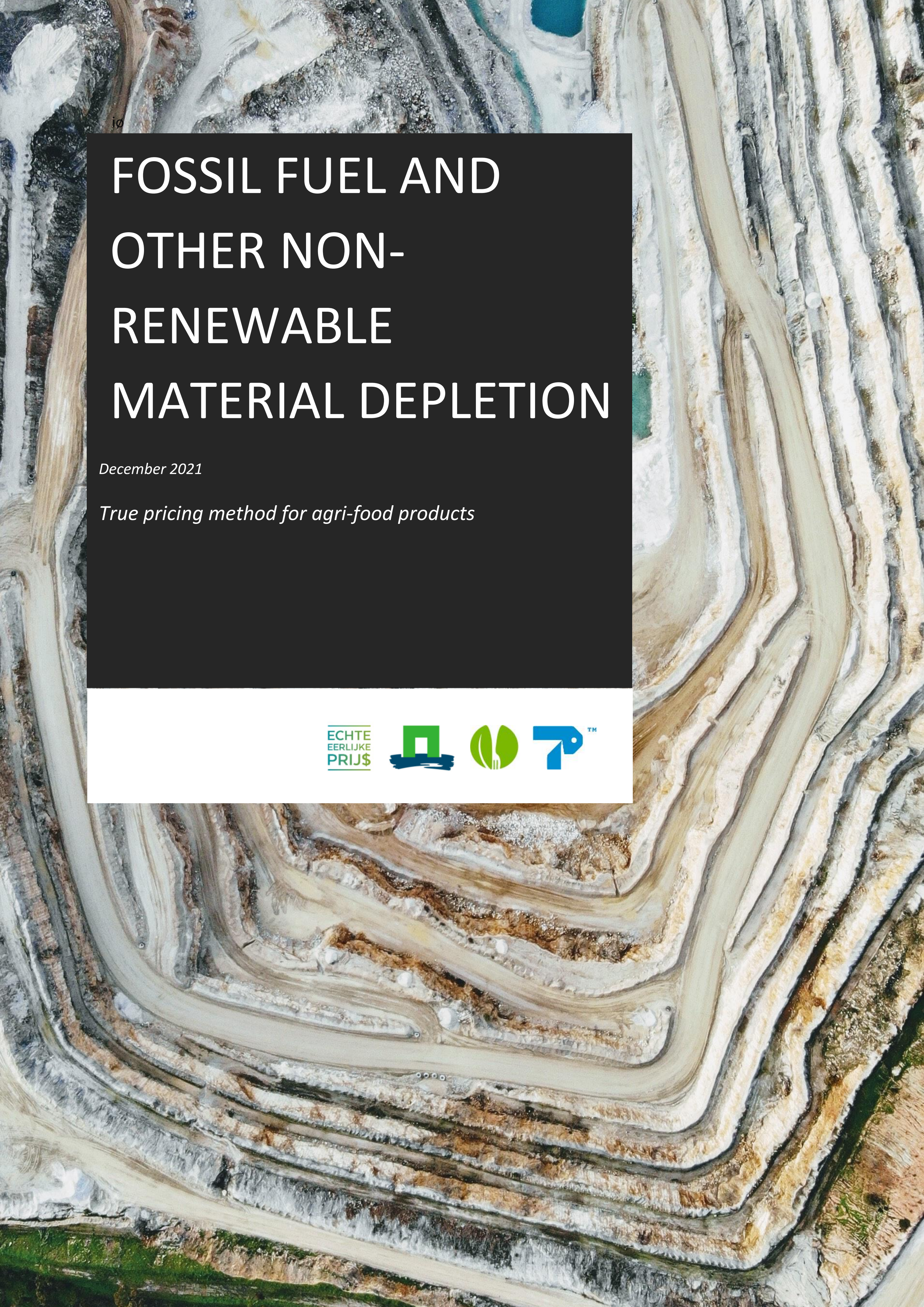


FOSSIL FUEL AND OTHER NON-RENEWABLE MATERIAL DEPLETION

December 2021

True pricing method for agri-food products

Fossil fuel and other non-renewable material depletion

Impact-specific module for true price assessment

True pricing method for agri-food products

December 2021

Authors:
Pietro Galgani[1,2]
Geert Woltjer[3]
Reinier de Adelhart Toorop[1]
Adrian de Groot Ruiz[1]

Acknowledgements: Willy Baltussen and Pietro Goglio, Wageningen Economic Research. Emmanouela Varoucha and Dimitra Kanidou, True Price. Mats Hoppenbrouwers, formerly True Price.

Acknowledgements: TKI TU en AF

Dit project ontvangt financiële steun van de Topsector Agri & Food en de Topsector Tuinbouw & Uitgangsmaterialen. Binnen de Topsector Agri & Food werken bedrijfsleven, kennisinstellingen en de overheid samen aan innovaties voor veilig en gezond voedsel voor 9 miljard mensen in een veerkrachtige wereld. Binnen de Topsector Tuinbouw en Uitgangsmaterialen werken bedrijfsleven, kennisinstellingen en de overheid samen aan innovaties op het gebied van duurzame productie van gezond en veilig voedsel en de ontwikkeling van een gezonde, groene leefomgeving.

