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Life-cycle impact assessment methods for physical energy scarcity: considerations and suggestions

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Abstract

Purpose Most approaches for energy use assessment in life cycle assessment do not consider the scarcity of energy resources. A few approaches consider the scarcity of fossil energy resources only. No approach considers the scarcity of both renewable and non-renewable energy resources. In this paper, considerations for including physical energy scarcity of both renewable and non-renewable energy resources in life cycle impact assessment (LCIA) are discussed.

Methods We begin by discussing a number of considerations for LCIA methods for energy scarcity, such as which impacts of scarcity to consider, which energy resource types to include, which spatial resolutions to choose, and how to match with inventory data. We then suggest three LCIA methods for physical energy scarcity. As proof of concept, the use of the third LCIA method is demonstrated in a well-to-wheel assessment of eight vehicle propulsion fuels.

Results and discussion We suggest that global potential physical scarcity can be operationalized using characterization factors based on the reciprocal physical availability for a set of nine commonly inventoried energy resource types. The three suggested LCIA methods for physical energy scarcity consider the following respective energy resource types: (i) only stock-type energy resources (natural gas, coal, crude oil and uranium), (ii) only flow-type energy resources (solar, wind, hydro, geothermal and the flow generated from biomass funds), and (iii) both stock- and flow-type resources by introducing a time horizon over which the stock-type resources are distributed. Characterization factors for these three methods are provided.

Conclusions LCIA methods for physical energy scarcity that provide meaningful information and complement other methods are feasible and practically applicable. The characterization factors of the three suggested LCIA methods depend heavily on the aggregation level of energy resource types. Future studies may investigate how physical energy scarcity changes over time and geographical locations.

Keywords Energy analysis · Life cycle impact assessment (LCIA) · Resources · Life cycle assessment (LCA) · Energy scarcity · Characterization factor · Energy type aggregation

1 Introduction

Energy use is commonly included as a resource impact category in life cycle assessment (LCA) studies. However, there is currently limited guidance on how to assess energy use in

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LCA. A United Nations Environment Programme/Society for Environmental Toxicology and Chemistry (UNEP/SETAC) task force provides recommendations on the assessment of mineral resources in LCA, but not on the assessment of energy resources (Berger et al. 2020; Sonderegger et al. 2020). Assessing energy use entails aggregation of energy flows from different energy resource types, such as crude oil, biomass, and kinetic wind energy. There is no objectively correct way of performing such an aggregation, and several options are possible (Frischknecht et al. 1998; Sonderegger et al. 2017), which is reflected in the LCA literature. As further discussed in Sect. 1.1, however, existing life cycle impact assessment (LCIA) methods rarely consider the potential scarcity of different energy resource types, i.e., how the availability of an energy resource type might limit its use in society. Larger efforts

Table 1 Approaches for assessing energy use in life cycle assessment

| Approach	Unit	Description	Captures scarcity?	Source
Cumulative energy demand (CED)	MJ	Considers primary renewable, non-renewable and feedstock energy	No	Frischknecht et al. (2015)
Abiotic depletion fossil from CML	MJ	Equal to a fossil CED	No	van Oers and Guinée (2016)
Non-renewable energy from IMPACT2002+	MJ	Equal to a non-renewable CED	No	Humbert et al. (2012)
Fossil resource scarcity from ReCiPe	kg oil eq	Equal to the CED divided by the higher heating value of crude oil	No	Huijbregts et al. (2016)
Abiotic depletion fossil from previous ILCD version	kg Sb eq	Characterization factors calculated from the production and crustal content of fossil fuels	Only total fossil energy scarcity	European Commission-Joint Research Centre (2011), van Oers et al. (2002)
Fossil fuel depletion from TRACI	MJ surplus	The additional amount of energy needed to extract one unit of fossil fuel	Only fossil energy scarcity	Bare (2002), Bare (2012)
Cumulative exergy demand (CExD)	MJ	Exergy content of primary energy resources (and other resources)	No	Bösch et al. (2006)
Cumulative exergy extraction from the natural environment (CEENE)	MJ	Exergy content of primary energy resources (and other resources)	No	Dewulf et al. (2007)
Thermodynamic rarity	MJ	Exergy required for producing resources from bare rock	Only for chemical elements	Valero and Valero (2015)
Solar energy demand (SED)	MJ solar eq	Sum of ultimate solar radiation, deep Earth heat and tidal energy requirement	Unclear	Rugani et al. (2011)
ESSENZ	Dimensionless	Socio-economic availability	Only short-term fossil energy scarcity	Bach et al. (2016)

have been put into assessing scarcity-related impacts of other resource types in LCA, such as mineral/elemental resources (Cimprich et al. 2019; Hélias and Heijungs 2019; Arvidsson et al. 2020; van Oers et al. 2020) and biotic resources (Crenna et al. 2018; Hélias et al. 2018; Odppes et al. 2021). Since the availability of different energy resource types has been critical for human development and well-being throughout history (Ponting 2007), we suggest that energy scarcity also deserves further elaboration.

1.1 State of the art

We identify 11 main approaches to energy use assessment in LCA in the literature (Table 1). Several of these approaches rely on inventory-level energy use indicators, which aggregate energy inventory flows (Arvidsson and Svanström 2016). The most common stand-alone inventory-level energy use indicator is the cumulative energy demand (CED), which is based on the principle of aggregating the total "energy harvested," meaning that all energy resources passing the boundary between nature and the technosphere should be

aggregated as per their energy content (Frischknecht et al. 2015). The CED aims at aggregating both renewable and non-renewable primary energy resource flows used for all kinds of purposes, both as energy carriers and as feedstock for materials. The energy use indicator in the IMPACT2002+ package, called non-renewable energy, is equivalent to a CED limited to non-renewable energy resources (Humbert et al. 2012). In the LCIA method package developed by the Institute of Environmental Sciences at Leiden University (CML), one impact assessment method is called abiotic depletion fossil and is equivalent to a CED indicator limited to fossil energy resources (van Oers and Guinée 2016). The fossil resource scarcity indicator in the ReCiPe package is obtained by dividing the higher heating value of extracted fossil resources by the higher heating value of crude oil (Huijbregts et al. 2016).[1] It is thus effectively equal to a CED indicator limited to fossil

