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Methodological insights of defining material criticality by assessing different electrolysis and fuel cell stacks

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ABSTRACT

Shifting economic sectors to a resource-efficient economy with zero net greenhouse gas emissions by 2050 faces major challenges for the European Union, which is highly dependent on material imports. Critical raw materials play a key role in a wide range of emerging technologies. In times of increasing demand, the assessment of critical raw materials is therefore of utmost importance. This study addresses methodological principles of various materials criticality indicators on product-level. Using the example of manufacturing different electrolysis and fuel cell stacks, these criticality indicators are applied, and the results are discussed. The case study demonstrated that alkaline electrolysis has the lowest criticality among the electrolyzers in seven out of nine criticality indicator evaluations. For fuel cells, the heavier stack concept shows lower criticality compared to the light-weight concept. One reason is the higher demand of rare earth elements and cobalt needed for manufacturing compared to heavier stack. Various rare earths are identified as critical in the manufacture of solid oxide electrolysis and fuel cell stacks. Iridium and nickel contribute most to criticality in the construction of proton exchange membrane electrolysis and alkaline electrolysis stacks, respectively. Five of nine indicators point to the same or similar criticality hotspots and can therefore set priorities for action in materials research for hydrogen and fuel cell systems. Nevertheless, when deciding for or against a material, one has to be aware that the criticality indicators use different sensitive sub-indicators which have an impact on the ranking of materials.

1. Introduction

With the European Green Deal (European Commission, 2019), the European Commission has once again stepped up its commitment to combat the climate crisis. In this context, the European Union (EU) is facing major challenges in terms of resources, as its economy depends highly on (raw) material imports (Dominish et al., 2019). In March 2023, the EU proposed a comprehensive package of measures to ensure a secure, diversified, affordable and sustainable supply of strategic raw materials (SRMs) and critical raw materials (CRMs) for the EU (European Commission, 2023b). SRMs are defined as materials that are important for green and digital transformation technologies as well as for defense and aerospace at EU level (European Commission, 2023b). CRMs are raw materials of a high importance to the economy of the EU and whose supply is associated with a high risk (European Commission, 2023b). CRMs are often subject to potential supply disruption which can hinder or even prevent the transformation of economic sectors towards a resource-efficient economy with zero net greenhouse gas emissions by

Abbreviations: AoP-NR, Area of Protection for Natural Resources; AWE, alkaline water electrolysis; C, consumption; CA, criticality assessment; CF, characterization factor; CRM, critical raw materials; CRMA, European critical raw materials act; CroferAPU, special steel; CroferH, Special steel; CS^v, Stack concept of Forschungszentrum Jülich GmbH; DtT, distance to target approach; EC, European Commission; EC-CA, material criticality assessment from the European Commission; EI, economic importance; EoL_{RIR}, end-of-life recycling input rate; EU, European Union; F'''20, stack concept of Forschungszentrum Jülich GmbH; FCH, fuel cell and hydrogen; GDC, gadolinium doped ceria; HHI, Herfindahl-Hirschman index; IR, import reliance; IRTC, international round table on materials criticality; LCA, life cycle assessment; LCC10, $LaMn_{0.45}Co_{0.35}Cu_{0.20}O_3$; LCI, life cycle inventory; LCIA, life cycle impact assessments; LCsA, life cycle sustainability assessments; LSCF, $La_{0.58}Sr_{0.40}Fe_{0.80}Co_{0.20}O_3$; MCF, $Mn_{1.0}Co_{1.9}Fe_{0.1}O_4$; MCI, material criticality indicator; MEErP, methodology for ecodesign of energy-related products; P, production; REE, rare earth element; PEMFC, polymer electrolyte membrane fuel cell; PEMWE, polymer electrolyte membrane water electrolysis; PGM, platinum group metal; SH2E, sustainability assessment of harmonized hydrogen energy systems project; SI, substitution index; SOEC, solid oxide electrolysis cell; SOFC, solid oxide fuel cell; SR, supply risk; SRM, strategic raw materials; WGI, world governance index; YSZ, yttria stabilized zirconia.

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2050. Many of them play a key role in emerging technologies such as renewable energy generation and storage, e-mobility, and digitization.

In this context, a large number of approaches have been developed over the last two decades to assess different aspects of availability of mineral resources. Various initiatives and authors have attempted to clarify the confusion of terms, such as rarity, scarcity, depletion and criticality, as well as the associated assessment methods. In 2017, the UN Environment Programme's Life Cycle Initiative (LCI-UNEP), set up an expert task force on mineral resources with the aim of harmonizing approaches in the field of Life Cycle Impact Assessments (LCIA) and Life Cycle Sustainability Assessments (LCSA) (Berger et al., 2020; Cimprich et al., 2019; Sonderegger et al., 2020). The International Round Table on Materials Criticality (IRTC) was launched in 2018 and continues to bring together international experts to address issues around the methodology, application, and future development of criticality assessments (CA) and LCSA methods (International Round Table Conference, 2023; Ku et al., 2024; Schrijvers et al., 2020). Still, to date there is no unified definition of material criticality in the LC(S)A community and thus no common basis for existing CA methods (Bachmann et al., 2022; Frenzel et al., 2017). The criticality of materials is context-dependent, and their definition and assessment is therefore necessarily linked to the perception of the target group (Bachmann et al., 2022). For this reason Mancini et al. (2018) asked "For whom is it critical?". Typically, the risk of a supply disruption is described in terms of socioeconomic factors (e.g., trade barriers, geopolitical conflicts, exploration restrictions, etc.). Vulnerability is usually interpreted in terms of the potential socioeconomic impacts of that supply disruption (Frenzel et al., 2017). Most CAs evaluate either the likelihood of a decline in supply, the likelihood of an increase in demand, or a combination of both (Schrijvers et al., 2020). Frenzel et al. (2017) have summarized this by the risk of price increases or price fluctuations and integrated it into a generalized algebraic equation for criticality expressed in monetary units. They argue that, according to classical risk theory, a single score could be obtained by multiplying an axis of "probability of supply disruption" by an axis of "vulnerability", which will be addressed in chapter 2.1 of our study. Results from criticality studies are often presented in a 2D matrix, where the axes are the probability of supply disruption and the vulnerability to that disruption (or the importance of the material) (Schrijvers et al., 2020). Other CAs result in an aggregated score (NEDO, 2009; NSTC, 2016). Although the European Commission also provides a list of CRMs European Commission (2017a, 2023b), it avoids a numerical aggregation of the criticality dimensions (Schrijvers et al., 2020). The CRMs are listed in strict alphabetical order to avoid any indication of relative criticality levels. It is pointed out that this is a specific political need (Blengini et al., 2017a; 2017b; Schrijvers et al., 2020).

To achieve more methodological clarity in resource assessments André and Ljunggren (2021) reviewed numerous studies and divided them into three main method categories: (i) LCIA, (ii) CA, and (iii) LCSA.

LCIA methods (i) for resource use reflect long-term impacts on the Area of Protection for Natural Resources (AoP-NR) caused by product systems, following an "inside-out" perspective (Arvidsson et al., 2020; Cimprich et al., 2019; Drielsma et al., 2016; Klinglmair et al., 2014; Koch et al., 2019; Sonderegger et al., 2020; 2017). "Inside-out" refers to the impact from product systems on the ecosphere (André and Ljunggren, 2021). In addition, over the last four years (2021–2024), several authors have addressed the concept of resource dissipation as a complement for criticality or as a replacement of issues like depletion (Beylot et al., 2021; Charpentier Poncelet et al., 2021; 2022; Lai and Beylot, 2023; Owsianiak et al., 2021; van Oers et al., 2024; van Oers et al., 2020).

CA methods (ii) identify resources that have high risk of supply disruption for specific stakeholders (e.g. companies, nations, regions, technologies). They focus on political, economic, and socioeconomic factors such as political stability, government interventions, and market imbalances to address concerns of short and medium term resource availability (André and Ljunggren, 2021) following an "outside-in" perspective (Arendt et al., 2020; Dewulf et al., 2016; Erdmann and Graedel, 2011; European Commission, 2017a; Glöser et al., 2015; Helbig et al., 2018; National Research Council, 2008; Shaw, 2015). "Outside-in" refers to impacts that emanate from the technosphere onto the system under study. However, most of the CAs are "snapshots" based on historical data, which allow to "solve yesterday's problem" rather than look ahead (Ku et al., 2024). Only few studies are dealing with future developments (Habib and Wenzel, 2016; Ioannidou et al., 2019; Knoeri et al., 2013; Riddle et al., 2015; Roelich et al., 2014; Yuan et al., 2020). They are based on demand scenarios (Habib and Wenzel, 2016), extrapolation of historic trends (Knoeri et al., 2013; Roelich et al., 2014), proxies (Habib and Wenzel, 2016), estimates of population and material intensity (Ioannidou et al., 2019), and agent-based methods (Knoeri et al., 2013; Riddle et al., 2015; Yuan et al., 2020).

Criticality assessments on product-level as part of LCSA methods (iii) also include some indicators of short-term supply risk. In contrast to classical CA, LCSA methods aim to connect criticality to a functional unit by characterization factors (CF) following the Life Cycle Assessment (LCA) logic (Bach et al., 2016; Campos-Carriedo et al., 2024; Cimprich et al., 2018; Gemechu et al., 2016; Kemna, 2011; Kolotzek et al., 2018; Lütkehaus et al., 2021; Mancini et al., 2018; Mori et al., 2021; Schneider et al., 2014; Tran et al., 2018).

