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Citation

Liang, Y., Kleijn, E. G. M., Tukker, A., & Voet, E. van der. (2022). Material requirements for low-carbon energy technologies: a quantitative review. *Renewable And Sustainable Energy Reviews*, *161*. doi:10.1016/j.rser.2022.112334

Renewable and Sustainable Energy Reviews 161 (2022) 112334

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Material requirements for low-carbon energy technologies: A quantitative review

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ARTICLE INFO

Keywords:
Energy transition
Material demand
Material intensity
Low-carbon technologies

ABSTRACT

Deployment of clean energy technologies will require a considerable amount of materials. The surge in demand for metals related to emerging energy technologies may hinder the energy transition. In this study we provide a comprehensive overview and analysis of existing work in this field, a solid quantitative baseline for material requirements of different energy technologies and quantitative information that can be used to generate learning curves for the material requirements of different energy technologies. We conducted a quantitative review of the material requirements of low-carbon energy technologies in 132 scientific publications, and provided a comparative analysis of detailed data including material intensity and lifetime data. Besides providing a large amount of structured quantitative data, the results of our work indicate that: (1) research on the demand for low-carbon technology related metals has received much attention since the 2010s; (2) around 80% of the publications focus on the global level while national level studies are underrepresented; (3) science-based future scenarios are the main means of estimating total future material requirements; (4) most studies foresee material constraints of large-scale implementation of low-carbon technologies and the secure and responsible supply of these materials is still the subject of discussion; (5) changes in metal intensity caused by technological development and material requirements for non-critical components are important though often overlooked.

1. Introduction

The low-carbon energy transition is the main pillar of climate change policy aiming to achieve the 'well below 2°' goal of the Paris Agreement (PA) [1] [2] [3]. It is also essential for achieving the UN 2030 Sustainable Development Goals (SDGs) [4]. The World Energy Outlook 2020 published by the International Energy Agency (IEA) shows a rise in the combined share of solar PV and wind in global generation from 8% in 2019 to almost 30% in 2030 [5], and according to the International Renewable Energy Agency (IRENA), 8500 GW of solar energy and 6000 GW of wind power will be installed, which would provide 60% of global electricity generation by 2050. Besides this, the global stock of electric vehicles (EVs) in 2050 would be more than 800 times that of 2015, reaching 965 million passenger cars [6].

Such ambitious plans can mitigate climate change but at the same time they will generate new opportunities and dilemmas related to the supply of the raw materials required for this transition [7]. Compared with fossil-fuel-based power systems, the transition to clean energy will be more mineral intensive [8]. Renewable energy technologies require complex composites and alloys, which in turn will significantly increase the demand for finite metals [9] [10] [11] [12]. This has also led to concerns that the successful transition to clean energy technologies may be limited by the availability or disruption of critical mineral supplies [13] [14] [15] [16]. Understanding whether minerals have potential constraints on the deployment of low-carbon technologies, and the extent of the restrictions, will help us identify possible mitigation

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Abbreviations: PV, photovoltaics; EVs, electric vehicles; CSP, concentrating solar power; T&D, transmission and distribution networks; AFVs, alternative fuel vehicles; FCVs, fuel cell vehicles; BEVs, battery electric vehicles; PHEVs, plug-in hybrid electric vehicles; ICEVs, internal combustion engine vehicles; CCS, carbon capture and storage; DD, direct drive; REEs, rare earth elements; PGMs, platinum group elements; IO, input-output model; MFA, material flow analysis; SD, system dynamic model; LCA, life cycle assessment; HTS, high-temperature superconductor; PMs, permanent magnets; c-Si, crystalline silicon cells; a-Si, amorphous silicon; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; DSSC, dye-sensitized solar cells; SOFC, solid oxide fuel cells; BOS, balance system; T/GW, ton/gigawatt.

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https://doi.org/10.1016/j.rser.2022.112334
Received 9 March 2021; Received in revised form 11 February 2022; Accepted 26 February 2022

options or alternatives in advance, which is vital for the successful implementation of the energy transition [7].

In the last decade, a comparability analysis of existing scientific studies provides a relatively clear picture of metal requirements for low-carbon technologies in different dimensions and perspectives. The spatial boundaries of these studies involve different geographic ranges, from globally [17-21], and regionally [22-24], to nationally [10] [14] [25-29]. Research on the material requirements for low-carbon technologies is also becoming more diverse, with abundant research on wind power [24] [30-34], PV [35-40] and concentrated solar power (CSP) [41-43]. The deployment of low-carbon energy technologies will also lead to a corresponding large-scale expansion of energy transmission and distribution networks (T&D) and a need for storage capacity [44]. Furthermore, infrastructure to buffer the intermittency of renewables such as wind and solar might also be needed [11] [45] [46-47]. As for energy end-use, electric and hydrogen-electric drivetrains will gradually replace internal combustion engines [48] [49]. Not only are alternative fuel vehicles (AFVs) considered to be a cleaner and more efficient passenger transportation solution, but a new type of energy storage device can also be used to some extent for buffering the intermittency [50-53]. The demand for lithium, cobalt, manganese, nickel and other battery metals could increase more than threefold in the next decade, and the development of fuel cell vehicles (FCVs) might also lead to a growth surge in the demand for platinum group elements (PGEs) [49] [54-59].

Several reviews have identified gaps and progress of materials use in energy transition. In 2011, Graedel discussed the availability of energy-related metals, specifying that the deployment of advanced energy technology will use some critical materials, and that these materials often lack effective substitutes. Starting from metals availability, he stated that, as the availability of metals used by modern technologies is dynamic, any indicator would require constant reassessment [60]. In the intervening years, some scholars have reviewed the resource needs of specific low-carbon technologies, such as wind energy [30], PV [35], and Li-ion batteries [59]. Buchholz and Brandenburg reviewed the supply-demand as well the price of raw materials related to clean energy technologies. They argued that despite the high degree of uncertainty about the future demand for related raw materials, there are significant supply risks [46]. In 2020, Watari et al. selected 88 academic publications focusing on the analysis of the future (after 2020) and reviewed the needs of the 48 minerals involved in the renewable energy systems. They concluded that the difficulty in obtaining detailed and reliable data for the metal intensity of different technologies will seriously inhibit the progress of scientific research [61]. Subsequently, Lee et al. considered a series of changes and impacts on the mineral raw material market that may be caused by the energy transition, including security of supply, supply chain issues, investment strategy, innovation, and policy trends, and pointed out that a better understanding of low-carbon technologies and their material concerns is an important step towards the goal of decarbonization [62].

As mentioned above, all these studies have increased the understanding of the material requirements of low-carbon technologies from a multi-dimensional perspective. However, a systematic comprehensive quantitative overview of the detailed data on materials demand for low-carbon technologies is still lacking. This requires a detailed comparative study of datasets, scopes, methodologies and approaches.