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[1] It can be noted that there is no standard value for the higher heating value of crude oil. A typical span is 42–47 MJ/kg. In ReCiPe 2016, a value of 45.8 MJ/kg is used based on Jungbluth and Frischknecht (2010).
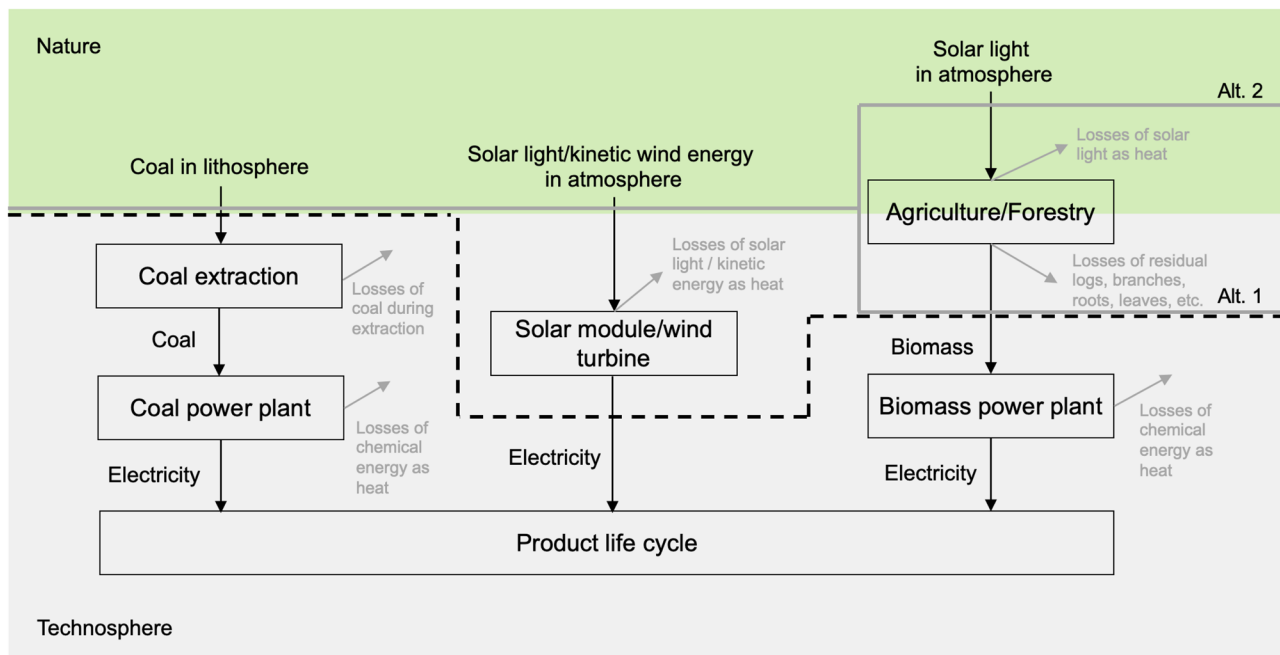
Fig. 1 The black dashed line shows the system boundary of most inventory-level energy use indicators in LCA, such as the cumulative energy demand (CED), for some example energy resource types (coal, solar, wind, and biomass) used to produce electricity. The whole gray line shows the boundary between nature and the technosphere. Alt. 1 assumes that agriculture and forestry are considered parts of nature, while alt. 2 assumes they are parts of the techno-sphere. Black arrows show energy flows and gray arrows show energy losses. The figure shows how most inventory-level energy use indicators in LCA place some processes normally seen as parts of the technosphere (e.g., solar modules) as parts of nature, thereby considering some energy losses (those below the dashed line) but not others (those above the dashed line)

energy resources but scaled before aggregation using the energy content of crude oil.

Inventory-level energy use indicators in general have the drawback of disregarding differences in scarcity between energy resource types by aggregating e.g. 1 MJ of coal and 1 MJ of crude oil, although crude oil is much rarer than coal (Rogner et al. 2012). In addition, inventory-level energy use indicators that include both renewable and non-renewable energy resource types, like the CED, often do not maintain a consistent system boundary between nature and the technosphere. Fossil fuels and other stock-type energy resources are considered harvested when extracted from the stock in the lithosphere. However, for solar and wind energy, the CED makes the pragmatic assumption that the electricity leaving the energy-generating device is harvested (Frischknecht et al. 2015), effectively making solar modules and wind turbines parts of nature and not the technosphere (Fig. 1).[2] This inconsistent assumption about the system boundary between nature and the technosphere means that substantial amounts of energy that will never reach the user (energy losses in Fig. 1) are included for some energy resource types, but not for others.

Going beyond the inventory level, a previous version of the ILCD guidelines recommends an older version of the abiotic depletion fossil indicator by CML from the early 2000s (European Commission-Joint Research Centre 2011), where the fossil energy use is converted into kg antimony (Sb) equivalents and based on annual production and crustal content of all fossil fuels (van Oers et al. 2002). This indicator thus only considers fossil energy resource types and treats them as one single energy recourse type regarding scarcity. Although the most recent version of the ILCD guidelines instead advocates the current CML abiotic depletion fossil approach that aggregates fossil inventory flows (Fazio et al. 2018), this approach recommended by a previous ILCD version is still in use (Fig. S1, Supporting Information (SI)). In the LCIA package TRACI, the energy use indicator is called fossil fuel depletion and is measured as MJ "surplus," meaning the additional amount of energy needed to extract one unit of fossil fuel in the future (Bare 2002, 2012). This indicator thus does not reflect any actual

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[2] However, the production of these devices may still be included in the inventory. Hence, they are simultaneously inside and outside the boundary between the technosphere and nature.

extraction of fossil energy, but how much extra energy it will cost to extract energy in the future due to the considered extraction.[3] While only including fossil energy resource types, the fossil fuel depletion indicator does assign different characterization factors (CFs) to different fossil resource types, like crude oil and coal. In fact, it even provides different CFs within the same fossil resource type, such as for different types of coal. Since increased extraction of fossil energy is expected to lead to increased energy demand of extraction in the future, the fossil fuel depletion indicator can be seen as an indicator of fossil energy scarcity.

Several energy-related LCIA methods have the aim of quantifying either the exergy or the solar energy used in a product system, together referred to as thermodynamic accounting methods by Sonderegger et al. (2020). The cumulative exergy demand (CExD) is calculated by multiplying the primary energy use with exergy-to-energy ratios, having values close to one for most energy resource types (Table S1, SI). This means that for most energy resources, CExD≈CED. Furthermore, the CExD is explicitly not an indicator of resource availability or scarcity (Bösch et al. 2006). The cumulative exergy extraction from the natural environment (CEENE) is another example of an exergy-based method (Dewulf et al. 2007), with CFs called X factors which are also close to one for many energy resource types (Table S1, SI). A notable feature is that the CEENE does not provide specific X factors for the energy resource types geothermal, solar, and biomass, but instead considers them dealt with in the CF for land occupation provided in the CEENE method. A final example of an exergy-based method is the thermodynamic rarity method, which considers the exergy required for producing a resource from common bare rock (referred to as Thanatia, the dead planet) to the market (Valero and Valero 2015). However, CFs for this method have so far only been calculated for chemical elements (Valero et al. 2018), and it remains unclear if there is an analogous procedure for energy resources other than uranium. It is, for example, not obvious how to define a thermodynamic reference state for energy resources corresponding to common rock in the case of chemical elements.

In a similar vein, the solar energy demand (SED) method intends to convert energy (and other resources) into the corresponding amount of solar energy required to produce them, using CFs called solar energy factors (Rugani et al. 2011). The SED is based on previous work on the concept of emergy, which is the amount of the ultimate energy

resource types (solar radiation, deep Earth heat, and tidal energy) required to produce a product (Rugani and Benetto 2012). However, Rugani et al. (2011) write that "it is not clear whether SED [is] correlated to the actual availability or scarcity of resources."

Finally, the integrated assessment method ESSENZ provides CFs for four fossil resource types: crude oil, hard coal, lignite, and natural gas (Bach et al. 2016). Those are based on socio-economic availability (also referred to as criticality), which is influenced by 11 factors, including company concentration, trade barriers, and price fluctuations. ESSENZ thus considers the more short-term scarcity of fossil resources.

A literature review of the current practices in LCA case studies (provided in Section S1, SI) shows that out of these different methods for assessing energy use in LCA, the most frequent are inventory-level energy use indicators, either as stand-alone indicators or as part of LCIA packages, as well as the energy use indicator from TRACI and the one recommended in the previous version of the ILCD guidelines.

1.2 Aim of the study

As shown in the state-of-the-art description in Sect. 1.1, there currently exist few LCIA methods that capture potential scarcity of different energy resources, and no method that captures the scarcity of both renewable and non-renewable energy resource types (Table 1). The aim of this paper is therefore to discuss how LCIA methods for energy scarcity might be constructed and to sketch preliminary proposals of LCIA methods that consider energy scarcity. Such methods should preferably answer the following question: How much does energy resource extraction contribute to the potential scarcity of energy resources? Considering the limitations identified in existing methods for energy use assessment in LCA (Sect. 1.1), proposals of LCIA methods for energy scarcity should preferably go beyond state of the art by:

1. Considering the relative potential scarcity of several different energy resource types, preferably both renewable and non-renewable.
2. Applying a consistent nature-technosphere system boundary so that energy losses are considered in a consistent manner between energy resource types.

