Critical mineral constraints in global renewable scenarios under 1.5 °C target

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Abstract
To avoid catastrophic climate change, the world is promoting a fast and unprecedented transition from fuels to renewables. However, the infrastructures of renewables, such as wind turbines and solar cells, rely heavily on critical minerals like rare earths, indium, etc. Such interactions between climate targets, energy transitions, and critical minerals were widely overlooked in the present climate scenario analysis. This study aims to fill this gap through an introduction of metal–energy–climate nexus framework with its application on global energy transition towards a carbon-neutral (or below 1.5 °C) target, in which six state-of-the-art integrated assessment models (IAMs) under different shared socioeconomic pathways were applied. Our analysis revealed that climate mitigation is expected to boost significantly the critical mineral demand by 2.6–267-fold, which varies greatly by IAM models. Solar power development may be constrained by tellurium (Te) and selenium (Se) shortage, while wind power will be jeopardized by the limited scalability of rare earth production. Moreover, a more sustainable pathway may come at higher demand for critical minerals along with higher renewable ratios. Consequently, a holistic investigation of the interaction of mineral, energy, and climate systems is highly recommended for future scenario designing.

1. Introduction
Carbon emissions from global energy system have contributed significantly to the increase in atmospheric greenhouse gas (GHG) concentrations (IEA 2018, IPCC 2022). The successful global transition to renewable energy system is the key to tackling climate change as well as meeting future energy needs (Figueres et al 2018). According to the Paris Agreement, all nations should cooperate for keeping the global-mean temperature increase below 2 °C and pursuing efforts to limit it below 1.5 °C above pre-industrial levels (termed 1.5 °C targets hereafter) (Hulme 2016). This requires an unprecedented roll-up of renewable infrastructure, such as wind turbines, solar panels, and so on worldwide (Davis et al 2018). However, the present climate and GHG scenarios have typically paid scant attention to the minerals implications necessary to realize a low-carbon future. Given that renewable energy systems are more dependent on critical minerals such as rare earth, and gallium than traditional fossil fuel-based ones (American Physical Society 2011, IEA 2021), there is an urgent need to incorporate mineral constraints into future energy planning as well as climate policymaking.

Recently, the importance of linking the supply of minerals (or metal) with the transition of energy
system has attracting growing attention from different perspectives (World Bank 2020, Wang et al 2022). For instance, some studies explored the energy requirement in extracting and processing metals from mineral types (Giurco et al 2014) and its impact on social-economic systems (Peng et al 2019), especially on bulk metals such as iron (Zhang et al 2017), aluminum (Liu et al 2013), copper (Elskhaki et al 2018), and metal industry (Norgate and Haque 2010). The indispensability of critical minerals in renewable infrastructure growth has been explored from another perspective on metal–energy nexus (Wang et al 2019, 2022, Ren et al 2021). On the global level, some researchers like (Elskhaki and Graedel 2013) estimated the requirement of various metals in the future development of electricity generation technologies and urged the management of their supply risks. Meanwhile, such mineral concerns have also been explored for the renewable (i.e. PV and wind power) development in different nations such as the United States (Nassar et al 2016), Germany (Viebahn et al 2015), China (Elskhaki and Shen 2019), Japan (Miyamoto and Kosai 2019), and others. The projection on the metal requirement in those previous studies was widely linked to energy scenarios (e.g. Stamp et al 2014, Månberger and Stenqvist 2018, Takuma et al 2018) from international and national official roadmaps. Nearly all studies expressed concerns of mineral shortage or supply risks in achieving various renewable transition targets. However, the present established socioeconomic scenario models, in particular the integrated assessment models (IAMs), rarely capture product and material cycles at the level of detail necessary to link resource efficiency and climate change (Pauliuk et al 2017, Wolfram and Hertwich 2019). For instance, the recent OECD report stated that more detail and a better connection between technology-detail (‘bottom-up’) and aggregated macroeconomic (‘top-down’) representations is needed (McCarthy et al 2018).