Deze rapportage maakt deel uit van de PPS AF18051/ TU18104 'Echte en Eerlijke Prijs voor Duurzame Producten'[4].

Cover image by Dion Beetson on Unsplash.

[1] True Price, Haarlemmerplein 2, 1013 HS Amsterdam, www.trueprice.org
[2] Corresponding author: pietro@trueprice.org
[3] Wageningen Economic Research, Pr. Beatrixlaan 582 - 528, 2595 BM Den Haag, https://www.wur.nl/nl/Onderzoek-Resultaten/Onderzoeksinstituten/Economic-Research.htm

[4] For more information on the *PPS True and Fair Price for Sustainable Products*, please refer to https://www.wur.nl/nl/project/Echte-en-eerlijke-prijs-voor-duurzame-producten.htm

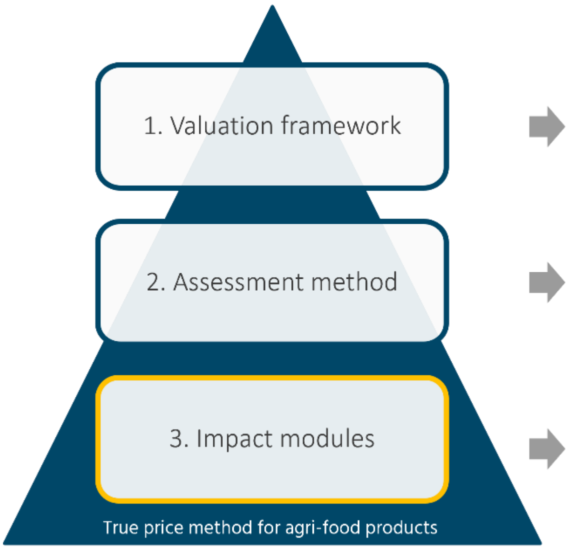
Relation to other components of the true price methodology for agri-food products

This ***Fossil fuel and other non-renewable material depletion - Impact-specific module for true price assessment*** *was developed by True Price and Wageningen Economic Research within the PPS True and Fair Price for Sustainable Products.*

This document contains the key methodological aspects to measure and value two impacts of agri-food products and value chains: fossil fuel depletion and other non-renewable material depletion.

This impact-specific module is complemented by five other ***Natural capital modules*** *and seven* ***Social and human capital modules****. The other natural capital modules are: 1) Contribution to climate change; 2) Soil degradation; 3) Land use, land use change, biodiversity and ecosystem services; 4) Air, soil and water pollution; 5) Scarce water use. These impact-specific modules are preceded by the* ***Valuation framework for true pricing of agri-food products****, which contains the theoretical framework, normative foundations and valuation guidelines, and the* ***Assessment Method for True Pricing of Agri-Food products****, which contains modelling guidance and requirements for scoping, data and reporting (Figure 1).*

Together, these documents present a method that can be used for true pricing of agri-food products, and potentially other products as well.



Content	Audience
Theoretical framework, normative foundations, definitions and valuation guidelines based on the True Price principles	Experts & method developers
Steps and requirements for implementation (completeness, accuracy, data, reporting, …)	Experts & practitioners
Definitions, footprint indicators, monetization factors and data guidelines for specific impacts (e.g. climate change, health & safety, water use …)	Experts & practitioners

Figure 1: Components of the true price methodology for agri-food products. This document is one of the impact modules.

Table of Contents

1. Introduction

This document provides a method module for the assessment of the true price of an agricultural or horticultural product, within the public-private partnership 'Echte en Eerlijke Prijs'. It contains the key methodological aspects to measure and value two impacts of agri-food products and value chains: fossil fuel depletion and other non-renewable material depletion.

This module must be used together with the **True Pricing Assessment Method for Agri-food Products** (Galgani et al. 2021a). As for other impacts in true pricing, this methodology is compatible with Life Cycle Assessment (LCA).

This module is organised as follows: Section 2 provides the definitions on fossil fuel depletion and other non-renewable material depletion. Section 3 provides background information and the rationale for including this impact as part of the true price. Section 4 offers guidance for scoping and determining materiality within a true price assessment. Section 5 presents the footprint indicator of the impacts and Section 6 contains the modelling approach per impact. Section 7 provides the monetisation approach. Finally, Section 8 provides an overview of key items for further research, as well the limitations of the research. In addition, a glossary of key terms and two annexes are provided at the end of the document. The first annex discusses the link with rights in international agreements, while the second annex gives additional information on ReCiPe characterisation factors.

2. Definitions

Fossil fuel depletion and other non-renewable material depletion are two environmental impacts of agri-food products. They are defined as follows:

- **Fossil fuel depletion** is the reduction in future availability of fossil fuels caused by the primary extraction of fossil fuels linked to fuel use, energy use and to produce other inputs, such as mineral fertilizer. Extraction of crude oil, hard coal, and natural gas bears external societal costs because the stock of these materials is reduced for present and future generations (Huijbregts et al., 2017).