In Sect. 2, we discuss a number of considerations for LCIA methods for energy scarcity. These considerations represent different parts of the equation applied in LCIA, where an environmental or resource impact score (IS) is calculated by multiplying inventory analysis results q for certain elementary flows i at locations k with a CF that

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[3] In the work by Sonderegger et al. (2020), this is referred to as a "future efforts method." The fossil fuel depletion indicator in TRACI is based on the work by Goedkoop and Spriensma (1999).

tells the contribution of the elementary flow to the impact category j (Hauschild and Huijbregts 2015):

$$IS_j = \sum_{i,k} q_i \times CF_{i,j,k} \qquad (1)$$

Section 2.1 discusses which impact(s) j of energy scarcity to consider. Section 2.2 discusses which elementary flows i to include. Section 2.3 discusses which spatial resolution k to consider. Section 2.4 discusses how to calculate CFs for stock-, flow-, and fund-type energy resources, as well as how such energy resources could be aggregated. Section 2.5 discusses how inventory data q can be matched with the CFs. Based on these considerations, some preliminary suggestions of LCIA methods for physical energy scarcity are outlined in Sect. 3, of which one is illustrated in a well-to-wheel assessment of vehicle fuels. Finally, in Sect. 4, future research needs related to LCIA methods for energy scarcity are outlined.

2 Considerations for LCIA methods for energy scarcity

In this section, a number of considerations for an LCIA method for energy scarcity are discussed, including which energy scarcity impacts to consider, which energy resource types to include, and how to calculate CFs for different energy resource types. Attempts are made to provide reasonable guidance, weighing theoretical merits against the practical applicability of different options.

2.1 Energy scarcity impacts

Energy resource scarcity can be assessed from different perspectives, e.g., be based on physical, technical, or socio-economic availability (Sandén et al. 2014), i.e., theoretical availability versus the availability resulting from technical and societal constraints (e.g., economic, political, legal, and environmental) (Rogner et al. 2012). The physical or theoretical energy availability generally represents the amount of known energy resources that could theoretically be extracted to produce useful energy carriers at a net energy gain. Technical energy availability excludes parts of the resources for which no feasible conversion technology currently exists. Socio-economic energy availability reflects also how economic, environmental, and social factors could limit the amount of energy resources exploited due to, e.g., competition with other activities in favorable locations (like refraining from placing wind turbines in windy but densely populated areas). Both technical and socio-economic availabilities depend on parameters that may change drastically over time periods of > 10 years. The physical availability, on the other hand, depends on processes in nature and thus

stands a higher chance of being stable over longer time periods.[4]

Which perspective on natural resources is most relevant cannot be objectively established but depends on the question the assessment is aimed at answering (Steen 2006; Berger et al. 2020; Sonderegger et al. 2020). The suggestions provided in this paper are based on physical energy scarcity, thus answering a specified variant of the question posed in Sect. 1.2: How much does energy resource extraction contribute to the potential physical scarcity of energy resources? While being about energy rather than mineral resources, this question is essentially similar to the question that signifies so-called depletion methods focusing on the availability of mineral stocks according to Berger et al. (2020): How can I quantify the relative contribution of a product system to the depletion of mineral resources? The energy resource impact j considered in this work is thus that of physical energy scarcity. Regarding LCIA methods focusing on more near-term socio-economic aspects and supply risks, there is disagreement about whether such methods belong within the LCA method (Sonderegger et al. 2020). However, regardless, methods focusing on short-term supply risks may provide useful information to society, albeit not the kind of information sought here.

2.2 Energy resource types

Which energy resource types to include — and at what level of aggregation — is an important analytical choice in assessments of energy use. In an LCIA method for physical energy scarcity, lumping energy resource types together into broad categories (e.g., fossil resources as in some of the methods in Table 1) would mask their respective physical scarcities. On the other hand, it would be impractical to distinguish between too many sub-types, such as a large number of

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[4] Even estimates of physical availability may change, but to a much lesser degree. As geoscience progresses, estimates of available stock resources could improve. However, although resource estimates of crude oil, natural gas, and coal have varied (and increased slightly) since the mid-1900s, they have varied by less than an order of magnitude (Rogner et al. 2012). It is also possible that future greenhouse gas levels and resulting climate change will alter wind patterns, water flows in rivers, growth of biomass, and direct solar irradiation at the Earth's surface due to changed cloud patterns. However, these changes will probably not influence the order of magnitude availability of energy resource types at the global level. For example, increasing wind speeds have so far only increased the wind power capacity in the USA by about 2.5% (Zeng et al. 2019). The effects of increased greenhouse gas levels on biomass growth are yet poorly understood, possibly causing both increases (e.g., due to carbon dioxide fertilization) and decreases (e.g., due to changes in precipitation) (Rogner et al. 2012). River flow estimates suggest that some flows will increase while others will decrease (Döll and Schmied 2012; Schneider et al. 2013).

biomass types, since all energy resource types would need to be matched with data on their physical availability, as well as with elementary flow data in the inventory analysis. For example, about 20 biomass elementary flows are currently inventoried in LCA databases, most of which are different wood flows (Crenna et al. 2018). This sets one type of practical upper limit. In addition, these would each have to be matched with 20 different CFs based on physical resource estimates. It is not clear how to arrive at a physical resource estimate for a specific type of biomass due to ample possibilities for substitution between biomass types.

In an attempt to strike a balance, we suggest a set of nine commonly inventoried energy resource types for LCIA methods for physical energy scarcity: solar, wind, hydro, geothermal, biomass, natural gas, coal, crude oil, and uranium (in this study only the isotope U-235[5]). An LCIA method for physical energy scarcity would then include elementary flows i related to these nine energy resource types. These energy resource types have reasonable intra-type homogeneity and inter-type heterogeneity, e.g., different sub-types of biomass energy are qualitatively more alike than are biomass energy and wind energy. These nine energy resource types also cover most of the global energy use at the moment. If needed in the future, additional types could be included, such as marine energy, thorium or U-238, and other aggregations or disaggregations could be made, if found relevant. Which energy resource types will become relevant in the far (e.g., > 100 years) future is difficult to foresee, making their inclusion in LCA studies challenging (Frischknecht et al. 1998).[6]

2.3 Spatial resolution

The spatial boundary is a value-laden choice. Many LCIA methods assume a global boundary. There are global markets for many energy commodities (e.g., crude oil), and resources that have been used locally might become more widely traded with extensions of electric grids or with the emergence of new energy commodities, such as hydrogen. Therefore, a global LCIA method of physical energy scarcity, where all energy resources are regarded as global commons, might be relevant as a first step. However, the implication of such a choice is that, for example, biomass, geothermal energy, and crude oil are given the same CFs regardless of whether the extraction takes place in Sweden, Iceland, or

Saudi Arabia, in spite of the strongly varying availabilities of these resource types in the respective countries. Therefore, a global LCIA method for physical scarcity should preferably be followed up by regionalized alternatives. This would be in line with the general strive toward regionalizing LCIA (Mutel et al. 2018). In principle, it would be possible to calculate the physical energy availability in different regions of the world. Obtaining comprehensive data on regional energy stocks and flows might be challenging for some energy resource types, but there exist country-based data on the physical availability of some energy resource types (Rogner et al. 2012).

2.4 Characterization factors

There are different possible options for calculating CFs for physical energy scarcity. In general, scarcity refers to the potential shortage arising from supply and demand imbalances (Ljunggren Söderman et al. 2014). In LCIA, an environmental or resource impact score is calculated by multiplying inventory analysis results q with a CF that tells the contribution of the elementary flow to the impact category (Eq. 1). One option is to let q represent demand and the CF supply, while another is to consider both demand and supply aspects in the CF. In the first option, q represents the energy demand required to fulfill the functional unit of the study. In order for the impact score to reflect physical scarcity, the CF should be related to the supply, i.e., the physical availability of the elementary energy flow q. Since a high CF should imply a high potential for physical scarcity, the CF should be operationalized as the reciprocal physical availability of energy resources in nature. The CFs can in this way be seen as reflecting potential physical scarcity, since scarcity will arise if a high enough CF is paired with a high enough value of q. Schulze et al. (2020) refers to this approach as "system model A," in which the LCIA method considers and quantifies the availability of resources[7] in nature which are potentially usable in the technosphere.