Besides the more general discussion on methodologies, specific industries recognize the need to address the issue of critical materials for their sectors. One example is the fuel cell and hydrogen (FCH) sector, with its importance for the decarbonization of the European economy and for the energy transition (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019). The relevance of this sector in the decarbonization of European economies has been widely acknowledged, examined and forecast (Klütz et al., 2024; Koj et al., 2024; Thelen et al., 2024; Valente et al., 2020). Green hydrogen is a cornerstone for decarbonizing and coupling the energy, transportation, and industrial sectors (e.g. steel, chemistry) (Koj et al., 2024). The main advantage of green hydrogen compared to fossil fuels concerns the environmental performance, since the combustion of fossil fuels always releases carbon dioxide. Moreover, hydrogen has a high energy content per mass unit. Water electrolysis technologies offer the opportunity to utilize electricity from renewable energy sources to produce hydrogen, which can be used directly or as the basis for derived products in various sectors (e.g. heating, transport, chemicals). In this context, the REPowerEU plan published by the European Commission has set a target for 2030 of 10 million tons of domestic green hydrogen production supported by 10 million tons of green hydrogen imports (European Commission, 2022). The European electrolyzer manufacturers have agreed to increase their production capacity to 17.5 GW by 2025 (Koj et al., 2024). Up to 2250 TWh of hydrogen could be produced in Europe by 2050 (Valente et al., 2020). Furthermore, in an ambitious scenario, up to 4 million fuel cell electric vehicles could be in use in all areas of land transport in Europe by 2030 (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019).

It is already known that FCH technologies are highly dependent on SRMs and CRMs such as aluminum, cobalt, nickel, platinum group metals (PGMs), rare earth elements (REEs), strontium, and titanium (Bobba et al., 2020; Carrara et al., 2023; Kiemel et al., 2021; Lotrič et al., 2021; Mori et al., 2021; Stropnik et al., 2019). For example, Mori et al. (2021) evaluated materials used for two fuel-cell (solid oxide fuel cell (SOFC), polymer electrolyte membrane fuel cell (PEMFC)) and two water electrolysis technologies (alkaline water electrolysis (AWE), polymer electrolyte membrane water electrolysis (PEMWE)) using a single score obtained from three criteria - hazardousness, price and material criticality from a European Commission assessment (European Commission, 2020a) (hereinafter referred to as "EC—CA"),

In this context, this study addresses two research gaps: (i) the study deepens the methodological discussions on the integration of product-level criticality indicators as part of LCSA; (ii) the study quantifies and compares material criticality scores by various criticality indicators on product-level for FCH systems: three water electrolysis stacks and two fuel cell stacks. The outcomes and shortcomings are discussed and hurdles specific to FCH technologies are identified.

2. Methods and materials

In a recent review, Bachmann et al. (2022) recommended three methods for operationalizing criticality aspects into LCSA framework: the EC—CA method (European Commission, 2017a; 2023b), the GeoPolRisk method (Cimprich et al., 2018; Gemechu et al., 2016) and the ESSENZ method (Bach et al., 2016). In the following, these three approaches are compared to other criticality indicators, which also enhance the EC—CA method. The comparison is first conducted from a methodological perspective (chapter 2.1) and then the nine indicators are tested using a case study (chapter 2.2).

2.1. Criticality indicators at product-level as part of LCSA

Already in 2010, the first EC—CA was published - an assessment on critical raw materials at EU level, considering geopolitical and economic constraints (European Commission, 2010) and since then has been updated regularly (European Commission, 2014; 2017b; 2020a; 2023b), also methodologically (European Commission, 2017a). As a reminder, the European Commission defines CRMs as those that are “of high importance to the EU economy and whose supply is associated with a high risk”. For this, the EC—CA considers two indicators to assess the criticality of raw materials: (i) supply risk (SR) and (ii) economic importance (EI) of raw materials. Raw materials are classified as critical if they exceed criticality thresholds (SR $\geq$ 1.0 and EI $\geq$ 2.8) defined by experts for both indicators. The expert group consists of a mix of experts from national ministries, geological surveys, academia, consultants, extractive, downstream and recycling industries. The two criticality indicators are presented in a two-dimensional space where the axes represent the risk of supply chain disruption (SR) and the vulnerability of the European economic system to this risk (EI). In the most recent EC—CA update, 32 materials are classified as critical, 15 of them additionally as strategic (European Commission, 2023b). Though copper and nickel do not exceed both CRM thresholds, they are additionally included as SRMs. Detailed information about the calculation of SR and EI are explained in the methodology report (European Commission, 2017a) and are summarized in the supplementary material.

If the EC—CA method is used in its original sense - a material is considered to be critical or not according to the thresholds defined for SR and EI – this approach is called binary in this study. Here, criticality corresponds to the sum of all critical materials (mass flows of CRMs) contained in a product. A specific characterization factor (CF) is not calculated (Table 1, first line).

The EC—CA has been enhanced in the (recent) past for calculation of product-level criticality indicators (Campos-Carriedo et al., 2024; Kemna, 2011; Mancini et al., 2018; Tran et al., 2018; Zapp and Schreiber, 2021) as shown in the following.

In 2011, the Methodology for Ecodesign of Energy-related Products (MEErP) (Kemna, 2011) aimed to strengthen the sustainable supply of materials to the EU and to reinforce resources efficiency and recycling. For these two pillars, the MEErP project proposed an indicator using four key metrics (European consumption, import reliance, substitutability, end-of-life recycling input rate (EoL_{RIR})) (Table 1, second line).

Later, Mancini et al. (2018) used the SR of the EC—CA (European Commission, 2014) as CF in the impact assessment phase of an LCA and tested several implementation options using the life cycle inventory (LCI) of a laptop as an example. The results point out that the approach does not represent the relative difference in raw material security well when only SR is used as CF, because then the impact depends mainly on the masses considered in LCI. By using an exponent for SR in a second option, the criticality values are spread over a wider range, and at least some CRMs from the EC—CA can be identified among the resources. When SR is related to the annual mine production (P) (Table 1, third line), this option gives more importance to specialty metals, which are less mined globally.

Tran et al. (2018) used the product of SR and EI (European Commission, 2014) as CFs (Table 1, 4th line) as requested by Frenzel et al. (2017). The authors tested this approach on the LCIs of recycling

Table 1
Overview of characterization factors assessed by the methods considered in this work.

Characterization factor (CF)	Method description	Refs.
no CF is calculated	$Criticality = \sum_{i=1}^{n} m_{i,\ CRM}$ $m_{i,\ CRM}$ = Mass of a critical material i	Binary approach (European Commission, 2023b)
$CF_i = \frac{criticality_{Sb}}{C_i * IR_i * SI_{SR,\ i} * (1 - EoL_{RIR,\ i})}$	$criticality_{Sb}$: Material criticality of antimony C_i: European consumption of material i IR_i: Import reliance of material i $SI_{SR,i}$: Substitution index used for calculating SR $EoL_{RIR,\ i}$: End-of-life recycling input rate of material i	MEErP (Kemna, 2011)
$CF_i = \frac{SR_i}{P_i}$	SR_i: Supply risk of material i P_i: Global mining production of material i	Mancini et al. (2018)
$CF_i = SR_i * EI_i$	EI_i: Economic importance of material i	Tran et al. (2018)
$CF_i = \frac{SR_i}{(C_i * (1 - IR_i * (1 - EoL_{RIR,\ i})))}$		SH2E (1) (SH2E Project, 2024)
$CF = \frac{\frac{SR_i}{(C_i * (1 - IR_i * (1 - EoL_{RIR,\ i})))}}{(1 - EoL_{RIR})}$		SH2E (2) (Campos-Carriedo et al., 2024)
$CF = \frac{SR_i * EI_i}{(P_i - C_i * IR_i * (1 - EoL_{RIR,\ i}))}$		MCI this work
$CF_i = HHI_i * WGI_k * \frac{I_{i,k}}{I_i + P_{dom,\ i}} * p_i$	HH_i: Herfindahl-Hirschman Index of material i WGI_k: World Governance Index of country $I_{i,k}$: Imports of material i from country k I_i: Total imports of material i $P_{dom,i}$: Domestic production of material i p_i: Price of material i	GeoPolRisk (Gemechu et al., 2016)
$CF_i = nDtT_{scaled,c,i}$ $nDtT\ value_{i,c} = \frac{DtT\ value_{i,c}}{normalization\ value_i}$ $DtT - value_{i,c} = \left(\frac{indicator\ value_{i,c}}{target_c}\right)^2$	$DtT_{c,i}$: Distance-to-Target of an impact category and a material i nDtT: normalized DtT (further information about scaling can be found in suppl. material)	ESSENZ (Bach et al., 2016)

systems for alkaline and zinc-carbon batteries. The results show that the treatment of the black mass in the furnaces, which is a part of the battery collection and recycling system, accounts for the largest share of the overall criticality. The criticality is mainly caused by lime used in this process, although it is a non-critical material. Still, the combination of the product of SR and EI, together with large quantities in the LCI results in a high criticality score, which is not conclusive.

As one outcome of the SH2E project (SH2E Project, 2024), in which LCSA guidelines specifically for FCH systems were developed, an indicator for material criticality at product-level was presented (Zapp and Schreiber, 2021), hereafter referred to as SH2E (1) (Table 1, 5th line). It also takes into account SR and some key parameters from EC—CA (European Commission, 2020a) and its supporting information (European Commission, 2020b). Recently, Campos-Carriedo et al. (2024) have slightly modified the SH2E (1) indicator to SH2E (2) indicator (Table 1, 6th line) based on the latest EC—CA report (European Commission, 2023b) and its supporting information available from SCRREEN (European Commission, 2023a).

In order to take the benefits from the EC—CA method and Mancinis' most promising approach (CF = SR/P) (Mancini et al., 2018), we developed these SH2E indicators further, as follows: (1) first, we have included EI from the EC—CA method in Mancini's approach based on the classic risk definition (Frenzel et al., 2017), which describes the criticality of raw materials as the product of the probability of supply disruptions (here SR) and their economic consequences (here EI) (Glöser et al., 2015) (CF = SR * EI/P); (2) as global production alone is not sufficiently meaningful for assessing supply risk, we subtracted the European consumption (C) from the global production to gain the amount left available to the rest of the world-wide competitors, increasing the stress if it is very low: CF = SR * EI/(P - C); (3) additionally, we argue that a high European consumption is only critical if there is a high import reliance (IR) for the material and this material is not recycled in the EU. This leads to the formulation of the CF for our new Material Criticality Indicator (MCI) (Table 1, 7th line):

$$CF = \frac{SR_i * EI_i}{\left(P_i - C_i * IR_i * \left(1 - EoL_{RIR,\ i}\right)\right)} \quad (1)$$

Finally, the two methods that are not based on EC—CA but are nevertheless recommended by the community are briefly presented.