In this method, fossil fuel depletion is considered separately from the depletion of other non-renewable materials in line with LCA methodologies.

- **Other non-renewable material depletion** is the reduction in future availability of non-renewable materials as the consequence of the primary extraction of scarce, non-renewable material resources excluding fossil fuels, such as minerals. These bear external societal costs because the stock of these materials is reduced for present and future generations.

In short, fossil fuel depletion represents the impact of fossil fuel use in the production of crops, agricultural inputs and in other stages of food production and horticulture, while other non-renewable material depletion represents the impact of other material depletion, including use of minerals in fertilisers, materials in packaging, construction of buildings, production of machines, etc. This distinction is in line with LCA guidelines (EC, 2013a; Huijbregts et al., 2017).

3. Background and rationale for including as part of the true price

Fossil fuel depletion and Other non-renewable material depletion are drivers of unsustainability. The depletion of resources puts at risk the security and economic welfare of future generations – extraction and use of scarce resources deplete the reserves that are left for future generations (Klinglmair et al., 2012).

Use and depletion of fossil fuels are also directly related to environmental risks, such as climate change through energy-related CO_2 emissions (IEA, 2013, p.5) and pollution. The extraction of fossil fuel also bears socioeconomic risks, such as damage oil extraction-related disasters (see e.g., EPA, n.d.) or damages from earthquakes as a result of gas extraction (see e.g., De Groene Rekenkamer, 2013). However, these risks and negative effects are out of scope for the impact fossil fuel depletion, which focuses solely on actual depletion[5].

Fossil fuel depletion and other non-renewable material depletion are commonly included among environmental sustainability indicators for Life Cycle Assessment (Klinglmair et al., 2012; EC, 2013a; Huijbregts et al., 2017). On the other hand, it can be argued that materials scarcity is optimized through markets: as materials become scarce and more expensive new extraction technologies or alternative materials are developed. In such a case there is no societal problem. In reality, it is a matter of debate also in the field of economics whether depletion of scarce resources constitutes an external cost in the economic sense or not (De Bruyn et al., 2018, section 5.6). However, reducing the use of non-renewable materials is also a policy objective for the European Union (EC, 2013b). From the perspective of internationally accepted agreements on the rights of present and future generations, safeguard of natural resources, minimizing depletion of non-renewable resources and their sustainable management are goals stated in UN declarations, resolutions, and documents. In annex A, a more detailed discussion is provided on how material depletion is linked with these rights.

Considering the arguments above, economic actors are considered to have a responsibility to limit fossil fuel and other non-renewable material depletion in processes that are under their control. Fossil fuel and other non-renewable material depletion linked to a product are included as part of its true price gap.

4. Guidance for the scoping phase of a true price assessment

In a typical scoping phase of a true price assessment, the researcher should identify all relevant processes in the life cycle of the product (or steps in its value chain). This involves assessing which intermediate products are produced and what inputs are required. After that, it should be determined which impact must be quantified for each process in the life cycle – a so-called materiality assessment - by identifying all relevant processes that are expected to contribute more significantly to the total impact. This helps the analysis as it focusses attention on these processes in subsequent steps. This process should be done following the steps and requirements laid out in the *True Pricing Assessment Method for Agri-food Products (*Galgani et al. 2021a).

Relevant processes in agricultural value chains, that are expected to contribute materially to fossil fuel depletion are:

- all agricultural processes using mechanical equipment
- processes that require energy (electricity and fossil fuel), for the production of fertilizers and pesticides
- processes of drying and storing manure
- production of packaging

[5] Emissions are taken into account in the impact-specific modules: *Contribution to climate change* and *Air, soil, and water pollution*. Socioeconomic risks, ecological disasters and earthquakes are in scope in other modules such as *Air, soil, and water pollution* and those related to community health and safety and labour.

- animal feed production

Relevant processes in agricultural value chains, that are expected to contribute materially to other non-renewable materials depletion are:

- use of phosphorous-based fertiliser
- animal feed production
- production of packaging

Non-agricultural processes, such as food-processing, transport, logistics and waste management, are also typically linked to material depletion due to their reliance on electricity, fuel, and machinery. Infrastructure, such as machinery, factories, greenhouses, etc., also contributes to other non-renewable material depletion, but its materiality can be considered lower than the processes mentioned above.

5. Footprint indicators

Fossil fuel depletion and other non-renewable material depletion correspond to two indicators with the same names, following the ReCiPe life cycle impact assessment method (Huijbregts et al., 2017)[6]:

1. Fossil fuel depletion (kg oil eq), representing the non-renewable depletion of coal, gas and oil
2. Depletion of other non-renewable materials (kg Cu eq), defined as the extraction of materials such as metals and minerals[7].

Fossil fuels can also be characterised based on their function as energy carriers. In PEF, a lifecycle impact assessment method developed by the European Commission, fossil fuel depletion is expressed in MJ (Fazio et al., 2018). However, kg oil equivalents can be directly converted into MJ, and therefore it is not a fundamental issue how it is used. Here we chose to use the standard ReCiPe unit[8].