In the second option, the CF alone is made to reflect scarcity by including demand-related parameters in the CF, such as global extraction volumes as in the abiotic depletion fossil method recommended by the previous ILCD version. However, Finnveden (2005) has argued against including extraction of resources and other technospheric activities in CFs. The reason behind the argument is that including technospheric parameters in both the CF and q creates an ambiguity regarding the respective purposes of LCIA and

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[5] Natural uranium consists of 99.3% U-238 and 0.7% U-235. In current nuclear reactors, only U235 is used. The use of U-238 would require so-called breeder reactors.

[6] Far out in the universe and deep into matter, there may exist exotic energy resource types (such as black hole evaporation and sphalerons), which may be utilized by some future civilization (Tegmark 2017), but are currently more in the realms of science fiction.

[7] Schulze et al. (2020) discuss LCIA for abiotic (i.e., mineral) resource depletion and therefore only mention *stocks*, but presumably the "system model A" can encompass also extraction of *fund* and *flow* resources in nature which are potentially usable in the technosphere.

inventory analysis. From a scarcity perspective, the demand side is then considered twice — both in the CF and in q. This is redundant, introduces a risk of double counting, and creates interdependency between the CF and the inventory data because q is typically a subset of the global extraction.[8] In addition, as pointed out by Arvidsson et al. (2020), technospheric parameters generally change faster than parameters describing the natural system and thus the CFs will need more frequent updating if technospheric parameters are included. While this can be resolved through frequent updating, it constitutes a practical challenge and brings a risk that the CFs become outdated.

In Sects. 2.4.1–2.4.3, the approach of calculating CFs as the reciprocal physical availability of energy resources in nature is operationalized for stock-, flow-, and fund-type resources, respectively. Recent estimates of global physical availabilities at one significant figure are applied for this purpose.

2.4.1 Stock-type energy resources

Stock-type energy resources consist of deposits which are non-renewable and not replenishable, at least not over time scales relevant for humanity (Wall and Gong 2001). The mainstream hypothesis is that existing deposits of fossil fuels have been generated from biological substances: oil and gas from thermal decomposition as well as microbial processes, and coal from heat as well as pressure applied over geological time periods (Rogner et al. 2012). For uranium, new deposits form only very slowly as a result of geological processes involving redistribution of matter between and within Earth's crust, mantle, and core. Uranium in deposits also decays but very slowly: the half-life of the U-235 isotope is 700 million years. Therefore, fossil and nuclear resource types can be considered non-renewable stock-type energy resources with a fixed stock S. The larger the stock, the more available is the energy resource type in nature.

The four considered stock-type energy resources are partly located deep down in the Earth's crust and at low concentrations, for example at ca 1 ppm in the case of uranium (Rudnick and Gao 2014). Such diluted and/or deep-lying[9] stocks will therefore likely not become extracted for energy purposes at any point in the future. Estimates

of the exploitable share of stocks apply the terms reserves and resources. Whereas reserves refer to the currently economically exploitable part of the stock, resources refer to the sum of (i) proven amounts (including reserves) and (ii) unproven yet geologically potentially accessible amounts, which are not exploitable today but may become so in the future (Gaedicke et al. 2020). The physical availability of stock-type resources can therefore be approximated as the most inclusive resource estimates. Although subject to uncertainty (Rogner et al. 2012), their broad inclusion is likely to cover a notable share of the stock possible to extract at net energy gain.

The BGR Energy Study (Gaedicke et al. 2020), a prominent source of global resource estimates, reports coal resources (both hard coal and lignite) at approximately 500,000 EJ, which is in the same order of magnitude as other estimates (Rogner et al. 2012). It also reports crude oil resources (including conventional oil, shale oil, oil sand, extra heavy oil, and oil shale) at approximately 30,000 EJ (Gaedicke et al. 2020), which is similar to other recent estimates, although there also exist less inclusive estimates at 10,000–20,000 EJ (Rogner et al. 2012). For natural gas, a resource estimate (including conventional gas, shale gas, tight gas, coalbed methane, aquifer gas, and gas hydrates) at approximately 40,000 EJ is reported (Gaedicke et al. 2020). This also resembles other estimates, although the share of aquifer gas and gas hydrates included in the estimate will have a considerable influence on the results (Rogner et al. 2012). For uranium (U-235), a global resource estimate by the Nuclear Energy Agency and International Atomic Energy Agency (2020) includes conventional, known, and inferred uranium (US\$ < 260/kg U) as well as prognostic, speculative, and unconventional (byproducts of fossils and phosphates) uranium. The sum is approximately 30,000 EJ, which is, given the large uncertainties, not very far from the approximately 20,000 EJ for the same inclusive set of uranium categories as estimated earlier by Rogner et al. (2012). Furthermore, the conventional, known, and inferred uranium (US\$ < 260/kg U) category in the report from the Nuclear Energy Agency and International Atomic Energy Agency (2020) is estimated at 6000 EJ, which is the same result as obtained in the BRG report for this uranium category (Gaedicke et al. 2020).

2.4.2 Flow-type energy resources

Flow-type resources are constantly renewed and cannot become depleted (Wall and Gong 2001). For flow-type energy resources such as wind and solar, the stock on planet Earth is negligible, $S \approx 0$. Instead, their availability is proportional to the magnitude of their flow F. Hydropower is often counted as a flow-type energy resource too. Although some energy might be temporarily stored in hydropower dams,

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[8] Emission-related CFs generally do not have this problem because they only include parameters related to the elementary flow itself and/or the natural system. See, for example, the impact categories for climate change, stratospheric ozone depletion, ionizing radiation, fine particulate matter formation, photochemical ozone formation, terrestrial acidification, freshwater eutrophication, and toxicity in ReCiPe 2016 (Huijbregts et al. 2016).

[9] For example, the currently deepest mines (e.g., the Mponeng Gold Mine, South Africa) are approximately 4 km deep, while the crust is about 5–70 km deep.

Table 2 Estimated physical availabilities of nine energy resource types (with an accuracy of one significant figure)

Energy resource type	Stock (S) [EJ]	Flow (F) [EJ/year]	Estimation approach*	Source
Solar	–	3,000,000	Total solar irradiation reaching Earth's surface	Forster et al. (2021)
Wind	–	10,000	Kinetic wind energy at 0–200 m above Earth's surface	Jacobson and Archer (2012)
Biomass	0**	1,000	Maximum sustainable harvest estimated as one quarter of global net primary production in the undisturbed state	Sitch et al. (2003) and Field et al. (1998)
Geothermal	–	300	Total heat flow through the terrestrial surface	Hermann (2006)
Hydro	–	200	Total average river flows multiplied by the relative change in altitude of each river	Rogner et al. (2012)
Coal	500,000	–	Total resources	Gaedicke et al. (2020)
Natural gas	40,000	–	Total resources (conventional, shale gas, tight gas, coalbed methane, aquifer gas and gas hydrates)	Gaedicke et al. (2020)
Crude oil	30,000	–	Total resources (conventional, shale oil, oil sand, extra heavy oil and oil shale)	Gaedicke et al. (2020)
Uranium (U-235)	30,000	–	Total resources (conventional known and inferred, prognostic, speculative, and unconventional)	Nuclear Energy Agency and International Atomic Energy Agency (2020)

*For more details and uncertainties, see Sects. 2.4.1–2.4.3

**Assuming biomass is viewed as a renewable flow and not as a depletable stock, see Sect. 2.4.3

this storage can effectively be seen as occurring within the technosphere, similar to the storing of solar electricity in batteries, and is therefore not considered part of the physical availability of hydropower. Geothermal energy is often also considered a flow-type resource going from the deeper Earth to the crust due to continuous radioactive decay and the slow cooling of the Earth.[10] Depletion of local geothermal reservoirs might occur given a high enough extraction, but they will eventually become renewed again by natural processes (Mock et al. 1997).

