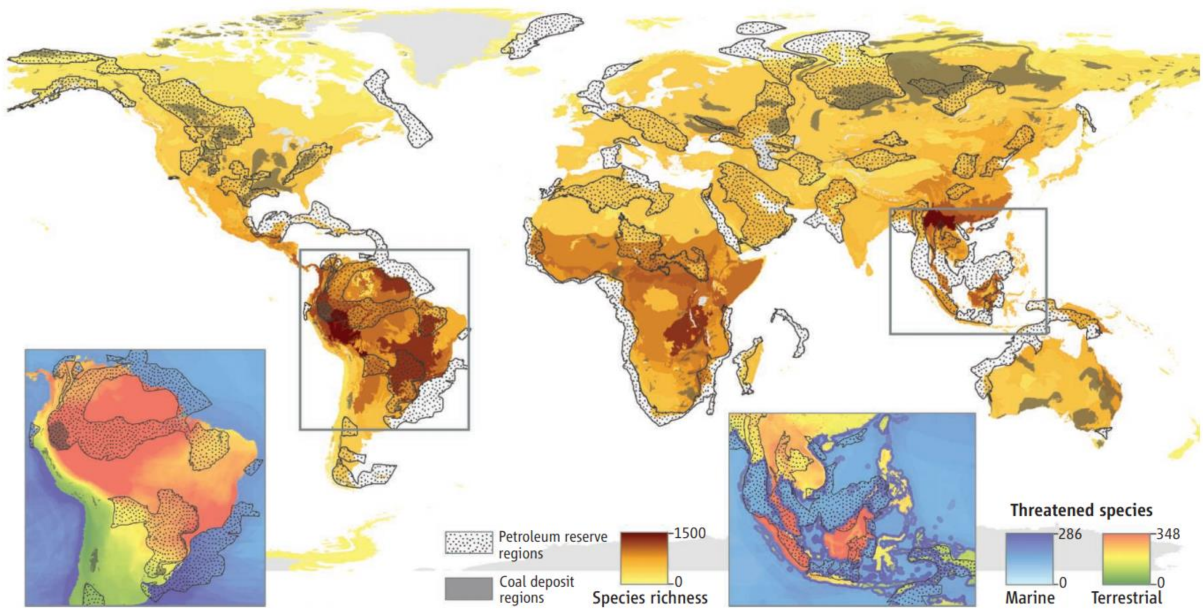


*Figure 1: Distribution of fossil fuel reserves and species biodiversity (Butt et al. 2013)*

## 1.2 Place of the oil & gas CommoTool in the GBS framework

The goal of the oil & gas CommoTool is to determine the **biodiversity impact factors for oil and gas extraction at country and EXIOBASE region level**. This report explains how the **biodiversity impact factors databases for oil & gas production** are constructed.

As a reminder, the evaluation of biodiversity impacts of economic activities with the GBS follows a stepwise approach according to the best data available at each step of the impact assessment (CDC Biodiversité 2020a). The oil & gas CommoTool provides biodiversity impact factors linking tonnages of oil & gas to impacts on biodiversity in MSA.km². It fits in the stepwise framework in two ways, as illustrated by Figure 2.

In default assessments, the results of the oil & gas CommoTool feed the M matrix dedicated to oil & gas documented in the EXIOBASE material account. The M matrices are the tables which gather biodiversity loss factors (in MSA.km²/t of commodity). They are combined to other matrices which translate monetary data into inventories of raw materials and emissions in the Input-Output modelling framework (CDC Biodiversité 2019).

In refined assessments, if "Inventory" data like fossil fuel quantities purchased or produced (Scope 1) are available, biodiversity impact factors linking tonnages of oil & gas to impacts on biodiversity in MSA.km² can be applied directly to the company's inventory.

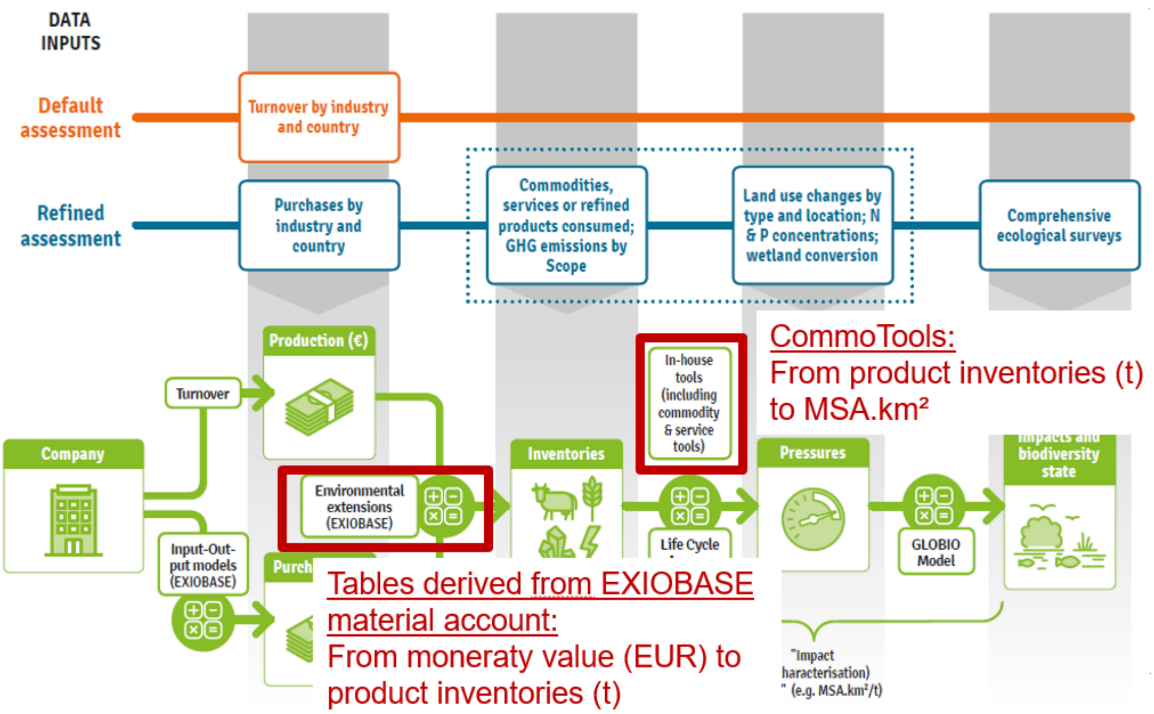


Figure 2: Oil & gas CommoTool in the GBS stepwise approach

# 1.3 Oil & gas CommoTool perimeter

## A OIL & GAS TERMINOLOGY

The *Energy Statistics Manual* (IEA 2004) distinguishes **primary energy commodities**, extracted or captured directly from natural resources (*e.g.* crude oil, hard coal, natural gas) from **secondary energy commodities**, which are produced from primary commodities (*e.g.* electricity, petroleum products). The distinction is also made between **renewable** (*e.g.* wind, solar, biofuels) and **non-renewable** (*e.g.* crude oil, coal) energy commodities. Finally, energy commodities are either **combustible** (*e.g.* biofuels, coal) or **non-combustible** (*e.g.* wind, hydraulic electricity).

The purpose of GBS CommoTools is to compute the biodiversity impact factors related to the production of raw materials in their most raw “out-of-the-field” form, excluding transformation processes as much as possible. Hence, secondary energy commodities are not included in this CommoTool. Due to time constraints, a choice was made to focus the CommoTool on **non-renewable combustible primary energy commodities**. Since coal is a solid fossil fuel, the biodiversity impact factors related to the different types of coal are computed within the mining CommoTool (CDC Biodiversité 2020c). **The CommoTool**

**described in this report includes only liquid oil & gas**, *i.e.* oil and natural gas. It is hereafter referred to as the "oil & gas CommoTool". Figure 3 illustrates the terminology and its perimeter of the oil & gas.