In this paper we will provide a comprehensive and state-of-the-art overview of metal requirements for the transition to a low-carbon energy system. The aim is to provide a dataset containing detailed material intensity and lifetime data collected from over 132 articles published between 1998 and July 2020, ranging in scope from global to local, from static analysis to dynamic analysis, retrospective (earliest to 1900) to prospective (to 2250), and covering single or several technologies and elements, as well as a summary of the methods and research scope of the selected papers.

2. Methodology

2.1. Definition of the metal requirement of the low-carbon energy technologies

2.1.1. Technologies included in this review

Here we focus on the material demand for energy generation, transmission and distribution (T&D), and end-use. As illustrated in Fig. 1, this paper included three main energy generation technologies: wind power, solar PV and CSP, including the corresponding sub-technologies. For the end-use sector we included: Battery Electric Vehicles (BEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Fuel Cell Vehicles (FCVs). Only light-duty passenger cars are included here, heavy-duty vehicles and two-wheel, three-wheel electric bicycles are beyond the scope of this review. For T&D we included: the electricity transmission network, Carbon Capture and Storage (CCS), energy storage facilities (stationary batteries/fuel cells), and hydrogen pipelines.

2.1.2. Literature review

A systematic quantitative literature review method allows reliable assessments to check the current progress of specific research topics. This study used the following queries in Web of Science (WOS): "*energy transition*", "*energy transformation*", and also metal-related search terms: "*metal demand*", "*metal constraints*", "*metal requirement*", "*metal bottleneck*", and words representing low-carbon technologies: "*wind*", "*solar*", "*photovoltaics*", "*electricity*", "*hydrogen*", "*electric vehicle*", "*fuel cells*", "*CCS*", *etc*. The timeframe of the search was unlimited but the results were restricted to studies published in English. The complete list of terms and their related variants, as well as the results for each stage of screening, are displayed in Table S1 of Supporting **Information (SI)**.

The criteria for selecting the literature are presented in Fig. 2. The search in WOS resulted in 1551 records. Article types include journals and proceedings, while books, reports and book chapters were excluded. Duplicate records were deleted as well as records without full text papers, which resulted in 1406 records. These records were filtered based on the following criteria: (1) the focus should be on the metal demand of the energy transition, rather than the energy demand of mining; (2) the paper should provide information on the type of low-carbon technologies and type of metals; (3) the publication should be published in a peer-reviewed journal. This resulted in 45 articles that met our research scope. In addition to the records from WOS, 87 articles were derived from snowballing and other references. These two parts together constitute the main literature list of this paper: a total of 132 papers, of which 18 are review/overview/perspective/viewpoint/commentary/discussion studies, while the rest are general full-length research papers. We also screened out the citations of the top 20 cited articles (Table S1 of **SI**), which are all cited more than 100 times.

2.2. Extraction of quantitative data from the papers

Relevant information from the selected papers was analyzed, including: technologies, materials, research method, and geographical and temporal scope. Besides, quantitative data on metal intensity, technical lifetime were extracted from provided tables, figures and corresponding appendices. In practice this was done in one of the following ways: (1) the data was directly obtained from the text or tables, (2) if the data in the text was given in intervals, the mean value was taken, (3) the information provided in figures was converted into numbers with the help of GetData Graph Digitizer [63], (4) in some cases some transformations of given data were needed to acquire the data required in this review. Since these technologies are developing rapidly, it is important to also record the year of collection of the data or the date for which the given data is representative according to the authors. If this information was not available, the publication date was used (18 data points in 8 papers, see Table S7).

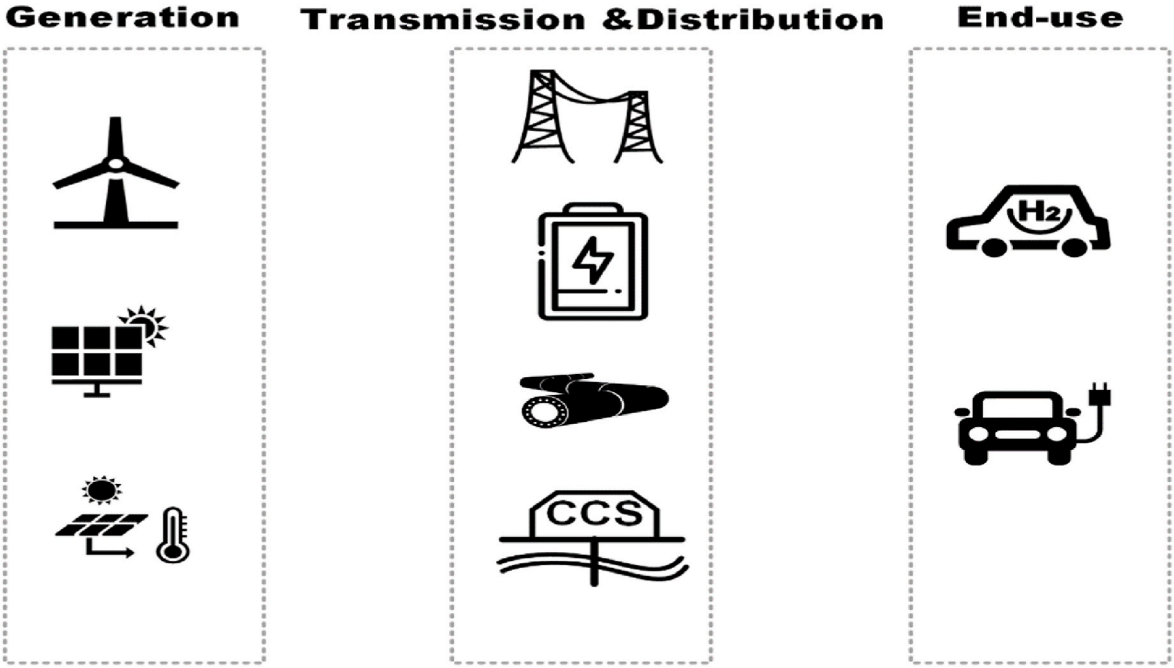


Fig. 1. Technologies included in this review.

