POLITECNICO DI TORINO
Repository ISTITUZIONALE

An integrated approach for advancing material criticality assessment in the renewable energy transition: insights from Switzerland and Italy

Original
An integrated approach for advancing material criticality assessment in the renewable energy transition: insights from Switzerland and Italy / Martin Del Campo, F., Spinello, M., Fiore, S., Binder, C.R.. - In: ENVIRONMENTAL RESEARCH. ENERGY. - ISSN 2753-3751. - 3:1(2026). [10.1088/2753-3751/ae3c16]

Availability:
This version is available at: 11583/3011847 since: 2026-06-10T07:07:29Z

Publisher:
IOP

Published
DOI:10.1088/2753-3751/ae3c16

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

15 June 2026

ENVIRONMENTAL RESEARCH
ENERGY

PURPOSE-LED PUBLISHING™

Part of the
ENVIRONMENTAL RESEARCH
SERIES

PAPER • OPEN ACCESS

An integrated approach for advancing material criticality assessment in the renewable energy transition: insights from Switzerland and Italy

To cite this article: Francisco Martin del Campo *et al* 2026 *Environ. Res.: Energy* **3** 015007

View the article online for updates and enhancements.

You may also like

- Overlooked factors in predicting the transition to clean electricity
  Nick Martin, Cristina Madrid-López, Gara Villalba-Méndez et al.
- Reducing material requirements while decarbonising the Spanish economy: from a green growth to a postgrowth paradigm
  Emmanuel Aramendia, Jaime Nieto, Iñigo Capellán-Pérez et al.
- The sustainable materials roadmap
  Magda Titirici, Sterling G Baird, Taylor D Sparks et al.

This content was downloaded from IP address 101.57.172.144 on 10/06/2026 at 07:58

ENVIRONMENTAL RESEARCH
ENERGY

Check for updates

PAPER

OPEN ACCESS

RECEIVED
28 October 2025

REVISED
19 December 2025

ACCEPTED FOR PUBLICATION
22 January 2026

PUBLISHED
6 February 2026

Original content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence.

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

An integrated approach for advancing material criticality assessment in the renewable energy transition: insights from Switzerland and Italy

Francisco Martin del Campo[1,*], **Matilde Spinello**[2], **Silvia Fiore**[2] **and Claudia R Binder**[1]

[1] École polytechnique fédérale de Lausanne (EPFL), School of Architecture, Civil and Environmental Engineering (ENAC), Laboratory on Human-Environment Relations in Urban Systems (HERUS), CH-1015 Lausanne, Switzerland

[2] Politecnico di Torino, Department of Environment, Land and Infrastructure Engineering (DIATI), Corso Duca degli Abruzzi 24, 10129 Torino, Italy

[*] Author to whom any correspondence should be addressed.

E-mail: francisco.felixmartindelcampo@epfl.ch and fran.martindelcampo@gmail.com

Keywords: critical raw materials, energy transition, circularity, material flow analysis, criticality assessment

Supplementary material for this article is available online

Abstract

Photovoltaic (PV) panels and wind turbines are key renewable energy technologies for carbon neutrality, yet their deployment relies on critical raw materials (CRMs). Existing criticality assessments predominantly emphasize 'external' dimensions, encompassing global and regional factors like production volumes, supply concentration, and geopolitical dependencies, while often overlooking country-specific or 'internal' dimensions, including national deployment trajectories, material demand growth, and recycling capacity. This study addresses this gap by proposing an integrated, multi-scalar methodology for assessing material criticality in renewable energy technologies that explicitly incorporates both external and internal dimensions. The methodology was tested on Italy and Switzerland. Material flow analysis is combined with an adapted criticality matrix incorporating three adjustment factors: BT deployment gaps, projected material-specific demand growth, and recycling maturity, with a focus on materials related to PV panels and wind turbines. Materials are assigned a criticality score from 0 (lowest) to 6 (highest). Results show that technology deployment drive sharp increases in demand for several materials (e.g. silicon, silver, zinc), with Switzerland exhibiting higher criticality scores than Italy due to steeper projected growth and narrower recovery windows. Comparison with the EU CRMs list reveals alignment for several materials (e.g. rare earth elements), while others (e.g. indium, selenium) emerge as nationally critical despite being overlooked or undifferentiated in regional assessments. These findings underscore the value of national-level material criticality assessments for manufacturing economies and for technology importers. The proposed framework supports policymakers and stakeholders in anticipating material supply bottlenecks and informs strategic planning for supply diversification, recycling, and circularity.

1. Introduction

Energy transition is crucial for limiting carbon emissions and mitigating climate change. However, achieving this transition will require vast quantities of resources, particularly critical raw materials (CRMs), which are essential for manufacturing renewable energy technologies such as wind turbines and photovoltaic (PV) solar panels [1]. As indicated by the European Union (EU), CRMs are materials of high economic importance, with a lack of suitable, affordable substitutes, and with a high risk of supply disruption due to their concentration of extra-EU sources, e.g. China and Turkey providing 100% and 98% of the EU's supply of heavy rare earth elements and boron respectively [2].

© 2026 The Author(s). Published by IOP Publishing Ltd

According to the critical minerals market review made in 2023 by the International Energy Agency (IEA), the demand for critical minerals has risen significantly since 2017, reaching nearly 10 million tons in 2022. This demand is projected to more than double by 2030 and exceed 30 million tons by 2050 across all proposed scenarios [3]. The IEA also highlights the increasing reliance of low-carbon power generation technologies on CRMs, with material demand in the energy sector having grown by 50% since 2010 and expected to triple by 2040 [4]. These projections underscore the potential for supply chain vulnerabilities and negative socio-environmental impacts in resource-extracting countries. Such risks are becoming more pronounced as cleaner energy technologies, particularly renewables, introduce new material mixes in their manufacturing, thereby intensifying pressures on supply chains [3, 5, 6].

Many countries, including the EU, Canada, the United States, Australia, the United Kingdom, China, South Korea, and Japan have also developed national CRM lists, strategies and assessment frameworks, each grounded in distinct methodological priorities. For example, the U.S. Department of Energy published the 2025 CRM list with 60 materials, including 10 extra from the 2022 list [7], emphasizing selection based on strategic importance for the energy sector and supply risk indicators [8]; in 2023, the EU released its fifth list of CRMs under the CRMs Act (see supplementary data S10), which also sets threshold targets for operations happening in the EU, e.g. 10% mining, 40% refining and 25% recovered and recycled [9]. That CRM Act identifies 34 CRMs (16 are considered 'strategic') based on parameters such as economic importance and supply risks [5]; Japan's system names 35 minerals as critical in 2025 [10], with selection criteria leaning towards material importance, the degree of external dependence, and the likelihood of threats to national and public safety due to external actions [11–13]; Canada names 34 materials as critical in 2024, with an additional 3 from the 2021 list [14], applying selection criteria based on a joint economic importance vs supply risk index linked to national value chains [15, 16]; the UK identified 34 minerals as critical in its 2024 assessment vs 18 in 2021, with selection criteria focusing mainly on global supply risk and the country's economic vulnerability [17]. Australia's assessment has identified 31 critical minerals and it is updated approximately every 3 years [18]. Their strategy prioritizes global strategic, technological, economic and policy changes [18, 19]. China does not have a regularly updated public CRM list in the same formal sense as the other countries mentioned above. Instead, its strategic materials approach defines groups of 'critical materials' for strategic industry and national security purposes [20, 21]; Similarly, South Korea has designated strategic materials via government policies and periodically updates them, but the exact number varies by source and policy stage. The assessment criteria mostly prioritizes import dependence, supply diversification, and the role of secondary supply through recycling to secure key materials for battery, EV, and semiconductor industries [22, 23].

Although these lists serve broader industrial and strategic objectives rather than the energy transition alone, their diversity illustrates the absence of a unified approach to defining criticality. Formal CRM lists in the EU, US, Canada, Japan, Australia, and the UK coexist with less transparent materials designations in countries such as China and South Korea, making comparisons difficult. As a result, some materials appear consistently while others are specific to individual national interests. This variation highlights differences in how criticality is defined and operationalized across national contexts. At the same time, many countries still lack national CRM strategies altogether. A consistent yet adaptable assessment framework could provide a common baseline while allowing countries to tailor priorities to their needs [24]. Developing such a framework requires establishing transparent, systematic criteria for identifying priority materials and evaluating the factors that influence their criticality across different national contexts [3, 25].

1.1. Challenges in material criticality assessments and identified research gaps

Existing literature reports that material criticality has been assessed through diverse approaches, often distinguished by their focus on either external or internal dimensions [26, 27]. External assessments typically examine global or regional factors such as production volumes, supply concentration, and geopolitical dependencies. Examples of frameworks for external assessments include the EU criticality methodology or the U.S. Department of Energy Criticality Matrix [2, 8]. These employ a two-dimensional structure, but differ in scope and focus: the former spans multiple industrial sectors, evaluating *Economic Importance & Supply Risks*, whereas the latter specifically targets the energy sector, evaluating *Importance to Energy & Supply Risks*.

Internal assessments, by contrast, consider country-specific contexts, including deployment trajectories, material demand growth, and recycling capacity, such as the criticality ranking approach proposed by the International renewable energy agency [28]. Among studies addressing internal dimensions, material flow analysis (MFA) is the most common method for forecasting CRMs demand and capturing the evolution of energy systems [27, 29]. However, most studies focus on global or regional scale [8, 30, 31] and often emphasize a narrow selection of materials relevant to national security or specific industries (e.g. telecommunications) [32–36].

Despite these contributions, national-level assessments remain limited and often focus on a single country's energy system [37, 38]. They rarely capture supply risks dynamics or adaptive capacity [26, 39]. Additionally, as highlighted by Zhang *et al* [25], further emphasized by Montana *et al* [27], and recently discussed in public discourse [40], transparency in selecting 'critical' materials is lacking, with many frameworks (such as those developed by the countries discussed previously) relying on expert judgment rather than standardized criteria. Overall, most assessments rely on fixed baselines, failing to capture evolving material demand, which would differentiate between what is genuinely vital to a country and what is merely of importance.

Specifically, we identify the following knowledge gaps:

- External (global/regional) assessments dominate material criticality studies, overlooking the internal (country-specific) context of material demand, supply risks, and technological shifts that influence long-term supply stability.
- Transparency issues in material selection criteria contribute to inconsistencies in national and regional CRMs classifications (e.g. critical vs strategic materials).
- Limited integration of global/regional and country-specific perspectives restricts the applicability of material criticality studies for country-specific decision-making.
- Existing assessment frameworks vary substantially in methodological structure. These inconsistencies limit cross-country comparability and their interpretation of criticality when applied to national energy transitions.