Several comments about the perimeter:

- wastes due to the production of oil & gas are out of the oil & gas CommoTool perimeter. Wastes can potentially have a significant impact on biodiversity depending on the extraction technique and how they are managed. They take different forms, solid inert wastes, polluted water, drilling muds that can have various types of impacts on biodiversity. Wastes impacts need to be properly addressed in GBS next version,

- only inland impacts from onshore/ offshore extraction is considered in the oil and gas CommoTool as we don't have enough data about marine biodiversity impacts,

- impacts caused by linear infrastructures associated to the extraction site such as power lines, railways, pipelines are not taken into account,

- impacts due to prospection are not considered.

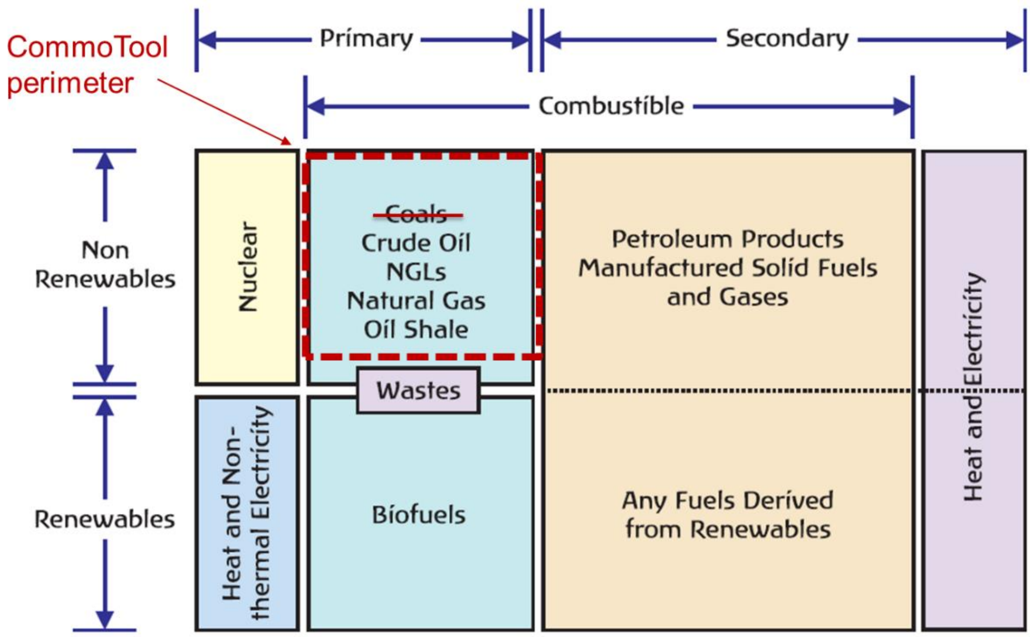


*Figure 3: Terminology for energy commodities and perimeter of the oil & gas CommoTool (IEA 2004)*

As illustrated in Figure 4, oil and natural gas production can be done using different extraction techniques depending on the nature of the commodity and on site-specific geological configuration. Natural gas comprises gases occurring in underground deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both “non-associated” (“dry”) gas originating from fields producing hydrocarbons only in gaseous form, and “associated” (“wet” or “liquid”) gas produced in association with crude oil as well as methane recovered from coal mines (colliery gas). Natural gas liquids include ethane, propane, butane (normal and iso-), (iso)pentane and pentanes plus (sometimes referred to as natural gasoline or plant condensate). Unconventional gas includes tight sand gas (produced from reservoir rocks with low permeability) and shale gas (trapped within shale formations). Crude oil is the most common form of oil, while unconventional oil includes tight sand oil and shale oil.

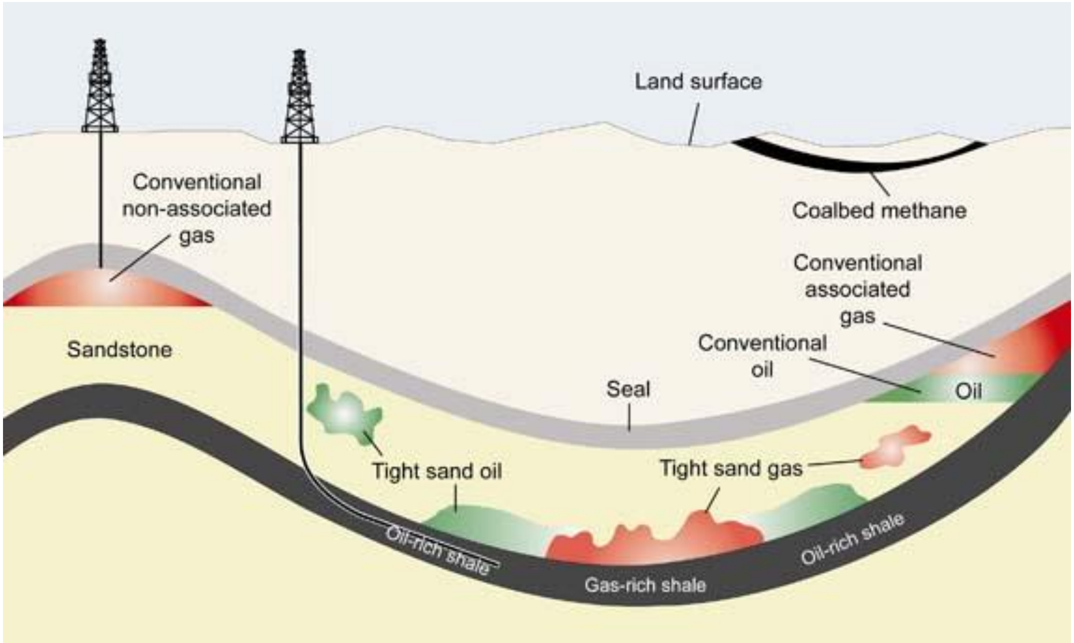


*Figure 4: Schematic geology of conventional and unconventional oil and natural gas resources. Source: US Energy Information Administration*

All these different configurations lead to very different extraction techniques with very different impacts in nature and amount. Oil and gas production are summarised in Figure 5. We see that in sometimes, oil, gas and even coal production processes can be mixed:

- Natural gas liquids (NGL), associated gas and crude oil are the outputs of oil production;
- Non-associated gas is the output of natural gas extraction;
- Colliery gas is an output of coal production.

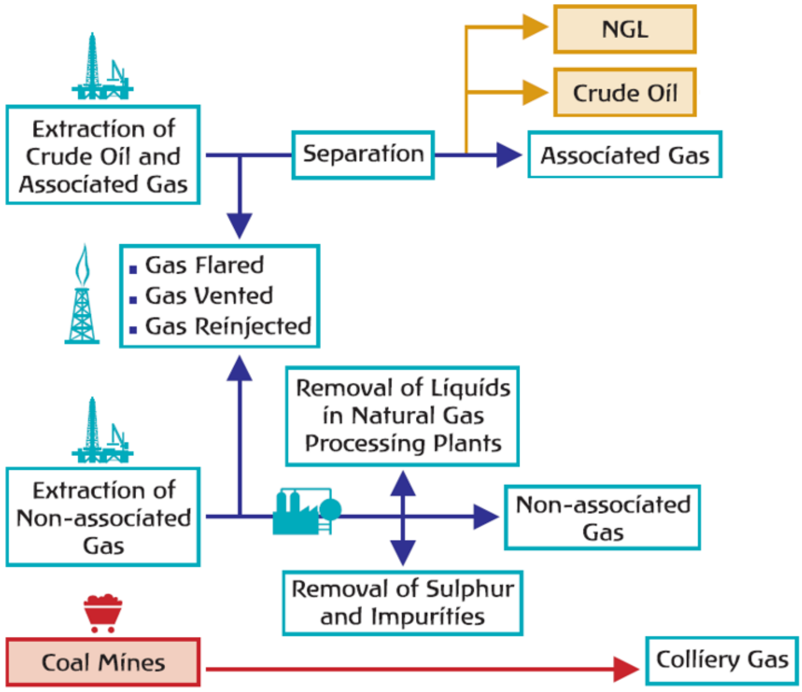


*Figure 5: Simplified flow chart of oil and natural gas production (IEA 2004)*

## B COMMOTOOL ITEMS AND PRESSURE CONSIDERED

The oil & gas CommoTool provides biodiversity impact factors related to the production of **crude oil and natural gas** per GLOBIO country and per EXIOBASE region.