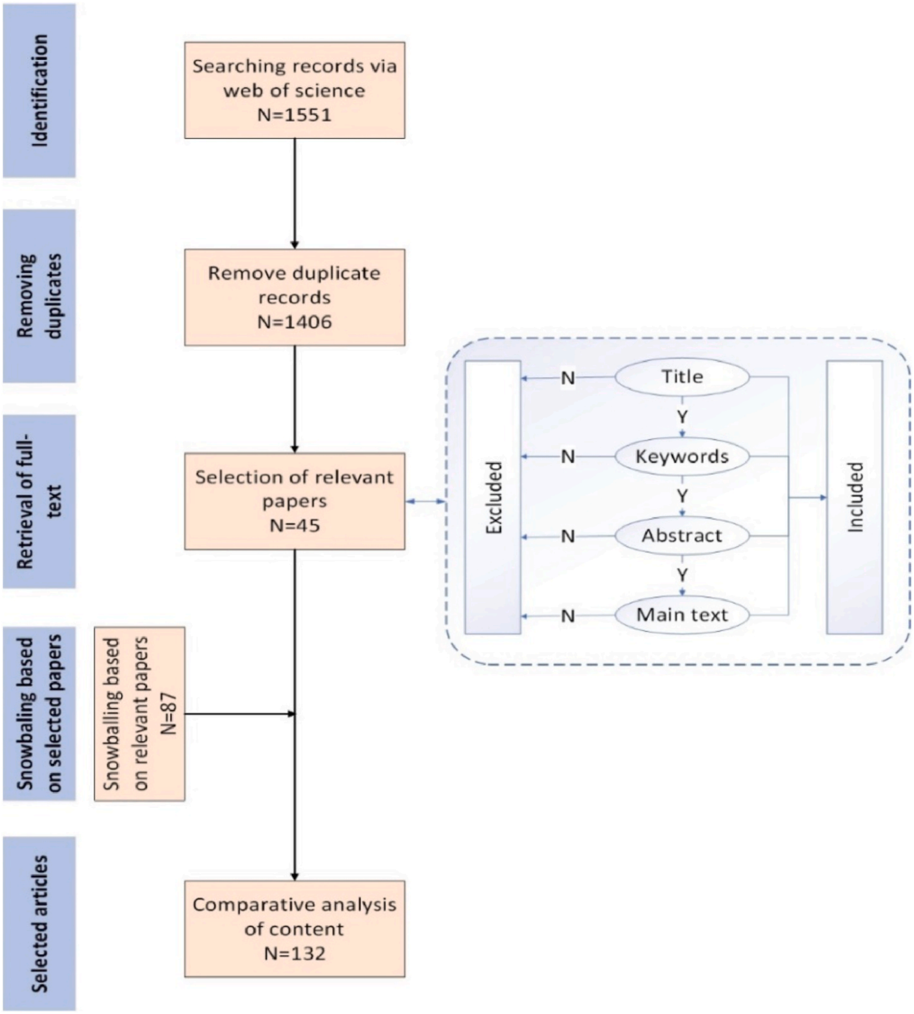


Fig. 2. Design of the literature screening process.

3. Results

3.1. Analysis of the main characteristics of the studies

It is very clear that the research on the demand for materials related to the energy transition has aroused great research interest over the past decade (See Fig. S1). The number of articles published since 2010 accounts for 94% of the total number of articles. Characteristics of general articles (excluding review/discussion/commentary/viewpoint, etc. articles) of the main literature are analyzed below.

3.1.1. Temporal and geographical scope

The total number of general articles is 114. Fig. 3 (a) presents the summary of the temporal scope of 109 general papers (5 papers did not include specific time boundaries). The temporal scope of these papers ranges from 1900 to 2250 and more than 89% of papers take a prospective approach. Over half of the prospective studies choose 2050 as the final year for their projections. Only four papers used a static analysis and reported metal demand for one specific year.

When looking at the geographical boundaries of the literature as given in Fig. 3 (b), the number of publications is distributed from the global level (77) and the regional level (5) to the national level (32). Only a limited amount of country-specific research was found, mainly for China, the U.S. and some European countries. All five studies with a regional scope focused on Europe.

3.1.2. Materials

In total, 61 elements are mentioned in the selected papers: 55 metals and 6 non-metallic elements (Fig. 3 (c)). Overall, the number of types of elements studied has become increasingly diverse over time. REEs have received the most attention: 49.6% of the papers included these metals. Lithium has been widely discussed as one of the crucial ingredients for batteries for EVs and energy storage. Of the 26 papers mentioning cobalt, another ingredient of batteries, more than two-thirds of them have been published in the past 5 years. The research interest in base metals remains stable over time; copper plays a crucial role both in the technologies and the T&D network.

3.1.3. Technologies

Fig. 3(d) illustrates the distribution of target technologies in 113 general publications, of which 57 are related to solar PV, followed by 52 related to wind power. In wind-power-related papers, wind energy is generally further classified according to different sub-technologies: about 60% of the papers divide wind power into offshore and onshore according to the location of the wind farm and 20% are divided into direct drive (DD) and geared turbines. Five articles consider both location and technology, and give a more detailed classification of wind energy. There are many different PV technologies. The specific composition of each PV sub-technology is introduced in detail in section 3.2.2.

3.1.4. Methods, tools and scenarios

In addition to the statistics of the target technologies and elements, the methods and scenarios used in different studies are given in Table 1. Modeling is widely used (106 papers, 80.3%). Scenario analysis is used in many of the model/simulation methods; these scenarios are established in prospective analysis to quantify the annual increase of low-carbon energy technologies. Future demand for materials for these technologies can be quantified based on these scenarios. Table 1 summarizes which scenarios are most frequently used. There are 57 articles where the authors define their own scenarios. The other articles use scenarios taken from different international organizations, the most frequently used being the International Energy Agency (IEA) (28 papers). In addition to global-level scenarios, some national-scale scenarios are also indicated below.

3.2. Metal intensity data for different low-carbon technologies

A quantified overview of the use of different elements in low-carbon technologies is given in Table S4 (**SI**). REEs are used in permanent magnets (PMs) that in turn are used in motors in EVs and generators in wind turbines. Platinum is used as a catalyst in fuel cells, and gallium and indium are used in thin-film solar cells. Bulk metals such as steel, copper, and aluminum are the backbone of the development of all low-carbon technologies. Only a small number of articles (13) take a dynamic approach considering changes in material intensity due to technological improvements (Table 2).

3.2.1. Wind power

There are more than 600 valid data points for the materials intensity of wind power; the time range of these data is 2000–2050. Taking into account changes in technology and markets, data that is too old may not be fully adapted to the current situation. We have listed the data points of the most recent year (2016 and after) in Fig. 4, and the data points of all-time ranges are displayed in **SI** (Fig. S2). Onshore and offshore wind turbines have many similarities in design, technology, and material composition, and there are also some differences in the turbine itself and wind energy farms. Compared with land-based wind turbines, offshore wind turbines generally face more severe extreme weather tests and need to be more resistant to corrosion and withstand stronger winds; the maintenance difficulty of offshore wind power is higher in terms of cost and technology.