Different estimates of the global physical availability of flow-type resources are available. The estimates considered here include resources available near the surface of the Earth, excluding potential resources at very high altitudes and in the deep interior of the planet, which are unlikely to be possible to extract at net energy gains. Forster et al. (2021) report the solar irradiation (direct and diffuse) reaching the surface at 185 W/m^2, which multiplied by the Earth's surface becomes approximately 3 million EJ/year, in line with the estimate by Sandén et al. (2014). For wind, Jacobson and Archer (2012) estimate the physical availability at 0–200 m above the surface, thereby excluding high-altitude jet streams, by considering the share of kinetic wind energy possible to extract without causing the air flow to slow down considerably. This results in about 8000 EJ/year. However, Jacobson and Archer (2012) apply a

maximum theoretical energy conversion efficiency of 59.3% (the Betz factor). In LCA, specific conversion efficiencies that represent the actual wind turbine technology assessed are typically applied in the inventory data underpinning q. Therefore, we divide their number by the Betz factor, resulting in some 13,000 EJ/year or about 10,000 EJ/year with one significant figure, which is within the 6000–16,000 EJ/year range reported by Rogner et al. (2012). For hydro, Rogner et al. (2012) assess the theoretical ("gross") availability of hydropower based on average river flows multiplied by the relative change in altitude of each river ("mass of runoff × gravitational acceleration × height above sea level" for most rivers), giving about 200 EJ/year. Hermann (2006) similarly reports the gravitational exergy of precipitation that reaches the ocean through the world's major rivers at about 7.2 TW, which translates to 230 EJ/year. The geothermal physical energy availability is estimated in Sandén et al. (2014) based on Hermann (2006), as the entire heat flow through the terrestrial surface of the Earth at about 320 EJ/year. Stefansson (2005) reports the same heat flow at approximately 10 TW, which converts to the same value of 320 EJ/year or approximately 300 EJ/year. These estimates of the physical availability of solar, wind, hydro, and geothermal energy are listed in Table 2.

2.4.3 Fund-type energy resources

Fund-type resources are renewable, but can become depleted given a high enough extraction (Wall and Gong

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[10] Possibly in roughly equal proportions, see Gando et al. (2011).

2001). A fund is thus a special kind of stock that can generate a flow, with biomass being the prime example in a global energy context. For biomass, both the flow F and the underlying stock S are non-negligible. This is particularly true for long-lived biomass types, such as forest trees, but to a lesser extent also for short-lived agricultural crops, such as wheat and corn. In addition, there is an interdependency between F and S for biomass, since the flow depends on the stock. The net availability of biomass energy thus needs to be calculated through a model that considers the interdependency of F and S. The physical net availability of biomass might be operationalized as the maximum sustainable harvest that can be extracted from the stock over an indefinite period. Assuming logistic growth, the change in biomass given a continuous harvest h can be calculated using the Verhulst model (Milner-Gulland and Mace 1998):

$$\frac{dY}{dt} = r \times Y \times \left(1 - \frac{Y}{K}\right) - h \qquad (2)$$

where Y is the stock of biomass energy, t is time, r is the growth rate, and K is the carrying capacity. Note that Y corresponds to S, and h corresponds to F. By assuming steady state ($dY/dt = 0$), it can be calculated that the maximum continuous harvest that can be sustained without continuously decreasing the biomass stock Y is equal to $h = K \times r/4$ (Caughley and Sinclair 1994).

The term $K \times r$ represents biomass growth (and decay) at steady state of the undisturbed system, and at the global level, hence, could be interpreted as the potential net primary production (NPP_0). NPP_0 is the annual amount of solar energy converted to chemical energy in biomass by primary producers minus the energy used by the primary producers themselves in the absence of human interventions.[11] The NPP_0 is often measured as fixed carbon per year (Pg C/year). Sitch et al. (2003) estimate the total terrestrial (above- and below-ground) NPP_0 at 70 Pg C/year. Assuming a 50% carbon content and 19 kJ/kg dry biomass give 2660 EJ/year.[12] Field et al. (1998) estimate the oceanic[13] net primary production (NPP) (i.e., including the current human appropriation) at 49 Pg C/year, which given

the same assumptions as above equates to 1860 EJ/year.[14] Since the human appropriation of the oceanic NPP_0 is currently limited, we here assume that the NPP_0 is approximately equal to the NPP of oceans. The total terrestrial and oceanic NPP_0 thus becomes approximately 4500 EJ/year, which divided by four as in $h = K \times r/4$ gives a maximum sustainable harvest of about 1000 EJ/year. This value thus corresponds to the maximum flow F that the biomass stock (or fund) S can provide over an indefinite time (Table 2). Since the biomass energy availability is now operationalized as a theoretically maximized flow, it can be compared to the other flow-type energy resources; biomass is notably less available than solar and wind, yet more available than geothermal and hydro.

2.4.4 Aggregating all energy resource types

As noted in Sects. 2.4.1–2.4.3, there are from the perspective of physical resource availability three groups of energy resource types. If the fund-type resource biomass is modeled as a flow type — a possibility outlined in Sect. 2.4.3 — two groups remain: stock type and flow type. There is a fundamental difference between these two groups: the availability of stock-type energy resources depends on the size of their stocks, measured as the quantity energy (e.g., in EJ), while the availability of flow-type energy resources depends on the size of their flows, measured as the quantity energy per time (e.g., in EJ/year). Aggregating these two groups into a composite indicator would therefore require one of two strategies. The first strategy would be to divide the availability of stock-type energy resources with a time parameter T, so that it also gets the unit EJ/year. The interpretation of T would then be the time during which the stocks are allowed to become depleted, i.e., in essence, a time horizon beyond which the energy availability of humanity is considered out of scope.[15] The second, and fully equivalent, strategy would be to multiply the availability of flow-type energy resources with a time parameter T, so that it also gets the unit EJ. The interpretation of T would then be for how long the continuous generation of energy by the flow-type energy resources would be considered. In both cases, the time horizon can be thought of in the same way as for emission-related impact categories, such as climate change, where a value

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[11] A tiny fraction of the NPP_0 does not stem from solar energy but the chemical energy in compounds used by chemoautotrophs.

[12] Other studies arrive at similar values for the terrestrial NPP_0, such as 66 Pg C/year (Haberl et al. 2007) and 2420 EJ/year (Rogner et al. 2012).

[13] Although humans, being land-living organisms, generally find it easier to exploit the terrestrial NPP_0, it can be noted that there are large and rapidly increasing aquacultural activities around the globe, partly for food but also for energy and materials (Bostock et al. 2010; Adeniyi et al. 2018).

[14] Again, other studies arrive at similar values for the oceanic NPP, such as 52 Pg C/year (Westberry et al. 2008; Silsbe et al. 2016).

[15] Alternatively, an equivalent interpretation is that each year, a certain share (the reciprocal of the chosen time horizon) of the stock is allowed for use. Given such a use, the stock will decrease exponentially instead of becoming abruptly depleted after the chosen time horizon, e.g., 100 years, because 1% of the stock is less in year $t+1$ than it was in year t.

of 100 years is often applied as default when comparing the relative impact of different greenhouse gases. The choice of time horizon is value-laden, reflecting the degree of short-/long-termness in responsibility for global energy resources (Huijbregts et al. 2016). Shorter time horizons will, for energy resources, result in comparatively higher availability of stock-type energy resources, since either the stocks become distributed over fewer years, or the flows will have fewer years to supply energy.