In general, those previous studies had two major limitations for a holistic view and management for the ongoing energy system transition. Firstly, the future renewable will strongly depend on social-economic conditions as well as climate change mitigation pathways (Riahi et al 2017). Indeed, as revealed in various IAM studies (Rogelj et al 2018), the future renewable growth scenarios are highly sensitive to settings on population, economic, climate, and other factors. The linkages between energy scenarios with social-economic growth can help to provide endogenous renewable scenario settings and assist corresponding policymaking in energy and climate. Secondly, the mineral constraints are not only determined by the mineral supply stage but are closely linked to its flows and stocks along its life cycle from mining, production, in-use, and end-of-life. For instance, the secondary resource (i.e. urban mine) from those obsolete products can substitute part of raw material needs (Fishman and Graedel 2019). Besides, the material efficiency strategies (Allwood et al 2011), such as extended product lifetime, less material for the same service, production with higher yield rate, etc., can greatly contribute to material criticality mitigation (Wang et al 2018, Wang and Kara 2019). However, there is a lack of a nexus framework to incorporate all involved mineral, energy, and climate systems together.

To fill such needs, this study will firstly propose the metal–energy–climate (MEC) nexus by integrating those three systems into one framework. The corresponding quantitative approaches for linking material flows and stocks to energy infrastructure under various climate targets will also be given thereafter. Secondly, this framework based on the investigation of six available IAMs will be applied to quantify the mineral demand for supporting global renewables growth to avoid a 1.5 °C rise, in which six representative metals (i.e. neodymium—Nd, dysprosium—Dy, cadmium—Cd, tellurium—Te, selenium—Se, indium—In) are selected. The strategies for efficient metal use and recycling are also explored by integrating different shared socioeconomic pathways (SSPs). The rest of this paper is organized as follows: This framework and scenario settings will be fully explained in section 2. Section 3 will provide our results regarding renewable infrastructure changes and their associated critical mineral demand under different IAMs and SSPs. Section 4 offers a detailed discussion of our findings on the interaction of the metal supply risks, energy planning, and the achievability of climate targets. The final section concludes our contributions and future works.

2. Method and material

2.1. MEC nexus framework

This study proposes an MEC nexus framework to explore the interaction between metal, energy, and environment systems in figure 1. The climate scenario system is presented by different climate scenarios with different representative concentration pathways (RCPs). Among all available emission pathways, RCP 1.9 is the pathway that follows the goal of the Paris Agreement, which limits global warming to below 1.5 °C above the pre-industrial level. Thus, only RCP 1.9 is selected for this study, given its high preference for our sustainable future (Rogelj et al 2018). The detailed model structure and scenario settings are given in section S3 of supplementary information.

The energy system is the core of MEC nexus that bridges all systems together. Under different climate targets and SSPs, future renewable growth across the world can be obtained in IAMs. Notably, with rapid shifting from fuels to renewables, the global energy system is gradually changing from carbon-based (e.g. coal, oil, gas) to critical metals-based (e.g. Dy, Nd, In, Cd, Te, Wang et al 2020). This emerging
linkage requires a qualitative analysis of the dynamics of renewable infrastructure to metal demand, which is captured with the following stock-driven model:

(a) For each energy technology infrastructure, its annual inflow required for the addition to in-use stock (or infrastructure capacity) is obtained as follows:

\[
\text{Inflow}_C(t) = \Delta \text{Stock}_C(t) - \sum_{x=0}^{t-1} \text{Inflow}_C(x) \times \text{EF}(\tau, t-x)
\]

(1)

where EF is the end-of-life function that determines the possibility of previous inflows with mean lifetime \( \tau \) to be phased out at present, which follows various lifetime distribution functions (i.e. Normal, Weibull, etc.) and Weibull distribution function is selected here. The in-use stock can be directly obtained from infrastructure capacity (unit: GW). Meanwhile, the \( \Delta \text{Stock}_C(t) \) is the stock change from last year, and the initial inflow equals the initial stock.

(b) For each type of studied mineral, its final demand \( \text{FInflow}_M(t) \), end-of-life flows \( \text{Outflow}_C(t) \), primary mineral demand \( \text{Inflow}_M(t) \), and material in-use stocks \( \text{Stock}_C(t) \) are determined as follows, respectively:

\[
\text{FInflow}_M(t) = \text{Inflow}_C(t) \times \text{MI}_M(t)
\]

(2)

\[
\text{Outflow}_C(t) = \sum_{x=0}^{t-1} \text{Inflow}_C(x) \times \text{MI}_M(x) \times \text{EF}(\tau, t-x)
\]

(3)

\[
\text{Inflow}_M(t) = \text{FInflow}_M(t) - \text{Outflow}_C(t)
\]

\[
\times \text{RR}_M(t)
\]

(4)

\[
\text{Stock}_C(t) = \sum_{x=0}^{t-1} \text{FInflow}_M(x) - \text{Outflow}(x)
\]

(5)

where \( \text{MI}_M(t) \) is the metal intensity of energy infrastructure at time \( t \), \( \text{RR}_M(t) \) is the end-of-life recycling rate of studied mineral at time \( t \). Notably, the metal cycle system aims to provide the foundation for tracking metal flows and stocks along its entire life cycle from mining, refining, manufacturing, in-use, to end-of-life. The starting points for quantifying metal flows and stocks within the in-use and recycling stage are based on equations (2)–(5).