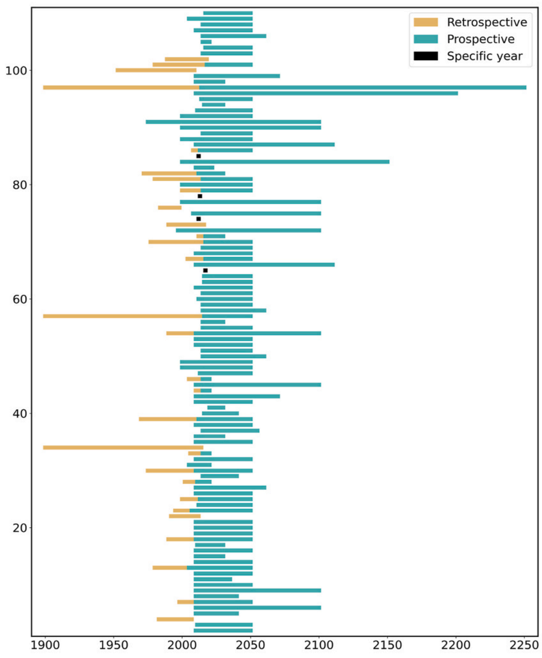
Direct-drive wind turbines almost always contain large NdFeB permanent magnets (PMs); some gearbox wind turbines will also use smaller PMs. The use of metals such as neodymium, dysprosium, and praseodymium is shown in Fig. 4 (b). One novel technology is based on high-temperature superconductor (HTS) generators, and the material most likely to be used for these would be YBCO (yttrium-barium-copper-oxide), which would inevitably also need to use REEs [72]. However, since this technology is still in the early stages of development, the data available is very limited and is therefore not presented here [68,73].

3.2.2. Solar energy

Solar energy is considered to be one of the renewable energy sources with highest potential. The relevant data, including solar PV and concentrated solar energy (CSP), have also been extracted. The intensity data of 21 PV material in the existing main literature covered around 500 data points (**SI**). By further collating the intensity data since 2016, it has been found that, unlike other technologies, the data points of PV have been reduced by about 54%. Based on the existing research objects, we have summarized several types of solar PV sub-technology, including crystalline silicon cells (c-Si, 1st generation), as well as thin-film solar cells (2nd generation), including amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS). Compared to the 1st generation solar cells using metallic silver as a conductor, the semiconductors used in thin-film solar cells are composed of indium, gallium, copper, cadmium, tellurium, etc., so the intensity data for silver in Fig. 5 only exists in the absence of PV sub-technology for classification, and c-Si solar cell related papers. The sources and specific values of the content data of various elements in PV are listed in Fig. S3 of **SI**. The third-generation solar cells, such as organic solar cells [74] and dye-sensitized solar cells (DSSC), require metals such as lead, platinum, and ruthenium, but as they are still in the laboratory stage, very little metal intensity data is available [42,75–78], they have not been considered yet.

3.2.3. Alternative fuel vehicle

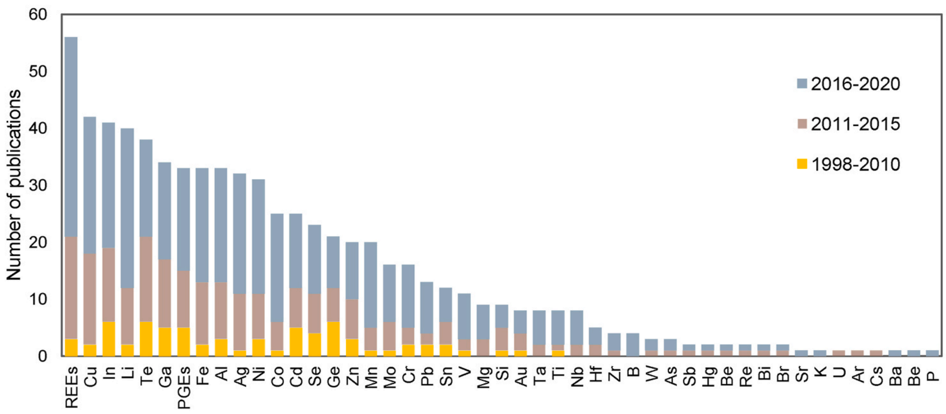
A total of 40 elements are mentioned in AFVs, including 469 data points, and the number of elements and data points in 2016 (the time of data) and after are 37 and 343 respectively. Among them, 52 papers have analyzed EVs (including battery electric vehicles (BEVs) and hybrid plug-in electric vehicles (PHEVs)), and 26 have analyzed FCV



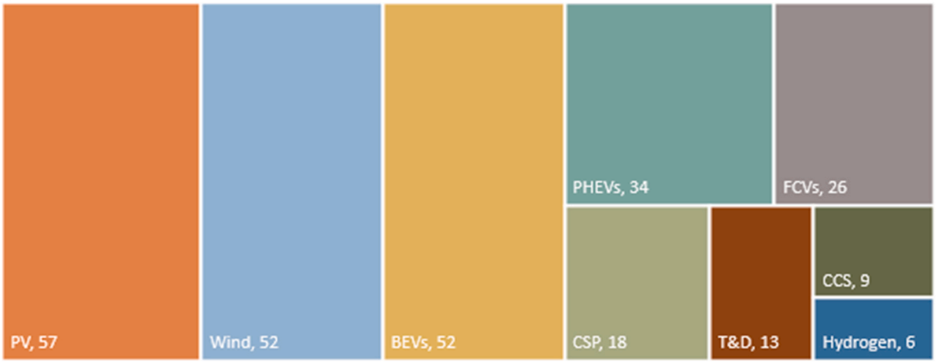
(a)

Global		77
Regional		5
	European	5
Country		32
	China	11
	The U.S.	7
	UK	4
	Germany	4
	Denmark	2
	Australia	1
	Spain	1
	France	1
	India	1
	Japan	1

(b)



(c)



(d)

Fig. 3. General characterization of the papers. (a) The temporal scope for the 85 papers that specify this; **(b)** The geographical scope; **(c)** The elements studied (REEs and PGEs are groups of elements); **(d)** Technologies included in the study.

Table 1
Research methods and scenarios (Since the literature list needs to be updated, the number here is currently inaccurate).