"Natural gas is composed of mainly methane (CH4), or the simplest hydrocarbon chain. It is colourless, odourless, tasteless, and is lighter than air. It is gaseous at any temperature over –107.2o C and its specific gravity of 0.6 is lower than air. The quality and composition of natural gas varies greatly depending on the reservoir, field or formation from which it is extracted. When natural gas is produced, it contains a number of other components such as CO2, helium, hydrogen sulphide, nitrogen, water vapour and other contaminants which may be corrosive or toxic. Before natural gas can be used commercially, it needs to undergo a process in order to remove undesirable components. However, this removal process may not eliminate all impurities, as the quantities of these included in the gas are sometimes too small. The value of natural gas is determined by the energy content, which depends largely on the purity of the gas and on the number of carbon atoms per unit of volume (IEA 2004)

"The chemical composition of crude oil consists mainly of compounds of hydrogen and carbon, called hydrocarbons. There are many varieties of crude oil, because crude oil contains a wide range of hydrocarbons, depending on the location where it is found. The hydrocarbons in crude oil vary from the lightest to the heaviest, and these characteristics of the individual crude oils may determine the price. A crude oil containing many heavier hydrocarbons and fewer lighter ones is considered a heavy crude oil, while in the reverse case, one calls it a light oil. Since the composition of a crude oil is dependent on the location where it was found, the oil is usually given the name of the region or place where it comes from. Moreover, one often refers to crude produced from one reservoir, field, or region as a crude stream. Apart from hydrocarbons, crude oil when it first comes out of the ground may contain salts, some of which might be corrosive, and sulphur. Salts are removed by a process of desalting. Sulphur may also be an undesirable characteristic for processing and quality and may need to be removed. The concentration of sulphur in crude oils varies from below 0.05% to more than 5% in some crudes – generally 170 the higher the density of the crude oil, the greater the sulphur content. Low-sulphur crudes are often referred to as sweet crudes, while high-sulphur varieties are sour crude. Sulphur can be removed by desulphurisation." (IEA 2004)

To deal with this variety of physical characteristics for crude oil and natural gas, in the oil & gas, impact factors are expressed in MSA.km$^2$ per metric tonne assuming a Net Calorific Value (NCV) of 42.3 MJ/kg for crude oil and 44.1 MJ/kg for natural gas.

Those NCV values derive from the Product Environmental Footprint database that is used to determine various pressure intensities in the oil and gas commoTool. With this standard, we ensure that even if oil or natural gas considered may have different physical properties depending on where they come from, the tonnage used of the impact factors refers to the same amount of energy.

Pressures accounted for in the oil & gas commoTool are:

Terrestrial pressures: land use (LU), encroachment (E), fragmentation (F), climate change (CC);

Aquatic pressures: land use in catchment of rivers (LUR) and wetlands (LUW), wetland conversion (WC), hydrological disturbance due to water use ($HD_{Water}$) and climate change ($HD_{CC}$).

Please see (CDC Biodiversité 2020d; 2020b) for more details on the terrestrial and aquatic pressures included in the GBS. Ecotoxicity and marine biodiversity impacts are not included in this version of the CommoTool.

# 2 Oil & gas CommoTool overview

## 2.1 Dimensioning the biodiversity impact of oil & gas production

In the oil & gas CommoTool, the dimensioning step determines the biodiversity impact of crude oil and natural gas in each selected geographical region. The general concept is that **biodiversity impact factors** (expressed in MSA.km$^2$ per unit of pressure) calculated for terrestrial and freshwater biodiversity (CDC

Biodiversité 2020d; 2020b) are combined to **relevant data related to oil & gas** such as land use (transformation and occupation) at the extraction site level, water consumption, GHG emissions. At the end of the computation process, **the biodiversity impact factors** obtained **(in MSA.km$^2$ per tonne of fuel commodity)** can be declined at different geographical scales.

To make a parallel with the LCA framework, the oil & gas CommoTool uses several types of data and characterisation factors, as described in Figure 6. For instance, for land use, a given tonnage of fossil fuel plays the role of the **LCA inventory** data in the GBS. It is linked to an occupied area, which is a **midpoint**, through a **midpoint characterisation factor** based on the drilling technique. The midpoint is linked to an **endpoint impact** in MSA.km$^2$ through a **midpoint to endpoint characterisation factor** which corresponds to the impact intensities in MSA.km$^2$/unit of pressure (here the area dedicated to drilling). The impact factors in MSA.km$^2$/t constituting the oil & gas CommoTool are a **combination of the midpoint and endpoint characterisation factors.**

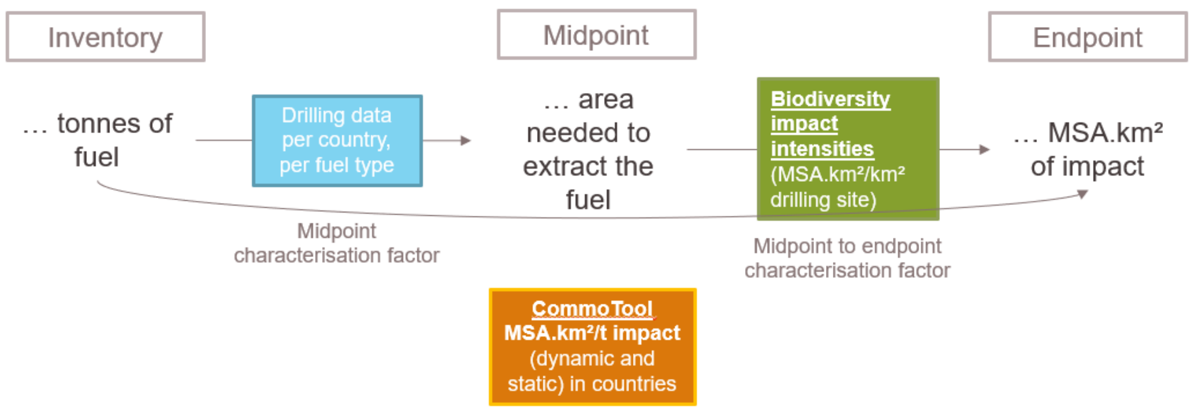


*Figure 6: Impact factors used or constructed in the oil & gas CommoTool within the LCA framework*

## 2.2 Attributing the impacts of oil & gas production

More specifically:

Climate change: climate change impact is assessed based on a pressure-impact relationship involving GHG emissions (CDC Biodiversité 2020d).100% of the CC impacts associated to GHG emitted by fossil fuel production are attributed to it. Scope 3 downstream emissions are not attributed to fossil fuel production in GBS 1.0 (but will be in future versions).

Land use: there is no land use category for drilling in GLOBIO cause-effect relationships and no data on land occupation of drilling sites in GLOBIO-IMAGE outputs. We thus rely on literature to evaluate land use occupation and land conversion for fossil fuel production. The impacts of LU change and occupation within the drilling sites are attributed to oil & gas production. It is important to have in mind that the drilling site is considered as a reference for land use associated impacts, not the concession which is a common administrative nomenclature for the oil and gas sector but not well suited for land use transformation and occupation areas evaluation as those areas usually represent a small and variable fraction of the concession.

Encroachment and Fragmentation: in GLOBIO cause-effect relationships, these pressures are caused only by "human" land uses, *i.e.* land uses where human activity is predominant: croplands, cultivated grazing and urban areas (CDC Biodiversité 2020d). We consider that oil & gas extraction and processing sites belong to a "human" land use type, therefore causing both encroachment and fragmentation. The general attribution rule described in the terrestrial module review document (CDC Biodiversité 2020d) is followed and impacts are attributed on the basis of the surface area of extraction and processing sites. For the same reason that for LU, concession area is not used for E evaluation.

Atmospheric nitrogen deposition: **in default assessments**, the impacts dimensioned (relying partly on the GLOBIO-IMAGE framework) originate only from croplands and urban areas, so none is attributed to oil & gas production. This limitation seems reasonable: in LCA databases, nitrogen emissions for both processing and extraction phases are negligible.