The GeoPolRisk method (Cimprich et al., 2019; Gemechu et al., 2016) includes indicators similar to the EC—CA approach. The supply risk of raw materials is primarily determined from the perspective of the resource demanding country, considering the import share of the demanding country from the supplying country, the global share of a supplying country in the production of a certain commodity and the geopolitical stability of that country (Table 1, 8th line). Cimprich et al. (2018), Santillán-Saldivar et al. (2021) added substitutability and recycling rates as vulnerability-reducing parameters to the GeoPolRisk approach. Finally, Santillán-Saldivar et al. (2022) have demonstrated the potential of GeoPolRisk to be operationalized in LCSA studies using a case study on Li-ion batteries.

The ESSENZ approach, which is an extension and update of the former ESP method (Schneider et al., 2014), determined the resource efficiency of abiotic materials on the product-level, considering 21 social, environmental and criticality impacts (Bach et al., 2016). The CFs are based on global averages. The indicator values for availability and criticality are placed in relation to target values, applying the distance to target approach (DtT) (Table 1, 9th line). These targets were established based on expert judgment (for further methodological details see the supplementary materials).

Table 1 summarizes the information about the nine approaches given above in mathematical form and thus allows a clear presentation of the similarities and differences of the CFs used in this study.

For the calculation and comparison of the different CF outcomes in this work, SR, EI, IR, SI, and EoL_{RIR} are obtained from the latest EC—CA report (European Commission, 2023b). C_i is retrieved from its supporting information available from SCRREEN (European Commission, 2023a). Since the methodological update in 2020 the European Commission provides two IR numbers: IR for extraction and for processing stage. For defining criticality, the European Commission always takes the higher IR value for each material, which represents the worst case. This strategy is also used for this work. The global mining production (P_i) is gained from U.S. Geological Survey (2023). SR, EI, IR, SI, EoL_{RIR}, C_i, and P_i are listed in Table 2. Contrary to the criticality value of antimony based on data from 2006 to 2007 ($criticality_{Sb} = 451$) used in the original MEErP approach, we have updated this value to 668 ($criticality_{Sb}$) taking into account the figures from the latest EC—CA report (European Commission, 2023b) and from SCRREEN (European Commission, 2023a).

The GeoPolRisk's CFs were calculated using the GeoPolRisk Python module supplied by Koyamparambath (2023) that allows the assessment of a geopolitical related supply risk of a resource from the perspective of a country, region, trade bloc, and company. For this assessment, the region "EU-28″ was chosen. As the Python library does not contain data for seven materials (borates, silica sand, strontium, niobium, iridium, platinum, vanadium), required for this analysis, the quantities and shares of the global producer countries and the EU's supplier countries as well as their World Governance Indices (WGI) from the World Bank and the prices of the resources were gathered in advance and filled into the Python model (details can be found in supplementary material S2). For the ESSENZ's CFs we applied those supplied in Cimprich et al. (2019). While the full ESSENZ method considers in total 21 indicators covering environmental aspects, societal acceptance, physical resource accessibility, and socioeconomic issues we only cover the latter (11 indicators) in this work due to relevance and comparability. The CFs of GeoPolRisk and ESSENZ used can be found in the supplementary materials (Table S2).

According to the LCA logic, the obtained CFs multiplied by the quantities (mass (m) of the considered resources (i)) from the LCI results in the criticality score at product-level (Eq. (2)).

$$Criticality = \sum_{i=1}^{n} CF_i * m_i \ 1 \quad (2)$$

2.2. Case study

The different criticality approaches presented in the previous chapter 2.1 are applied to various FCH systems discussed in the course of a future hydrogen economy. In order to address the importance of the associated raw material criticality, this work identifies the methodological differences as well as strengths and shortcomings of the different approaches shown in Table 1 using a case study.

The case study includes the manufacturing of three types of electrolysis stacks (AWE, PEMWE, SOEC) and two types of anode-supported solid oxide fuel cell stacks (SOFC F'''20 and CS^V stack concept) developed at the Forschungszentrum Jülich (Harboe et al., 2020). The difference between the two fuel cell stack concepts is on the one hand the thicker anode substrate (550 μm Ni/8YSZ) of the F'''20 stack compared to 275 μm in case of the light-weight design CS^V. On the other hand, the contact layers are LCC10 and LSCF for the F'''20 and CS^V stack. (Table 3) The LCI's of the three electrolysis stacks were taken from Zhao et al. (2020) and refer to the functional unit (FU) of 1 m^2 of stack area, taking into account the non-active area of the stacks as well. The LCI's of the two planar 5 kW_{el} SOFC stacks stem from an earlier publication of the authors (Harboe et al., 2020). Composite materials such as perovskites (e.g., LSCF), mixed oxides (e.g., 8YSZ, 3YSZ, GDC), and glass solder as well as the special steels (e.g., CroferAPU, CroferH) are disaggregated by molecular weights and given as raw material flows (Table 3). CroferAPU and CroferH contain 22 % chromium, less than 1 % shares of manganese, titanium, lanthanum and in the case of CroferH additional niobium and 2 % tungsten. Organic components like solvents, binder, ink materials, rubber etc. are not considered as they are not of

Table 2
Overview of the parameters used for the calculations.

LCI flows	SR[a]	EI[a]	SI[a]	IR[a]	EoL_{RIR} [%][a]	European consumption[b] [t]	Global production[c] [t]
Aluminum	1.2	5.8	0.86	0.89	32	1.54E+07	6.90E+07
Barite	1.3	3.5	0.92	0.74	0	5.06E+05	7.90E+06
Borate	3.6	3.9	0.99	1	1	4.20E+04	3.02E+06
Cerium	4.0	4.9	0.97	1	1	2.67E+03	5.77E+04
Chromium	0.7	7.2	0.93	0.42	21	1.22E+06	4.10E+07
Cobalt	2.8	6.8	0.98	0.81	22	1.76E+04	1.90E+05
Gadolinium	3.3	3.3	0.59	1	1	11.3	1.97E+03
Iridium	3.9	6.4	0.97	1	12	0.92	7.23
Iron	0.5	7.2	0.95	0.77	31	1.25E+08	1.60E+09
Lanthanum	3.5	2.9	0.97	1	1	645	4.28E+04
Manganese	1.2	6.9	1	0.96	9	4.81E+05	2.00E+07
Molybdenum	0.8	6.7	1	1	30	2.85E+04	2.50E+05
Nickel	0.5	5.7	0.92	0.75	16	3.00E+05	3.30E+06
Niobium	4.4	6.5	0.96	1	0.6	1.22E+04	7.90E+04
Platinum	2.13	6.9	0.95	1	12	72	190
Silica sand	0.3	3.1	0.93	0	1	3.20E+07	3.80E+08
Strontium	2.6	6.5	0.97	0	0	4.93E+04	3.40E+05
Titanium	1.6	6.3	1	1	1	1.51E+06	9.50E+06
Tungsten	1.2	8.7	0.96	0.8	42	431	8.40E+04
Vanadium	2.3	3.9	0.92	1	6	1.27E+04	1.00E+05
Yttrium	3.5	2.9	0.90	1	1	510	5.13E+03
Zinc	0.2	4.8	0.80	0.56	34	1.96E+06	1.30E+07
Zirconium	0.8	3.5	0.97	1	12	2.31E+05	1.40E+06

[a] provided by the latest EC—CA report (European Commission, 2023b).
[b] provided by EU factsheets SCRREEN 2023 (European Commission, 2023a).
[c] provided by USGS (U.S. Geological Survey, 2023).

mineral origin (Table 3).

The CFs are applied to the foreground FCH systems, as suggested by the SH2E guidelines. The final criticality score is obtained by multiplying the mass of each raw material according to the bill of materials (BoM) (Table 3) and the calculated CF of the corresponding material (according to Eq. (2)). Since this work focuses on the manufacture of FCH systems and not on the entire life cycle, the findings are aimed at the design of current and future FCH systems and thus support technology developers in selecting appropriate materials.

3. Results and discussion

In a first step the CFs for the various materials used in the electrolysis and fuel cell stacks are determined according to the different criticality approaches, to show their variances and to discuss the methodological advantages and shortcomings. Second, the impact which these variances will have on the outcome of an LCA will be tested using a case study.

3.1. Ranking of materials based on criticality indicators

In total 24 materials are considered for the stacks under study. The calculated CFs according to the formulas given in Table 1 show a large spread (large scale differences from E-10 to $E+13$, see also supplementary material, Table S2). For better comparison, they are transformed using the min-max normalization function (Eq. (3)):

$$z = \frac{x - min(x)}{[\max(x) - \min(x)]} \tag{3}$$

where x is an original value and z is the normalized value. The normalized results are visualized in Table 4 using a color scale (green: non-critical, yellow: medium critical, orange: almost critical, red: critical). ESSENZ is missing CFs for six inventory flows considered in the case study. As Cimprich et al. (2019) have already pointed out, GeoPolRisk and ESSENZ each apply a single CF value for all rare earths as a group, rather than distinguishing between individual rare earths. This is an important limitation as the supply risks are probably not the same for all rare earths.