1.2. Study contribution and objectives

This study addresses the lack of integrated approaches by combining external and internal dimensions of material criticality. While national CRM lists often reflect domestic priorities, they seldom use explicit, transparent metrics for demand, technological change, or long-term supply stability. Our methodology integrates both dimensions to provide a harmonized, context-sensitive assessment that accounts for global constraints and national ambitions. Specifically, this study:

- Examines *country-specific CRMs dependencies and compares them to a regional CRM list*, highlighting key national and regional-level classification differences.
- Compares *material criticality between countries*, considering factors such as energy mix, industrial capacity, and policy objectives.
- Examines the *broader implications of country-specific CRMs classifications for supply security and energy transition strategies*, emphasizing the need for adaptive resource policies that align with national priorities while ensuring resilience in material supply chains.

To contextualize the methodology, we specifically focus on wind turbines and PV solar panel technologies, with application in Italy and Switzerland: two countries with distinct energy transition pathways, material dependencies, and geopolitical contexts. We analyze (a) the external dimension through an adapted U.S. Department of Energy's criticality matrix [8], capturing global production volumes, supply concentration, and geopolitical dependencies; and (b) the internal dimension, using MFA, to assesses country-specific recycling capacity, technology deployment timelines, and national energy targets.

This approach facilitates transparent cross-country comparison, aligns with existing CRM methodologies where relevant, and supports strategic national decisions on technology selection, diversification of trade partners, investments in recycling infrastructure, and industrial innovation, even in non-manufacturing contexts. As global competition for critical materials intensifies, having visibility over national vulnerabilities helps policymakers design more resilient, forward-looking energy and resource strategies.

1.3. Case study selection: Italy and Switzerland in the energy landscape

Italy and Switzerland, as neighboring European countries, share similar external (global/regional) contexts, including exposure to global supply chain vulnerabilities, geopolitical dependencies, and resource concentration risks. However, their distinct internal (county-specific) contexts, such as national energy transition strategies, starting energy baseline, recycling capacity, industrial needs, infrastructure, and technological priorities, create valuable contrasts for analysis.

Neither country is a major manufacturer of PV panels or wind turbines, however emerging industrial activity suggests a shift toward localized production capability. Italy now hosts the *3Sun Gigafactory*

Table 1. Energy landscape overview for Italy and Switzerland (source [49–52]:).

Category	Italy	Switzerland
Current electricity generation (2023)	*Fossil fuels:* ∼54% (gas, coal, oil) *Hydropower:* ∼16% *Geothermal:* ∼2% *Solar:* ∼12% *Wind:* ∼9%	*Fossil fuels:* <1% *Hydropower:* ∼56% *Nuclear:* ∼33% *Solar:* ∼6% *Wind:* <1%
Installed solar power (GW), current, mid-term, and long-term	*2023:* 31.56 *2030:* 77 *2050:* 207	*2023:* 4.76 *2030:* 9.8 *2050:* 37.5
Installed wind power (GW), current, mid-term, and long-term	*2023:* 12.33 *2030:*19.3 *2050:* 47	*2023:* 0.09 *2030:* 0.3 *2050:* 2.2

in Catania, which is now Europe's most automated solar-cell and module plant, aiming to scale Europe's annual production from 200 MW to 3 GW by 2025 [41, 42]. In Switzerland, while no large-scale PV manufacturing exists, the country hosts several niche enterprises in wind component production, from composite and blade engineering firms such as *Gurit*, to precision machinery manufacturers like *StarragTornos* involved in blade and turbine component fabrication [43].

Both countries are thus heavily dependent on imported low-carbon technologies and are therefore exposed to geopolitical risks transmitted through global supply chains. This exposure is primarily mediated by high import reliance on a limited number of supplier countries, notably China, which dominates the global production and processing of several critical materials used in wind and solar technologies, as well as key manufacturing stages of these technologies [20, 21, 44]. As part of the European market, Italy and Switzerland are therefore indirectly affected by trade policies, export controls, and industrial strategies implemented by major producing regions such as China, the EU, and the United States [45], which shape availability, prices, and supply security. For import-reliant nations with limited domestic production, such geopolitical dynamics directly influence national material criticality and energy transition resilience. Besides, the increasing global competition for low-carbon technologies adds further pressure, especially as demand for solar panels and wind turbines is expected to rise in alignment with global decarbonization efforts [46, 47].

Another aspect influencing material criticality in Italy and Switzerland is the role of policy frameworks and institutional structures governing resource management, trade, and industrial strategies. While both countries operate within the broader regulatory landscape of the EU's CRMs Act and Green Deal objectives [2, 48], their national policies differ in implementation and prioritization. Italy, as an EU member state, aligns its resource strategy with European directives, emphasizing market-driven mechanisms and industrial innovation to enhance material security. Switzerland, although not an EU member, closely follows European market regulations while maintaining independent trade agreements and industrial policies that impact its supply chain resilience.

Regarding their energy targets, a key distinction between the two countries lies in their current electricity generation and the degree of adoption of renewables required to achieve their 2050 carbon neutrality targets. Italy remains heavily reliant on fossil fuels, with natural gas and coal accounting for nearly 54% of its total electricity generation mix. Renewables are led by hydropower (∼16%), solar (∼12%), and wind (∼9%) [49]. In contrast, Switzerland already has a low-carbon electricity generation, with hydropower providing nearly 56% of total electricity production, followed by nuclear power (∼33%), solar (∼6%), and wind (<1%) [50].

Despite progress in deploying solar and wind power, both Switzerland and Italy face a significant gap in decarbonizing its electricity grid by 2050. This is reflected in their respective targets for solar and wind capacity expansion. Italy plans to more than double its current installed solar power and more than quadruple its wind power capacity by 2050. Switzerland, although starting from a smaller base and planning to phase out nuclear power, also aims for a substantial scale-up of renewables, targeting nearly a tenfold increase in solar capacity and more than a twentyfold increase in wind capacity by 2050 [51, 52] (table 1). This highlights the importance of securing access to low-carbon technologies under potential supply constraints. In both cases, long-term planning must account not only for capacity targets but also for material availability and material deployment evolution strategies.

Together, the two countries provide a contrasting yet complementary pair of case studies: similar exposure to global supply chain and other risks, but divergent national contexts, mid- and long-term energy pathways, and technology deployment trajectories. These characteristics make Italy and Switzerland an appropriate and informative setting for illustrating the integrated methodology proposed in this study.

2. Methodology and data

The study employs an integrated approach that combines both the external (global/regional) and internal (country-specific) dimensions to evaluate material criticality in Italy and Switzerland for the medium (2030) and long term (2050), focusing specifically in two renewable energy technologies: wind turbines, and PV solar panels. The rationale for the selection of countries and technologies is presented in section 1.3.

The objective is to demonstrate the proposed integrated methodology rather than to provide a comprehensive assessment of all renewable technologies or countries. The framework is designed to be extensible and applicable to broader technology portfolios in future analyses, including temporal assessments to identify emerging criticality thresholds and to inform strategies for enhancing resilience under evolving deployment and policy scenarios. Figure 1 shows the conceptual diagram used on this study.

The assessment of the external dimension is based on an adaptation of the 2023 criticality matrix developed by the U.S. Department of Energy, which assesses factors such as global production volumes, supply concentration, and geopolitical dependencies of materials used in energy applications [8]. The matrix provides an intuitive, straightforward, stepwise methodology for material selection and criticality evaluation, addressing a key limitation of other frameworks. In this study, the matrix is applied using predominantly regional (European) indicators, complemented by global datasets where region-specific information is not available, thereby establishing a baseline classification of CRMs at a regional scale.

The internal dimension builds on MFA to capture country-specific factors that influence criticality, including current material stocks, recycling capacity, and projected material demands. Here, the internal dimension, operationalized through MFA, is understood as a quasi-dynamic approach that incorporates periodic updates and scenario-based forecasting, without aiming for real-time continuous monitoring [53, 54]. This perspective refines the broader assessment by situating material dependencies within national trends, targets and starting baselines.

By combining these approaches, this methodology allows for (a) assessing and comparing Italy's and Switzerland's material dependencies; (b) evaluating their alignment or divergence from the EU-wide CRMs list; (c) assessing of broader implications on national energy transition strategies and material criticality; and (d) reflecting on key challenges and opportunities for CRMs strategy development, providing methodological insights, and options for increasing resilience through local action by highlighting potential material vulnerabilities under specific technology and deployment scenarios. The framework is designed to accommodate temporal updates and scenario comparisons, enabling the monitoring of potential criticality tipping points, the re-evaluation of CRM classifications under changing deployment targets or policies, and the adjustment of key input parameters to reflect evolving material supply conditions. This approach ensures that material criticality assessments are not only reflective of global supply constraints but also responsive to national policy frameworks, industrial priorities, and sustainability goals. Additional materials related to the calculations and evaluations of each part of the methodology proposed can be found in the supplementary data.

2.1. Material selection

Material selection was based on material composition adopted in solar PV panels and wind turbines retrieved from literature [31], together with estimates of material composition [*material*], material intensities [*tons per gigawatt*], and end-of-life (EoL) values [*years*] per renewable energy (sub)technology as presented in table 2.

National targets of new renewable capacity per year (2023–2050) were used to forecast future deployment. This annual capacity was categorized by technology and sub-technology according to evolving market shares, enabling yearly estimates of material demand. Projections from the high demand scenario (HDS) from the Joint Research Centre was adopted [1]. This scenario aligns with the European Green Deal's ambition of near-complete decarbonization by 2050 [48] and includes differentiated projections for PV, onshore and offshore wind turbines.

For solar PV, the evolution of sub-technology market shares (e.g. CIGS, CdTe, a-SI) was modeled using a linear interpolation between data points reported for specific years under the HDS. Similarly, the wind turbine market share over time (onshore and offshore) was derived from HDS projections. Linear

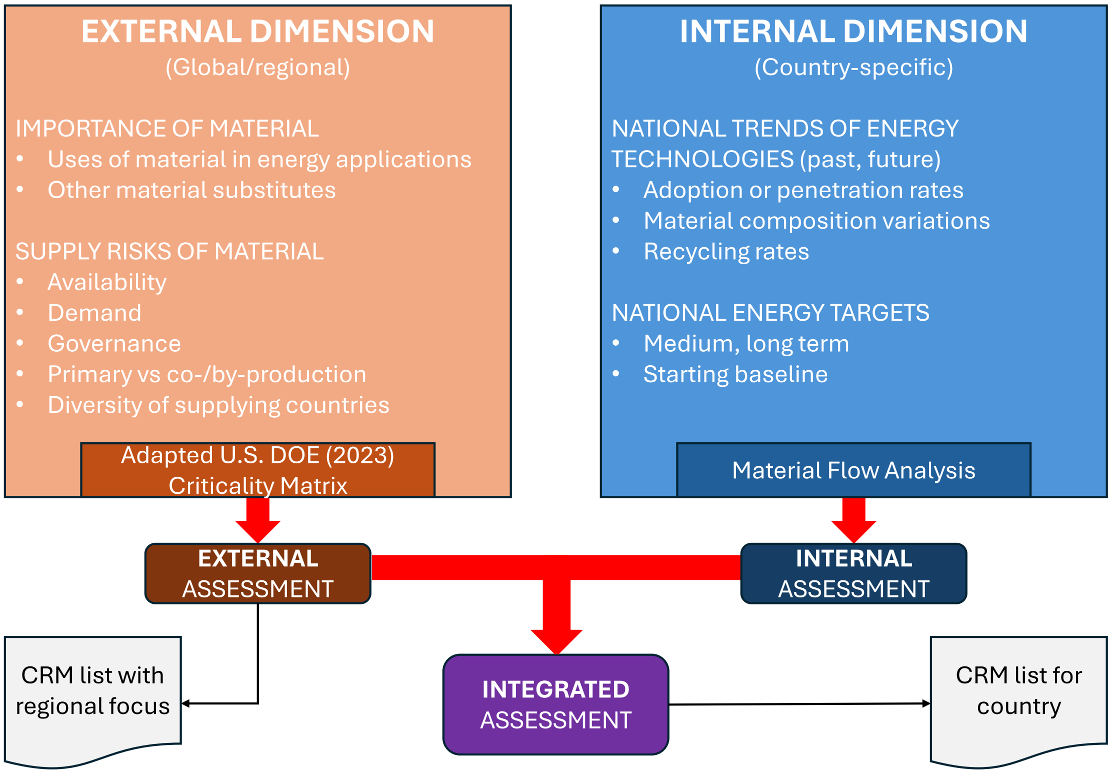

Figure 1. Conceptual framework of the study: an integrated approach for advancing critical raw materials assessment in the renewable energy transition.

interpolation was again used to fill gaps between known values, allowing the disaggregation of yearly installed capacity by sub-technology. Full methodological details and data sources are provided in the supplementary data.