Since the aggregation of the two energy resource type groups introduces the ethical consideration of how to value the future, this aggregation could be omitted if only resource types belonging to one group are evaluated, or if the assessor prefers to consider the two groups separately and leave such ethical considerations to the receiver of the results. However, renewable energy capacity and its share of the total capacity is increasing in the global energy system, leading to an energy system with significant shares of both stock- and flow-type energy resources — as opposed to the largely stock-type energy system that has been prevalent over the past 100 years. It is also clear from Table 2 that although, e.g., geothermal energy is a non-depletable flow-type energy resource, the physical availability of, e.g., coal is still so high that it would take about 2500 years for geothermal energy to accumulate an equal amount of energy. Given shorter time perspectives of, say, 100 years, coal is thus more available than is geothermal, which is due to the comparatively slow transfer of geothermal energy through the terrestrial surface. Although flow-type energy resources cannot become depleted in the same sense as stock-type energy resources, they are limited in size and might be temporarily "depleted," i.e., not available for other purposes. It might therefore be of interest in some cases to relate the potential scarcity of the two groups of energy resource types to each other using the strategy outlined above.

2.5 Inventory data

When considering the physical energy availability in nature for the calculation of the CF, the inventory data q should represent energy resources passing from nature (i.e. the lithosphere, atmosphere, hydrosphere and biosphere) into the technosphere (i.e. human-managed processes as typically depicted in LCA flowcharts). Life-cycle inventory data energy flows as found in contemporary LCA databases, such as Ecoinvent (Wernet et al. 2016), typically follow the system boundaries of the CED and similar inventory-level energy use indicators. As noted in Sect. 1.1, this system boundary (black dashed line in Fig. 1) does not correspond to the nature-technosphere boundary for solar, wind, and hydropower energy. This means that for these energy resource types, inventory data energy flows as found in

databases, here called q', need to be modified by an energy conversion factor η in order to obtain q:

$$q_i = q'_i/\eta_i \tag{3}$$

The value of η is technology-dependent and will vary over time. Typical conversion factors representing the technology level towards the end of the 2010s are 0.17 for solar light to solar electricity in photovoltaic modules (Fraunhofer Institute for Solar Energy Systems 2018), 0.40 for kinetic wind energy to wind electricity, and 0.90 for potential energy in river heads to hydropower electricity (Sandén et al. 2014).

Agriculture and intensive forestry can be seen both as parts of nature and of the technosphere (Crenna et al. 2018). If agriculture and forestry are viewed as parts of nature, the biomass harvested becomes equal to q (alternative 1 in Fig. 1). However, agriculture and forestry can also be seen as parts of the technosphere, with q then equal to the total biomass growth or even the utilization of solar irradiation for biomass growth[16] (alternative 2 in Fig. 1). Both these perspectives are theoretically possible to apply as long as q and the energy availability used to calculate the CF refer to the same energy flow. The probably simplest approach would be to consider agriculture and forestry as parts of nature rather than the technosphere, i.e., alternative 1 in Fig. 1, with the harvested biomass being equal to q. Thereby, the energy conversion factor becomes equal to 1 for biomass, since the biomass harvested from agriculture and forestry is typically what is reported in LCA databases.

For geothermal energy and all non-renewable energy types, the (primary) energy harvested from nature is generally inventoried and compiled in LCA databases; thus, the energy conversion factor for both geothermal energy and non-renewable energy types is equal to 1. Note that other conversion factors than the ones provided here might be required if q' has been inventoried in other ways. Note also that some energy resource types, such as coal and biomass, are sometimes reported in terms of mass in inventories. Some energy resource types, such as natural gas, can even be reported in terms of volume. In such cases, the mass- or volume-based inventory data need to be converted into energy based on the energy content of the resource, which can be operationalized as the higher heating value as recommended by Frischknecht et al. (2015).

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[16] Setting q at the level of solar irradiation would require a different estimate of energy availability than the NPP_0 discussed in Sect. 2.5, e.g., the solar energy required to generate the NPP_0. The end result should, in general, be the same with the smaller CF compensated for by a larger q, but with the possible advantage of enabling modelling of specific agriculture and forestry systems in the inventory analysis.

3 Proposals of LCIA methods for physical energy scarcity

In this section, three midpoint-level LCIA methods for physical energy scarcity are suggested based on the considerations in Sect. 2: (i) a physical energy scarcity indicator for stocks, (ii) a physical energy scarcity indicator for flows, and (iii) a composite physical energy scarcity indicator. The third LCIA method is then illustrated in a well-to-wheel study for vehicle propulsion fuels. The proposed methods can be referred to as "generalized" depletion methods according to the typology by Sonderegger et al. (2020), since they consider the potential depletion of physical energy stocks but also temporary depletion of flows.

3.1 Physical energy scarcity indicator for stocks

A physical energy scarcity indicator for stocks with a global perspective (PESI-sg, in MJ coal equivalents) and with CFs called physical energy scarcity potentials for stocks (PESP-sg, in coal equivalents) might be calculated according to:

$$\left.\begin{array}{l} \text{PESI-sg} = \sum_l \text{PESP-sg}_l \times q_l \\ \text{PESP-sg}_l = \left.\frac{1}{S_l}\middle/\frac{1}{S_{coal}}\right. \end{array}\right\} \qquad (4)$$

where l is a stock-type energy resource. In order to allow for an intuitive interpretation of the PESP-sg, they are scaled with a reference resource type, in the same way as greenhouse gases are scaled with the reference emission carbon dioxide in global warming potentials (IPCC 2013). Coal was selected for this purpose since it is the most abundant of the stock-type energy resources considered.[17] The PESP-sg is thus dimensionless, but is assigned the unit "coal equivalents" for clarity. The unit of the entire PESI-sg thus becomes "MJ coal equivalents." Using data on S from Table 2, PESP-sg values can be calculated and are shown in Table 3. Uranium has the highest PESP-sg, probably because there are limited amounts of deposits with high-enough concentrations to be considered minable, even given the most inclusive resources estimate by the Nuclear Energy Agency and International Atomic Energy Agency (2020), which considered conventional (known and inferred), prognostic, speculative, and unconventional uranium. Indeed, uranium has a relatively low crustal concentration (ca 1 ppm) (Rudnick and Gao 2014), which in turn is correlated with the availability

Table 3 Characterization factors for the three proposed LCIA methods for physical energy scarcity. PESP-sg: physical energy scarcity potential for stocks, PESP-fg: physical energy scarcity potential for flows, PESP-cg$_{100}$: composite physical energy scarcity potential with a 100-year time horizon. All of these have a global perspective, hence the denotation "g"

Energy resource type	PESP-sg (coal equivalents)	PESP-fg (solar equivalents)	PESP-cg$_{100}$ (solar equivalents)
Solar	–	1	1
Wind	–	300	300
Biomass	–	3000	3000
Geothermal	–	10,000	10,000
Hydro	–	20,000	20,000
Coal	1	–	600
Natural gas	10	–	8000
Crude oil	20	–	10,000
Uranium (U-235)	20	–	10,000

of elements in the crust (Rankin 2011). The more abundant coal has the lowest PESP-sg.