Two methodological issues relating to the MEErP, SH2E (1) and SH2E (2) indicators should not remain unmentioned. If the import reliance (IR) of a material is 0 (0 %), meaning that the material is entirely extracted and processes within the EU, the MEErP formula (Table 1) results in an infinite CF. The material is classified as critical even though it is not dependent on external suppliers. This applies to strontium and silica sand for the case study materials and overall, it concerns 16 resources such as gold, hafnium, tellurium, noble gases, and sulfur. If the IR of a material is 1 (100 %) and at the same time its EoL_{RIR} is 0 (0 %) (i.e. no end-of-life recycling in the EU), a methodological problem arises for the SH2E (1) and SH2E (2) indicators. Here, the CFs will also become infinite, as there is no internal primary and secondary production of the material. This applies to niobium in the case study and for four more of the 82 resources in the EC—CA (beryllium, lithium, scandium, phosphorous). In particular, the lack of lithium is a major disadvantage of both SH2E indicators, as lithium is often used for storage technologies.

For the materials considered it can be observed that iridium presents the highest CF for almost all indicators taken into account. Only when using Tran's indicator, niobium overtakes iridium in terms of criticality. Also, for Tran's approach some minerals are classified as medium critical or almost critical (including iron, chromium, silica sand, zinc, and zirconium), which the other methods classify as less critical. Using Mancini's indicator 16 of the 24 materials are defined as non-critical, which is the highest number. In contrast, copper is the only material that is defined as non-critical by using Tran's indicator. Platinum, niobium, vanadium, and the rare earth elements gadolinium, cerium, yttrium, and lanthanum also have a high criticality score for almost all methods.

3.2. Contribution analysis of material criticality scores using the case study systems

Figs. 1 and 2 show the relative shares of materials in the overall score (%) for the manufacture of three electrolyzer with 1 m^2 stack area (including non-active area of the stacks) (Fig. 1) and two different 5 kW fuel cell stacks (Fig. 2) using the nine criticality approaches. The absolute figures can be found in Table S3 in the supplementary material.

In the case of AWE (Fig. 1a), five different materials are used according to Zhao's LCI (Zhao et al., 2020), with nickel having the highest

Table 3
LCI of the stack manufacturing for the different electrolysis and fuel cell stacks.

Stack type	Bill of material	Raw material	Mass of raw material (kg)
AWE (Zhao et al., 2020)	Stainless steel	Chromium	3.84E-01
		Iron	1.64E+00
		Molybdenum	5.82E-02
	Nickel, Nickel plate, Nickel sulfide coating	Nickel	7.23E+00
	Zirfon	Zirconia	9.03E-04
	Polyphenylene sulfide	-	-
PEMWE (Zhao et al., 2020)	Stainless steel	Chromium	1.96E-01
		Iron	8.35E-01
		Molybdenum	2.96E-02
		Nickel	1.24E-01
	Titanium plate, Titanium felt	Titanium	9.69E+00
	Platinum catalyst, Platinum coating, Platinum powder	Platinum	4.30E-02
	Iridium oxide catalyst	Iridium	1.30E-02
	Ink materials	-	-
	Carbon paper	-	-
	Nafion 115	-	-
	Rubber gasket	-	-
SOEC (Zhao et al., 2020)	Glass solder	Aluminium	2.11E-02
		Barite	9.64E-03
		Borates	8.00E-04
		Silica	5.96E-03
		Vanadium	4.48E-04
		Zinc	6.43E-04
	Stainless steel	Chromium	3.39E+00
		Iron	1.20E+01
		Titanium	1.08E-02
	$Mn_{1.5}Co_{1.5}O_4$	Cobalt	1.61E-02
	$Mn_{1.5}Co_{1.5}O_4$, Stainless steel	Manganese	7.29E-02
	Nickel oxide, Nickel powder	Nickel	9.81E-02
	LSCF, Stainless steel	Lanthanum	3.97E-02
	LSCF	Strontium	1.19E-02
	Gadolinium Doped Ceria (GDC)	Cerium	4.39E-02
		Gadolinium	1.23E-02
	8YSZ/3YSZ	Zirconia	1.05E-01
	Yttrium oxide	Yttrium	2.66E-02
	Tape casting slurry	-	-
	Organics (solvent, binders, pore formers)	-	-
SOFC, F'''20 concept (Harboe et al., 2020)	Glass solder	Aluminium	4.23E-02
		Barite	9.64E-01
		Borates	8.00E-02
		Silica	5.96E-01
		Vanadium	4.48E-02
		Zinc	6.43E-02
	CroferAPU, CroferH	Chromium	3.39E+01
		Manganese	8.37E-01
		Iron	1.18E+02
		Lanthanum	1.23E-01
		Niobium	3.31E-01
		Titanium	1.24E-01
		Tungsten	1.10E+00
	8YSZ	Yttrium	2.65E-01
		Zirconia	1.53E+00
	$La_{0.58}Sr_{0.40}Fe_{0.80}Co_{0.20}O_3$ (LSCF), $LaMn_{0.45}Co_{0.35}Cu_{0.20}O_3$ (LCC10), $Mn_{1.0}Co_{1.9}Fe_{0.1}O_4$ (MCF)	Cobalt	4.42E-01
		Strontium	6.21E-02
		Copper	2.92E-02
		Manganese	2.40E-01
		Lanthanum	4.61E-01
		Iron	9.78E-02
	Nickel oxide, Nickel mesh	Nickel	3.40E+00
	Gadolinium Doped Ceria (GDC)	Cerium	2.98E-02
		Gadolinium	8.37E-03
SOFC, CS^V concept (Harboe et al., 2020)	Glass solder	Aluminium	4.02E-02
		Barite	9.16E-01
		Borates	7.60E-02
		Silica sand	5.66E-01
		Vanadium	4.26E-02
		Zinc	6.11E-02
	CroferH	Chromium	9.17E+00
		Iron	3.10E+01
		Lanthanum	3.34E-02
		Manganese	3.34E-01
		Niobium	2.50E-01
		Titanium	4.17E-02
		Tungsten	8.34E-01
	Nickel oxide, Nickel mesh	Nickel	2.95E+00
	$Mn_{1.0}Co_{1.9}Fe_{0.1}O_4$ (MCF), $La_{0.58}Sr_{0.40}Fe_{0.80}Co_{0.20}O_3$ (LSCF)	Cobalt	7.30E-01
		Iron	3.40E-01
		Lanthanum	5.55E-01
		Manganese	3.18E-01
		Strontium	2.42E-01
	Gadolinium Doped Ceria (GDC)	Cerium	4.68E-02
		Gadolinium	1.31E-02
	8YSZ	Zirconia	1.40E+00
		Yttrium	2.43E-01

amount with >7 kg, followed by iron with 1.6 kg and chromium with 0.4 kg. The lowest amount of zirconia (0.9 g) is nearly four orders of magnitude smaller than the highest weight. As none of the five materials exceeds the criticality thresholds of the EC—CA approach and only nickel is included as SRM (European Commission, 2023b), it is the sole item in the binary approach. Although only 60 g of molybdenum is used, its score ranges between 15 and 35 % for MEErP, Mancini, both SH2E indicators and the new MCI. The comparatively low molybdenum global production and European consumption is the reason for its relatively high share of the overall score according to the underlying CF formulas (Table 1). Specifically, the result of the SH2E indicators contradicts the expectation that lower consumption leads to lower risks. Tran's approach is the only one that also highlights iron and chromium. Here, the high amount of materials used is dominating the results. The GeoPolRisk CF of molybdenum (1487) is much higher than that of the other four materials, followed by nickel (460). Nevertheless, nickel contributes significantly more to the GeoPolRisk score than molybdenum as nickel is required in much larger quantities for the manufacture of 1 m^2 stack area. The same applies to ESSENZ.

The manufacturing of the PEMWE stack requires titanium, platinum, and iridium in addition to four materials already needed for AWE (molybdenum, nickel, chromium, iron). Again, Tran's approach shows the most represented materials in terms of mass; titanium with > 9 kg followed by iron with 0.84 kg (Fig. 1b). Although four materials are classified as critical or strategic (titanium, nickel, platinum, iridium) according to EC—CA (European Commission, 2023b), nickel, platinum, and iridium are hardly visible in the binary approach. Only titanium is highlighted due to its high quantity required. This changes completely

Table 4
Ranking of material criticality based on different indicators (normalized values).