An overview of the footprint indicators is presented in Table 1.

Table 1: Overview of Fossil fuel depletion and Other non-renewable material depletion

Footprint indicator(s)	Unit	Suggested modelling approach
Fossil fuel depletion	kg oil-eq/unit output	ReCiPe (Huijbregts et al., 2017)
Depletion of other non-renewable materials	kg Cu-eq/unit output	ReCiPe (Huijbregts et al., 2017)

6. Modelling approach

This method suggests using LCA or the results of existing LCA studies to quantify the footprint indicators for the two impacts. If this is not feasible, the researcher can estimate the footprint indicators based on

[6] Other existing LCA method standards are available for the quantification of material depletion, such as the UNEP SETAC Life Cycle Initiative and the EU's Product Environmental Footprint. These express non-renewable material indicators in kg Sb-eq.
[7] For a full list of materials, please refer to Table B.2 in Annex B: ReCiPe characterisation factors
[8] 1 MJ = 2.38×10^{-02} kg oil-eq (Goedkoop et al., 2009, Table 13.2, p.122, see Resource: Energy)

available data (such as the use of input of fuel, (agro-) chemicals and materials, or generated waste) using simplified modelling.

This chapter describes how the footprint indicators can be calculated from data on resource extraction using formulas based on LCA and characterisation factors from ReCiPe (Huibregts et al., 2016). It also describes how the indicators could be estimated based on other data points.

All types of resource use are converted to kg oil- and copper (Cu) equivalents using respectively energy content and scarcity midpoint characterisation factors from ReCiPe (Huijbregts et al., 2017). These factors express the Fossil Fuel Potential and mineral resource scarcity of a resource *x,* respectively. For fossil fuels, this is defined as the ratio between the energy content of a fossil resource *x* and the energy content of oil. For material depletion, the factors represent mineral resource scarcity and measure how scarce each material is in comparison to copper. Tables B.1 and B.2 in Annex B: ReCiPe characterisation factors, present the factors for various resources. Hierarchist midpoint factors are used for the characterisation.

Existing LCA studies for similar products or databases that provide information on the resource depletion impact of products similar to the specific product under study can be used to assess materiality in a quantitative way. Relevant fossil fuels and a longlist of other non-renewable material from ReCiPe (Huijbregts et al., 2017, Tables 12.2 and 13.1) are provided in Annex A.

6.1. Fossil fuel depletion

Fossil fuel depletion is calculated for processes where it is in scope using the following formula:

(1) $$FDEP = FFE_t \times OILEQ_t$$

Where $FDEP$ is fossil fuel depletion (in kg oil-eq/unit output*),* FFE_t is fossil fuel extraction by type *t* (in kg/unit output or MJ/unit output of the process under study) and $OILEQ_t$ is the oil equivalent characterisation factor by type *t* (in kg oil-eq/kg or kg oil-eq /MJ). Types (*t*) represent crude oil, natural gas, hard coal, brown coal, and peat (Huijbregts et al., 2017, p.104).

Formula 1 allows for the conversion of different energy carriers into kg oil-eq/unit output (where unit output is the unit in which the output of the process is measured, e.g., kg of produce). In this part (quantification) of the true price method fossil fuels are compared on an energy content perspective, rather than the scarcity perspective. This is line with ReCiPe, where midpoint factors for fossil fuel depletion are based on energy content (Huijbregts et al., 2017). The scarcity aspect of fossil fuel resources is included in the monetisation step of the method. All fossil fuels are considered substitutes of each other. Oil is taken as the only one for which scarcity cost is calculated, for the sake of simplicity. This approach is derived from midpoint characterisation in ReCiPe (see Section 7).

An example of how this formula can be used on a farm level is that, for a farm that requires 10 Nm^3 of natural gas per unit output, and with a characterisation factor for natural gas equal to 0.84 kg oil-eq /Nm^3 (Huijbregts et al., 2017, p. 104), then FDEP is equal to 8.4 kg oil-eq per unit output.

The fossil fuel extraction per type can be quantified with LCA or with the result of existing LCA studies. When this is not possible, it can be estimated using factors of primary energy use (also called 'cumulative energy demand' in MJ) from fossil sources for various agro-chemicals, fuel, electricity, and materials including packaging used and management of the wastes produced in the process under study - e.g., factors estimating the fossil energy requirements per unit of fertiliser that is manufactured. These factors are often available in environmental impact assessment tools and scientific literature.