Categories		Number of Papers
Methodology		
Modeling		100
Scenario analysis		86
Material flow analysis (MFA)		37
Other models		24
Life cycle assessment (LCA)		9
System dynamic model (SD)		6
Input-output model (IO)		4
Review		18
Other methods		16
Case Study		4
Scenario	**Description**	86
Own scenario		57
IEA	World Energy Outlook and other reports published by IEA	28
Greenpeace	Advanced Energy [R]evolution (AER) scenario presented by Greenpeace 2015	5
NDRC (China)	National Development and Reform Commission scenarios in China	4
UNEP	Global Environmental Outlook (GEO-3)	3
WEC	World energy scenarios, 2016	3
IPCC	Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011	3
DECC (UK)	DECC 2050 Pathways Analysis	2
EIA (the U.S.)	Annual energy outlook published by EIA	2
SSP	The Shared Socioeconomic Pathways	2
EPIA	Photovoltaic Electricity Empowering the World 2011	2
GWEC	The Global Wind Energy Outlook “advanced scenario'' of the GWEC	2
MERGE (Europe)	Mobile energy resources in grids of electricity deliverable, 2011	1
EREC (Europe)	“Advanced International Policy Scenario” drawn by EREC	1
IDA (Denmark)	A Smart Energy System Strategy for 100% Renewable Denmark	1
DEA (Denmark)	Energy Scenarios for 2020, 2035 and 2050	1
ANCRE (France)	Decarbonization via electricity (In French)	1
DOE (the U.S.)	Wind Vision: A New Era for Wind Power in the United States	1
SGERI (China)	China’s Energy and Power Development Outlook developed by the State Grid of China	1
World Bank	The Growing Role of Minerals and Metals for a Low Carbon Future	1
IRENA	Global Energy Transformation—A Roadmap to 2050	1
WWF	The Ecofys Energy Scenario; 100% Renewable Energy by 2050	1
Shell	Scramble scenario	1
GEA	GEA-supply, conventional transportation, full portfolio scenario	1

* Some papers use more than one method or scenario, so the sum of the various sub-methods in the table exceeds the total number of articles, and the sum of different scenarios exceeds the total number of articles using scenario analysis. Details of the corresponding abbreviations in this table are shown in Table S3 of **SI.**

technology. The metal intensity data in different AFVs are shown in Figs. 6 and 7 respectively), and the data points of all time ranges are detailed in **SI** (Fig. S4-6).

As shown in Fig. 6, BEVs do not contain any PGEs, and PHEVs have a certain demand for platinum, palladium, and rhodium. The content of battery-related elements in BEVs is higher than that in PHEVs. Although many countries have vigorously promoted the electrification of automobiles, certain technical problems are extremely difficult to solve in the short term, such as charging efficiency, mileage, and the effect of temperature on performance. Therefore, BEVs still have a long way to go to completely replace traditional internal combustion engine vehicles (ICEVs), and PHEVs as a transition product will still have a certain market share in the foreseeable future.

Among FCV-related elements, platinum is used as a catalyst in PGE fuel cells, which has the largest number of data points, ranging from 4 to 22 g per vehicle (Fig. 7). FCVs require a built-in hydrogen storage tank and a (relatively small) battery system or a supercapacitor to improve the energy conversion efficiency of the vehicle. Thus, materials such as lithium and cobalt found in batteries are also essential in FCVs [80–82].

3.2.4. *Other technologies*

Compared with the number of studies on the material requirements of wind, solar, and AFVs, there are few studies on the metal demand that focus on energy transmission and distribution, CCS, and electrolysis and hydrogen pipelines. The energy transition will require a significant increase in the network for electricity transmission, for which large amounts of copper and aluminum will be required, Both niobium and vanadium are highly relevant to CCS, according to the World Bank [83]. The deployment of CCS will also raise the demand for titanium. If hydrogen is used as a buffer for the intermittency of wind and solar energy, this will require the use of large fixed solid oxide fuel cells (SOFC) containing elements such as nickel, lanthanum, cerium, yttrium, etc. [18]. The specific material intensity data of these technologies are shown in the **SI**.

3.3. *Lifetime distribution for different low-carbon technologies*

In addition to material intensity, lifetime is another crucial parameter for accounting for material requirements of energy technologies. For wind turbines, the technical life is assumed to be between 12 and 40 years; the average lifetime of offshore wind power is longer than land-based wind power. Only one paper considered repowered wind turbines with a service life of 12 years [84]. From the data shown in Fig. 8, the average service life of wind energy is more than or equal to 20 years, but the actual decommissioning life may be shorter [85]. PV’s minimum service is 20 years, the mean value of lifetime for different PV technologies is between 25 and 27 years. The energy transmission facilities have a relatively longer lifetime. Evidence from the Netherlands proves that in general the lifespan of cables is 50 years: the lifetime of some overhead cables may even exceed one hundred years [86], while for China, this value is 40 years [47]. Material requirements for the transmission network has often been ignored in previous studies, so this article did not harvest abundant data about this. Some articles mention the lifespan of grid storage batteries [87] and stationary fuel cells [88,89]. Most studies contain assumptions about the fixed lifetime of these technologies. Some use lifetime distribution functions (such as Weibull and normal function) and a few articles consider lifetime extension with the development of technology to reduce the uncertainty caused by assuming a constant lifetime. All lifetime data found in the selected literature are given in the **SI** (Table S6).

4. Discussion

4.1. *Literature review*

All papers in our final selection were journal papers. Grey literature was not explored in our literature survey, but we also list some report information that may include possible relevant data in Table S8. During the review process, we found there are three reports were frequently cited, two published by the Joint Research Centre (JRC) of European Commission [90,91] and the one published by the U.S. Department of Energy (DOE) [92]. We also tracked that two newest JRC reports [93,

Table 2
List of papers considering changes in material content caused by future technological development.

Wind	Solar	AFVs	Data scale	Time point/range of "future" data	Description	References
	✓		Global	2020–2050	Linear interpolation is used from 2020 to 2040, and the content assumed to remain stable from 2040 to 2050	[64]
✓			Denmark	2017 and 2050	70% of the 2017 level used for material intensities in 2050	[10]
✓	✓		China	2030 and 2050	Material contents changes for different scenarios	[14]
✓			The U.S.	2016–2050	Assumed technological changes caused changes in material intensity	[34]
		✓	Global	2015 and 2030	Lithium intensity changes	[65]
		✓	Global	2015–2050	Platinum intensity changes	[66]
		✓	Global	2050	The materials content declines	[67]
✓	✓		The U.S.	2020 and 2040	Metal content changes under conservative, neutral optimistic three scenarios	[29]
✓	✓		Germany	2025 and 2050	Metal intensity change in future situation	[68]
	✓		Global	2020–2050	Linear interpolation is used from 2020 to 2050 by VENSIM software	[69]
	✓		Global	2010 and 2020	Different metal content	[70]
		✓	Global	2010–2050	Assuming the platinum loading declines as technology improves	[71]
	✓		Global	2008 and 2020	Different metal content	[36]