By focusing on a defined subset of technologies with differing material compositions and deployment trajectories, the framework's functionality and sensitivity can be effectively demonstrated, showing how it responds to variations in material demand and deployment patterns.

2.2. The adapted criticality matrix

The external dimension assessment was based on an adapted version of the Criticality Matrix developed in 2023 by the U.S. Department of Energy [8] (table 3). The matrix focuses specifically on the importance of a given material for energy and decarbonization. It evaluates two key factors: 'Importance to Energy' and 'Supply Risk' with each factor represented as a weighted average of several sub-factors, scored on a scale from 1 to 4. Importantly, this assessment is not country-specific, but rather applies at the regional or global level, providing a material-based benchmark against which national contexts can be contrasted in later steps of our methodology.

The adapted matrix (table 4) works as follows: a specific material is placed on the matrix based on its importance to energy (vertical axis) and the likelihood of a supply restriction (horizontal axis). The degree of criticality increases moving from the lower-left to the upper-right corner. Materials scoring 3 or higher on both axes of the matrix are classified as *critical*. Those scoring 3 or higher on one axis and 2 on the other are considered *near critical*. All other materials are classified as *non-critical*.

2.3. The MFA

The MFA draws on a combination of regional and national data sources to capture trends in energy technologies and energy transition targets from 2000 to 2050. Specifically, the evaluation of input and output flows, as well as existing material stocks required information on installed power capacity, technology market developments, material intensities by year and technology, and national recycling rates. To this end, we looked into EU projections of raw material demand for PV and wind technologies [31], reports from the Swiss Federal Office of Energy on wind energy plants [56], statistics from the Gestore dei Servizi Energetici (GSE) on renewable electricity in Italy [57], the IEA's *Renewables 2023* analysis and

Table 2. Material composition (material), material intensities [tons per gigawatt], and end-of-life values (years) per renewable energy (sub)technology (source [31]:).

Photovoltaic solar panels. Average lifetime: 20 years

	All technologies						c-Si		CdTe		CIGS				a-Si	
Material composition (material intensities)	Concrete (t/MW)	Steel (t/MW)	Plastic (t/MW)	Glass (t/MW)	Al (t/MW)	Cu (t/MW)	Si (t/MW)	Ag (t/GW)	Cd (t/GW)	Te (t/GW)	Cu (t/GW)	In (t/GW)	Ga (t/GW)	Se (t/GW)	Si (t/GW)	Ge (t/GW)
2010	60.7	67.9	8.6	46.4	7.5	4.6	7.0	84.0	116.0	132.0	25.3	43.0	11.0	107.0	163.0	73.0
2018							4.0	20.0	85.0	95.0	24.0	27.0	7.0	60.0	150.0	48.0
2020							3.9	18.0	77.0	87.0	23.0	22.0	6.0	51.0	145.0	48.0
2030							3.5	11.0	60.0	70.0	17.5	17.0	4.5	40.0	130.0	32.0
2040							3.5	6.0	44.0	50.0	16.2	12.0	3.0	25.0	120.0	24.0
2050							3.0	5.0	35.0	40.0	15	10.0	2.5	20.0	110.0	20.0

Wind turbines. Average lifetime: 20 years for onshore, and 25 years for offshore

Material composition (material intensities)	Concrete (t/GW)	Steel (t/GW)	Polymers (t/GW)	Glass (t/GW)	Al (t/GW)	B (t/GW)	Cr (t/GW)	Cu (t/GW)	Dy (t/GW)	Fe (t/GW)	Mn (t/GW)	Mo (t/GW)	Nd (t/GW)	Ni (t/GW)	Pr (t/GW)	Tb (t/GW)	Zn (t/GW)
DD-EESG	369000	132000	4600	8100	700	0	525	5000	6	20100	790	109	28	340	9	1	5500
DD-PMSG	243000	119500	4600	8100	500	6	525	3000	17	20100	790	109	180	240	35	7	5500
GB-PMSG	413000	107000	4600	8400	1600	1	580	950	6	10800	800	119	51	440	4	1	5500
GB-DFIG	355000	113000	4600	7700	1400	0	470	1400	2	18000	780	99	12	430	0	0	5500

PV panels sub-technologies: 1st generation crystalline silicon (c-Si); 2nd generation thin film cadmium telluride (CdTe); 2nd generation thin film copper indium gallium diselenide (CIGS); 2nd generation thin film amorphous silicon (a-Si). Wind turbines sub-technologies: Direct Drive Electrically Excited Synchronous Generator (DD-EESG); Direct Drive Permanent Magnet Synchronous Generator (DD-PMSG); Gearbox Electrically Excited Synchronous Generator (GB-PMSG); Gearbox Double-Fed Induction Generator (GB-DFIG).

Table 3. The 2023 U.S. Department of energy's criticality matrix (source [8]:).

Factor	Metrics
Importance to energy	[a]**Energy demand (70%)**: importance of both materials and the technologies that use them to the future of energy, including technologies that produce, transmit, store, and conserve energy. It measures: • The use of a material in energy applications, in terms of its market share for energy application • The importance of the specific sub-technology in which a material is present, in terms of adoption or penetration rate on the market of the sub-technology **Substitutability limitation (30%)**: potential to reduce or substitute a material in its energy applications
Supply risk	[b]**Basic availability (40%):** assessed by the extent to which global supply can meet demand for the material [c]**Competing technology demand (10%):** expected growth in demand for non-energy applications of the material, expressed using *compound annual growth rate* (CAGR) values. **Political, regulatory, and social factors (20%):** supply risks associated with these. It measures: • Political, social, and regulatory factors (10%): Supply risk based on the *World Bank's World Governance Indicators* (WGIs) values. • Environmental factors (10%): evaluated using the Yale University's *Environmental Performance Index* (EPI) values. **Co-dependence on other markets (10%):** reflects how a material is produced, i.e. whether it is produced as a primary product or as a co/by-product of other processes. **Producer diversity (20%):** measured by the market concentration and diversification of supplying countries. This metric uses the *Herfindahl–Hirschman Index* (HHI), a common measure of market concentration.

[a] To ensure more reliable results for both the medium and long term, the first measure (use of a material in energy applications) has been excluded due to the lack of available reports and the uncertainty surrounding future market projections, particularly for the long term.
[b] In this study, basic availability considering the European level.
[c] The *compound annual growth rate* (*CAGR*) has been replaced in this study with the *Recycling Rate* of the material in its energy applications, which is a common metric in other criticality assessments, such as the EUs methodology [55].

forecast report [50], national survey reports on PV applications in Switzerland and Italy [58, 59], as well as additional GSE [60] and ANEV (Italian Wind Energy Association) publications [61]. More specifically, this approach considers the following components:

Starting baseline stock of materials: establishes a reference point for assessing the current availability of materials within the energy system, highlighting discrepancies between installed capacity and future targets. The material stock at a given year is estimated by balancing material inflows (new materials added through technology expansion) and outflows (materials reaching EoL). Equation (1) quantifies the stock of materials accumulated over time:

$$S_i = S_{i-1} + M_{\mathrm{in},i} - M_{\mathrm{out},i} \quad (1)$$

where:

S_i = stock of materials for the sub-technology at year i, in tons [t];
S_{i-1} = stock of materials for the sub-technology at year $i-1$, in [GW];
$M_{\mathrm{In},i}$ = material inputs for the sub-technology at year i, in tons [t];
$M_{\mathrm{Out},i}$ = material outputs for the sub-technology at year i, in tons [t].

Projected future material demand: accounts for expected inflows required to meet national energy transition goals, incorporating variations in technology adoption rates and material compositions. The total material inputs for a given year are estimated using equation (2):

$$M_{\mathrm{In},i} = \left((\mathrm{CP}_i - \mathrm{CP}_{i-1}) \times \left(\frac{S_{\mathrm{st},i}}{100} \right) \right) \times \mathrm{MI}_{\mathrm{st},i} \quad (2)$$

Table 4. The adapted criticality matrix, scoring metrics and thresholds for criticality assessment.

Factor	Metrics: *Name*	Metrics: *Weight*	Score: 1	Score: 2	Score: 3	Score: 4
Importance to Energy	Energy demand	0.7	Market share of the most dominant specific sub-technology <10%	Market share of the most dominant specific sub-technology ⩾10%	Market share of the most dominant sub-technology ⩾25%	Market share of the most dominant sub-technology ⩾50%
	Substitutability limitations	0.3	**Perfect or near-perfect** substitutes are available at material and system levels with **little to no limitations or concerns.**	Substitutes are available at either material or system levels with **minor limitations or concern**s.	Substitutes are available at either material or system levels with **major limitations or concerns.**	**No substitutes** are available at either the material or system levels.
Supply risk	Basic availability	0.4	**No concerns** about existing capacity to meet medium/long term demand.	**Minor concerns** about existing capacity to meet medium/long term demand.	**Major concerns** about existing capacity to meet medium/long term demand.	**Grave concerns** about existing capacity to meet medium/long term demand.
	Recycling rate	0.1	The recycling rate of the material from its energy application is from 75 to 100%.	The recycling rate of the material from its energy application is from 50% to 75%.	The recycling rate of the material from its energy application is from 25% to 50%.	The recycling rate of the material from its energy application is from 0% to 25%.
	Political, regulatory, and social factors	0.1	WGI < 3	3 ⩽ WGI ⩽ 4.5	4.5 ⩽ WGI ⩽ 6	WGI > 6
	Environmental factors	0.1	EPI > 60	45 ⩽ EPI ⩽ 60	30 ⩽ EPI ⩽ 45	EPI < 30
	Co-dependence on other markets (must meet both criteria)	0.1	May or may not be produced as a co- product of other metals.	Production (>50%) is as co-product or as a by-product of other metals.	Significant (>75%) production is as co-product or as a by-product of other metals.	100% production is as co-product or as a by-product of other metals.
			Produced as a main product in most circumstances.	Produced as a main product in some circumstances OR there is excess by-product supply in the market.	May be produced as a main product in some circumstances AND there is no excess by-product supply in the market.	Not produced as a main product anywhere in the world AND there is no excess by-product supply in the market.
	Producer diversity	0.2	HHI < 2500	2500 ⩽ HHI ⩽ 3332	3333 ⩽ HHI ⩽ 4999	HHI ⩾ 5000

WGI = *World Governance Indicators*; EPI = *Environmental Performance Index*; HHI = *Herfindahl–Hirschman Index.*

where:
$M_{\text{In,i}}$ = material inputs for the sub-technology at year *i*, in tonnes [t];
CP_i = cumulative power for the sub-technology at year *i*, in [GW];
CP_{i-1} = cumulative power for the sub-technology at year *i*−1, in [GW];
$S_{\text{st},i}$ = share of sub-technology at year *i*, in percentage [%];
$\text{MI}_{\text{st},i}$ = material intensity of sub-technology at year *i*, in $[\frac{t}{\text{GW}}]$.