Land use in catchment of rivers: in GLOBIO-Aquatic cause-effect relationships, only "human" land uses contribute to the pressure land use in catchment for rivers. As explained above for the fragmentation and encroachment pressure, we consider that drilling sites (extraction and first transformation) belong to "human" land use type. Thus, LUR impacts are attributed to drilling sites in proportion of their share of the total human area in the watershed.

Land use in catchment of wetlands: in GLOBIO-Aquatic model, land uses contribute to the pressure land use in catchment for wetlands depending on their management intensity. Only land uses with a management intensity equals to 0%, *i.e.* natural land use types, do not contribute to that pressure. LUW impacts are attributed to drilling sites in proportion of their share of the total intensity-weighted area in the watershed.

Wetland conversion: **in default assessments**, we consider that drilling site contains the same proportion of wetlands as their country or region and impacts are attributed to them based on the land transformation they cause. **In refined assessments**, when company data reveal wetland conversion within the drilling site, 100% of the impacts is attributed to oil & gas production.

Hydrological disturbance: in the GBS, the HD related impacts are split between climate change, water network infrastructures and direct water use. HD related to direct water use (referred to as $HD_{Water}$ in the remaining of this report) is attributed to blue water consumption. Drilling activities can use dedicated infrastructure on the water network such as dams for energy production. The energy production impacts will be treated in the next version of the GBS tool. For other types of water infrastructure linked to drilling activities, no global data is available. Thus, HD related to infrastructures is not attributed to the oil & gas industry. 100% of the HD due to climate change (referred to as $HD_{CC}$ in the remaining of this report) is attributed to the Scope GHG emissions generated by oil & gas production.

Freshwater eutrophication: in GLOBIO-IMAGE outputs, only croplands and urban areas are considered as sources of N and P leaching into aquatic ecosystems (Jan H. Janse, Bakkenes, and Meijer 2016). Thus, in



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**default assessments**, only the impacts caused by croplands and urban areas are dimensioned (CDC Biodiversité 2020b) so none is attributed to oil & gas production. This limitation seems reasonable: in LCA databases, nitrogen emissions for both processing and extraction phases are negligible.

# 3 Dimensioning the impact of oil & gas production – Default assessment

## 3.1 Data used

### A SPATIAL PRESSURES AND GHG EMISSIONS

The Product Environmental Footprint (PEF) is a methodology by the European Commission's Joint Research Centre (JRC) which is based on Life Cycle Assessment. Joined to the *Environmental Footprint* LCIA method is the PEF LCA dataset, both resulting from a three-year multi-stakeholder testing period. The dataset gathers input and output data for hundreds of processes, including oil and natural gas production. Crude oil and natural gas related processes are listed in Table 1. The processes are regionalized, 8 regions are distinguished for crude oil production, while 37 regions are distinguished for natural gas.

Land transformation and GHG emissions data from PEF are used in the GBS. The data is located in the **output table** of each PEF LCA process and are expressed for the production of 1 kg of output.

The processes consider a **single product, crude oil or natural gas, taking into account the national or regional mix of extraction techniques.** In fact, for both products, the output product is a "mix" of conventional versus non-conventional technologies as well as a mix of onshore versus offshore production. For national offshore production, for land use, only a pipeline transport between the oil or gas field and the shore is considered. No land use is accounted for the platform at sea. For national onshore production no specific pipeline is modelled.

PEF process data suffer from 2 limitations:

1. The countries or regions covered are limited with 7 countries and 1 region for crude oil and 36 countries and 1 region for natural gas. This meaning that for countries or regions that are not covered in PEF, a regional or global average is going to be used to compute impact factors,

2. The processes cover the **entire supply chain of crude oil and natural gas**, thus including well drilling, fossil fuel production and processing, as well as transportation to the refinery. This perimeter does not perfectly fit the perimeter of the CommoTool presented in Section 1.3, as the CommoTool perimeter does not include transportation to the refinery. It is also assumed that this perimeter matches that of EXIOBASE extraction industries (cf Section 5.2). In future versions of the GBS tool, additional data might be used to isolate transportation related land transformation and GHG emissions.

In future versions of the GBS tool, additional data will be used to differentiate notably conventional and non-conventional extraction techniques so it could be used in a refined assessment where the extraction type is known.

*Table 1: Crude oil and natural gas production related processes in the PEF database*

| PEF process name |
|---|
| Crude_oil_mix__consumption_mix__to_consumer_AU |
| Crude_oil_mix__consumption_mix__to_consumer_BR |
| Crude_oil_mix__consumption_mix__to_consumer_CN |
| Crude_oil_mix__consumption_mix__to_consumer_EU_27 |
| Crude_oil_mix__consumption_mix__to_consumer_IN |
| Crude_oil_mix__consumption_mix__to_consumer_JP |
| Crude_oil_mix__consumption_mix__to_consumer_RU |
| Crude_oil_mix__consumption_mix__to_consumer_US |
| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____AT |
| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____AU |
| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____BE |
| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____BG |
| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____BR |
| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____CA |
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| Natural_gas_mix__consumption_mix__to_consumer__technology_mix__medium_pressure_level____1_bar____EU_27 |
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## B WATER CONSUMPTION

To assess water consumption due to the extraction of oil and gas, we use water-use coefficients from (Mielke, Anadon, and Narayanamurti 2010). In the paper, authors refer to the U.S. Geological Survey's definitions for water withdrawal as the "water removed from the ground or diverted from a surface-water source for use," and water consumption, as "the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment."

In their report, Mielke and al. focus on the consumptive use of water during the extraction phase for different energy, different extraction technique and different phases of energy production. Water-use coefficients cover groundwater and surface water. Their study focuses primarily on U.S. data which is a limitation for the GBS. As they state in the report, "global extrapolation from the U.S. data for resource extraction is less likely to be accurate as the U.S. water consumption is a function of both physical conditions (e.g., geology for oil and gas; soil and climate for biofuels) and regulatory requirements (e.g., regulations requiring processing and recycling of water), conditions and requirements that can vary greatly from one geography to the next."

Coefficients are summarized in Table 2.

| Commodity | Extraction technique | Water use cofficient (gal per MMBtu) |
|---|---|---|
| Crude oil | Primary secondary | 62 |
| Crude oil | EOR | 64 |
| Crude oil | Oil sands | 29 |
| Crude oil | Shale oil | 22 |
| Natural gas | Conventional gas | 0 |
| Natural gas | Shale gas | 1,3 |

*Table 2: Water-use coefficients (Mielke, Anadon, and Narayanamurti 2010)*

For crude oil and natural gas, a global average of the water use coefficient is computed and applied to all countries and regions. Coefficients in the report are expressed in gal per MMBtu. We convert them in $m^3$ per tonne.

PEF water data is not used as we didn't find it consistent compared to literature.

In the next version of the oil and gas commoTool, we are planning to take into account the national or regional extractive technique mix to compute a more representative national or regional water use coefficient. Also, additional literature should be used to consider national specificities and not only rely on US figures for water coefficient related to each extraction techniques.

## 3.2 Methodology to compute biodiversity impact factors related to oil & gas production

### A REGIONAL ALLOCATION FOR PEF DATA

In the section, we describe how impact factors are generated for countries and EXIOBASE regions. As described in 3.1A, PEF data for land transformation and GHG emissions are only available for a limited number of geographies. For country impact factors, when PEF data is available for a given country, it is used as such if the country belongs to the European Union (EU-27), PEF data for this region is used. Otherwise, a global average computed considering all available countries equally weighted is used.

For EXIOBASE regions, if the region is a country for which PEF data is available, then it is used as such. If the region is a group of countries and PEF data is available for a fraction of them, then we used the average for those countries. Finally, if the region is a group of countries and if PEF data is not available for all of them, then global average is used.