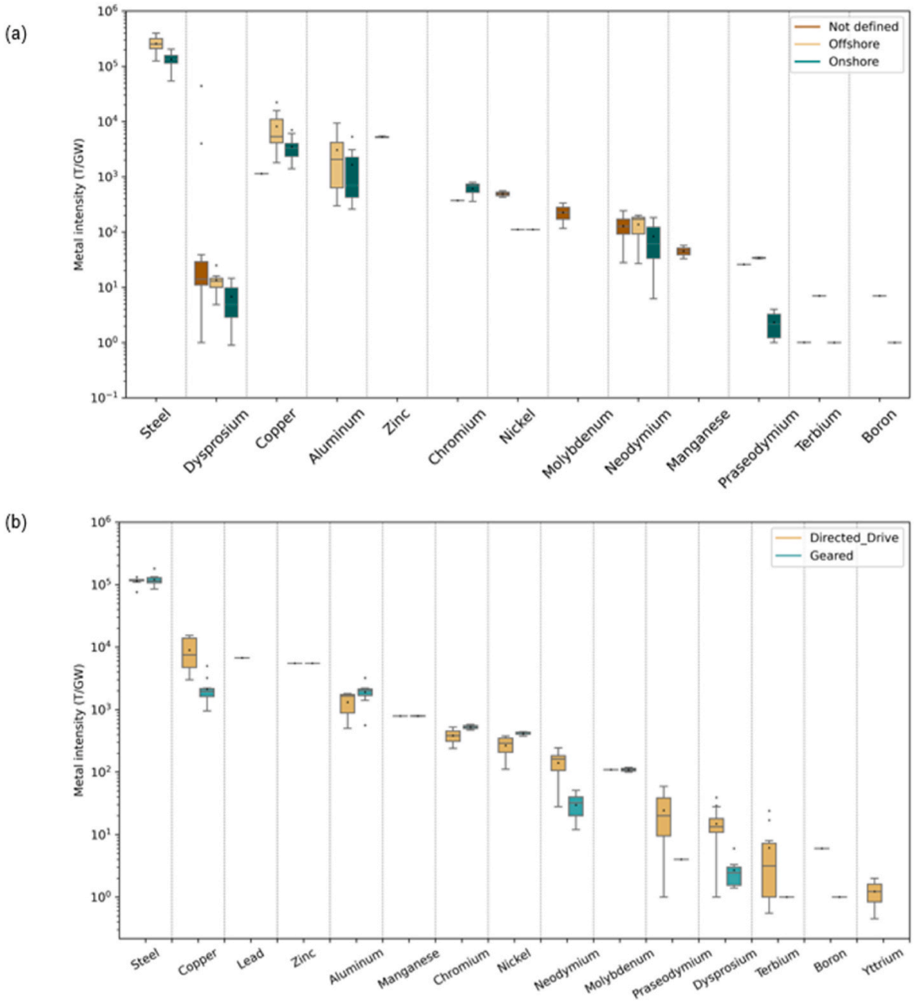


Fig. 4. The material intensity in different wind technologies after 2016.

94], and the World Bank report [83] as well. A review of the data used in these reports revealed that the data sources used as a basis for these reports have been included in our analysis.

Scenario analysis is found to be the mainstream method for calculating the material demand of energy transition in prospective research. Furthermore, most articles conclude that material constraints may become a stumbling block to the energy transition. However, national-level studies are still scarce and, there are still gaps in the analysis of the actual availability of materials, including those related to responsible sourcing and the geopolitical security of supply. It is necessary to continue to explore this further in future research.

4.2. *Material intensity data*

In this study we provide a quantitative overview of material intensity and lifetime data related to technologies essential for the energy transition. The technologies and corresponding materials included are listed in Table S3. This type of data is often used to produce quantified

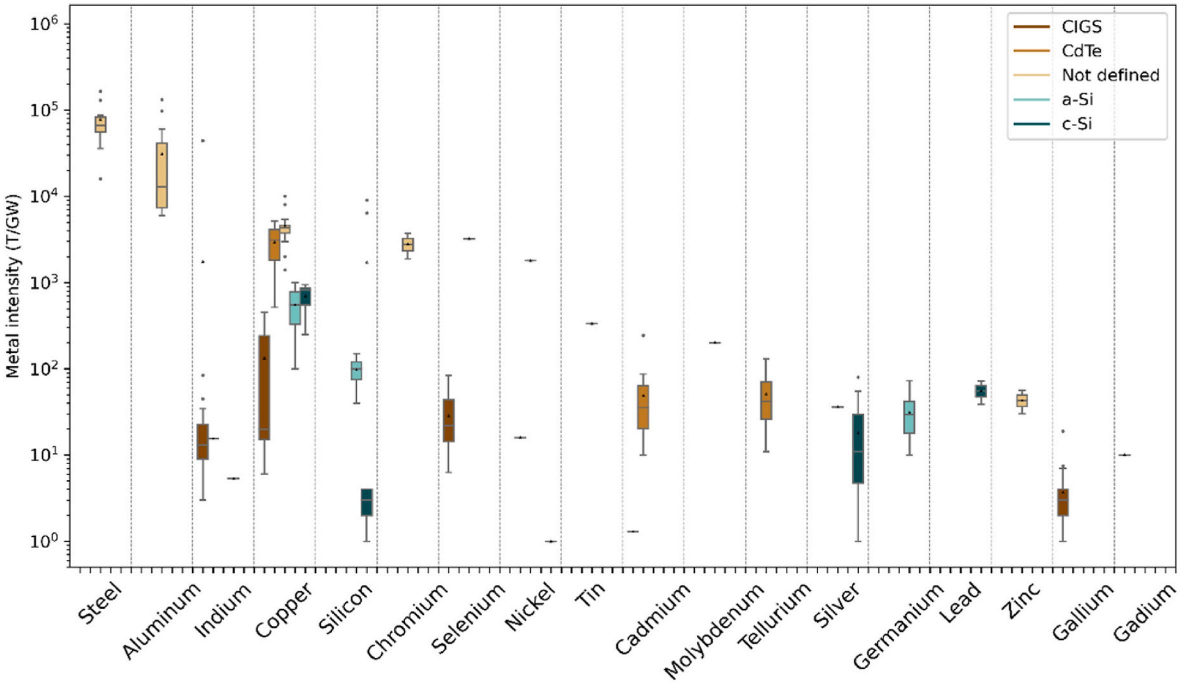


Fig. 5. The metal intensity of PV after 2016.

Besides solar PV, there is a total of 19 papers related to CSP technology. The main metals mentioned in these studies are more than 10 elements such as silver and copper, but through clear review, almost all the data in these studies are derived from the same original data source [43,79]. The specific data about the material type and intensity for CSP are displayed in **SI** (Table S5).