Potential material recovery: this identifies opportunities to offset primary raw materials (PRMs) needs by reintegrating secondary raw materials (SRMs) into the supply chain. The materials reaching EoL each year are estimated using equation (3):

$$M_{\text{Out},i} = \left((\text{CP}_{i-L} - \text{CP}_{i-L-1}) \times \left(\frac{S_{\text{st},i-L}}{100}\right)\right) \times \text{MI}_{\text{st},i-L} \tag{3}$$

where:

$M_{\text{Out},i}$ = material outputs for the sub-technology at year *i*, in tons [t];
CP_{i-L} = cumulative power for the sub-technology at year *i*_*L*, in [GW];
CP_{i-L-1} = cumulative power for the sub-technology at year *i*_*L*_*1*, in [GW];
$S_{\text{st},i-L}$ = share of sub-technology at year *i*_*L*, in percentage [%];
$\text{MI}_{\text{st},i-L}$ = material intensity of sub-technology at year *i*_*L*, in $[\frac{t}{\text{GW}}]$;
L = average lifespan of the sub-technology, in time (years).

The potential amount of SRMs recovered through recycling is estimated using equation (4):

$$\text{SRM}_{\text{In},i} = M_{\text{Out},i} \times \left(\frac{\text{RR}_i}{100}\right) \tag{4}$$

where:

$\text{SRM}_{\text{In},i}$ = secondary raw material inputs at year *i*, in tones [*t*];
$M_{\text{Out},i}$ = material outputs for the sub-technology at year *i*, in tons [*t*] (from equation (2));
RR_i = national recycling rate at year *i*, in percentage [%].

2.4. The integrated material criticality

To refine the initial classification of material criticality (i.e. *non-critical, near-critical, critical*) for a given country and energy technology, an integrated criticality adjustment approach was applied. The baseline scale was defined as *critical* = 3, *near-critical* = 2, and *non-critical* = 1, derived from the initial criticality matrix and used as the starting point for subsequent adjustments. The adjustment factors were informed primarily by the MFA, incorporating elements that reflect national progress in the energy transition and circularity potential, and relying on three key aspects:

Baseline-to-target gap (BT): this factor accounts for the country's progress toward its projected installed capacity in each technology (e.g. PV, wind turbines). A large gap between current and target values signals higher material criticality, as rapid deployment is likely to strain supply chains,

$$\text{BT}_i = \text{Current installed capacity/Projected installed capacity}.$$

Demand growth (*D*): this reflects the expected growth in demand for a given material over the transition period. Steep increases in demand indicate a greater risk of future supply constraints,

$$D_i = \text{Projected Demand/Current demand}.$$

Recycling maturity (RM): this factor captures the level of recycling infrastructure and effectiveness for critical metals. Higher RM could mitigate supply risks by increasing the contribution of secondary materials,

$$\text{RM}_i = \text{Recycling maturity at year } i.$$

As mentioned above, the criticality adjustment follows a three-level baseline scale: critical = 3, near-critical = 2, and non-critical = 1. Each factor (BT gap, demand growth, and RM) can increase or decrease the material's criticality level according to defined thresholds and rules summarized in table 5.

Table 5. Proposed integrated criticality adjustment criteria.

Factor	Condition	Criticality adjustment	Description
Baseline to target gap (BT)	BT $<$ 20% (Large gap)	Increases by 2 levels	The country is far from its target; high deployment pressure expected.
	20% $<$ BT $<$ 50% (Moderate gap)	Increases by 1 level	Moderate deployment effort still needed.
	BT $\geqslant$ 50% (Small gap)	No change	Country is already halfway or closer to target
Demand growth (D)	$D > 5$ (High demand growth)	Increase by 2 levels	Material demand is expected to grow more than fivefold by target year.
	$2 > D > 5$ (Moderate demand growth)	Increase by 1 level	Material demand is expected to double or more by target year.
	$D \leqslant 2$ (Low demand growth)	No change	Demand stays stable or increases modestly.
Recycling maturity (RM)	RM $>$ 60% (high maturity)	Decrease by 1 level	Mature infrastructure, well-established recovery systems for metals and E-waste
	30 $>$ RM $>$ 60% (medium maturity)	No change	Developing but functional systems with selective efficiency
	RM $\leqslant$ 30% (low maturity)	Increase by 1 level	Emerging or limited recycling capacity, poor traceability and recovery

The final adjusted criticality level for each material, by technology and by country, was obtained by cumulatively applying all adjustment factors to the baseline assessment for 2030 and 2050. Starting from the baseline scale (*non-critical* = 1, *near-critical* = 2, *critical* = 3), the adjustment process allowed values to increase by up to +5 or decrease by −1, depending on the three adjustment factors. In theory, this produced a possible range from 0 to 8; however, since the resulting values in this study only reached up to 6, we standardized the scale to range from 0 (lowest criticality) to 6 (highest criticality) for consistency and interpretability. Our approach enables a more granular evaluation of criticality that accounts not only for intrinsic supply risks and energy relevance but also for evolving demand dynamics, national deployment progress, and RM.

3. Results

3.1. The adapted criticality matrix

The analysis of 21 materials relevant to wind and PV solar technologies (figure 2) revealed that by 2030 materials such as terbium, neodymium and dysprosium (materials primarily used in wind turbines and part of the rare earth element group) are initially classified as 'critical' due to both high importance to energy and supply risk. By 2050, praseodymium will join the 'critical' category, reinforcing the growing dependence on rare earths in clean energy systems. On the 'near-critical' front, boron and praseodymium are flagged in 2030, while silicon, chromium, aluminum, and gallium are added by 2050, which are materials often used in solar PV systems or structural components. Most of the materials assessed remain 'non-critical', reflecting a generally stable risk profile for most elements in the renewable energy supply chain. Taken together, these findings not only reaffirm the centrality of rare earth elements but also point to a set of additional materials that will likely become more critical in the long run (e.g. chromium, molybdenum). Our results therefore provide a transparent, forward-looking basis for anticipating which materials could justifiably enter future revisions of the EU's CRM list, ensuring alignment between long-term deployment trajectories and material criticality assessments.

3.2. The MFA

The MFA was conducted for both Italy and Switzerland, focusing on PV solar panels and wind power technologies, and assessing their associated material inputs, outputs, and stocks over time. While the complete MFA includes structural materials like concrete, steel, and glass, the summarized results (figure 3) concentrate mainly on technology-specific materials like silver, cadmium, tellurium (for PV solar panels), and rare earth elements like neodymium, dysprosium, and terbium (for wind turbines). Aluminum, steel, and copper, although highly relevant, were excluded from the figures, as they are predominantly part of the structural components and not the energy-generating core of the PV modules or

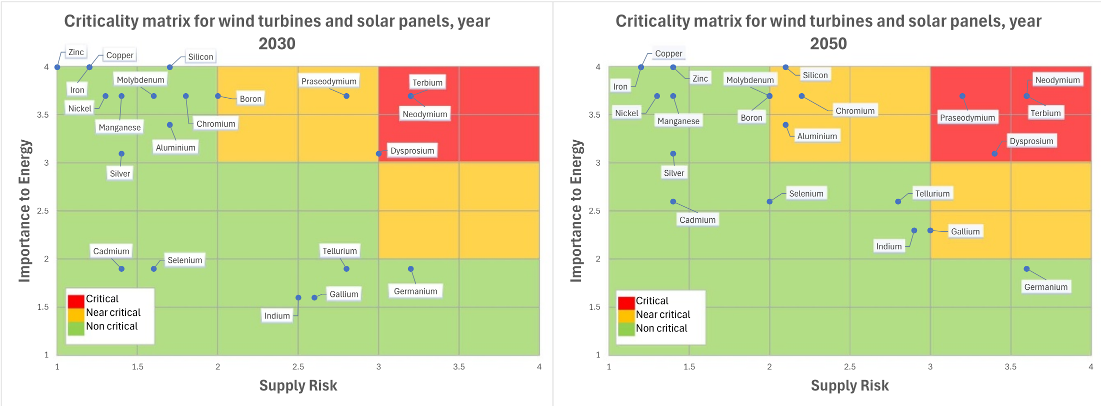

Figure 2. Results of the adapted criticality matrix for PV and wind technologies, for mid (2030) and long terms (2050).