### B SPATIAL PRESSURES : LU, E, F, WC, LUR, LUW

Land transformation in PEF is defined as the new area needed to produce a given quantity of product, in other words it quantifies the area of land converted due to the product production. To evaluate the associated biodiversity impact, we first have to evaluate which fraction of the land conversion occurred over terrestrial ecosystems and which fraction occurred over wetlands. We use a similar approach to the one applied in the mining CommoTool (CDC Biodiversité 2020c). Since the exact locations of the extraction sites are unknown (unlike for mines), we use national or regional averages of the proportion of wetland areas over the terrestrial areas. By multiplying the area converted by this ratio, this leads to an assessment of the wetland areas assumed to have been converted. The remainder of the converted area was thus converted from non-wetland areas.

For the **terrestrial land use pressure**, we compute the impact factor by multiplying the non-wetland converted area by *(remaining MSA% - extraction site MSA%)*. We consider here that MSA% for extraction sites is the same for oil and gas than for mining commodities, therefore equal to 0%. The remaining MSA% (i.e. the level of biodiversity present, which is equal to one minus the total static impacts) of the area being converted is based on national and regional averages (since the location of the site is unknown).

For **wetland conversion**, we consider that the conversion to a drilling site leads to a total loss of aquatic biodiversity. We also consider here that converted wetland is pristine (MSA% = 100%). This leads to an overestimation of the wetland conversion impacts.

To summarize, land use and wetland conversion dynamic impact factors are computed as follow:

$$Impact\ factor\ LU^{dynamic}_{country} = PEF\ land\ transformation \times (1 - wetland\ ratio\%_{country}) \times (MSA\%_{country} - 0)$$

$$Impact\ factor\ WC^{dynamic}_{country} = PEF\ land\ transformation \times wetland\ ratio\%_{country} \times (100\% - 0)$$

With: $Impact\ factor\ LU^{dynamic}_{country}$ = dynamic impact factor for land use pressure in MSA.km² per tonne of fuel commodity

$Impact\ factor\ WC^{dynamic}_{country}$ = dynamic impact factor for wetland conversion in MSA.km² per tonne

$PEF\ land\ transformation$ = PEF land transformation in km² per tonne

$MSA\%_{country}$ = national average for remaining MSA% in %

$wetland\ ratio\%_{country}$ = national average of proportion of wetland areas over the terrestrial areas in %

To compute static impact for factors for LU and WC, we face a methodological challenge that we have not yet solve adequately. The challenge is to grasp data that would allow us to link the size the area of an extraction site to its annual production, the same way it is done in the Mining commoTool using the relationship proposed by (Kobayashi, Watando, and Kakimoto 2014). Even just estimating the typical area of an extraction site with an associated typical annual production would help us to conduct a first evaluation. Unfortunately we were not yet able to find such data in the scientific literature and therefore we decided to make the rough assumption that the global average ratio between the area converted and the area occupied for oil and gas is the same as for mining (4.85%). We are very aware that this assumption is a major limitation for impact factors deriving from the occupied area which are static impact factors for LU and WC and both static and dynamic impact factors for E, F, LUR and LUW.

**The terrestrial static land use** impact factor is computed as follow:

$$Impact\ factor\ LU^{static}_{country} = (100\% - 0\%) \times occupied\ area \times (1 - wetland\ ratio\%_{country})$$

$$Impact\ factor\ LU^{static}_{country} = \frac{PEF\ land\ transformation}{global\ ratio\ converted/occupied_{mining}} \times (1 - wetland\ ratio\%_{country})$$

And **wetland conversion static** impact factor is computed as follow:

$$Impact\ factor\ WC^{static}_{country} = \frac{PEF\ land\ transformation}{global\ ratio\ converted/occupied_{mining}} \times wetland\ ratio\%_{country}$$

With: $Impact\ factor\ LU^{static}_{country}$ = static impact factor for land use pressure in MSA.km² per tonne

$Impact\ factor\ WC^{static}_{country}$ = static impact factor for wetland conversion in MSA.km² per tonne

$PEF\ land\ transformation$ = PEF land transformation in km² per tonne

$wetland\ ratio\%_{country}$ = national average for wetland ratio in %

$global\ ratio\ converted/occupied_{mining}$ = global average ratio between converted and occupied land per tonne for mining commodities

To compute the dynamic and static impact factors for E, F, LUR and LUW we use intensities computed in the terrestrial (CDC Biodiversité 2020d) and aquatic (CDC Biodiversité 2020b) modules that we apply to the occupied area per tonne described and computed previously. We consider that extracting areas for oil and gas belong to "human land uses" and are therefore responsible for the encroachment, fragmentation and land use in catchement pressures. The land use in catchment for wetlands pressure depends on the land use intensity of the source. Since we assume drilling sites have an MSA% of 0%, their intensity weighted area is equal to their whole occupied area.

The impact factors are computed as follow for each pressure X:

$$Impact\ factor\ X_{country}^{static\ or\ dynamic} = occupied\ area \times Intensity\ X_{country}^{static\ or\ dynamic}$$

$$Impact\ factor\ X_{country}^{static\ or\ dynamic} = \frac{PEF\ land\ transformation}{global\ ratio\ converted/occupied_{mining}} \times Intensity\ X_{country}^{static\ or\ dynamic}$$

With: $Impact\ factor\ X_{country}^{static\ or\ dynamic}$= static or dynamic impact factor for pressure X (E, F, LUR or LUW) in MSA.km² per tonne

$PEF\ land\ transformation$=PEF land transformation in km² per tonne

$global\ ratio\ converted/occupied_{mining}$= global average ratio between converted and occupied land per tonne for mining commodities

$Intensity\ X_{country}^{static\ or\ dynamic}$= static or dynamic intensity for pressure X (E, F, LUR or LUW) in MSA.km² per km² from the terrestrial and aquatic GBS modules

## C CLIMATE CHANGE IMPACT FACTORS: CC AND $HD_{CC}$

The contributions of a certain quantity of GHG emission to terrestrial Climate change (CC) and freshwater Hydrological disturbance due to climate change ($HD_{CC}$) pressures are assessed by specific functions explained in the terrestrial (CDC Biodiversité 2020d) and freshwater module papers (CDC Biodiversité 2020b), namely `ghg_get_emission_MSA_impact()` and `ghg_get_emission_MSA_impact_aquatic()`. Practically, both functions compute a **biodiversity impact in MSA.km² linked to a given GHG emission in tonnes $CO_2$-eq**.

We combine these impact intensities to oil and gas GHG emission data to come up with impact factors expressed per tonne of commodity. These emission data come from PEF for commodity related products as explained in section 3.1A.

### D HYDROLOGICAL DISTURBANCE: $HD_{WATER}$

For **hydrological disturbance from direct water use** pressure, we use impact intensities for **withdrawn water expressed in MSA.km² per m³** from the GBS aquatic module (CDC Biodiversité 2020b). In the central calculation mode, the impact intensities from the central calculation mode ("wm" for weighted-mean in the code) are used.

These are combined to water coefficients from (Mielke, Anadon, and Narayanamurti 2010) described in section 3.1B to come up with impact factors expressed per tonne of commodity.