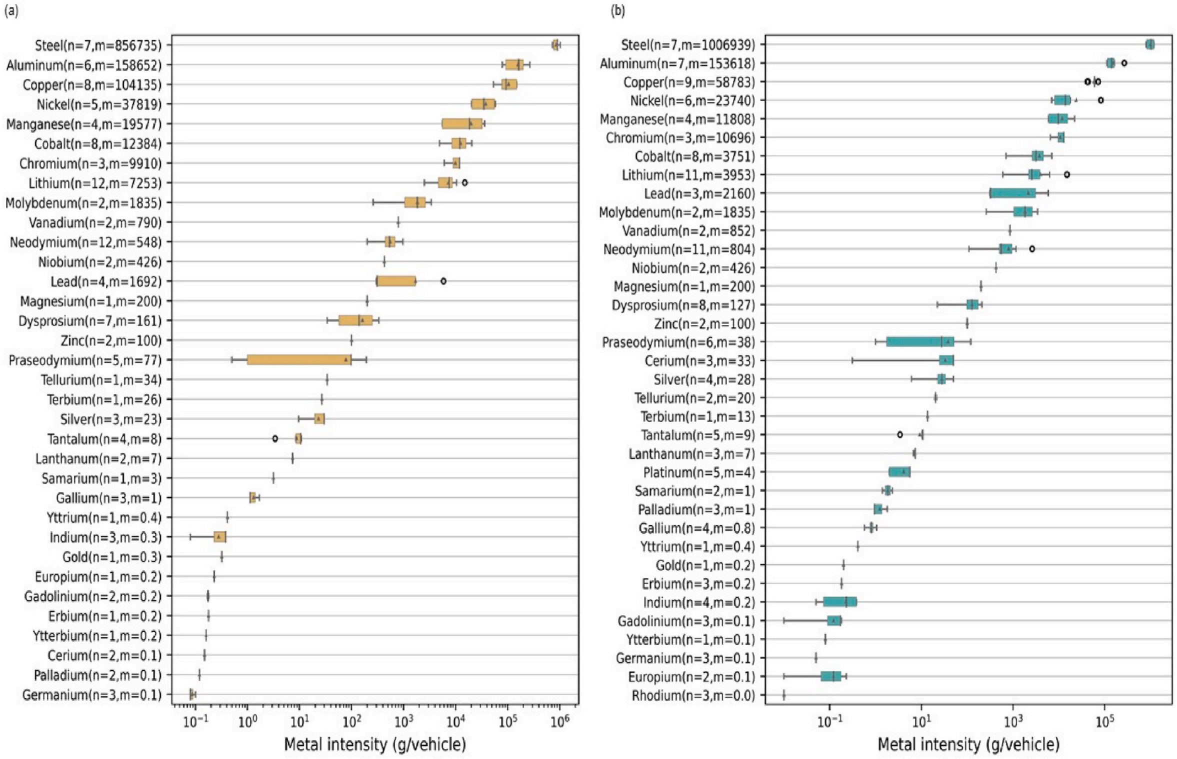


Fig. 6. Metal intensity data from source after 2016 of BEVs (a) and PHEVs (b). The data is visualized on a log10 scale. Annotation 'n' represents the number of the data dots, and 'm' means the mean value of intensity for each element.

scenarios for material requirements of different energy transition scenarios. The results show that there is a wide range of material intensity and lifetime data provided in the literature, which is mainly due to differences in assumptions. When calculating the material requirements of the energy transition, these variations in the data can significantly influence the results. Since most articles do not distinguish between different strengths and types of iron and steel, we simply classify them as 'steel', which means the demand for some alloying elements may be

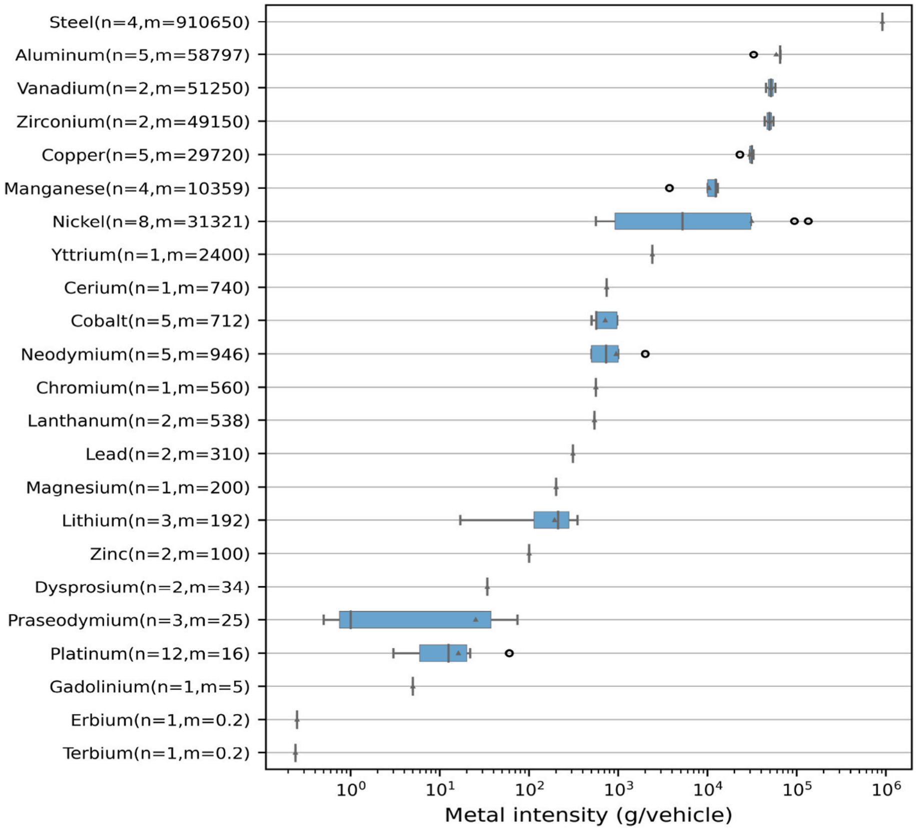


Fig. 7. The material intensity of FCVs after 2016. The data is visualized on a log10 scale. Annotation 'n' represents the number of the data points, and 'm' stands for the mean value of intensity for each element.