6.2. Other non-renewable material depletion

Other non-renewable material depletion is calculated for processes where it is in scope using the following formula:

$$MDEP = RE_t \times SCARCITY_t \quad (2)$$

Where $MDEP$ is material depletion (in kg Cu-eq/unit output), RE_t is resource extraction by type t (in kg/unit output) and $SCARCITY_t$ is a resource-specific scarcity factor by type t (in kg Cu-eq/kg). Types (t) represent 70 mineral resources, including minerals used to produce fertilisers, metals and other non-renewable materials (Huijbregts et al., 2017, p. 90-92). Refer to Table B.2. in Annex B: ReCiPe characterisation factors for an overview. An example of how this formula can be used on a farm level is that, for a farm that requires 100 kg of phosphorus as fertiliser per unit output (e.g., per ton of produce), and with a resource-specific scarcity factor for phosphorus equal to 0.167 kg Cu-eq /kg phosphorus (Huijbregts et al., 2017, p. 99), then MDEP is equal to 16.7 kg Cu-eq per unit output.

The resource extraction per type can be quantified with LCA or with the result of existing LCA studies. When this is not possible, it can be estimated using a factor of the resource requirements for the various agro-chemicals and materials used by the process under study (e.g., factors estimating the kg of phosphorous, potash, calcium, copper or magnesium extracted per unit of agrochemical used). These factors are often available in environmental assessment tools and scientific literature.

6.3. Data requirements

Quantification of the depletion of fossil fuel or other non-renewable materials from agricultural processes and agricultural value chains, entails collecting data in the relevant value chain steps.

Several options are available for data collection:

1. Estimate material depletion based on LCA studies for selected supply chain steps (e.g., transport, processing, farming, waste management, etc) and other process data, such as the use of inputs (agro-chemicals, fuel, electricity and materials including packaging, etc) in combination with factors representing material use per unit of input used. For the Netherlands https://www.agrimatie.nl/ may be a useful data source for energy use, fertiliser use and use of pesticides.
2. Make use of data in LCA databases, such as Ecoinvent, GaBi, Agri-footprint, World Food LCA Database, and more.
3. Rely on published Life Cycle Assessment (LCA) of the food product under study.

7. Monetisation

An overview of the monetisation factors Fossil fuel depletion and Other non-renewable material depletion is presented in Table 2.

Table 2: Monetisation factors for fossil fuel depletion and other non-renewable material depletion. All values are expressed in 2020 price level. Original values are inflated and converted, if needed, to euros.

Indicator	Monetisation unit	Monetisation factor
Fossil fuel depletion	EUR_{2020}/kg oil-eq	0.446
Depletion of other non-renewable materials	EUR_{2020}/ kg Cu-eq	0.225

The monetisation factors represent compensation costs, expressing the future loss of economic welfare in the society, due to increased extraction costs in the future (increased scarcity) of either fossil fuels or non-renewable materials (Huijbregts et al., 2017)[9]. These costs, and subsequently the monetisation factors, are based on the Surplus Cost Potential (SCP). The SCP is the average cost increase for all future resource extractions, as quantified via cumulative cost-tonnage relationships. It represents the (economic) burden that current resource extraction puts on future situations. This definition closely links with the concept of externalities that are measured in a typical LCA, i.e., the cost that affects a party who did not choose to incur that cost (Vieira et al., 2016).

This is a remediation cost, representing the compensation cost for the damage to future generations caused by resource depletion today. It is important to clarify that the monetary value given here does not represent an alternative to the market price or a long term private marginal cost of materials. While the SCP approach includes current and projected extraction costs of non-renewable resources, due to increased consumption, these should be viewed as an external societal cost, added on top of the market price rather than an alternative to the market price. This follows the definition of environmental costs in the true price presented in the **Valuation Framework for True Price Assessment of Agri-Food Products** (Galgani et al., 2021b, p. 6). A discussion of the distortions in the market price for fossil fuels and other non-renewable materials is therefore out of scope[10].

More specifically, for **fossil fuel depletion**, the monetisation factor is estimated based on the SCP approach developed by ReCiPe (Huijbregts et al., 2017). This factor represents only the costs of fossil fuel depletion and not the cost of CO_2 emitted when fuels are consumed in agricultural processes, which is included in the *Contribution to climate change* module. The factor assumes that fossil fuels with the lowest costs are extracted first. Increases in fossil fuel extraction cause either a change in production techniques (e.g., enhanced oil recovery) or lead to sourcing from costlier locations (e.g., from Arctic regions). This, when

[9] Please refer to the Valuation Framework for True Price Assessment of Agri-food Products (Galgani et al., 2021b, p. 11-12) for a detailed discussion on the concept of remediation and the cost types to carry out remediating activities – restoration cost, compensation cost, prevention cost and retribution cost.

[10] As noted in the Valuation Framework, '*Market prices may already incorporate penalties paid and environmental taxes that are used to restore damage caused by violation of international rights. These taxes and penalties are already included in the market prices and counting them in the true price gap should be avoided. This problem is at this moment not addressed by the framework.*' (Galgani et al., 2021b). These penalties and taxes are commonly based on costs of emissions and therefore not further discussed in this module.

combined with the expected future extraction of a fossil fuel resource, leads to the estimated SCP (Huijbregts et al., 2017, p. 95).