	Binary	MEErP	Mancini	Tran	SH2E (1)	SH2E (2)	MCI	GeoPolRisk	ESSENZ
Aluminium		1.1E-07	3.2E-08	2.3E-01	1.7E-08	1.3E-08	2.7E-08	7.1E-06	3.5E-06
Barite		1.5E-06	3.3E-07	1.5E-01	2.8E-07	3.2E-07	1.7E-07	1.3E-06	n.a.
Borate		5.6E-05	4.8E-06	4.8E-01	5.4E-04	6.1E-04	2.7E-06	3.6E-06	n.a.
Chromium		5.7E-07	3.1E-08	1.6E-01	5.1E-08	4.6E-08	3.1E-08	9.5E-07	7.7E-06
Cobalt		3.8E-05	3.1E-05	6.6E-01	1.2E-05	1.1E-05	3.1E-05	3.8E-04	1.4E-03
Iron		0.0E+00	0.0E+00	1.1E-01	2.3E-10	1.2E-10	0.0E+00	2.8E-07	0.0E+00
Manganese		3.5E-06	1.1E-07	2.8E-01	9.9E-07	1.0E-06	1.1E-07	5.5E-06	1.2E-05
Nickel	a	2.1E-06	3.4E-07	8.7E-02	1.3E-07	1.2E-07	2.9E-07	2.8E-05	5.2E-05
Zinc		1.8E-07	3.0E-08	2.0E-02	5.1E-09	3.7E-09	2.1E-08	4.0E-06	8.1E-06
Lanthanum		4.6E-04	1.5E-04	3.5E-01	4.4E-03	5.0E-03	6.4E-05	1.1E-04	1.5E-03
Strontium		n.f.	3.1E-05	5.9E-01	1.4E-06	1.6E-06	2.8E-05	1.5E-05	n.a.
Cerium		2.5E-04	1.3E-04	6.8E-01	2.8E-03	3.1E-03	9.4E-05	1.1E-04	1.5E-03
Gadolinium		3.7E-03	3.1E-03	3.7E-01	5.5E-02	6.2E-02	1.6E-03	1.1E-04	1.5E-03
Zirconium		6.2E-06	1.6E-06	8.5E-02	1.3E-06	1.3E-06	9.0E-07	8.2E-06	1.1E-04
Yttrium		3.0E-03	1.2E-03	3.5E-01	1.4E-03	1.1E-03	5.0E-04	1.1E-04	1.5E-03
Silica sand		n.f.	2.0E-09	1.9E-02	0.0E+00	0.0E+00	6.4E-10	0.0E+00	1.1E-05
Vanadium		2.1E-04	4.3E-05	3.0E-01	2.5E-04	2.7E-04	2.4E-05	1.4E-04	n.a.
Titanium		2.3E-06	2.0E-07	8.2E-02	3.1E-06	3.5E-06	1.7E-07	6.3E-06	1.3E-05
Tungsten		4.6E-05	2.6E-05	3.6E-01	6.0E-06	4.0E-06	3.3E-05	2.0E-07	n.a.
Niobium		3.7E-04	2.0E-04	1.0E+00	n.f.	n.f.	1.9E-04	1.0E-03	n.a
Copper	a	7.3E-08	7.3E-09	0.0E+00	1.6E-09	7.1E-10	4.0E-09	1.4E-05	1.5E-07
Molybdenum		8.4E-05	5.9E-06	1.8E-01	8.4E-06	6.7E-06	5.7E-06	9.2E-05	2.1E-04
Platinum		1.3E-02	2.1E-02	5.1E-01	7.0E-03	7.0E-03	3.0E-02	3.6E-01	1.0E+00
Iridium		1.0E+00	1.0E+00	8.7E-01	1.0E+00	1.0E+00	1.0E+00	1.0E+00	n.a

a) copper and nickel do not meet the thresholds of EC—CA, but are included as SRMs (European Commission, 2023b); n.f. not feasible as the formula leads to an infinite CF (Table 1); n.a. CFs are not available; red: critical; orange: almost critical; yellow: medium critical; green: non-critical.

for MEErP, Mancini, both SH2E indicators and the new MCI, where iridium dominates the risk followed by platinum. The results are determined by several orders of magnitude lower annual global mine production and EU consumption of iridium compared to the other materials used. The GeoPolRisk CFs for platinum and iridium are six to seven orders of magnitude higher than those of the other materials, which is reflected in the score. It must be pointed out that the material price is a highly sensitive parameter in determining the GeoPolRisk CFs. For example, the price used for calculating CFs for platinum and iridium is three orders of magnitude higher than that for niobium, vanadium, molybdenum, and cobalt, and even four orders of magnitude higher than that for REEs. Since there is a missing CF for iridium in ESSENZ, only platinum is visible for the PEMWE system due to its high CFs.

With 18 different materials, the LCI of the SOEC stack contains significantly more materials than those of AWE and PEMWE. This can be seen, for example, in the binary, GeoPolRisk, and ESSENZ approach (Fig. 1c). The binary approach highlights the importance of nickel, manganese and various REEs in decreasing order based on their quantities. Tran's approach again accents the high material demand of iron (12 kg) and chromium (3.4 kg). MEErP, Mancini and the MCI indicator show very similar results and give the most prominent importance to REEs, especially to yttrium and gadolinium. The European gadolinium consumption, which is orders of magnitude smaller than that of the other materials, reinforces the contribution of gadolinium in particular

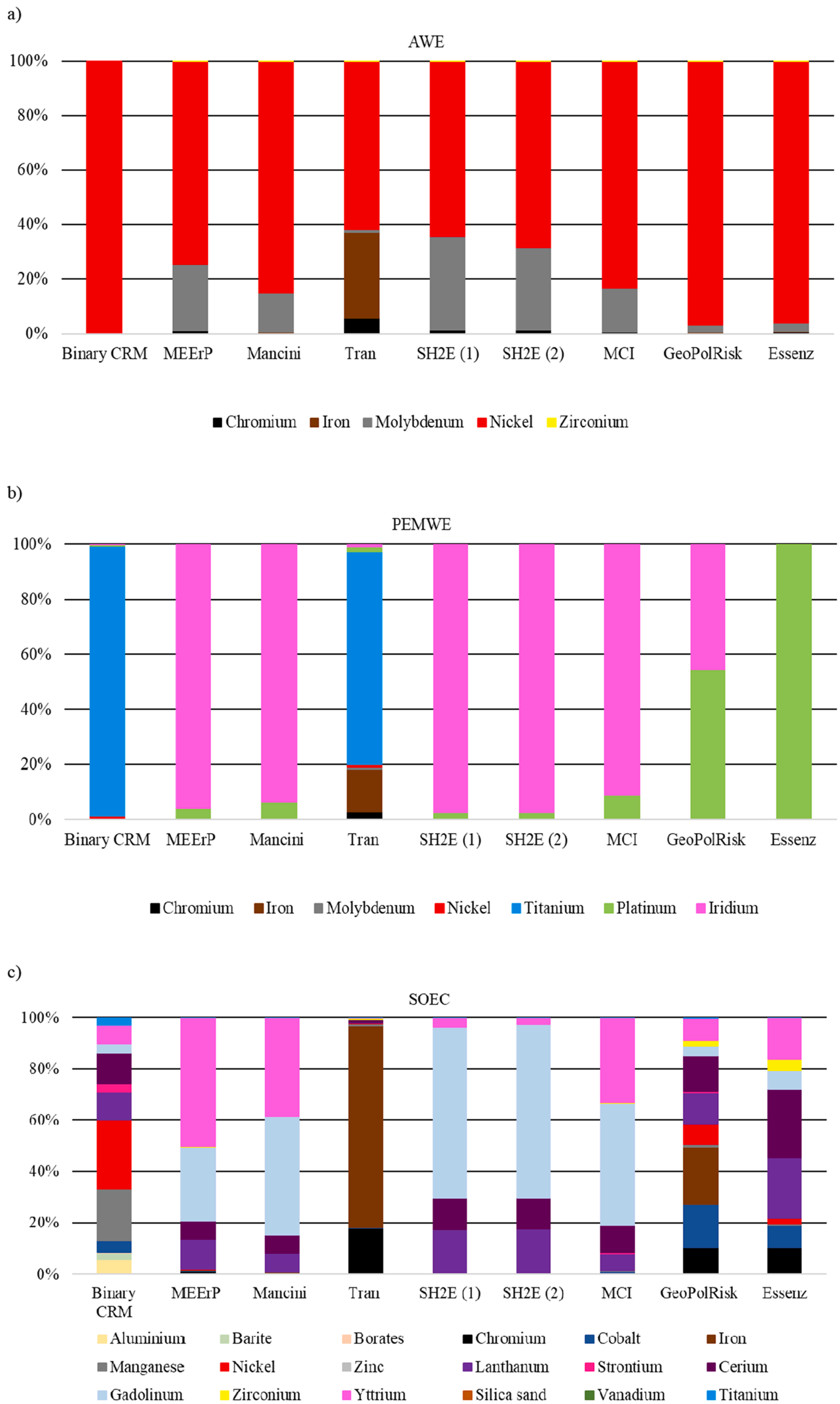

Fig. 1. Contribution analysis of materials to the overall score using different criticality indicators.

to the overall criticality scores of the SH2E indicators. As the very low gadolinium consumption is in the denominator of their CF formula, it is the crucial factor, as there is hardly any recycling in the EU and all REEs have to be 100 % imported (IR = 1). This effect is less pronounced when production values are used, as in the case of Mancini and MCI, however the REEs remain in focus. The GeoPolRisk diversifies the importance to chromium, cobalt, iron, nickel, and the REEs. Reasons for the GeoPolrisk result are, on the one hand, the very high CF for cobalt (6235), which is not identified in any other approach, and that for all REEs (1853). On the other hand, the high quantities of iron and chromium, which represent