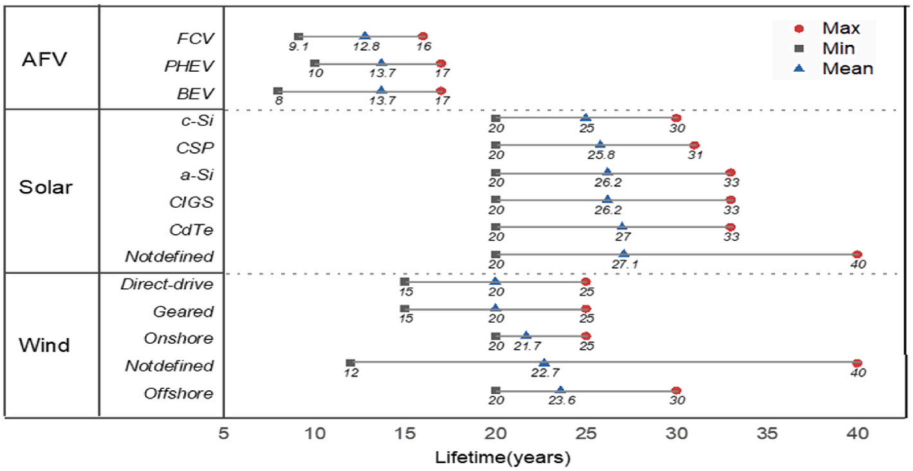


Fig. 8. Lifetime value used in different technologies.

underestimated. For some other materials, such as commonly used fiber glass or expensive carbon fiber for the blades of wind turbines, recycling is problematic and needs attention [95]. However this is outside the scope of this article. Another issue is that we found some outliers in the post-2016 data that cannot be explained easily. These might be caused by the assumption of future technological innovation or differences in data sources.

4.3. *Classification of technologies*

The classification of technologies used in this paper is based on that most commonly used in the literature list. Some papers further subdivide wind power according to different types of turbines based on some technical parameters and/or the type of generator [96,97]. The same is true for EVs where some papers subdivide EVs based on differences in the type of battery used [55,81].

Some papers relating to wind power do not distinguish between the turbines as such and the whole system including foundations, array cables, transformers etc. For minor elements like REEs used in PMs, it is clear that they are only used in the generator, but others like steel and copper can be used in the turbines as well as the infrastructure of the windfarm. In the event that only the metals in the turbine are considered, the material requirements for wind power will be underestimated. Clarifying the system boundaries will help to make better estimations of actual energy requirements.

4.4. Service lifetime

Only one article mentioned the lifespan and the possibility of repowering wind turbines, i.e. upgrading the turbine [84]. Using statistical formulae, such as probability density functions to simulate product life distribution, can reduce the uncertainty caused by lifetime assumptions, and lifetime changes caused by technological innovation cannot be ignored. There are huge regional differences in the lifetime of energy transmission networks. Hierarchical consideration of lifetime, such as replacing the battery to extend the life of EVs and upgrading the turbine to repowered wind turbines may also have potential [84,98]. The vast majority of the literature uses the assumed lifetime data, but there is often a difference between the actual technical/economic lifetime and the assumed lifetime [99]. Further development of the technology, effective maintenance of infrastructure and extending product longevity may all alleviate the pressure on demand.

5. Conclusions

In this study we performed a systematic review of 132 papers, published between 1998 and July 2020, related to the materials requirements of low-carbon energy transition. These articles were selected based on queries within the WOS database and snowballing based on relevant literature. A comparative analysis was made of the existing literature's research scopes, methods, and objects. In addition, detailed data on material content, technology lifetime, material-technology correlation, and material-energy nexus were discussed. The main conclusions can be summarized as follows:

(1) Trends in studies on material requirements of the energy transition.

Research interest in this field has experienced a growth surge in this time period. Although the focus on the material demand for low-carbon technologies can be traced back decades, most of the increase has taken place since the 2010s. A large proportion of the papers focus on a prospective approach. From a geographic perspective, most research focuses on the global scale (Fig. 3(d)), with some studies being done on the regional level of the EU. Few studies were found that focus on the national level. Of those, most focus on some developed countries such as the U.S. and Germany, as well as emerging economies, mostly China. Country-level studies would provide not only more regionalized data implementation on specific technologies and connected to that material requirements, but also on national policies and differences between industrialized and developing economies. There are huge differences in the availability and resilient supply of materials, which involve more complex factors such as trade, geopolitics, and resource endowments. Since security of supply is now seen as a highly relevant topic, high-resolution data and transition strategies tailored to local conditions are of crucial importance.

(2) Research methods and objects.

Modeling and simulation, including scenario analysis, are most frequently used to estimate future material demand. Many studies focus on the material requirements of energy generation technologies and end-use sector. Nearly all studies only cover the "critical components" in the target technologies (e.g. wind turbines and PV panels). However, especially for offshore wind power, large quantities of materials such as steel and concrete are required for the foundation and other infrastructure. These materials used here are often difficult to recycle due to technical and economic factors and should therefore be included in assessments of the material intensity. Similarly, for PV most studies focus purely on the PV cells/panels while materials required for the electronics in the balance system (BOS) and the supporting structures are often ignored. Meanwhile, only few studies consider the materials requirements of transmission network and energy storage infrastructure. With the dispersed and intermittent nature of wind power and solar energy, large-scale construction and operation of these technologies will face new challenges in energy storage and transmission, and the demand for materials for the transmission and distribution networks will also soar.

(3) Quantified material intensity data.

Low-carbon technologies related materials cover most of the elements in the periodic table, especially some critical raw materials. In current literature, most attention is paid to the scarce metals in high-tech components. Most studies assume a constant composition over a period of ten years or more; very few studies consider changes in material composition over time due to technological innovation. In order to produce more accurate demand scenarios, it is crucial to take a more dynamic approach towards the material intensity of energy technologies. Compared with the number of articles on geographic boundaries on national and regional scales, most articles focus on the global level. However, it is likely that, like fossil fuel power plants, there will be significant differences in material intensity between equipment used in different countries. Focusing only on "critical components" as the research object and ignoring the metal demand of other parts will result in the total material requirements of different technologies being underestimated.

(4) Broader implications for the material concerns in low-carbon energy system

After some 15 years of scientific research, the material requirements of energy transition are now considered an important topic amongst policymakers and energy experts. This is highlighted by the fact that the IEA recently published a dedicated report on the topic [100], as well as the many recent initiatives that focus on the resilience of the material supply chains in which the energy transition is identified as one of the most important factors that drive rapidly growing demand. Our research shows that the scientific focus is now on prospective, often scenario-based studies that include technological development, and the introduction of completely new technologies as well as trends in demand from other sectors. We show that there is wide range in the data for material requirements of specific energy technologies. Besides this, we identified gaps in the data for specific technologies and regions. We believe that this study can help future research by providing: (1) a comprehensive overview and analysis of existing work in this field, (2) a solid quantitative baseline for material requirements of different energy technologies, and (3) information that can be used to generate learning curves with regard to material use per energy unit.

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.

* The references listed below are limited to those cited in the main text. For the complete list and detailed information of this review, please see **SI**.

Acknowledgment

This work was supported by the China Scholarship Council (grant No. 201908510229).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112334.

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