## 3.3 Example

We compute impacts for the fictive sourcing summarized inTable 3. This sourcing is designed to illustrate two types of granularity, at the product level with multiple products from the United States and at the country level with oil and natural gas produced in various countries. Table 4 provides a summary of the values of the midpoints involved in the footprint calculation. The `GBStoolbox` package contains the example file `example_commodity_oil&gas.rda`. The successive application of `commodity_pre_treatment(commodity_type = "oil&gas")` and `commodity_evaluator(commodity_type = "oil&gas")` leads to the results displayed below.

| Country Name | Commodity | Quantity (tonnes) |
|---|---|---|
| United States | Crude oil | 1000 |
| United States | Natural gas, at consumer | 1000 |
| France | Natural gas, at consumer | 1000 |
| Russian Federation | Natural gas, at consumer | 1000 |

*Table 3: Example fictitious supply summary*

| Commodity name | Country | GHG emission intensity (kg $CO_2$eq per tonne) | Land transformation intensity ($m^2$ per tonne) | MSA% remaining | Wetland ratio | LUR MSA intensity $MSA.m^2/km^2$ | LUW MSA intensity $MSA.m^2/km^2$ | Mielke Water intensity ($m^3$ per tonne) |
|---|---|---|---|---|---|---|---|---|
| Crude oil | United States | 330 | 2,51 | 54% | 14% | 1 114 | 61 427 | 5,8 |
| Crude oil | Australia | 268 | 1,22 | 76% | 4% | 29 | 44 632 | 5,8 |
| Natural gas | France | 507 | 0,92 | 30% | 1% | 1 005 | 7 794 | 0,1 |
| Natural gas | United States | 530 | 2,36 | 54% | 14% | 1 114 | 61 427 | 0,1 |
| Natural gas | Russian Federation | 674 | 1,11 | 79% | 10% | 1 985 | 27 153 | 0,1 |

*Table 4: Example – summary of the midpoints associated to the fictitious supply*

# A PRODUCT ANALYSIS

Table 5, Table 6 and Table 7 reveal the impacts assessed for the fictitious supply, focusing on the differences between crude oil and natural gas in the same country: the United States.

| | | Terrestrial ($MSA.m^2$) | | Aquatic ($MSA.m^2$) | |
|---|---|---|---|---|---|
| Product Name | Country | Dynamic | Static | Dynamic | Static |
| Crude oil | United States | 2 606 | 35 119 | 378 | 6 869 |
| Natural gas | United States | 3 407 | 32 961 | 364 | 6 409 |

*Table 5: Example - product analysis - total figures*

| | | Terrestrial split ($MSA.m^2$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Dynamic | | | | Static | | |
| Product Name | Country | LU | E | F | CC | LU | E | F |
| Crude oil | United States | 1 162 | - | - | 1 444 | 23 969 | 7 993 | 3 157 |
| Natural gas | United States | 1 091 | - | - | 2 315 | 22 496 | 7 502 | 2 963 |

*Table 6: Example - product analysis - terrestrial results split*

| | | Aquatic split ($MSA.m^2$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dynamic | | | | | Static | | | |
| Product Name | Country | WC | LUR | LUW | HD water | HD CC | WC | LUR | LUW | HD water |
| Crude oil | United States | 361 | 0 | 2 | 0 | 14 | 3 813 | 54 | 2 961 | 41 |
| Natural gas | United States | 339 | 0 | 2 | 0 | 23 | 3 579 | 50 | 2 779 | 1 |

*Table 7: Example - product analysis - aquatic results split*

Main comments:

- for terrestrial biodiversity, the dynamic footprint is significantly higher for natural gas, mostly due to climate change as GHG emissions intensity is higher for natural than for gas in the United-States. We remind that Scope 3 downstream is not considered here,

- for the static footprint, total results are in the same range for both terrestrial and aquatic biodiversity,

- for aquatic biodiversity, WC is predominant for the dynamic footprint, WC and LUR are predominant for the static footprint

- HDwater share is overall small for both static and dynamic footprints. Crude oil has a higher HDwater impact due to its higher water use intensity.

## B COUNTRY ANALYSIS

| | | Terrestrial ($MSA.m^2$) | | Aquatic ($MSA.m^2$) | |
|---|---|---|---|---|---|
| **Product Name** | **Country** | **Dynamic** | **Static** | **Dynamic** | **Static** |
| Natural gas | France | 2 483 | 9 072 | 34 | 294 |
| Natural gas | Russian Federation | 3 738 | 26 137 | 137 | 1 794 |
| Natural gas | United States | 3 407 | 32 961 | 364 | 6 409 |

*Table 8: Example - product analysis - total figures*

| | | Terrestrial split | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Dynamic ($MSA.m^2$) | | | | Static ($MSA.m^2$) | | |
| **Product Name** | **Country** | **LU** | **E** | **F** | **CC** | **LU** | **E** | **F** |
| Natural gas | France | 269 | - | - | 2 214 | 5 548 | 1 958 | 1 566 |
| Natural gas | Russian Federation | 792 | - | - | 2 946 | 16 323 | 8 499 | 1 314 |
| Natural gas | United States | 1 091 | - | - | 2 315 | 22 496 | 7 502 | 2 963 |

*Table 9: Example – country analysis - terrestrial results split*

| | | Aquatic split | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Dynamic ($MSA.m^2$) | | | | | Static ($MSA.m^2$) | | | |
| **Product Name** | **Country** | **WC** | **LUR** | **LUW** | **HD water** | **HD CC** | **WC** | **LUR** | **LUW** | **HD water** |
| Natural gas | France | 12 | 0 | 0 | 0 | 22 | 128 | 19 | 146 | 2 |
| Natural gas | Russian Federation | 107 | 0 | 0 | 0 | 29 | 1 136 | 43 | 593 | 22 |
| Natural gas | United States | 339 | 0 | 2 | 0 | 23 | 3 579 | 50 | 2 779 | 1 |

*Table 10: Example – country analysis - aquatic results split*

Main comments:

- we observe a high variability in the results for all the global buckets: aquatic/terrestrial and dynamic/static,

- terrestrial land use dynamic for France are much lower due to a combination of both low land transformation intensity and low remaining MSA%. The first factor also implies a low static impact,

- CC dynamic footprint is significantly higher for Russia as GHG emissions intensity are higher too,

- WC dynamic and static footprints in France are relatively lower due to a low land transformation intensity and a low wetland ratio, for the opposite reason, the footprints in the United States are comparatively much higher.

## 3.4 Tests

To control the consistency of the impact factors at a global level, we conduct tests where we compute global impacts and global pressure quantities based on 2017 world production figures from the IEA. The idea is to control for each pressure and each pressure-linked impact, whether the global estimation is in a realistic range. To gauge the consistency of those global estimates, we use several benchmarks:

- GLOBIO-IMAGE global impacts estimates (static and dynamic) (Alkemade et al. 2009; J. H. Janse et al. 2015),

- IPCC GHG emissions global annual estimate for 2017 (Masson-Delmotte et al. 2018),

- AQUEDUCT global annual water consumption for 2011 (Gassert et al. 2014),

- GBS mining CommoTool global estimation for land transformation and occupation (CDC Biodiversité 2020c)

Table 11 provides figures for crude oil and Table 12 for natural gas. Overall global pressure and impact levels are in a plausible range, meaning that we do not encounter odd figures obviously too high or too low. Still several points have to be addressed and need further investigation. Among those:

- global annual land transformation is several times higher for oil (x1.9) and natural gas (3.2x) compared to mining extraction,

- global land occupation for 2020 is several times higher for oil (x3.4 and 105 000 km², roughly the size of Iceland) and natural gas (5.8x and 179 000 km², roughly the size of Cambodia) compared to mining extraction. It is estimated to amount to,

annual global GHG emissions represent 4.0% of global emissions for oil, 5.9% for natural gas. We remind that this includes only extraction, process and transport at refinery and not downstream burning of those fuels. Therefore, those figures are probably too high and will be investigated,

- annual global water consumption represents 1.2% of global water consumption for oil, 0.01% for natural gas,

- impact caused by wetland conversion (dynamic) is high, accounting for 19.2% of the global impacts due to wetland conversion (assessed in GLOBIO-IMAGE outputs) for oil and 24.4% for natural gas. Overall the impacts on aquatic dynamic are a small share of the global impacts. This is due to a relatively low value for the intensity-weighted surface area occupied by oil & gas (0.4% and 0.7% of the global intensity-weighted area respectively). Since the LUW impact is quantified based on this intensity-weighted surface, the share of oil & gas is relatively limited. LUW being the main aquatic pressure globally, oil & gas share of global impacts is relatively limited overall.