For **other non-renewable material depletion**, the monetisation factor similarly represents the damage to future generations because of the contribution towards natural resource scarcity, estimated based on a Surplus Ore Potential (SOP)[11] and a SCP for metals. The monetisation approach in ReCiPe assumes that the primary extraction of a mineral resource will lead to an overall decrease in ore grade (the concentration of that resource in ores worldwide). This will increase the amount of ore produced per kilogram of mineral resource extracted. The cost arises from the principle that mining sites with higher grades or with lower costs are the first to be explored (Huijbregts et al., 2017, p. 87).

8. Limitations and items for further development

8.1. Limitations

- CE Delft, in one publication concerning shadow prices of environmental impacts, argues that to consider depletion of (non-renewable) materials as external costs can be problematic. The authors conclude that '*while it is certainly possible to estimate external costs for (resource scarcity) impacts, the resultant figures are very uncertain*' (De Bruyn et al., 2018, p 76). Therefore, CE Delft didn't calculate a price for it, taking a different standpoint than the rights-based true pricing approach taken here. This implies one must be prudent in using the estimates of the environmental price for other purposes.
- Different types of fossil fuels (e.g., oil, coal, and gas) are not always good substitutes for each other. Therefore, the question arises whether energy content is a good indication of their relative scarcity in the future. Coal is for example much more abundant than oil and gas as an energy source. ReCiPe also provides separate SCP factors for coal and natural gas, so this could also be considered. However, it is common practice in LCA to base midpoint characterisation on energy content (an approach used both by ReCiPe and PEF) and therefore also in this module it is chosen to do so and use oil equivalents. Nonetheless, future work could be made more accurate from an economic perspective when the depletion and monetisation factor of different fossil fuel types is taken into account separately.
- For fossil fuels its future use is mainly determined by its contribution to climate change, and therefore, depletion seems not an important issue, if fossil resources will not be used as fuel in the future. This may be an argument to use a price of 0 for fossil fuel depletion. However, fossil fuel would still be useful as raw material for production. Therefore, we followed the standard LCA approach to include fossil fuel depletion, as it imposes higher costs for extraction on future generations.
- Packaging material is relevant to material depletion but not directly addressed in this module. Packaging is not solely connected to material depletion, because it also relates to climate change, pollution, land use and potentially other factors. It is possible to estimate the total impact of packaging based on all method-specific modules developed within this True pricing method for agri-food products. Even though packaging is not explicitly explained in the available modules, users can consider packaging production as part of the supply chain of a product under study and include it in their assessments.

---

[11] SOP represents the extra amount of ore mined per additional unit of resource extracted.

8.2. Items for further development

- Collection of data (standard factors to streamline the estimation of fossil fuels and other non-renewable materials in agri-food products and chains).
- Review of other approaches for deriving monetisation factor for resource depletion, such as Environmental Priority Strategies (EPS) impact assessment method by the Swedish IVL and their applicability for true pricing purposes.
- Review the method in light of other or more detailed approaches for quantifying resource depletion, such as the UNEP SETAC method for mineral depletion or the work of Vieira and Huijbregts (2018).
- Investigation of opportunities to better estimate the effects on the future costs of the fossil fuels and different non-renewable materials.
- An appendix with the true prices of different packaging materials should be included in future versions of the modules to address the lack of explicit quantification of the costs of packaging.

References

Brundtland, G.H. (1987). *Our Common Future: Report of the World Commission on Environment and Development*. Geneva, UN-Document A/42/427 Retrieved from http://www.un-documents.net/ocf-ov.htm

De Bruyn, S., Ahdour, S., Bijleveld, M., de Graaff, L., Schep, E., Schroten, A., & Vergeer, B. (2018). Environmental Prices Handbook 2017 Methods and numbers for valuation of environmental impacts. *Delft University of Technology*. Available from https://cedelft.eu/publications/environmental-prices-handbook-2017/

De Groene Rekenkamer. (2013). *Aardbevingen in Nederland door gaswinning*. Retrieved from https://groene-rekenkamer.nl/1819/aardbevingen-nederland-door-gaswinning/

Environmental Protection Agency (EPA). (n.d.). *Deepwater Horizon – BP Gulf of Mexico Oil Spill*. Retrieved from https://www.epa.gov/enforcement/deepwater-horizon-bp-gulf-mexico-oil-spill

European Commission (EC). (2013a). Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union*, L 124.

European Commission (EC). (2013b). Decision No 1386/2013/EU of the European Parliament and of the Council of 20 November 2013 on a General Union Environment Action Programme to 2020 'Living well, within the limits of our planet'. *Official Journal of the European Union,* L 354.

Fazio, S. Castellani, V. Sala, S., Schau, EM. Secchi, & M. Zampori, L. (2018). *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods*. Joint Research Centre. doi:10.2760/671368

Galgani, P., Woltjer, G., & de Adelhart Toorop, R. (2021a). *True pricing assessment method for agri-food products*. (forthcoming)

Galgani, P., Woltjer, G., de Adelhart Toorop, R., & de Groot Ruiz, A. (2021b). *Valuation framework for true price assessment of agri-food products*. Available from https://trueprice.org/true-price-resources/

Goedkoop, M., Heijungs, R., Huijbregts, M.A., De Schryver, A., Struijs, J., & van Zelm, R. (2009). ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint level. First edition. Report i: Characterization. Ruimte en Milieu, Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer.