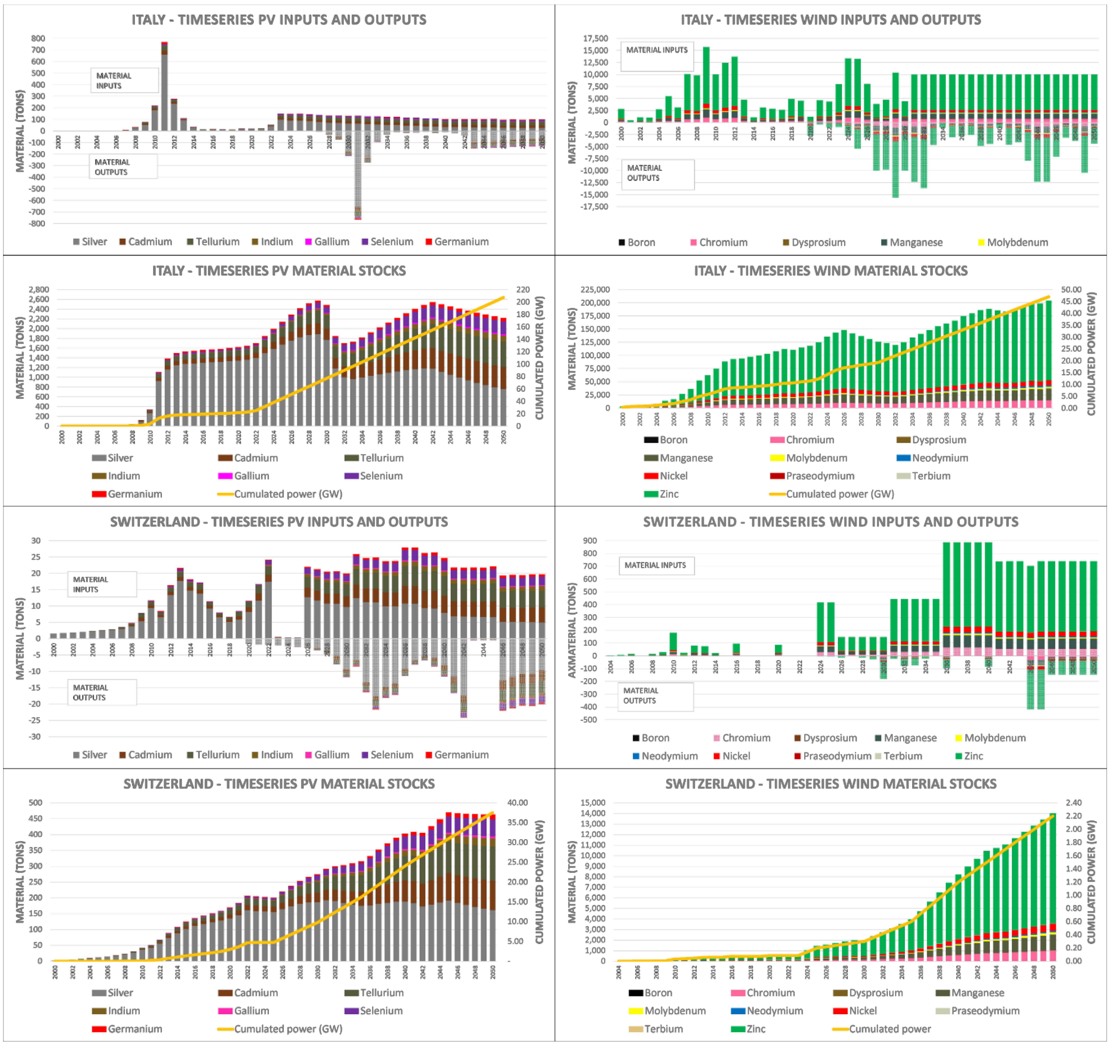

Figure 3. Application of MFA: material inputs, outputs, and stocks of PV and wind technologies, for Italy and Switzerland.

turbines. Similarly, silicon was excluded from PV-specific material figures since it accounts for over 90% of the total PV solar panels' material mass. Instead, the figures highlight the remaining material shares. The full material inventory is available in the supplementary data.

Solar PV—Italy and Switzerland

As shown in the previous figures, Italy experienced a sharp spike in PV deployment around 2011–2012, which resulted in highly concentrated material inputs and projected material outputs starting around 2030 due to expected module EoL. Switzerland, in contrast, followed a more gradual deployment path, leading to more stable material accumulation over time and delayed output peaks closer to 2050.

Additionally, although c-Si continues to dominate the global PV market, thin-film technologies are gaining ground due to their distinct material profiles. Market projections under a HDS suggest that the global share of thin-film PV will grow from 4.6% in 2018%–23% by 2050 [31]. This projected increase in the adoption of thin-film technologies is particularly relevant, as it is expected to significantly raise future demand for materials such as cadmium, tellurium, selenium, indium, and germanium. In Italy, demand for these PV-specific materials is projected to more than triple by 2050 compared to 2023 levels (a growth factor of ∼3.5×). In Switzerland, the relative increase is even more substantial, with a growth factor of ∼5.5× due to a smaller initial deployment base.

Wind—Italy and Switzerland

In the wind turbines sector, Italy showed significant wind power deployment around 2007–2012, resulting in earlier and more dynamic shifts in material demand. This early adoption results in material outputs (due to turbine dismantling) projected to begin around 2035. By 2050, the demand for technology-specific materials, particularly rare earths, is expected to almost double compared to 2023 levels. In contrast, Switzerland, starting from a minimal wind power deployment between 2015 and 2023, will require a sharp acceleration in installations after 2024, potentially resulting in a twentyfold increase in technology-specific material demand by 2050 to reach targets.

Potential for secondary material recovery—Italy and Switzerland

The study also assessed the potential to recover SRMs from dismantled PV solar panels and wind turbine systems, using standard EoL assumptions (20 years for PV solar panels and onshore wind turbines; 25 years for offshore wind turbines). In Italy, the steady pace of installations and subsequent dismantling cycles improves the alignment between input needs and recovery outputs, particularly between 2045 and 2050. This suggests promising substitution potential for PRMs with SRMs.

In Switzerland, larger quantities of materials may become available for recovery due to concentrated deployment peaks, especially around 2040. However, the potential to align recovered materials with future demand appears weaker due to mismatches in the timing of installations and decommissions.

Considering wind technologies in both countries, the potential to offset PRMs demand with SRMs exists, particularly in Italy, where recovery outputs in 2030 and 2045 better align with forecasted material inputs. Switzerland again faces more challenges due to compressed timelines and delayed outputs.

3.3. The integrated criticality: applying the adjustment factors

The results of the integrated material criticality assessment (figure 4) build upon the operationalized MFA by applying a multi-dimensional scoring system to each material and technology, incorporating country-specific deployment trajectories, projected demand growth, and RM. As shown here, materials are assigned a criticality score from 0 (lowest) to 6 (highest), reflecting the cumulative outcome of the adjustment factors.

In the PV solar panels sector, both Italy and Switzerland exhibit comparable and rising criticality scores for key materials, reflecting broader European and global supply chain dependencies. While most PV-specific materials fall within scores of 1–2 by 2030 (lowest criticality), several others, in particular gallium and aluminum, reach scores of 4 or higher by 2050 (highest criticality). This is largely driven by the accelerated deployment scenarios and growing global market shares of sub-technologies, highlighting strategic vulnerabilities in future supply chains.

In wind turbines technologies, the criticality landscape is dominated by rare earth elements, especially neodymium, dysprosium, praseodymium and terbium, which score 5 or 6 by 2050 in both Italy and Switzerland. These materials are essential for permanent magnet generators in modern wind turbines, and their elevated scores are driven by high demand growth projections. Switzerland shows a steeper increase in final criticality for rare earth elements, with all materials scoring 4 or higher by 2050, explained by its delayed but rapid deployment push post-2024.

Between the two countries, Italy's earlier and larger PV deployment translates into higher criticality for PV-specific materials such as gallium and aluminum, whereas Switzerland's delayed but steeper wind expansion after 2024 amplifies its criticality on rare earth elements. These diverging trajectories point to distinct timing and intensity of material vulnerabilities across the two national contexts.

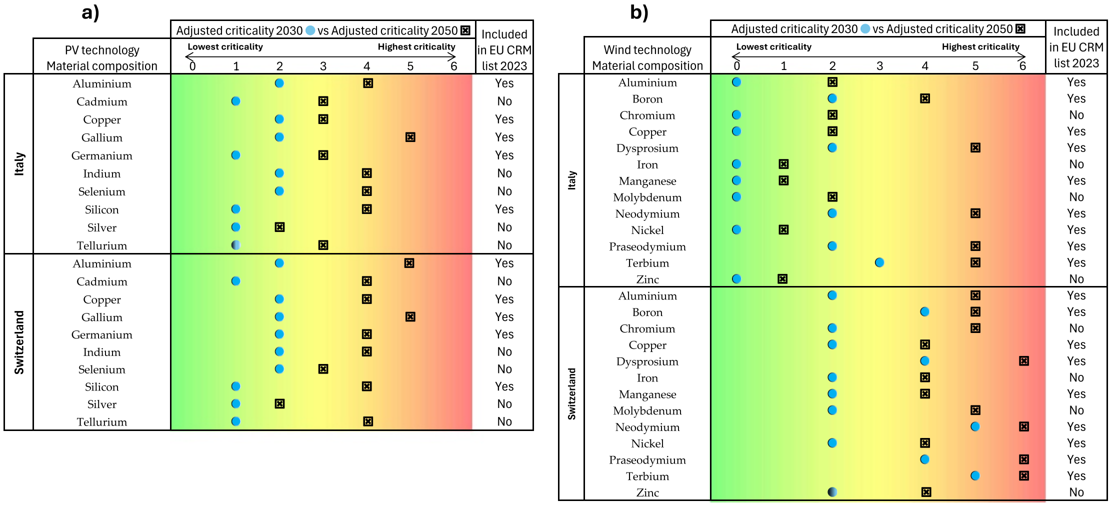

Figure 4. Results of the integrated material criticality assessment for (a) PV solar panels and (b) wind turbines technologies, for mid (2030) and long terms (2050) in Italy and Switzerland, applying a ranking from 0 (lowest criticality, green) to 6 (highest criticality, red), alongside a comparison with the EU CRM list 2023.

Comparison with the EU CRM list 2023 [5] highlights both alignment and divergence patterns. Several materials (e.g. aluminum, gallium, germanium, neodymium, praseodymium, dysprosium, terbium) are consistently identified as critical in both the framework and the EU list, whereas others (e.g. cadmium, selenium, zinc, molybdenum) appear as highly critical but are not currently listed in the EU CRM list. These differences are largely technology-specific and illustrate how deployment trajectories influence national criticality outcomes.

4. Discussion

This study sets out to address the lack of integrated approaches to material criticality by combining the external dimension of global supply risks with the internal dimension of national deployment dynamics. Using Switzerland and Italy as case studies, our goal was not only to assess and compare material dependencies but also to show how country-specific trajectories align or diverge with EU-wide CRM lists. By interpreting our results against existing literature, the discussion highlights (i) how regional classifications could overlook national stress profiles, (ii) the influence of diverging energy strategies on material dependencies, (iii) the continued relevance of criticality assessments for non-manufacturing countries, and (iv) methodological implications for building transparent and context-sensitive assessments. Together, these insights point to the need for adaptive policies that complement EU-wide frameworks with national-level strategies for resilient and sustainable supply chains.

4.1. Bridging regional frameworks and national realities in CRMs classification

In parallel to MFA and material criticality assessments, it is essential to position national material vulnerabilities and dependencies within a broader regional context. While the EU CRMs list provides a unified regional framework [9], it does not allow for classification by varying levels of criticality or strategic importance, nor does it consider country-specific contexts. Our results show that rare earth elements like dysprosium, neodymium, praseodymium, and terbium consistently rank highest in our national-level criticality assessments for both Italy and Switzerland, aligning with their designation in the EU CRMs Act as both CRMs and Strategic Raw Materials within the Heavy Rare Earth Elements group [2]. Yet, while the CRMs designation is grounded in transparent indicators such as supply risk and economic importance, the parallel creation of a 'strategic' subset introduces ambiguity, as there is no clear methodological framework, to the authors knowledge, for why certain materials are placed under the 'strategic' status while others are not. The proposed assessment addresses this limitation through a consistent and reproducible methodology across materials, thereby avoiding the need for ad hoc distinctions between 'critical' and 'strategic,' and instead highlighting how national energy strategies drive material stress profiles.