| | Pressures | | | |
|---|---|---|---|---|
| **Calculation mode** | **Land transformation ($km^2$)** | **Land occupation ($km^2$)** | **GHG emissions (kg CO2eq)** | **Water consumption (m3)** |
| **Central** | 5 095 | 105 057 | 1.3E+12 | 2.6E+10 |
| **Conservative** | 11 112 | 229 107 | 1.6E+12 | 4.3E+10 |
| **Benchmark** | 2 702 | 30 952 | 3.2E+13 | 2.2E+12 |
| **Central %** | 188.6% | 339.4% | 4.0% | 1.2% |
| **Conservative %** | 411.3% | 740.2% | 5.0% | 2.0% |

| | Terrestrial dynamic | | | | | Terrestrial static | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Calculation mode** | **Total** | **LU** | **E** | **F** | **CC** | **Total** | **LU** | **E** | **F** |
| **Central** | **7 769** | 2 164 | 3 | 0 | 5 602 | **76 782** | 44 613 | 21 633 | 10 536 |
| **Conservative** | **12 140** | 5 138 | 71 | 0 | 6 931 | **293 877** | 105 940 | 103 205 | 84 732 |
| **Benchmark** | **274 975** | 109 855 | 13 413 | 586 | 151 120 | **34 230 451** | 25 500 860 | 6 354 241 | 2 375 351 |
| **Central %** | **2.8%** | 2.0% | 0.0% | 0.0% | 3.7% | **0.2%** | 0.2% | 0.3% | 0.4% |
| **Conservative %** | **4.4%** | 4.7% | 0.5% | 0.0% | 4.6% | **0.9%** | 0.4% | 1.6% | 3.6% |

| | Aquatic dynamic | | | | | Aquatic static | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Calculation mode** | **Total** | **WC** | **LUR** | **LUW** | **HDwater** | **HDCC** | **Total** | **WC** | **LUR** | **LUW** | **HDwater** |
| **Central** | **255** | 192 | 0 | 5 | 2 | 56 | **6 174** | 2 026 | 87 | 2 212 | 1 848 |
| **Conservative** | **1 812** | 1 594 | 3 | 66 | 81 | 69 | **46 871** | 16 853 | 289 | 13 089 | 16 640 |
| **Benchmark** | **7 397** | 999 | 272 | 4 881 | 623 | 623 | **2 493 220** | 561 363 | 50 940 | 1 285 831 | 595 085 |
| **Central %** | **3.4%** | 19.2% | 0.1% | 0.1% | 0.3% | 8.9% | **0.2%** | 0.4% | 0.2% | 0.2% | 0.3% |
| **Conservative %** | **24.5%** | 159.6% | 1.1% | 1.3% | 12.9% | 11.0% | **1.9%** | 3.0% | 0.6% | 1.0% | 2.8% |

*Table 11:Consistency check results for oil*

| Calculation mode | Pressures | | | |
|---|---|---|---|---|
| | Land transformation (km²) | Land occupation (km²) | GHG emissions (kg CO2eq) | Water consumption (m3) |
| Central | 8 704 | 179 459 | 1.9E+12 | 3.0E+08 |
| Conservative | 28 054 | 578 440 | 3.3E+12 | 6.1E+08 |
| Benchmark | 2 702 | 30 952 | 3.2E+13 | 2.2E+12 |
| Central % | 322.2% | 579.8% | 5.9% | 0.01% |
| Conservative % | 1038.4% | 1868.9% | 10.3% | 0.03% |

| Calculation mode | Terrestrial dynamic | | | | | Terrestrial static | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Total | LU | E | F | CC | Total | LU | E | F |
| Central | **11 716** | 3 440 | 4 | - | 8 272 | **125 516** | 70 929 | 36 734 | 17 853 |
| Conservative | **24 112** | 9 565 | 78 | - | 14 470 | **764 866** | 197 210 | 399 868 | 167 787 |
| Benchmark | **274 975** | 109 855 | 13 413 | 586 | 151 120 | **34 230 451** | 25 500 860 | 6 354 241 | 2 375 351 |
| Central % | **4.3%** | 3.1% | 0.0% | 0.0% | 5.5% | **0.4%** | 0.3% | 0.6% | 0.8% |
| Conservative % | **8.8%** | 8.7% | 0.6% | 0.0% | 9.6% | **2.2%** | 0.8% | 6.3% | 7.1% |

| Calculation mode | Aquatic dynamic | | | | | | Aquatic static | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | WC | LUR | LUW | HDwater | HDCC | Total | WC | LUR | LUW | HDwater |
| Central | **334** | 243 | 0 | 8 | 0 | 82 | **5 728** | 2 573 | 144 | 2 989 | 22 |
| Conservative | **1 851** | 1 630 | 3 | 73 | 1 | 144 | **45 553** | 17 230 | 820 | 27 306 | 197 |
| Benchmark | **7 397** | 999 | 272 | 4 881 | 623 | 623 | **2 493 220** | 561 363 | 50 940 | 1 285 831 | 595 085 |
| Central % | **4.5%** | 24.4% | 0.1% | 0.2% | 0.0% | 13.2% | **0.2%** | 0.5% | 0.3% | 0.2% | 0.0% |
| Conservative % | **25.0%** | 163.2% | 1.2% | 1.5% | 0.2% | 23.1% | **1.8%** | 3.1% | 1.6% | 2.1% | 0.0% |

*Table 12: Consistency check results for natural gas*

# 4 Dimensioning the impact of oil & gas production – Refined assessment

If the assessed entity can provide **customed and more precise data on land use change and occupation, water withdrawal and consumption or GHG emissions** related to the drilling sites they operate or from which their commodities are sourced, the refined data can be used to replace the values from the literature, USGS, PEF, GLOBIO-IMAGE and our own assumptions.

# 5 Linkage with the input-output approach

As explained in the report dedicated to the input-output (IO) approach (CDC Biodiversité 2019), the terrestrial impacts due to climate change are computed based on the $D_{CC}$ and $M_{CC}$ matrices for all {region; industry} pairs. They thus rely on the GHG emissions documented in EXIOBASE emission account and the direct application on the pressure-impact relationship related to CC. This section thus deals with all pressures except CC.

Linking the output of the oil & gas CommoTool to the IO framework presents 2 difficulties. The first one is intrinsic to EXIOBASE and related to the computation of the $D_{LUEFN\_oil\_gas}$ matrix. The second one is the match between EXIOBASE and the CommoTool items, thus affecting the computation of the $M_{LUEFN\_oil\_gas}$ matrix.

## 5.1 D matrix

As other $D_{LUEFN}$ matrices, $D_{LUEFN\_oil\_gas}$ matrix documents the quantities of commodities extracted per million euros of production of each {region; industry} in t/mEUR. It is computed based on the EXIOBASE material account. The items of the material account related to oil & gas are listed in Table 13. EXIOBASE material account items are made up of three parts:

1. The extraction type, used or unused. Most often only the "used" extraction quantities are of interest for the GBS, since "unused" extraction relies to quantities that are not directly the commodities of interest (overburden related to metal ore extraction, leaves and roots of crops);
2. The item type, which enable to easily retrieve the items related to each commodity type, here "Fossil Fuel";
3. The item name.

Items related to Peat and Natural gas liquids are in grey because the related quantities are null in EXIOBASE. Consequently, **Peat and Natural gas liquids cannot be included in the GBS default assessment**.

*Table 13: Fossil fuel items in EXIOBASE material account*

| EXIOBASE material account item |
|---|
| Domestic Extraction Used – Fossil Fuels: Total |
| Unused Domestic Extraction - Fossil Fuels - Anthracite |
| Unused Domestic Extraction - Fossil Fuels - Coking coal |

| |
|---|
| Unused Domestic Extraction - Fossil Fuels - Sub-bituminous coal |
| Unused Domestic Extraction - Fossil Fuels - Lignite/brown coal |
| Unused Domestic Extraction - Fossil Fuels - Other bituminous coal |
| Unused Domestic Extraction - Fossil Fuels - Crude oil |
| Unused Domestic Extraction - Fossil Fuels - Natural gas |
| *Unused Domestic Extraction - Oil & gas - Natural gas liquids* |
| *Unused Domestic Extraction - Oil & gas - Peat* |

First, note that coal sub-products are classified as fossil fuels in EXIOBASE material account, so that, although the biodiversity impact factors related to coals are computed in the mining CommoTool (CDC Biodiversité 2020c), the IO linkage can only be done simultaneously with the computation of $D_{LUEFN\_oil\_gas}$ matrix. The computed quantities of coal products per {region; industry} in t/mEUR are then exported into $D_{LUEFN\_mining}$ matrix documenting the quantities of mined raw materials per million euros of production.