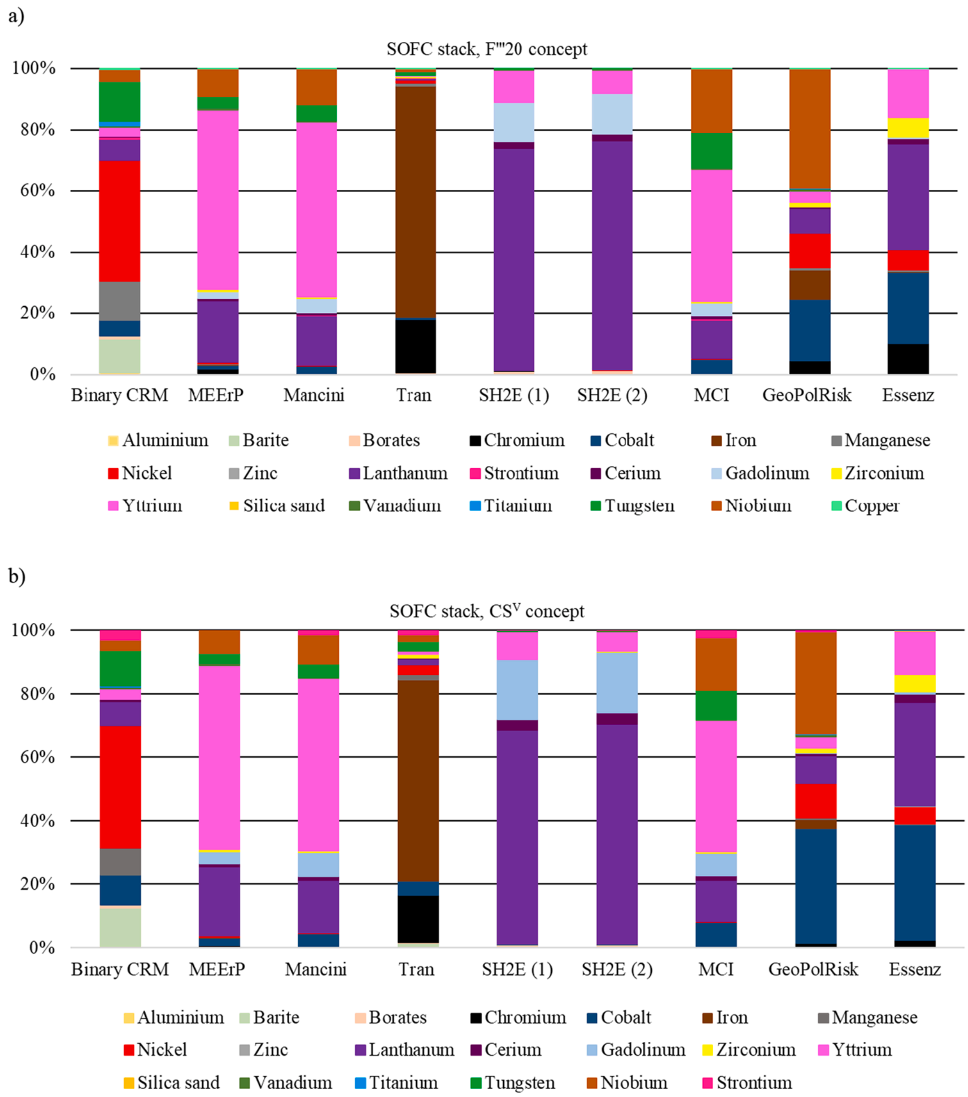

Fig. 2. Relative share of materials used for the manufacturing of two SOFC stacks on the overall score of different criticality indicators.

nearly 80 % and 20 % of the LCI, respectively, become apparent again. The SOEC criticality score calculated with ESSENZ is similar to the GeopolRisk result. However, ESSENZ emphasizes REEs (CF: 1.1E+11) more than cobalt (CF: 9.4E+10) compared to GeoPolRisk. As already mentioned above, the sensitive parameter “price” for cobalt is almost four times larger than the average price assumed for all REEs in the GeoPolRisk approach, which is, however, questionable. Aluminium, barite and manganese, although critical in EU-CA, are not regarded as critical hotspots by any approach except the binary one.

The two SOFC stacks use the same 20 materials but in very different quantities (Table 3). The F’’’20 stack also requires copper for the LCC10 contact layer. The F’’’20 stack has a weight of about 160 kg, of which iron (118 kg) and chromium (34 kg) are the main components of the special steel CroferAPU. The CS^V stack weighs only around 50 kg (31 kg iron, 9 kg chromium) due to the more favorable geometry and the resulting material savings in CroferH special steel. However, the relative criticality scores are hardly influenced by the different stack weights (Fig. 2). Tran’s approach once again stresses the high material demand for iron and chromium. The binary approach shows all CRMs and SRMs weighted by their quantities. MEErP, Mancini and MCI reach similar conclusions. They highlight the REEs yttrium and lanthanum and, by a significant distance, tungsten, and niobium (both components of the special steel CroferH). In the case of the SOFC stacks the ratio of the quantity of yttrium to gadolinium is 18:1 and 32:1 for the CS^V and the F’’’20 stack, respectively. Therefore, in the case of MEErP, Mancini and MCI, the share of yttrium to the overall criticality score is more dominant for the SOFC than for SOEC stacks, where the ratio of yttrium to gadolinium is only 2:1. The same applies to the SH2E indicators for gadolinium and lanthanum. The ratio of the quantity of lanthanum to gadolinium is 70:1 and 45:1 for the F’’’20 and CS^V stack, respectively, but in case of SOEC the same ratio is only approx. 3:1. In addition, lanthanum has the third lowest EU consumption after gadolinium and yttrium among the 21 materials used for the stacks. Since the EU consumption, in case of the SH2E indicators, is in the denominator of the formula, the same effect occurs here as already described for gadolinium in the SOEC. As a reminder, both SH2E indicators show no values for niobium, as the formulas for this material lead to an infinite CF. GeoPolRisk shows a high contribution of cobalt and niobium to the overall score due to the high CFs caused by the high prices followed by nickel and the REEs. ESSENZ shows a similar picture to GeoPolrisk as far as chromium, cobalt, nickel and the REEs are concerned. However, the relative distribution is different due to the missing CFs of niobium and tungsten.

3.3. *Material criticality of the case study systems*

A technology-based comparison is presented in Figs. 3 and 4. Fig. 3 displays the absolute criticality scores of the production of 1 t of

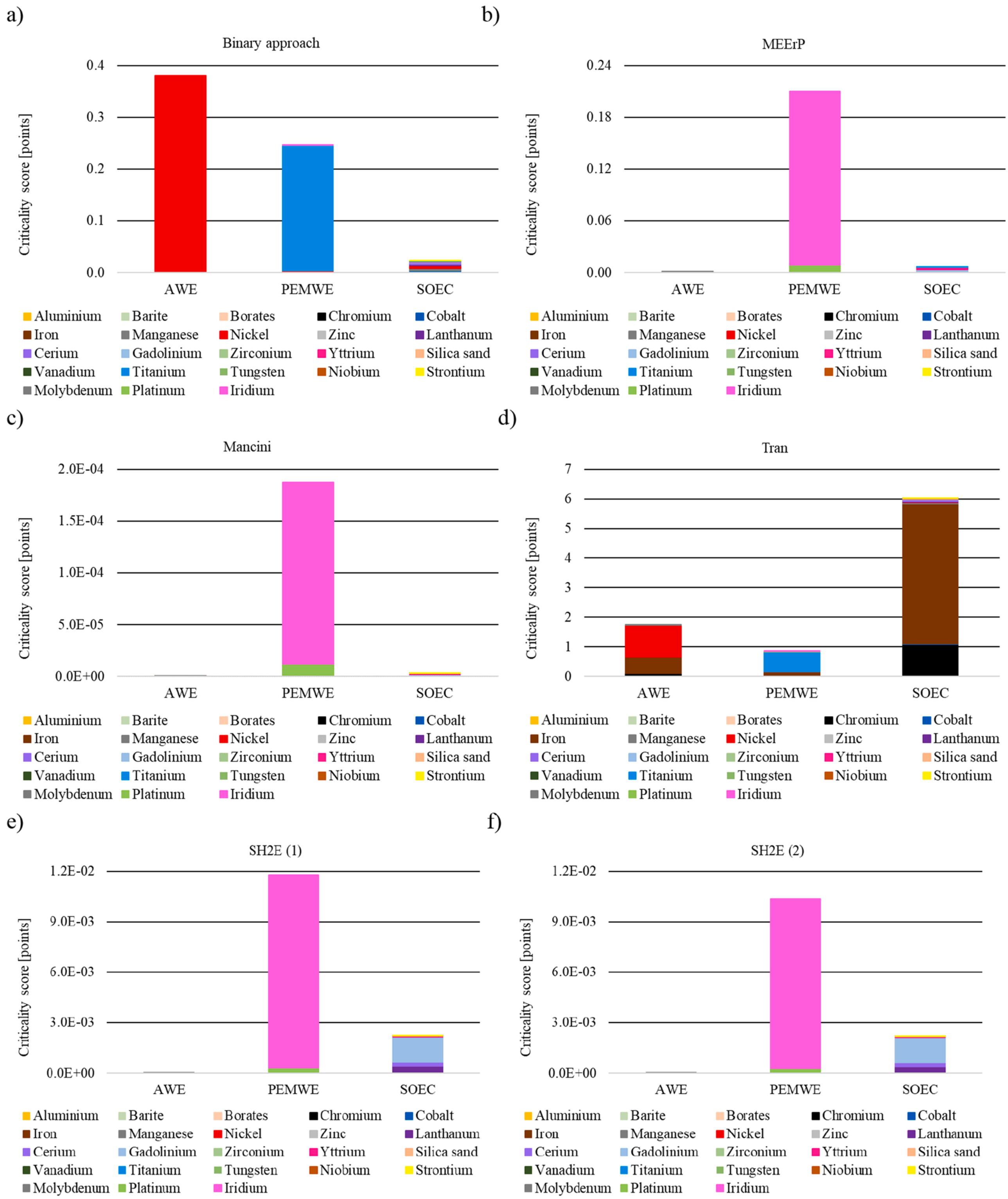

Fig. 3. Criticality scores of the different criticality indicators to produce 1 t hydrogen using three different electrolysis stacks.

hydrogen using the three electrolysis types, considering their different hydrogen production capacities during their service life. Hydrogen production of 19 t, 40 t, and 16 t was assumed over the lifetime of AWE, PEMWE, and SOEC, respectively (Zhao et al., 2020). AWE performs best in seven out of nine approaches in terms of criticality. SOEC performs worst only in Tran's approach, due to the dominance of the bulk materials iron and chromium. AWE followed by PEMWE perform worst in the binary approach, as nickel (> 7 kg for AWE) and titanium (> 10 kg for PEMWE) are by far the most used CRMs for manufacturing, while SOEC needs only small amounts of CRMs. PEMWE achieved the worst results in seven out of nine approaches, due to their high iridium and platinum scores (reminder: ESSENZ has no iridium values) which is driven by its low global production and EU consumption as already mentioned above.