In addition to reaffirming the high relevance of rare earths, our results also point to the emergence of other materials such as indium, selenium, and tellurium. These elements were previously identified by studies on the decarburization of the EU energy sector [62–64] which are not currently captured by the EU CRMs list but are likely to become critical in the medium to long term. Their appearance in our assessments reflects how national deployment trajectories can elevate the importance of materials that remain invisible in aggregated regional frameworks. For instance, Italy's earlier large-scale adoption of solar PV, incentivized through national objectives, translates into higher exposure to PV-related CRMs such as gallium and aluminum, whereas Switzerland's more gradual but wind-oriented trajectory amplifies reliance on rare earth elements like neodymium and dysprosium. These differentiated profiles underscore how national energy strategies shape not only the scale but also the composition of material stress, creating distinct material stress profiles that remain undetected when assessments are limited to EU-level frameworks.

It should be noted, however, that EU-wide criticality assessments already capture supply risks at a sufficient resolution and sufficiently granular basis to guide policy [1]. This perspective suggest that regional lists provide coherence and legitimacy, even if they sometimes miss specific national vulnerabilities. Nevertheless, our findings indicate that country-level perspectives are not in contradiction with the EU framework but rather serve as a complementary layer, helping to identify material risks that would otherwise remain invisible when viewed only through a regional lens.

Our research exemplifies this approach through CRMs designations with country-level assessments that factor in deployment scale, evolving material compositions, and recovery potential, especially as countries operationalize their national energy strategies under broader global and/or regional energy targets. Our findings suggest that EU-wide CRMs lists serve as an essential foundation, but material criticality may manifest more acutely or differently at the national level, particularly for technology-specific transitions such as PV and wind power.

4.2. Material criticality in national energy strategies

Building on the limitations of regional CRMs classifications, the differentiated final criticality scores observed between Italy and Switzerland highlight the need for adaptive strategies at the national level to manage material dependencies. As shown in our integrated assessment, even with similar long-term energy goals, differences in deployment timelines, material demand growth, and EoL recovery potential may result in distinct material criticality profiles. For example, Italy's early solar and wind deployment amplifies material outputs and substitution potential by mid-century, as expanding installed capacity and maturing recycling streams begin to offset primary material needs. Other studies have come to similar results [65], indicating that Italy's rapid expansion of renewable capacity is likely to moderate long-term supply risks through earlier development of secondary material markets and technological substitution pathways. On the other hand, Switzerland faces more concentrated input requirements and delayed recoverability, potentially increasing exposure to material stress dynamics in the 2040s. This is aligned with studies [66] showing that Switzerland's slower renewable expansion, combined with high import dependence and limited domestic recycling capacity, could intensify late-decade material bottlenecks. This contrast highlights the role of deployment timing in shaping national material stress pathways.

In addition, technology-specific energy strategies can exacerbate these dynamics by creating structural dependencies. Once countries commit to scaling up renewable technologies like PV solar panels and wind turbines, they become increasingly dependent on the continuous supply of specific materials required to maintain, expand, and eventually replace these systems. This structural dependency links the success of the energy targets to the availability and accessibility of a limited set of CRMs [31, 67]. Several studies have shown that such technology lock-ins could emerge not only from physical infrastructure and industrial specialization but also from institutional and market feedbacks that reinforce material path dependencies [68, 69]. Without robust circularity strategies, material substitution research, and diversified supply chains, this lock-in may expose national energy systems to long-term vulnerabilities, as highlighted by recent analyses of CRM scarcity, recycling constraints, and geopolitical concentration of supply [29, 70, 71].

Local governments, however, could play a proactive role in mitigating these vulnerabilities by improving downstream interventions. For example, environmental criteria in public procurement, repair and reuse policies, and traceability standards for imported components offer avenues for local governments to influence the sustainability of CRMs use. Several recent studies show that e.g. Green Public Procurement frameworks could shift market incentives and supply chain practices when criteria include lifecycle costs, recycled content, and environmental performance of suppliers [72, 73]. Policies promoting repair, remanufacturing, refurbishment and direct reuse have also been identified as effective for reducing demand for virgin materials and slowing resource depletion [74, 75]. Although local actions may not influence global extraction practices directly, they could reduce environmental pressure through better EoL management and contribute to more responsible and resilient material demand.

Our findings suggest that effective material governance should not rely solely on broad regional CRM lists. Instead, it requires forward-looking planning tools that integrate both external and internal dimensions [76–79]. Also, tailoring material criticality assessments to national contexts enables more informed decisions about strategic supply chain, domestic recycling capacity, innovation incentives, and potential trade diversification. Ultimately, integrating CRMs planning into energy policy design improves both the resilience and sustainability of national energy transitions.

4.3. Why criticality still matters for non-manufacturing countries

A key question that arises when conducting national-level criticality assessments is whether such efforts are necessary in countries that do not manufacture renewable energy technologies domestically. Italy and Switzerland, for instance, are very likely to import renewable energy power capacities while having marginal national productions. This does not diminish the relevance of national-level material criticality assessments. On the contrary, several important considerations justify this approach.

First, this external market dependency makes them susceptible to global CRMs supply disruptions, price volatility, and geopolitical risks that can delay or constrain technology deployment. For example, supply of minerals like lithium, cobalt, rare earths, and others is increasingly concentrated and exposed to export restrictions and political instability, which have already caused or threaten delays in clean-tech material supply and driven sharp price fluctuations [44, 67, 80]. Understanding which materials are critical to their own energy transition allows these countries to anticipate and plan for deployment bottlenecks, supporting a more resilient pathway toward their energy targets. Yet, the extent to which certain materials constitute structural bottlenecks remains debated. A study by [81] suggest that rare earth disruptions are largely cyclical and politically driven rather than geological, while [82] point to untapped recycling and recovery potential as a key mitigation pathway. In PVs, although thin-film materials appear increasingly critical, this risk may be overstated if crystalline silicon continues to dominate global markets [83]. Such divergent projections also highlight the importance of scenario-based assessments that integrate market evolution, recycling potential, and substitution.

Second, criticality assessments highlight a country's role in the circular economy through EoL recovery and recycling. Current EU recycling rates for rare earth elements remain below 1%, stressing the need to expand capacity [84, 85]. Countries could potentially play a strategic role in recycling high-value components, supporting EU-wide circularity goals, and possibly establishing niche industrial capacities for resource recovery, repair, or remanufacturing [86]. This material recovery could partially mitigate future CRMs demand, but its effectiveness strongly depends on the timing and scale of deployment cycles.

Third, national-level data enables countries to align better with regional industrial strategies, like the EU's CRMs Act, and to push for targeted interventions or strategic reserves [77, 87]. Without country-specific assessments, opportunities for trade diversification, R&D funding, or policy innovation may go untapped.

Finally, identifying material vulnerabilities allows national governments to prioritize lower-risk technologies, promote substitution research, or support material-efficient design through procurement standards or innovation funding, among other measures [3, 88]. In this light, national material criticality assessments are increasingly essential, as they provide a planning tool for governments to reduce exposure, enhance resilience, and better align material needs with long-term energy and industrial policy goals.

4.4. Criticality assessment: a reflection on the approach

The integrated criticality assessment presented in this study builds upon and extends criticality matrices and material flow analyses, aiming to capture a more nuanced assessment of material criticality in the context of national energy transitions. The original US DOE Criticality Matrix is based on tiers like non-critical, near critical, and critical, which serves as a useful benchmark but limit granularity. Our expanded scoring range (0–6) was proposed to reflect more continuous variations in material criticality, capturing finer distinctions between materials and eventually supporting prioritization in policy and planning contexts.

Each adjustment factor contributes complementary insights: the BT gap highlights deployment pressures but is technology- rather than material-specific; the demand growth (D) factor introduces material differentiation but depends on uncertain assumptions about future technology mixes; and the RM factor reflects national circularity baselines (∼60% recovery for both Italy and Switzerland) but lacks material specificity. A more refined approach would incorporate recovery efficiencies by material (e.g. aluminum, copper, rare earth elements) and align them with evolving recycling targets and infrastructure.

Compared with broader assessments [2, 3, 89], our approach confirms similar trends of rising CRMs dependence, but provides greater resolution at the national scale by incorporating deployment timing, recovery potential, and technology-specific material intensities. This reinforces the importance for national-level criticality assessments that complement, rather than replace, generic CRMs lists.

Regarding the relative influence of external versus internal factors, the framework is designed to retain these dimensions analytically distinct while allowing them to interact through adjustment factors. In the cases of Italy and Switzerland, external factors such as the market share of the most dominant specific sub-technology, or co-dependence on other markets largely determine the baseline classification of material criticality. Internal factors then modulate this baseline by shaping *when, how fast*, and *through which technologies* materials are deployed and recovered. For example, differences in deployment timing and technology mix explain why similar materials exhibit divergent adjusted criticality levels between the two countries, despite sharing comparable exposure to global supply risks. While the present study does not quantitatively decompose the relative contribution of each factor, the results suggest that external factors set structural constraints, whereas internal factors drive national differentiation and policy-relevant variation.

5. Conclusions

This study proposed an integrated approach to assess material criticality in national energy transitions, applied to Italy and Switzerland. By combining internal and external criticality indicators with internal, country-specific adjustment factors (namely deployment gaps, material-specific demand growth, and recycling maturity) the framework captures how material criticality evolves over time and differs across national contexts. Findings show that Italy and Switzerland exhibit distinct material criticality profiles, with Switzerland displaying higher adjusted criticality scores for several materials due to sharper renewable technology deployment and compacted material recovery timelines. In particular, materials such as rare earths, gallium, and aluminum emerge as highly critical, especially in the context of wind technologies relying on permanent magnets. Comparison with the EU-wide CRMs list indicates both alignment and divergence: while several materials identified as critical at the EU level (e.g., rare earth elements) also emerge as highly critical at national level, other materials (e.g. indium, selenium) emerge critical in country and technology-specific context despite receiving limited emphasis in regional assessments. This highlights the importance of complementary, country-specific assessments that account for deployment pathways, technology choices, and circularity opportunities.

Future work could extend and strengthen the framework along several dimensions. First, expanding the technological scope beyond wind and solar, and applying the framework to additional countries, would enable broader benchmarking against established national and regional CRM lists and assessment of sensitivity to technological portfolios. Second, temporal extensions could support dynamic analyses of implementation timelines, policy updates, and emerging criticality thresholds, allowing CRM classifications to be updated as deployment targets, market conditions, or supply risks evolve. Third, improvements in data granularity, especially for material-specific recycling rates and circularity indicators, would enhance robustness. Fourth, while the criticality matrix provides structure and comparability and MFA introduces system-level dynamics, further refinement would strengthen attribution and interpretability. Explicit disaggregation of internal and external drivers would enhance the framework's usefulness. Finally, assessing cumulative criticality across multiple technologies remains an important avenue for understanding systemic resilience. Overall, the proposed framework is designed to be extensible and adaptable, providing a structured basis for more context-sensitive and resilient policy and planning decisions under evolving conditions.