3.2 Physical energy scarcity indicator for flows

A physical energy scarcity indicator for flows with a global perspective (PESI-fg, in MJ solar equivalents) and with CFs called physical energy scarcity potentials for flows (PESP-fg, in solar equivalents) might be calculated according to

$$\left.\begin{array}{l} \text{PESI-fg} = \sum_m \text{PESP-fg}_m \times q_m \\ \text{PESP-fg}_m = \left.\frac{1}{F_m}\middle/\frac{1}{F_{solar}}\right. \end{array}\right\} \qquad (5)$$

where m is a flow-type energy resource. The PESP-fg values are scaled with a reference resource type, which was taken to be solar energy since it is the most abundant of the flow-type energy resources considered. The PESP-fg is dimensionless, but is assigned the unit "solar equivalents" for clarity. The unit of the entire PESI-fg thus becomes "MJ solar equivalents." Using data on F from Table 2, PESP-fg values can be calculated and are shown in Table 3. Solar energy gets the lowest PESP-fg because of the large abundance of incident solar light on Earth. Contrary, hydro gets the highest PESP-fg because high-altitude water bodies, such as alpine rivers and lakes, are comparatively rare on Earth.

3.3 Composite physical energy scarcity indicator

Given a goal to relate the physical scarcity of stock-type and flow-type energy resources to each other, a composite physical energy scarcity indicator with a global perspective (PESI-cg, in MJ solar equivalents) and with CFs called

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[17] This is similar to the selection of silicon as reference resource for the mineral resource LCIA method called the crustal scarcity indicator (CSI), which was done since silicon is the most abundant element in the Earth's crust (Arvidsson et al. 2020).

composite physical energy scarcity potentials (PESP-cg, in solar equivalents) might be calculated according to

$$
\left.\begin{aligned}
\text{PESI-cg}_T &= \sum_n \text{PESP-cg}_{n,T} \times q_n \\
\text{PESP-cg}_{n,T} &= \frac{1}{F_n + S_n/T} \bigg/ \frac{1}{F_{solar}}
\end{aligned}\right\} \tag{6}
$$

where n is any of the nine considered energy resource types (Sect. 2.2). As discussed in Sect. 2.4.4, a time horizon T is needed to aggregate stock- and flow-type energy resources. The PESP-cg values are also scaled with the availability of the most abundant energy resource type, which again is solar energy. The PESP-cg is thus assigned the unit solar equivalents, giving the whole PESI-cg the unit of MJ solar equivalents. Using data on F and S from Table 2, PESP-cg values can be calculated and are shown in Table 3. A time horizon of 100 years is used as illustration. In addition, Fig. 2 shows how the PESP-cg values of the nine energy resource types depend on the time horizon. Solar energy has the lowest PESP-cg due to its abundance. Given long enough time horizons, all flow-type energy resources get lower PESP-cg values than those of the stock-type energy resources. However, given time horizons of 10–100 years, some stock-type energy resources — in particular coal — exhibit lower PESP-cg than some flow-type energy resources.

3.4 Example illustration: well-to-wheel assessment of vehicle fuels

Vehicle fuel is an area where many different energy resource types, both stock- and flow-types, are currently used or are envisioned to be used in the future (Edwards et al. 2014). It is thus an example of an area where it might be of interest to aggregate and compare the use of many kinds of energy resource types based on their relative physical scarcity. The PESI-cg with a 100-year time horizon, described in Sect. 3.3, is therefore used here to illustrate its application in well-to-wheel assessments covering the production and use of eight passenger vehicle fuels in Sweden: (i) fossil diesel, (ii) compressed natural gas (CNG), (iii) rapeseed methyl ester (RME), as well as the electricity propulsion scenarios: (iv) wind power, (v) solar power, (vi) hydropower, (vii) coal power, and (viii) nuclear power. The functional unit is set to 1 vehicle kilometer (vkm). The average vehicle fuel consumptions assumed per 100 km are 5 L diesel, 4 kg CNG, 6 L RME, and 20 kWh electricity, respectively. The inventory data sources for the fuels are shown in Table S3 in the SI. The production of the vehicle is not included in well-to-wheel studies, only production and transport of the fuel, including capital goods required (Nordelöf et al. 2014). Swedish datasets were selected, if available. Otherwise, datasets for Europe, or in one case, Germany, are selected. The study is attributional and considers the fuels as produced approximately in the late 2010s. In addition, energy conversion factors are applied as described in Sect. 2.5.

The results for the PESI-cg$_{100}$ are shown in Fig. 3. Nuclear power has the largest physical scarcity impact of all assessed fuels, followed by diesel, hydropower, RME, and CNG. Coal power, solar power, and wind power all have comparatively low physical scarcity impacts. This result is not surprising considering the comparatively low PESP-cg$_{100}$ values of coal, solar, and wind energy (Table 3). It is
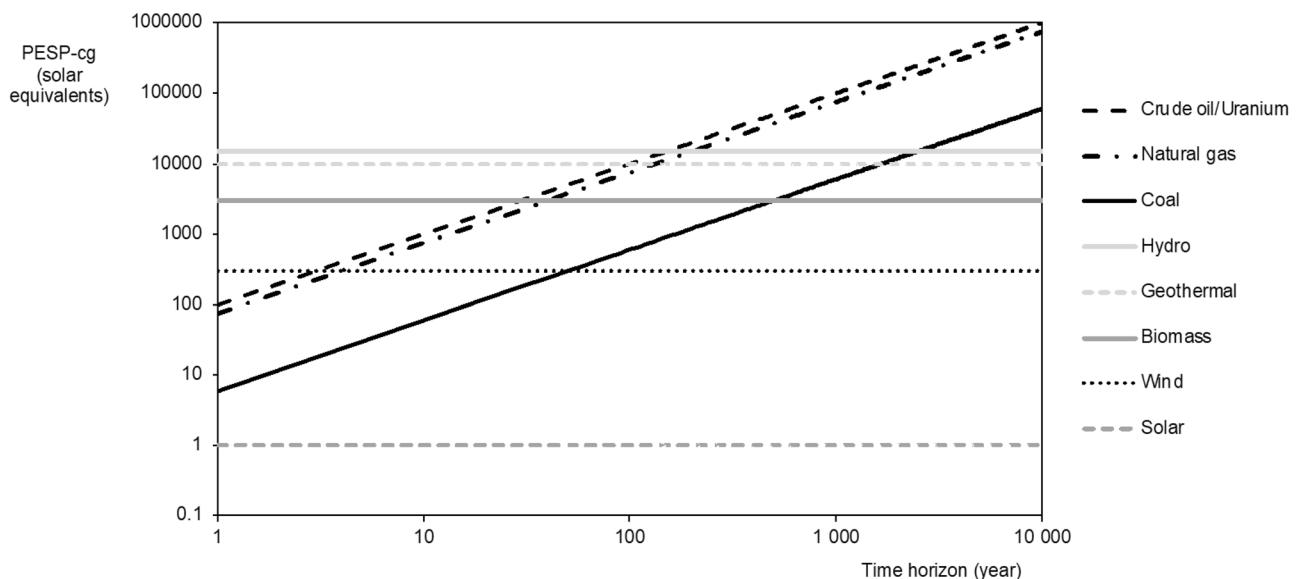
Fig. 2 Composite physical energy scarcity potentials with a global perspective (PESP-cg) for the nine considered energy resource types as a function of time horizon. Crude oil and uranium have been collapsed since they have the same value. Note the logarithmic axes
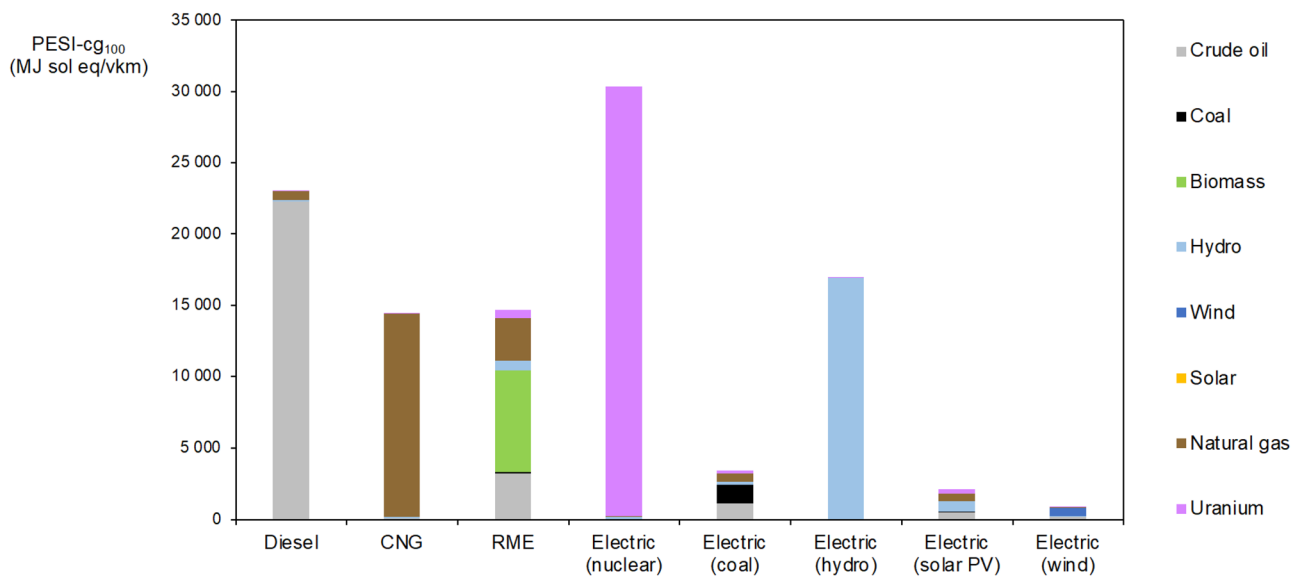
Fig. 3 Results for eight passenger vehicle fuels assessed by the composite physical energy scarcity indicator with a global perspective (PESI-cg) and a 100-year time horizon. CNG: compressed natural gas, RME: rapeseed methyl ester, sol eq: solar equivalents, vkm: vehicle kilometers, PV: photovoltaics