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M. D. M., ... & van Zelm, R. (2017). ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. report I: characterization; RIVM Report 2016-0104. *National Institute for Human Health and the Environment, Bilthoven*.

International Energy Agency (IEA). (2013). *World Energy Outlook 2013*. Available from https://www.iea.org/reports/world-energy-outlook-2013

Klinglmair, M., Sala, S., & Brandão, M. (2014). Assessing resource depletion in LCA: a review of methods and methodological issues. *The International Journal of Life Cycle Assessment, 19*(3), 580-592. https://doi.org/10.1007/s11367-013-0650-9

United Nations (UN) (1972). *Declaration of the United Nations Conference on the Human Environment. Stockholm*. Retrieved from https://www.un.org/ga/search/view_doc.asp?symbol=A/CONF.48/14/REV.1

United Nations (UN) General Assembly. (2018). *Resolutions adopted by the Human Rights Council on 22 March 2018 37/8. Human rights and the environment*. Retrieved from: https://documents-dds-ny.un.org/doc/UNDOC/GEN/G18/099/17/PDF/G1809917.pdf?OpenElement

Vieira, M.D.M. & Huijbregts, M.A.J. (2018). Comparing mineral and fossil surplus costs of renewable and non-renewable electricity production. *The International Journal of Life Cycle Assessment,* 23, 840-850. https://doi.org/10.1007/s11367-017-1335-6

Vieira, M.D.M., Ponsioen, T.C., Goedkoop, M.J., & Huijbregts, M.A.J. (2016). Surplus Cost Potential as a Life Cycle Impact Indicator for Metal Extraction. *Resources, 5*(1), Article 2. https://doi.org/10.3390/resources5010002

Annex A: Link with internationally accepted agreements on the rights of present and future generations

International agreements recognize the importance of access to resources for future generations for the enjoyment of human rights:

- Declaration of the United Nations Conference on the Human Environment: "The natural resources of the earth must be safeguarded for the benefit of present and future generations" (UN, 1972, Principle 2).
- Declaration of the United Nations Conference on the Human Environment: "The non-renewable resources of the earth must be employed in such a way as to guard against the danger of their future exhaustion and to ensure that benefits from such employment are shared by all mankind" (UN, 1972, Principle 5).
- Resolution adopted by the Human Rights Council on 22 March 2018, 37/8, Human rights and the environment: "The impact of climate change, the unsustainable management and use of natural resources, the unsound management of chemicals and waste, the resulting loss of biodiversity and the decline in services provided by ecosystems may interfere with the enjoyment of a safe, clean, healthy and sustainable environment, and that environmental damage can have negative implications, both direct and indirect, for the effective enjoyment of all human rights (UN General Assembly, 2018).
- The so-called Brundtland Report 'Our Common Future': "The rate of depletion [for non-renewable resources] should take into account the criticality of that resource, the availability of technologies for minimizing depletion, and the likelihood of substitutes being available". And "Renewable resources [...] need not be depleted provided the rate of use is within the limits of regeneration and natural growth" (Brundtland, 1987, the concept of sustainable development).

Annex B: ReCiPe characterisation factors

Table B.1: Fossil fuel potentials (in kg oil-eq/unit of resource) for five fossil resources (Huijbregts et al., 2017, p. 96)

Fossil resource	Unit	Characterization factor
Crude oil	oil-eq/kg	1
Natural gas	oil-eq/Nm^3	0.84
Hard coal	oil-eq/kg	0.42
Brown coal	oil-eq/kg	0.22
Peat	oil-eq/kg	0.22

Table B.2: Midpoint characterization factors SOPs (in kg Cu-eq/kg) for 70 mineral resources and for the groups garnets, gemstones, platinum-group metals, rare-earth metals and zirconium minerals for three perspectives (Huijbregts et al., 2017, p. 90-92)