Data availability statement

The data that support the findings of this study are openly available from publicly accessible sources, are included within the article and detailed in its Supporting Information files, or are available from the corresponding author upon reasonable request.

Supplementary data available at https://doi.org/10.1088/2753-3751/ae3c16/data1.

Supplementary data 1 available at https://doi.org/10.1088/2753-3751/ae3c16/data2.

Supplementary data 2 available at https://doi.org/10.1088/2753-3751/ae3c16/data3.

Supplementary data 3 available at https://doi.org/10.1088/2753-3751/ae3c16/data4.

Supplementary data 4 available at https://doi.org/10.1088/2753-3751/ae3c16/data5.

Supplementary data 5 available at https://doi.org/10.1088/2753-3751/ae3c16/data6.

Acknowledgment

The authors gratefully acknowledge ERASMUS+ program for the mobility of Spinello, M. at EPFL for 6 months. The authors acknowledge the contribution of the HERUS team for their support on internal reviews of the paper. The research published in this paper was supported by EPFL and the ETH-Domain Joint Initiative program through the UrbanTwin project, as well as from the InnoSuisse Flagship Initiative under the project 'Flagship PFFS-21-03' *Blue City*. The authors bear sole responsibility for the conclusions and the results presented in this publication.

Author contributions

Francisco Martin del Campo 0000-0001-5963-7290
Conceptualization (lead), Data curation (lead), Formal analysis (lead), Investigation (lead), Methodology (equal), Validation (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Matilde Spinello
Data curation (equal), Formal analysis (equal), Writing – review & editing (equal)

Silvia Fiore 0000-0001-5949-0559
Conceptualization (equal), Methodology (equal), Supervision (equal), Writing – original draft (supporting), Writing – review & editing (equal)

Claudia R Binder 0000-0002-2921-9896
Conceptualization (equal), Funding acquisition (lead), Methodology (equal), Supervision (equal), Writing – review & editing (equal)

References

[1] Bobba S, Carrara S, Huisman J, Mathieux F and Pavel C European Commission 2020 *Critical Raw Materials for Strategic Technologies and Sectors in the EU: A Foresight Study* (Publications Office of the European Union) (https://doi.org/10.2873/58081)
[2] European Council Critical raw materials act: an EU critical raw materials act for the future of EU supply chains (available at: www.consilium.europa.eu/en/infographics/critical-raw-materials/) (Accessed 31 January 2025)
[3] International Energy Agency Critical minerals market review 2023—analysis (available at: www.iea.org/reports/critical-minerals-market-review-2023) (Accessed 31 January 2025)
[4] International Energy Agency The role of critical minerals in clean energy transitions—analysis (IEA) (available at: www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions) (Accessed 31 January 2025)
[5] European Commission Critical raw materials (available at: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en) (Accessed 31 January 2025)
[6] Desing H *et al* 2024 Mobilizing materials to enable a fast energy transition: a conceptual framework *Resour. Conserv. Recycl.* **200** 107314
[7] USGS About the 2025 list of critical minerals (available at: www.usgs.gov/programs/mineral-resources-program/science/about-2025-list-critical-minerals) (Accessed 12 December 2025)
[8] Bauer D J, Nguyen R T and Smith B J 2023 Critical materials assessment (U.S. Department of Energy) (available at: www.ourenergypolicy.org/resources/critical-materials-assessment/) (Accessed 31 January 2025)
[9] Grohol M and Veeh C 2023 *Study on the Critical Raw Materials for the EU 2023: Final Report* (Publications Office of the European Union) (https://doi.org/10.2873/725585)
[10] METI critical minerals (ministry of economy, trade and industry (METI)) (available at: www.meti.go.jp/policy/economy/economic_security/metal/index.html) (Accessed 10 December 2025)
[11] Barteková E and Kemp R 2016 National strategies for securing a stable supply of rare earths in different world regions *Resour. Policy* **49** 153–64
[12] METI Japan's new international resource strategy to secure rare metals (Agency for Natural Resources and Energy, METI) (available at: www.enecho.meti.go.jp/en/category/special/article/detail_158.html) (Accessed 10 December 2025)
[13] METI 2025 Policy for ensuring a stable supply of critical minerals (Ministry of Economy, Trade and Industry (METI)) (available at: www.meti.go.jp/policy/economy/economic_security/metal/250619_torikumihoshin.pdf)
[14] Natural Resources Canada Government of Canada releases updated critical minerals list (available at: www.canada.ca/en/natural-resources-canada/news/2024/06/government-of-canada-releases-updated-critical-minerals-list.html) (Accessed 12 December 2025)
[15] Government of Canada Let's talk Canada's critical minerals list and methodology (Let's Talk Natural Resources) (available at: www.letstalknaturalresources.ca/lets-talk-canadas-critical-minerals-list) (Accessed 10 December 2025)
[16] Government of Canada Critical minerals: an opportunity for Canada (available at: www.canada.ca/en/campaign/critical-minerals-in-canada/critical-minerals-an-opportunity-for-canada.html) (Accessed 10 December 2025)
[17] Mudd G *et al* 2024 UK 2024 criticality assessment: decarbonisation and resource management program *British Geological Survey, Nottingham, UK, Open Report OR/24/059* (British Geological Survey) (available at: www.ukcmic.org/reports/cmic.html) (Accessed 10 December 2025)
[18] Australian Government 2024 Australia's critical minerals list and strategic materials list *Department of Industry, Science and Resources* (Critical Minerals Office, Canberra, Strategy or plan) (available at: www.industry.gov.au/publications/australias-critical-minerals-list-and-strategic-materials-list) (Accessed 10 December 2025)

[19] Parliament of Australia 2025 Critical minerals in Australia *Parliament of Australia* (Science, Technology, Environment and Resources section, Policy brief Policy Brief, 2025-26) (available at: www.aph.gov.au/About_Parliament/Parliamentary_departments/Parliamentary_Library/Research/Policy_Briefs/2025-26/Criticalminerals) (Accessed 10 December 2025)
[20] China Briefing China's rare earth export controls—impact on businesses and industries (China Briefing News) (available at: www.china-briefing.com/news/chinas-rare-earth-export-controls-impacts-on-businesses/) (Accessed 10 December 2025)
[21] Shivaprasad A, Lv A and Parodi A 2025 What critical minerals are on China's export control list now? *Reuters* (available at: www.reuters.com/world/china/chinas-curbs-exports-strategic-minerals-2025-10-09/) (Accessed 10 December 2025)
[22] Cho H S and Nakano J 2025 The minerals security partnership under the South Korean leadership (available at: www.csis.org/analysis/minerals-security-partnership-under-south-korean-leadership) (Accessed 10 December 2025)
[23] MOTIE 2023 Strategies to secure core minerals to become a global powerhouse in high-tech industries *Korean Ministry of Trade, Industry and Energy (MOTIE)* (available at: www.korea.kr/briefing/pressReleaseView.do?newsId=156554864) (Accessed 10 December 2025)
[24] International Energy Agency Critical minerals policy tracker—data tools (IEA) (available at: www.iea.org/data-and-statistics/data-tools/critical-minerals-policy-tracker) (Accessed 31 January 2025)
[25] Zhang S E, Bourdeau J E, Nwaila G T and Ghorbani Y 2023 Emerging criticality: unravelling shifting dynamics of the EU's critical raw materials and their implications on Canada and South Africa *Resour. Policy* **86** 104247
[26] Martin N, Madrid-López C, Villalba-Méndez G and Talens-Peiró L 2022 New techniques for assessing critical raw material aspects in energy and other technologies *Environ. Sci. Technol.* **56** 17236–45
[27] Montana F *et al* 2025 Assessing critical raw materials and their supply risk in energy technologies—a literature review *Energies* **18** 86
[28] IRENA and NUPI 2024 Constructing a ranking of critical materials for the global energy transition (International Renewable Energy Agency (IRENA), Abu Dhabi) (available at: www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Oct/IRENA_Ranking_critical_materials_for_the_energy-transition_2024.pdf)
[29] Pommeret A, Ricci F and Schubert K 2022 Critical raw materials for the energy transition *Eur. Econ. Rev.* **141** 103991
[30] Schrijvers D *et al* 2020 A review of methods and data to determine raw material criticality *Resour. Conserv. Recycl.* **155** 104617
[31] European Commission. Joint Research Centre 2020 Raw materials demand for wind and solar PV technologies in the transition towards a decarbonised energy system (LU: Publications Office) (https://doi.org/10.2760/160859) (Accessed 31 January 2025)
[32] Rinaldi L, Rocco M V and Colombo E 2023 Assessing critical materials demand in global energy transition scenarios based on the dynamic extraction and recycling input-output framework (DYNERIO) *Resour. Conserv. Recycl.* **191** 106900
[33] Calvo G and Valero A 2022 Strategic mineral resources: availability and future estimations for the renewable energy sector *Environ. Dev.* **41** 100640
[34] Martínez-Hernando M-P, García-Franco E, Bolonio D, Ortega M F and García-Martínez M-J 2024 Life cycle sustainability assessment of the platinum supply chain in the European Union *Sustain. Prod. Consum.* **46** 679–89
[35] Grandell L and Thorenz A 2014 Silver supply risk analysis for the solar sector *Renew. Energy* **69** 157–65
[36] Bustamante M L and Gaustad G 2014 Challenges in assessment of clean energy supply-chains based on byproduct minerals: a case study of tellurium use in thin film photovoltaics *Appl. Energy* **123** 397–414
[37] van Oorschot J, Sprecher B, Roelofs B, van der Horst J and van der Voet E 2022 Towards a low-carbon and circular economy: scenarios for metal stocks and flows in the Dutch electricity system *Resour. Conserv. Recycl.* **178** 106105
[38] Martin N, Talens-Peiró L, Villalba-Méndez G, Nebot-Medina R and Madrid-López C 2023 An energy future beyond climate neutrality: comprehensive evaluations of transition pathways *Appl. Energy* **331** 120366
[39] Felipe-Andreu J, Valero A and Valero A 2022 Territorial inequalities, ecological and material footprints of the energy transition: case study of the cantabrian-mediterranean bioregion *Land* **11** 1891
[40] Russell C and Russell C 2025 Critical minerals is a meaningless term, needs new definition and strategy *Reuters* (available at: www.reuters.com/markets/commodities/critical-minerals-is-meaningless-term-needs-new-definition-strategy-russell-2025-02-12/) (Accessed 14 February 2025)
[41] Enel Group 3SUN Gigafactory (available at: www.enel.com/company/3sun-gigafactory) (Accessed 28 August 2025)
[42] European Investment Bank Italy: Europe's biggest solar gigafactory 3Sun secures €560 million financing from EIB and pool of Italian banks led by UniCredit and backed by SACE (available at: www.eib.org/en/press/all/2024-020-europe-s-biggest-solar-gigafactory-3sun-secures-eur560-million-financing-from-eib-and-pool-of-italian-banks-led-by-unicredit-and-backed-by-sace) (Accessed 28 August 2025)
[43] ensun GmbH Top 58 turbine blade manufacturers in Switzerland (ensun) (available at: https://ensun.io/search/turbine-blade/switzerland?) (Accessed 28 August 2025)
[44] Hoskins P and Bicker L China tightens export rules for crucial rare earths (BBC) (available at: www.bbc.com/news/articles/ckgzl0nwvd7o) (Accessed 11 October 2025)
[45] International Energy Agency Global overview—renewables 2024—analysis (IEA) (available at: www.iea.org/reports/renewables-2024/global-overview) (Accessed 31 January 2025)
[46] IEA 2022 Securing clean energy technology supply chains (International Energy Agency) (available at: https://iea.blob.core.windows.net/assets/0fe16228-521a-43d9-8da6-bbf08cc9f2b4/SecuringCleanEnergyTechnologySupplyChains.pdf)
[47] IEA State of energy policy 2024 (IEA) (available at: www.iea.org/reports/state-of-energy-policy-2024/key-findings) (Accessed 16 October 2025)
[48] European Commission 2021 The European green deal (available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en) (Accessed 14 February 2025)
[49] International Energy Agency Italy—energy mix (available at: www.iea.org/countries/italy) (Accessed 31 January 2025)
[50] International Energy Agency Switzerland—energy mix (IEA) (available at: www.iea.org/countries/switzerland/energy-mix) (Accessed 31 January 2025)
[51] Swiss Federal Office of Energy Energy perspectives 2050+ (available at: www.bfe.admin.ch/bfe/en/home/politik/energieperspektiven-2050-plus.html) (Accessed 5 March 2025)
[52] Ministero dell'Ambiente e della Sicurezza Energetica 2024 Piano Nazionale Integrato per l'Energia e il Clima (available at: www.mase.gov.it/sites/default/files/PNIEC_2024_revfin_01072024.pdf) (Accessed 5 July 2024)
[53] Wongsoonthornchai M, Scheidegger R, Kwonpongsagoon S and Bader H-P 2021 Analysis of time-dependent mercury flows through the use of thermometers and sphygmomanometers in Thailand *GEOMATE J.* **12** 65–70