2.2. Climate scenario settings

This study collected the future scenario settings on the global social-economic system and energy system based on six commonly available IAMs, including AIM, GCAM, IMAGE, MESSAGE, REMIND, and WITCH (Rogelj et al 2018). Those IAMs follow five different SSPs (i.e. SSP 1–5). Not all the IAMs run or have feasible solutions for every combination of SSPs and RCPs under the 1.5 °C target (with a radiative forcing of 1.9 W m\(^{-2}\)), the available results are summarized in table 1.

2.3. Linking mineral supply scenarios into SSPs

The SSPs are recently established as a critical part of new climate scenario framework to facilitate the integrated analysis of future climate impacts,
vulnerabilities, adaptation, and mitigation (Riahi et al 2017). Five narratives are designed in the absence of explicit additional climate policies, including sustainable development, regional rivalry, inequality, fossil-fueled development, and middle-of-the-road development (Neill et al 2017). One contribution of this work aims to extend SSPs with different mineral supply scenarios that may relate to climate change, which is missing in the current SSPs settings.

In our analysis, SSP1 represents a sustainable development pathway, calling for a higher installed capacity of low-carbon technology and lower resource intensity to mitigate climate change, so it adopts the optimistic parameter, with a higher technology mix of low-carbon technologies, an advanced material intensity reduction, a higher circularity, and an ideal extension of lifetime. However, using more advanced technologies (e.g. direct-drive and hybrid-drive wind turbines) may increase the material intensity compared to the normal ones (Wolfram and Hertwich 2019). In the SSP3, a resurgent nationalism with concerns about competitiveness and security may help raise the recycling to secure national resource security. However, the lack of international cooperation may defer technology improvement. The SSP5 may express neutral technology improvement with medium material intensity and lifetime extension. All factors in the SSP4 are assumed to be business as usual, while those in SSP2 are in the middle of SSP1 and SSP4. The detailed settings of each SSP are given in table 2 and section S3 of supplementary information.

Given the scope of this work mainly lies in the introduction of MEC framework and its application, this study only focused on six representative types of critical minerals (i.e. Nd, Dy, Cd, Te, Se, In) given their relatively high technical importance and supply risks (Liang et al 2022). The temporal boundary is set to be from 2000 to 2050 with a focus on the global level.

3. Results

3.1. Renewable transition for 1.5 °C target

Wind (onshore and offshore) and solar (cell PV) are typical power technologies constrained by minerals, and their magnitude of total installed capacity, newly added capacity, and end-of-service are

### Table 1. Climate pathways and renewable mix under 1.5 °C target.

| IAM       | SSPs             | Wind-2050 | Solar-2050 | Total electricity demand |
|-----------|------------------|-----------|------------|-------------------------|
|           |                  | Onshore   | Offshore   | Total PV | CSP | Total (SSP1–19) |
| AIM/CGE   | SSP1–19, (SSP2–19) | 10 284    | 0          | 10 284   | 7846 | 0 | 7846 | 22 510 |
| GCAM4     | SSP1–19, (SSP2–19, SSP5–19) | N.A.      | N.A.       | 4564     | N.A. | N.A. | 4052 | 12 027 |
| Image     | SSP1–9           | 1987      | 901        | 2887     | 3018 | 1979 | 4996 | 12 255 |
| Message-globiom | SSP1–19, (SSP2–19) | 5596    | 56         | 5652     | 6358 | 144 | 6052 | 22 085 |
| Remind-magpie | SSP1–19, (SSP2–19, SSP5–19) | N.A.   | N.A.      | 7369     | 12 360 | 2211 | 14 570 | 26 070 |
| Witch-globiom | SSP1–19, (SSP4–19) | 9254    | 1019       | 10 273   | 9475 | 885 | 10 361 | 26 408 |

Note: The wind and solar for GCAM and REMIND is assumed to be similar to the WITCH given its sophisticated modeling on energy technologies.