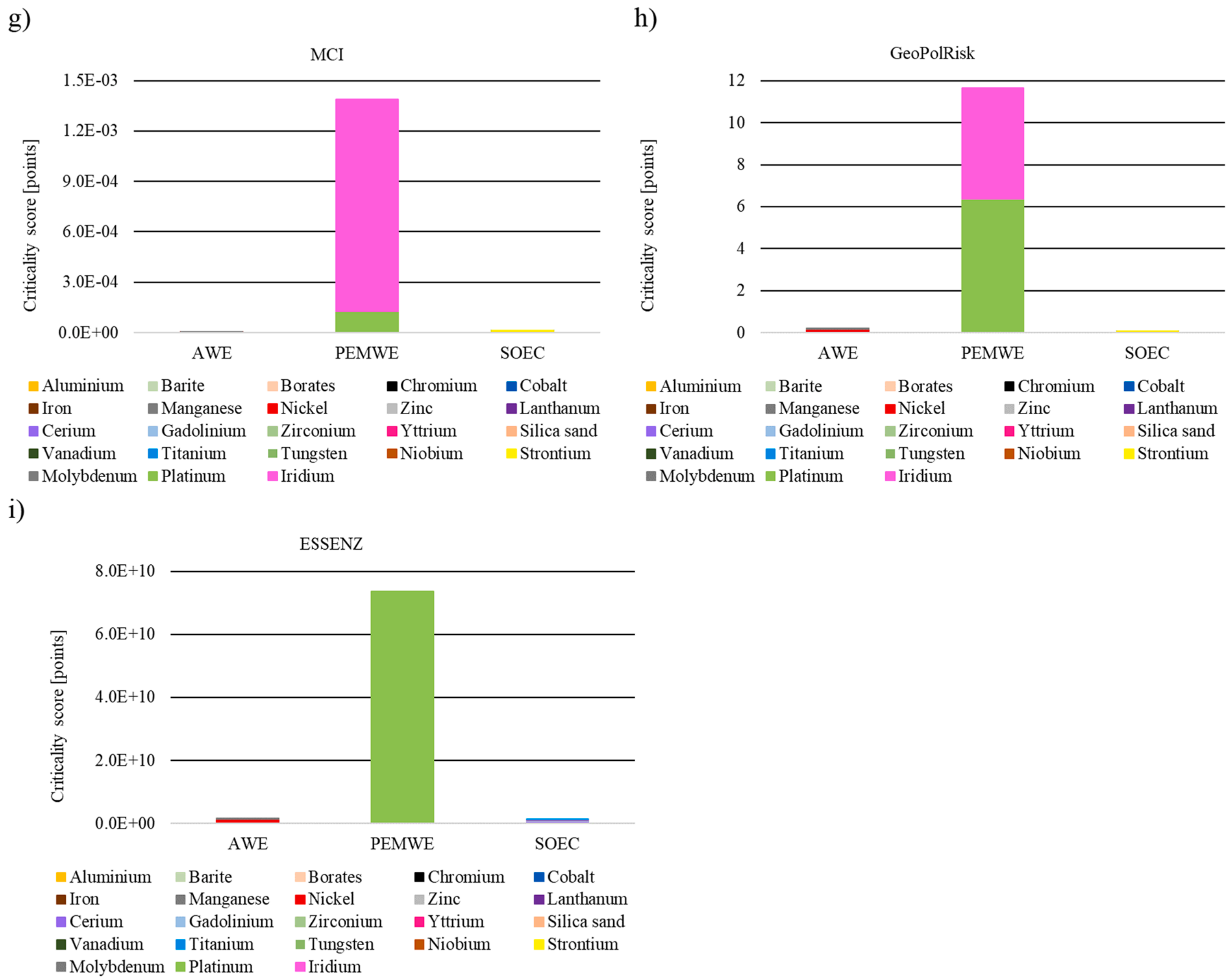

Fig. 3. (*continued*).

Fig. 4 shows the absolute criticality scores of the two fuel cell stacks, taking into account their different performances. To generate an output of 5 kW_{el}, 2.3 units of the F'''20 stack and 3.0 units of the CS^V stack are required (Harboe et al., 2020). As a result, it can be stated that the heavier F'''20 stack concept performs best for all criticality indicators, except for Tran's approach, which highlights the bulk materials iron and chromium as part of the special steels CroferAPU and CroferH. The reason for the lower ranking of the CS^V stack concept is on the one hand the higher number of CS^V stacks necessary to generate 5 kW_{el} output and on the other their higher demand of cerium, gadolinium, lanthanum, and cobalt compared to the F'''20 stack. MEErP, Mancini and the new MCI highlight also tungsten and niobium. The latter, together with cobalt, are the two hotspots at GeoPolRisk due to the similarly high prices. The absence of tungsten and niobium in ESSENZ and the lack of the latter in the two SH2E indicators impairs their validity, especially in the case of the SOFC stacks.

Most of the indicators considered in this study confirm the results of previous studies, particularly on the criticality of PGMs and REEs (Blagoeva et al., 2020; Bobba et al., 2020; Kiemel et al., 2021; Lotrič et al., 2020; Mori et al., 2021). Especially iridium and platinum (PEMWE) as well as various elements from the group of REEs and to some extent also niobium and tungsten (SOEC, SOFC) were often ranked as more critical than the materials used for AWE, with the exception of nickel as SRM.

3.4. *Features and limitations of criticality indicators*

The binary approach strictly follows the thresholds of the EC—CA method and consequently weights the CRMs and SRMs based on their mass flows and independent of other factors. Therefore, it also highlights materials, such as manganese or barite, which are not identified as critical by any other criticality approach. The emphasis on the weights in combination with the performance of the electrolysis type results also in a different ranking of the technologies compared to all other approaches.

This also applies to Tran's approach. The role of weights is even strengthened if non-critical materials are also included in the assessment. Then, bulk materials have the largest share of the total score, which does not seem conclusive. For example, iron and chromium are among the critical hotspots in Tran's assessment of SOEC and SOFC only because of their high economic importance (EI: > 7). Here, it contradicts the criticality definition of all other approaches (including the EC—CA approach, which the authors use), which allow to compensate for high economic importance with a very low supply risk.

The other five indicators, which rely also on European Commission's figures (MEErP, Mancini, SH2E (1), SH2E (2), MCI), mostly identify the same materials as critical hotspots with a few exceptions. However, the share of the individual materials in the overall criticality is in parts different. It has been exhibited that both global production (Mancini, MCI) and European consumption (MEErP, SH2E (1), SH2E (2)) are sensitive parameters when measuring resource criticality. However, those criticality approaches considering only consumption (MEErP,

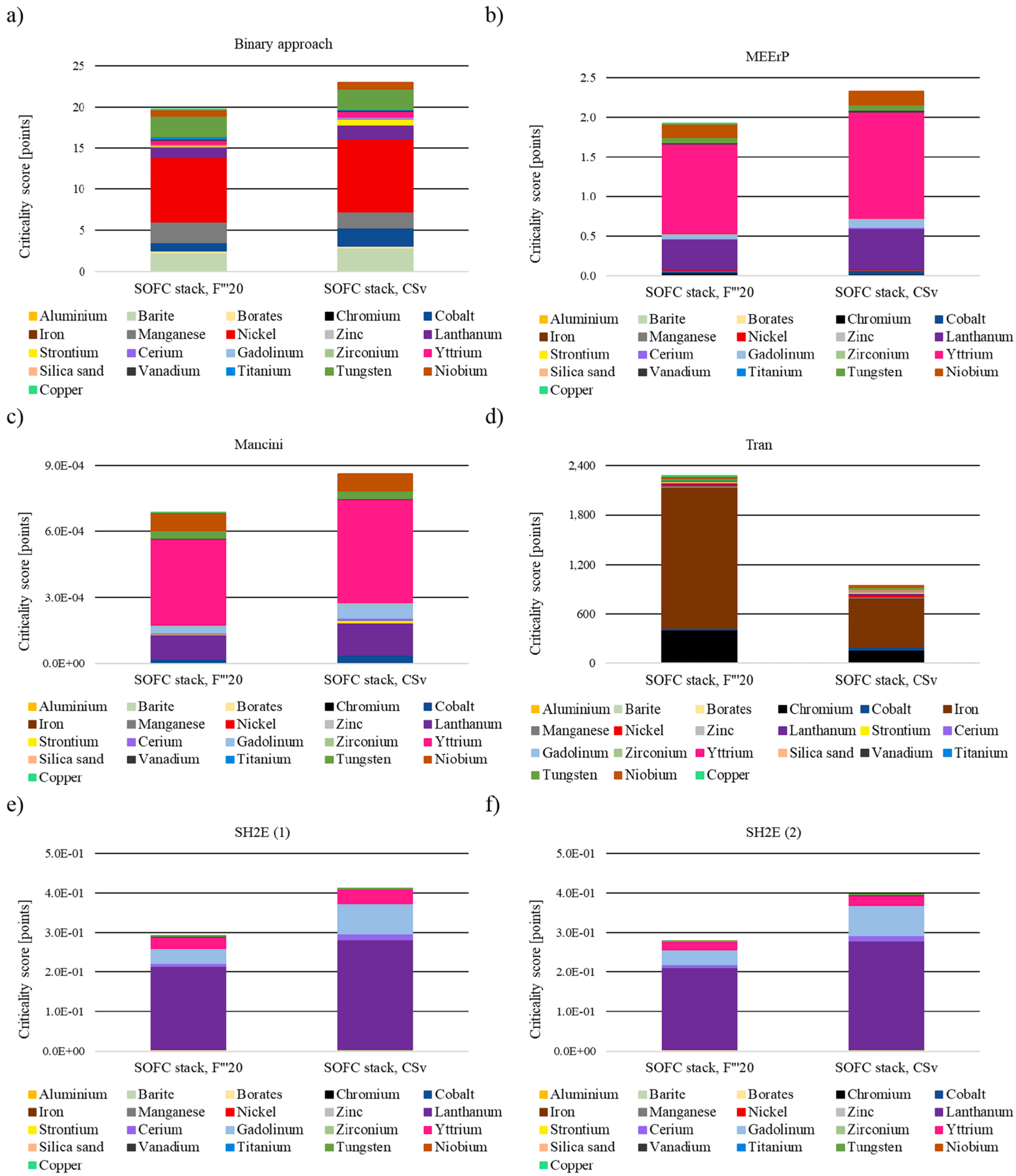

Fig. 4. Criticality scores of the different criticality indicators to produce 5 kW_{el} using two SOFC stack concepts.