Mineral resource	Chemical element	Individualist	Hierarchist	Egalitarian
Aluminium	Al	1.01E-01	1.69E-01	1.69E-01
Antimony	Sb	1.03E+00	5.72E-01	5.72E-01
Arsenic*	As	8.89E-02	1.31E-01	1.31E-01
Ball clay*		3.86E-03	7.09E-03	7.09E-03
Barite*		1.36E-02	2.28E-02	2.28E-02
Bauxite*		2.41E-03	4.58E-03	4.58E-03
Bentonite clay*		6.07E-03	1.08E-02	1.08E-02
Beryllium*	Be	8.42E+01	7.67E+01	7.67E+01
Bismuth*	Bi	2.77E+00	3.20E+00	3.20E+00
Boron*	B	7.77E-02	1.16E-01	1.16E-01
Cadmium*	Cd	2.32E-01	3.20E-01	3.20E-01
Caesium*	Ce	1.90E+04	1.18E+04	1.18E+04
Chromium	Cr	5.57E-02	9.51E-02	9.51E-02
Chrysotile*		2.21E-01	3.05E-01	3.05E-01
Clay, unspecified*		5.85E-03	1.04E-02	1.04E-02
Cobalt	Co	4.01E+00	6.57E+00	6.57E+00
Copper	Cu	1.00E+00	1.00E+00	1.00E+00
Diamond (industrial)*	C	1.02E+02	9.15E+01	9.15E+01
Diatomite*		3.07E-02	4.88E-02	4.88E-02
Feldspar*		8.90E-03	1.54E-02	1.54E-02
Fire clay*		1.95E-03	3.76E-03	3.76E-03
Fuller's earth*		8.61E-03	1.50E-02	1.50E-02
Gallium*	Ga	9.28E+01	8.38E+01	8.38E+01
Germanium*	Ge	3.89E+02	3.17E+02	3.17E+02
Gold	Au	5.12E+03	3.73E+03	3.73E+03
Graphite*	C	1.34E-01	1.92E-01	1.92E-01
Gypsum*		1.44E-03	2.83E-03	2.83E-03
Hafnium*	Hf	1.08E+02	9.67E+01	9.67E+01
Ilmenite*		2.40E-02	3.88E-02	3.88E-02
Indium*	In	1.15E+02	1.03E+02	1.03E+02
Iodine*	I	6.51E+00	7.09E+00	7.09E+00
Iron	Fe	3.82E-02	6.19E-02	6.19E-02
Iron ore*		1.02E-02	1.75E-02	1.75E-02
Kaolin*		1.46E-02	2.45E-02	2.45E-02
Kyanite*		3.15E-02	5.00E-02	5.00E-02
Lead	Pb	4.83E-01	4.91E-01	4.91E-01
Lime*		1.19E-02	2.02E-02	2.02E-02
Lithium	Li	2.42E+00	4.86E+00	4.86E+00
Magnesium*	Mg	6.14E-01	7.90E-01	7.90E-01
Manganese	Mn	3.76E-02	8.23E-02	8.23E-02
Mercury*	Hg	8.37E+00	8.96E+00	8.96E+00
Molybdenum	Mo	2.90E+01	2.92E+01	2.92E+01
Nickel	Ni	1.85E+00	2.89E+00	2.89E+00
Niobium	Nb	4.46E+00	5.20E+00	5.20E+00
Palladium*	Pd	6.37E+03	4.28E+03	4.28E+03
Perlite*		5.08E-03	9.16E-03	9.16E-03
Phosphorus	P	1.40E-01	1.67E-01	1.67E-01
Platinum*	Pt	1.38E+04	8.77E+03	8.77E+03

Table continues on next page

Table continued

Mineral resource	Chemical element	Individualist	Hierarchist	Egalitarian
Potash*		6.93E-02	1.04E-01	1.04E-01
Pumice and pumicite*		3.08E-03	5.76E-03	5.76E-03
Rhodium*	Rh	9.73E+03	6.34E+03	6.34E+03
Rutile*		1.24E-01	1.79E-01	1.79E-01
Selenium*	Se	1.28E+01	1.33E+01	1.33E+01
Silicon*		3.18E-01	4.28E-01	4.28E-01
Silver	Ag	1.61E+02	1.53E+02	1.53E+02
Strontium*	Sr	5.76E-02	8.75E-02	8.75E-02
Talc*		2.34E-02	3.78E-02	3.78E-02
Tantalum*	Ta	5.66E+01	5.29E+01	5.29E+01
Tellurium*	Te	1.85E+01	1.87E+01	1.87E+01
Thallium*	Tl	1.63E+03	1.20E+03	1.20E+03
Tin	Sn	5.23E+00	5.03E+00	5.03E+00
Titanium*	Ti	6.89E-01	8.79E-01	8.79E-01
Titanium dioxide*		3.88E-01	5.15E-01	5.15E-01
Tripoli*		2.14E-02	3.48E-02	3.48E-02
Tungsten*	W	7.19E+00	7.78E+00	7.78E+00
Uranium	U	3.58E+01	2.52E+01	2.52E+01
Vanadium*	V	3.49E+00	3.97E+00	3.97E+00
Wollastonite*		2.20E-02	3.58E-02	3.58E-02
Zinc	Zn	1.16E-01	1.53E-01	1.53E-01
Garnets*		2.99E-02	4.76E-02	4.76E-02
Gemstones*		1.25E+04	7.99E+03	7.99E+03
Platinum-group metals*		5.55E+03	3.76E+03	3.76E+03
Rare-earth metals*		2.75E+00	3.19E+00	3.19E+00
Zirconium minerals*		1.21E-01	1.75E-01	1.75E-01

* For these mineral resources ASOPs are extrapolated from price information.

Glossary

Fossil fuel potentials	The ratio between the energy content of a fossil resource and the energy content of crude oil (Huijbregts et al., 2017, p. 96).
Surplus Cost Potential	The average cost increase resulting from all future metal extractions.
Surplus Ore Potential	The extra amount of ore mined per additional unit of resource extracted.