[54] Moreau V and Massard G 2017 Material and energy flow analysis *Oxford Research Encyclopedia of Environmental Science* (https://doi.org/10.1093/acrefore/9780199389414.013.109)
[55] European Commission *et al* 2017 Methodology for establishing the EU list of critical raw materials: guidelines (Publications Office of the European Union: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs) (https://doi.org/10.2873/769526) (Accessed 17 February 2025)
[56] Swiss Federal Office of Energy Wind energy plants (map.geo.admin.ch) (available at: https://map.geo.admin.ch/#/map?lang=en¢er=2643293.41,1163244.22&z=1.224&topic=inspire&layers=ch.bfe.windenergieanlagen&bgLayer=ch.swisstopo.pixelkarte-farbe&catalogNodes=inspire) (Accessed 20 March 2024)
[57] Gestore dei Servizi Energetici Statistiche GSE sulle energie rinnovabili elettriche in Italia (available at: www.gse.it/dati-e-scenari/statistiche) (Accessed 27 January 2025)
[58] International Energy Agency 2023 National survey report of PV power applications in Switzerland—2022 (International Energy Agency—Photovoltaic Power Systems Programme) (available at: https://iea-pvps.org/national_survey/national-survey-report-of-pv-power-applications-in-switzerland-2022/) (Accessed 27 January 2025)
[59] International Energy Agency 2023 *National Survey Report of PV Power Applications in Italy—2022* (International Energy Agency—Photovoltaic Power Systems Programme) (available at: https://iea-pvps.org/national_survey/national-survey-report-of-pv-power-applications-in-italy-2022/) (Accessed 27 January 2025)
[60] Gestore dei Servizi Energetici 2012 Rapporto Statistico 2011—Impianti a fonti rinnovabili (Gestore dei Servizi Energetici) (available at: www.sunia.it/wp-content/uploads/2016/02/FontiRinnovabili_GSE2011.pdf)
[61] Associazione nazionale energia del vento 2023 Associazione nazionale energia del vento Brochure 2023 (Associazione nazionale energia del vento) (available at: www.anev.org/wp-content/uploads/2023/06/ANEV_brochure_2023.pdf)
[62] Joint Research Centre 2011 Critical metals in strategic energy technologies: assessing rare metals as supply-chain bottlenecks in low-carbon energy technologies (European Commission Joint Research Center) (available at: https://setis.ec.europa.eu/critical-metals-strategic-energy-technologies_en) (Accessed 13 June 2025)
[63] Euractiv Rare-earth shortage to hamper clean energy: EU study (Euractiv) (available at: www.euractiv.com/news/rare-earth-shortage-to-hamper-clean-energy-eu-study/) (Accessed 1 October 2025)
[64] Carrara S *et al* 2023 Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU: a foresight study *JRC Science For Policy Report*, No. 31437 (Publications Office of the European Union) (https://doi.org/10.2760/386650)
[65] Luu L Q, Nguyen T Q, Khakpour S, Cellura M, Nocera F, Nguyen N H and Bui N H 2025 Material demand and contributions of solar PV end-of-life management to the circular economy: the case of Italy *Sustainability* **17** 6592
[66] Hahn Menacho A J, Sacchi R, Bauer C, Panos E, McKenna R and Burgherr P 2025 The material-energy nexus in net-zero transition scenarios: exploring environmental trade-offs and uncertainties *Resour. Conserv. Recycl.* **218** 108251
[67] IRENA 2023 Geopolitics of the energy transition: critical materials (International Renewable Energy Agency (IRENA)) (available at: www.irena.org/-/media/Files/IRENA/Agency/Publication/2023/Jul/IRENA_Geopolitics_energy_transition_critical_materials_2023.pdf)
[68] Grafström J, Poelzer G and Pettersson J 2025 Barriers to circularity in the metals industry: an analytical framework of feedback and lock-in effects *Miner. Econ.* 1–13
[69] Unruh G C 2000 Understanding carbon lock-in *Energy Policy* **28** 817–30
[70] Eitan A and Hekkert M P 2023 Locked in transition? Towards a conceptualization of path-dependence lock-ins in the renewable energy landscape *Energy Res. Soc. Sci.* **106** 103316
[71] Kamran M, Raugei M and Hutchinson A 2023 Critical elements for a successful energy transition: a systematic review *Renew. Sustain. Energy Transit.* **4** 100068
[72] OECD, Ed 2024 Harnessing public procurement for the green transition: good practices in OECD countries *OECD Public Governance Reviews* (OECD Publishing) (https://doi.org/10.1787/e551f448-en)
[73] Diófási-Kovács O and Tátrai T 2025 Environmentally sustainable public procurement of construction projects—implementing circularity approach *Public Works Manage. Policy* **30** 137–62
[74] European Commission, Ed 2017 *Promoting Remanufacturing, Refurbishment, Repair, and Direct Reuse: As a Contribution to the G7 Alliance on Resource Efficiency 7–8 February 2017 Brussels, Belgium: Workshop Report* (Publications Office) (https://doi.org/10.2779/1810037)
[75] Psarommatis F, May G and Azamfirei V 2025 Product reuse and repurpose in circular manufacturing: a critical review of key challenges, shortcomings and future directions *J. Remanufacturing* **15** 273–310
[76] Castro-Sejin A, Mammadli A and Barakos G 2023 Criticality of raw materials—a clarification and redefinition of the term worldwide *Critical Minerals Conf. 2023, AusIMM* pp 3–16 (available at: https://espace.curtin.edu.au/handle/20.500.11937/93821) (Accessed 1 September 2025)
[77] Schicho M and Tercero Espinoza L 2024 Criticality assessment for raw materials: perspectives and focuses *Miner. Econ.* 1–18
[78] Nwaila G T, Bourdeau J E, Zhang S E, Chipangamate N, Valodia I, Mahboob M A, Lehohla T, Shimaponda-Nawa M, Durrheim R J and Ghorbani Y 2024 A systematic framework for compilation of critical raw material lists and their importance for South Africa *Resour. Policy* **93** 105045
[79] Wäger P 2011 Scarce metals—applications, supply risks and need for action *Not. Polit.* **27** 57–66 (available at: www.researchgate.net/publication/231513584_Scarce_metals_-_Applications_supply_risks_and_need_for_action)
[80] Bastianin A, Li X and Shamsudin L 2025 Forecasting the volatility of energy transition metals (arXiv:2501.16069)
[81] Månberger A and Stenqvist B 2018 Global metal flows in the renewable energy transition: exploring the effects of substitutes, technological mix and development *Energy Policy* **119** 226–41
[82] Binnemans K and Jones P T 2015 Rare earths and the balance problem *J. Sustain. Metall.* **1** 29–38
[83] Kavlak G, McNerney J, Jaffe R L and Trancik J E 2014 Growth in metals production for rapid photovoltaics deployment *2014 IEEE 40th Photovoltaic Specialist Conf. (PVSC)* pp 1442–7
[84] Gauss R *et al* 2021 Rare earth magnets and motors: a European call for action. A report by the rare earth magnets and motors cluster of the European raw materials alliance (European Raw Materials Alliance) (available at: www.eit.europa.eu/sites/default/files/2021_09-24_ree_cluster_report2.pdf)
[85] Alves Dias P, Bobba S, Carrara S and Plazzotta B 2020 The role of rare earth elements in wind energy and electric mobility: an analysis of future supply/demand balances (Publications Office of the European Union) (available at: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC122671/jrc122671_the_role_of_rare_earth_elements_in_wind_energy_and_electric_mobility_2.pdf?)

[86] European Environment Agency, Ed 2024 Accelerating the circular economy in Europe: state and outlook 2024 *EEA Report*, No. 2023, 13 (Publications Office of the European Union) (https://doi.org/10.2800/055236)

[87] Tercero Espinoza L *et al* (eds) 2024 *The Role of Research and Innovation in Ensuring a Safe and Sustainable Supply of Critical Raw Materials in the EU* (European Parliament) (https://doi.org/10.2861/54343)

[88] European Commission 2024 Science for policy brief: advanced materials for substitution in the clean energy sector (European Commission Joint Research Center, JRC136474) (available at: https://setis.ec.europa.eu/document/download/1ac68d55-705e-4b28-ad2a-3d681d4ca90d_en?filename=Advanced%20materials%20for%20CRM%20substitution_0.pdf)

[89] Encyclopedia Energy Développement mondial de l'éolien et criticité des matières premières (available at: www-echosciences–grenoble-fr.translate.goog/articles/xcx?_x_tr_sl=fr&_x_tr_tl=en&_x_tr_hl=fr&_x_tr_pto=wapp) (Accessed 28 August 2025)