SH2E (1), SH2E (2)) intensify criticality of materials with a very small consumption, such as gadolinium. Thus, a reduction in consumption would result in higher criticality scores, which is contradictious.

The new MCI represents a further development of Mancini's approach with the consideration of production and consumption in combination with import reliance (IR) and European secondary production (EoL_{RIR}) as risk-minimizing factors. The latter two factors are becoming increasingly important for the European economy, as raw material extraction mostly takes place outside Europe, often in countries with high political instability. To address this, the European Critical Raw Materials Act (CRMA) (European Commission, 2024) calls for countermeasures to ensure a secure and sustainable supply of critical raw materials. For example, the CRMA requires that at least 10 % of the EU's annual consumption for extraction and at least 40 % for processing should be covered by domestic capacities. In addition, at least 25 % of the EU's recycling activities should be covered by domestic capacities.

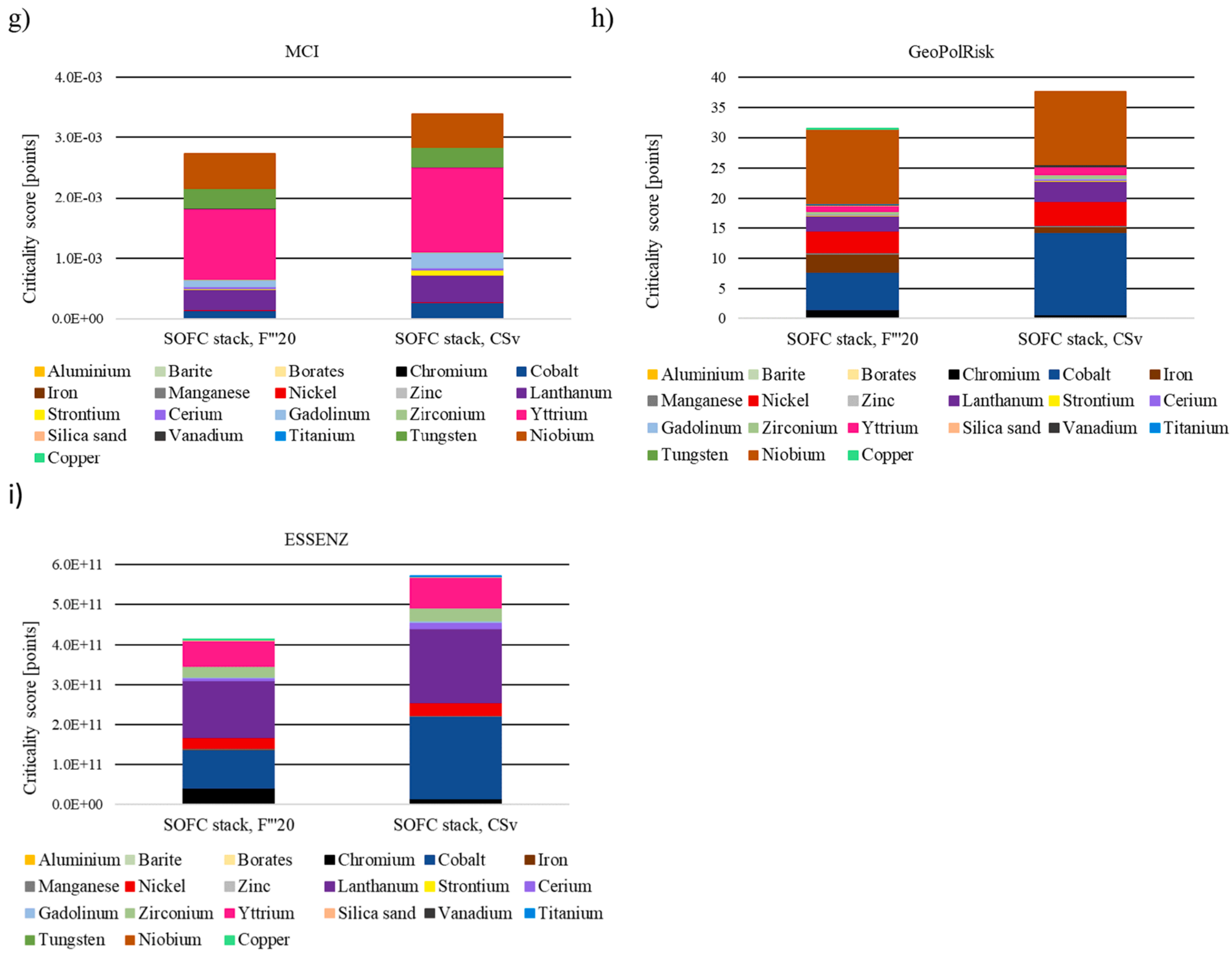

Fig. 4. (*continued*).

For these reasons, it is useful to include indicators such as IR and EoL_{RIR} in a criticality indicator, as the new MCI shows.

A major advantage of all criticality indicators that work with EC—CA figures (SR, EI, IR, EoLRIR, consumption) is the regular update with a high level of manpower to reflect ongoing changes in raw material production, commodity trading, and geopolitical conditions from a European perspective. This EU-centered perspective of the EC—CA method is intended for the criticality analysis here. Other methods, such as GeoPolRisk, offer greater flexibility in terms of regionalization in addition to the EU focus. The two methods that are not used European Commission's figures (GeoPolRisk, ESSENZ) show different results in relation to materials contributing to the criticality but not in the overall ranking of technologies. The differences when using GeoPolRisk are mainly caused by the inclusion of annual resource prices as very sensitive and volatile parameters. It should not remain unmentioned that GeoPolRisk has been extended in recent years with some additional parameters, such as substitutability (Cimprich et al., 2019), recycling (Santillán-Saldivar et al., 2021; 2020) and monetization (Santillán-Saldivar et al., 2022). Therefore, the calculation of the GeoPolRisk CFs depends significantly on the selected GeoPolRisk version. Nevertheless, GeoPolRisk scores highly on criteria such as applicability, operationality and scientific robustness.

ESSENZ considers a wider range of supply risk factors as the other approaches, such as demand growth, mining capacity, feasibility of exploration projects, price volatility, and compliance with social standards. In addition, environmental impacts such as climate change, acidification, eutrophication, and ozone depletion are also considered as part of the environmental dimension of a criticality analysis and thus overlap with LCIA categories. On the one hand, ESSENZ thus goes beyond the selection of sub-indicators used by the other methods, but on the other hand, this also results in a high level of effort for users in collecting and analyzing data for each of the 27 individual indicators, which are based on global, regional or company data. In addition, the weighting and integration of the various dimensions and indicators can be challenging. This complexity could be at the expense of practicability.

Overall, we recommend not using the binary approach and Tran's approach in the context of the LC(S)A. Additionally, the validity of some indicators is limited by the lack of materials considered and for others the results are mathematically infinite (MEErP, SH2E (1), SH2E (2)) in certain cases.

4. Conclusion

In this work we evaluated different product-level criticality indicators regarding their methodological characteristics and their ability to assess and quantify the criticality of materials for FCH technologies. All product-level criticality indicators were applied as characterization factors in terms of LCA logic, thus, demonstrating the feasibility of introducing material criticality into LC(S)A. Potential material criticality hotspots were identified and a technological comparison between different water electrolysis and fuel cell stacks were conducted. Conformities and differences of the various approaches became obvious, as results vary considerably, though based on the same LCI and data supplied by the European Commission.

Five of nine indicators analyzed point to the same or similar criticality hotspots and can therefore set priorities for action in materials research for FCH systems. Nevertheless, multiple indicators should be considered when deciding for or against a material, as each product-level criticality indicator focuses on different specific sub-indicators of criticality.

The case study addressed in this work has shown the lowest criticality for AWE among the electrolyzes in seven of nine cases. The F'''20 stack achieves the best result for eight out of nine indicators in terms of material criticality. Our study clearly highlights the need to focus material research on reducing iridium and platinum in PEMWE and REEs in SOEC and SOFC stacks. Nowadays, lanthanum is usually used in lanthanum-based perovskites for electrodes, gadolinium and cerium for barrier layers, and yttrium for yttria stabilized zirconia (3YSZ, 8YSZ) in electrolytes. Reducing their quantities or using alternatives could decrease the criticality of these FCH systems. Lesser use of special steels such as CroferAPU and CroferH in SOFC stacks could also reduce criticality, as these contain titanium, manganese, niobium, tungsten, and lanthanum.

Beyond the discussion about choice and weighting of suitable indicators to quantify the raw materials criticality (Frenzel et al., 2017), the time dimension should be given more consideration in future studies, as already suggested by Glöser et al. (2015), Glöser-Chahoud et al. (2016). Integration of future developments in material supply becomes an important topic for emerging technologies such as FCH systems. None of the existing approaches can provide this now as they all refer to historic data. In this context, dynamic material flow models can generate a better understanding of mineral extraction, import dependencies, sectoral use patterns or recycling potentials (Glöser et al., 2015). Such models allow for the analysis of numerous scenarios using stochastic models. This is an advantage over static criticality assessments by binary combination of supply risk and vulnerability. However, the problem of dynamics has not yet been sufficiently resolved, as the existing dynamic approaches are very limited and specific for only a few substances. The static approaches at the product-level, as presented in this study, can be considered as screening methods that allow a large number of materials to be evaluated with reasonable effort. Overall, criticality assessments would benefit from stronger future collaboration between materials and geoscientists, physicists, resource economists and LCA experts, as well as from cooperation beyond their own community.

Finally, greater computational power and integration into LCA software could facilitate practical application of product-level supply risk assessment.

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CRediT authorship contribution statement

Andrea Schreiber: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Petra Zapp:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Lavinia Reitz:** Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.rcradv.2025.200257.

Data availability

All data can be found in the supplementary material.

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