noteworthy that nuclear and hydro power, which are electricity supplies with relatively low emission-related impacts, including greenhouse gas emissions (Hertwich et al. 2015), receive relatively high PESI-cg$_{100}$ results. Contrary to electricity supplies like solar and wind power, there thus seems to be a trade-off for nuclear and hydro power between (i) mitigating greenhouse gas emissions by low-carbon electricity and (ii) maintaining physically scarce energy resources for future generations. For coal power, the trade-off is the opposite: While coal power (i) is infamous for its high greenhouse gas emissions, it (ii) is based on a physically much less scarce energy resource type than, e.g., fossil diesel. This shows the ability of the tested PESI-cg to help revealing such otherwise hidden trade-offs.

The PESI-cg$_{100}$ of diesel is dominated by crude oil energy resources. For CNG, natural gas dominates. For RME, biomass feedstock contributes notably together with several other energy resource types used upstream in the life cycle. This latter situation is also found for the PESI-cg$_{100}$ of coal power, where the use of other energy resource types upstream in the life cycle gives notable contributions because of the low PESP-cg$_{100}$ of coal. The hydro energy resource type, on the other hand, has a high enough PESP-cg$_{100}$ to dominate the PESI-cg$_{100}$ of hydropower electricity. For solar power, the solar energy is not dominating the PESI-cg$_{100}$, which is due to its low PESP-cg$_{100}$. Instead, other energy resource types used upstream in its life cycle contribute more, since the production of solar panels uses certain electricity according to the datasets used. Clearly, assumptions about the background system of such fuels are crucial, i.e., which energy resource types are used to produce the capital goods required in the conversion of the energy resource to convenient energy carriers. The results shown in Fig. 3 are based on production systems in the Ecoinvent database (version 3.6), listed in Table S3 in the SI. The PESI-cg$_{100}$ of solar and wind power could, however, become much lower if the energy inputs along their respective life cycles were instead provided by solar or wind power. A rough estimation indicates that the PESI-cg$_{100}$ of solar power fuel might become as low as 5 MJ solar eq. per vkm provided that all energy inputs along the life cycle are solar based, as compared to the PESI-cg$_{100}$ of 2000 MJ solar eq. per vkm based on the Ecoinvent background data. This demonstrates the possible use of the PESI-cg$_{100}$ in prospective studies with future energy supply scenarios and in studies applying product chain–specific datasets instead of generic data from databases. In addition, the PESI-cg$_{100}$ of solar power fuel could be further reduced given solar modules placed in more favorable locations than Sweden, for example, in Southern Europe or the Sahara Desert, where the solar insolation is roughly a factor of two higher (Sandén et al. 2014).

4 Future efforts toward LCIA methods for energy scarcity

Section 1.2 contained two criteria that we consider an LCIA method for energy scarcity should fulfill in order to go beyond state of the art. Regarding criterion (i), the three suggested LCIA methods in Sect. 3 do consider the relative

scarcity of energy resource types, specifically physical global energy scarcity. One of the three proposed indicators, the PESI-cg, enables an aggregation of both renewable (flow-type) and non-renewable (stock-type) energy resource types (and, with the rational applied for biomass, also fund-type resources). However, it does so at the cost of introducing a time horizon, which must be defined by the analyst or other parties. Although such time horizons are commonplace in LCA, and may help illustrating different ethical perspectives (Huijbregts et al. 2016), it is still a subjective parameter. Regarding criterion (ii), the three indicators have consistent nature-technosphere system boundaries due to the application of energy conversion factors as described in Sect. 2.5, although the exact values of these will change over time unless databases start reporting energy resource extraction at the nature-technosphere boundary for all energy resource types.

Regarding future developments, it would be relevant to investigate further how physical availability estimates, such as those in Table 2, have changed and might change over time. Although physical availabilities should be relatively stable over time, some will change over longer time periods. Besides potential new scientific knowledge on energy resource availability, the ongoing extraction of non-renewable energy resource types will eventually lead to a decrease in resource stocks S. It is also of value to explore other perspectives on energy scarcity than global physical scarcity. Such perspectives include more short-term and geographically localized scarcity, stemming not from global physical limitations of the energy resources but from, e.g., embargoes and bottlenecks in production systems as considered in, e.g., the ESSEZ method (Bach et al. 2016). In order to consider geographically localized scarcity, CFs would need to be developed for specific regions based on regional energy resource estimates. This should in principle be possible and physical energy resource estimates for, e.g., crude oil, natural gas, and biomass exist for some regions (Rogner et al. 2012).

It is important to note that the CFs of the three suggested LCIA methods depend heavily on the aggregation level of energy resource types. If we, for example, had considered the more aggregated energy resource type "non-renewable energy" (including coal, crude oil, natural gas and uranium), the use of uranium (U-235) would have had the same CF as coal, dramatically reducing its relative impact.[18] On the other hand, splitting an energy resource type, such as biomass, into a multitude of sub-types could result in much higher CFs for some individual sub-types, for example the

primary forest sub-type considered in the CED. While there is no universally correct choice, future studies might provide arguments for why alternative aggregation levels to the one proposed here are also relevant from certain perspectives.

Finally, for some renewable energy supply systems, metal availability might be a more severe issue than energy availability (Vidal et al. 2013), while other systems may be constrained by water availability (Berndes 2010). This highlights that in most contexts, LCIA methods for energy scarcity should be complemented with other methods capturing impacts of using non-energy resources. Also, as mentioned in Sect. 3.4, to identify trade-offs as made possible by the new indicators proposed here, emission-related impacts should be assessed as well.

Data availability The data that supports the findings of this study are available in Table 2, Table S2 (SI), and Table S3 (SI). Access to data underpinning Table S3 requires access to the Ecoinvent database.

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[18] This would have been similar to the abiotic depletion fossil approach recommended in a previous version of the ILCD guidelines, where all fossil energy resource types are given the same CF and thus equal scarcity (van Oers et al. 2002).

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