Second, the "used" extraction is not documented separately for each fossil fuel item but rather aggregated in the item "Fossil Fuels: Total". Hence, we need to rely on **assumptions to estimate the share of the used extraction related to each fossil fuel per {region; industry}**. Furthermore, it seems that no direct link exists between the unused and used quantities of each fossil fuel. EXIOBASE supplementary materials give no indication regarding what is designated as "unused extraction" for fossil fuels and the comparison of used and unused extraction quantities documented per {region; industry} does not lead to any mathematical relationship; notably, non-zero used extraction of "Fossil Fuels: Total" is sometimes associated to zero unused extraction. Also, contrary to our expectations, used and unused extractions are not restricted to EXIOBASE industries related to the extraction of fossil fuels. While we expected direct extraction to be reserved to extracting industries, positive used and unused extraction quantities are documented for 143 over the 163 industries. The total used extraction originating from industries not dedicated to fossil fuel production (industries other than industries 20, 21 and 22) amounts to 4.2% of the world extraction. Our opinion is that these documented extractions may be only due to internal model assumptions but getting the view of experts on that point would be useful. Based on the limited available information, assumptions were made to derive quantities of each fossil fuel extracted in t/mEUR for all {region; industry} pairs. Ideally, we would need EXIOBASE to provide us with the disaggregated used domestic extraction per {region; industry} and fossil fuel item. If this can be done in the future, or if additional information on the definition of unused extraction becomes available, the assumptions will be improved in future versions of the GBS tool.

Assumptions were made regarding the fossil fuel items extracted by each industry. Basically, the three industries related to fossil fuel extraction are assumed to extract 100% of the fuel concerned (coal, crude oil or natural gas). The split between coal sub-products is made based on a world average split. Other industries are assumed to extract the world average split. The assumptions are summarised in Table 14.

*Table 14: Fossil fuel items extracted by each industry (assumption)*

| ID | EXIOBASE industry | Extracted items | Proportion |
|---|---|---|---|
| 20 | Mining of coal and lignite; extraction of peat (10) | Coal sub-products documented in the mining CommoTool (lignite, sub-bituminous coal, bituminous coal, anthracite) | World average split of coal sub-products |
| 21 | Extraction of crude petroleum and services related to crude oil extraction, excluding surveying | Crude oil | 100% |
| 22 | Extraction of natural gas and services related to natural gas extraction, excluding surveying | Natural gas | 100% |
| ## | All other industries for which used extraction is documented | All items | World average split of all fossil fuels |

The world average split is computed based on publicly available US Energy Information Administration (US EIA) data for the year 2011 (year of EXIOBASE energy data, sourced from the International Energy Agency). US EIA data provide the world total primary energy production by source, listing notably coal production, crude oil production, dry natural gas production and NGLs production. Production is expressed in quadrillion Btu (British thermal unit[1]), which we converted to tons thanks to a two-step methodology:

1. Convert US EIA world production expressed in quadrillion Btu into MJ considering that

$$1 \text{ quadrillion Btu} = 1.055.10^{12} \text{ MJ};$$

2. Use fossil fuels Net Calorific Value to convert MJ into kg.

Unfortunately, coal sub-products are not distinguished in US EAI data, so that we used the weighted average net calorific value (NCV) of coal products to compute a unique conversion factor for all coal sub-products. The NCVs and weights used per coal sub-product are presented on Table 15. We use an average calorific value per coal sub-product (in MJ/kg) and use the share of each sub-product in the total world production of coal as weight. Few literature exists on the production of coal sub-products in tons. Yet we found that **lignite amounts to approximately 10% of extracted tons[2], thus we used 0.1 as weight for the NCV of lignite and equal weight (0.3) for the NCV of other sub-products**. Likewise, the calorific value of dry

[1] Btu (or BTU, for British thermal unit) is a unit of heat defined as to the amount of heat required to raise the temperature of one pound of water by one degree Fahrenheit. 1 quadrillion Btu = $10^{15}$ Btu. Approximately: 1 Btu = 0.2931 Wh.
[2] https://en.wikipedia.org/wiki/Coal

natural gas varies according to its sourcing. **NCVs of natural gas (36.45 MJ/kg) and crude oil (42.18 MJ/kg) are taken directly from EIA statistics.**

The obtained 2011 world total production per energy source and their corresponding share are presented on Table 16. We are still looking for the best fit data source to compute spatialised splits, future versions of the GBS will rely on spatialised splits if possible. Ideally, the data precision should enable the computation of fossil fuel splits for the EXIOBASE regions corresponding to the main fossil fuels producers. Insight from reviewers on the best publicly available data to use in this purpose would be much appreciated.

*Table 15: Net Calorific Value of coal sub-products. *: based on US EIA 2006*

| Coal sub-product | Average Net Calorific Value (MJ/kg) | Weight (share in total world production*) |
|---|---|---|
| Anthracite | 29.650 | 0.3 |
| Bituminous coal | 28.200 | 0.3 |
| Sub-bituminous coal | 24.050 | 0.3 |
| Lignite | 24.050 | 0.1 |
| Coal, all sub-products | 26.975 | - |

*Table 16: World energy production split for the year 2011 (US EIA)*

| Fossil fuel | Production for year 2011 (quadrillion Btu) | Corresponding mass (tons) | Share in total extracted tons (%) |
|---|---|---|---|
| Crude oil | 173.42 | $6.43.10^{9}$ | 30.4 |
| Coal, all products | 164.42 | $4.34.10^{9}$ | 45.1 |
| Natural gas | 121.00 | $3.50.10^{9}$ | 24.5 |

## 5.2 M Matrix

The M matrix gathers impacts factors in MSA.km$^2$/tonne of product for each fossil fuel item. Considering that the oil & gas CommoTool are crude oil and natural gas, the correspondence with EXIOBASE items documented in the D matrix is straightforward.

Impact factors at the EXIOBASE region level are computed similarly as presented in Section 3.2, based on average PEF land occupation and GHG emission data at the EXIOBASE region level. The PEF-EXIOBASE correspondence is kept simple:

- The land occupation and GHG emissions data documented in PEF processes related to individual countries that can be matched to EXIOBASE regions used directly;
- The land occupation and GHG emissions data documented in the PEF “EU 27” processes are used for all EXIOBASE regions belong to the “European Union” region group;
- The land occupation and GHG emissions global averages over all PEF processes are used for other EXIOBASE regions.

Using this correspondence and PEF average data to compute impact factors at the EXIOBASE region level implicitly assumes that PEF process perimeter matches EXIOBASE extraction industries (industries 20, 21, 22, cf Table 14). Although roughly exact, this might not be exactly the case. This assumption will be refined in future version of the tool if details on EXIOBASE industries delineation allows it.

# 6 Limits and perspectives

## 6.1 Underlying data limitations

- PEF processes document input and output flows related to production mixes for crude oil and natural gas, only implicitly distinguishing various technologies, notably conventional and non-conventional extraction,

- PEF data covers a limited number of countries and regions,

- PEF data perimeter does not exactly fit the perimeter of the CommoTool, EXIOBASE data and EXIOBASE industries,

- Literature for water intensity is exclusively based on US data.

## 6.2 Methodology limitations

- the methodology proposed to evaluate the land occupation based on ratio computed for mining commodities is very rough,

- only a central calculation mode is proposed for impacts factors, optimistic and conservative computation modes must be designed and evaluated,

- impact factors should be broken down by extraction techniques,

- associated extraction techniques combining coal, natural gas and oil should be addressed and evaluated,

- extraction site encroachment should be better addressed taking into account typical spatial configurations linked to annual production the same way it is done for mine sites in the mining CommoTool (CDC Biodiversité 2020c),

- impacts associated to linear infrastructures are only partially taken into account (land use and GHG emissions associated to pipes for offshore production from PEF data). Encroachment and fragmentation caused by them should be systematically addressed especially as production sites can be very isolated in natural areas,

- waste management and “business-as-usual” ecotoxicity should be considered,

- accidentology (oil spills…) and associated ecotoxicity should be considered.

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