### Table 2. Material-related strategies for different shared socioeconomic pathways.

| SSPs                | Technology mix       | Material intensity       | Material recycling       | Lifetime extension       |
|---------------------|----------------------|-------------------------|--------------------------|--------------------------|
| SSP1: sustainable   | Optimistic ('upscaling' roadmap) | Optimistic (fast intensity reduction) | Optimistic (high circularity) | Optimistic (high lifetime extension) |
| SSP2: middle of the road | Neutral ('mix' roadmap) | Neutral (middle intensity reduction) | Neutral (medium circularity) | Neutral (medium extension) |
| SSP3: regional rivalry | Conservative ('continuity' roadmap) | Conservative (business as usual) | Conservative (high circularity) | Conservative (business as usual) |
| SSP4: inequality | Conservative ('continuity' roadmap) | Conservative (business as usual) | Conservative (business as usual) | Conservative (business as usual) |
| SSP5: fossil-fueled development | Neutral ('mix' roadmap) | Neutral (middle intensity reduction) | Neutral (business as usual) | Neutral (medium extension) |

The detailed settings of the assumption of Optimistic, Neutral, Conservative of each material related strategy for each mineral under different SSPs can be found in Section S3 of supporting information.
Figures 2. Infrastructure change of stock capacity (A), newly-added capacity (B), and end-of-service capacity (C) related to future wind and solar power development.

Presented in figure 2. As the proxy of material requirements, the future infrastructure stocks of all three studied technologies grow substantially, with large disparities among SSPs and models. Compared to the stock in 2017, the total installed capacity of onshore and offshore wind and solar PV in 2050 increases by orders of magnitude ranged 24–173, 40–289 and 142–1183, respectively. The future infrastructure stocks are highest in a sustainability pathway (SSP1) since less reliance would be placed on alternative low-carbon power supply technologies such as fossil fuel with CCS and nuclear based on the SSPs narratives.

The newly added capacity from 2000 to 2050 shows rapid and steady growing trends with decadal fluctuations for all three studied technologies. The cumulative newly added capacities from 2000 to 2050 reach 1400–9419, 169–1111 and 473–5361 GW for onshore wind, offshore wind, and solar PV, respectively, while roughly 75% to 85% of installations occur after 2030. The infrastructures would gradually become obsolete when approaching their lifetime, and the embodied materials would enter the end-of-life stage for further treatment. As shown in figure 2(C), the end-of-service wind and solar devices soar after 2030 in all scenarios due to large cumulative installed capacities and increasing operating years. In 2050, additional installations of 13.2–82.2, 3.7–15.6, and 2.2–42.1 GW for onshore wind, offshore wind, and solar PV would be needed to replace the retired devices.

3.2. Critical mineral demand for 1.5 °C target
Climate mitigation is expected to boost the critical mineral demand significantly. The mineral required for the world to achieve 1.5 targets are presented in figure 3. On average, the deployment of wind power will require around 33.8 Kt of Dy and 413 Kt of Nd in total from 2000 to 2050, respectively. For the scale-up of photovoltaic (PV) technology, around 145 kt of Cd, 136 kt of Te, 41 Kt of Se, and 45 Kt of In will be required, respectively. Clearly, more stringent climate targets call for higher mineral demand. Compared to the results of ‘beyond 2 degree’ (B2D) scenario from IEA (2015), it is found our mineral demand estimates for 1.5 °C target are around 2–3 times (and six times) higher for wind-related (and solar-related) critical minerals, respectively. This indicates that expanding solar power for higher climate mitigation may bring severer pressure on the mineral supply of Cd, Te, Se, and In.

Notably, more sustainable SSP will induce a higher demand for critical mineral (in figure 3). For instance, the wind-related mineral requirement for most SSP 1 (i.e. sustainability pathway) are
highest among all scenarios (e.g. around twice that in REMIND model) even with most optimistic life cycle strategies. This is mainly because more renewables, especially wind power, will be required for sustainability pathways that induce higher mineral demand. However, given the mineral are harder to obtain, the feasibility of achieving sustainability pathways should be assessed on the mineral availability. On the other hand, the mineral demand in the next two decades (till 2030) is expected for less than 20% of total demand. Meanwhile, a faster growth is expected for the demand for all minerals after 2030.

3.3. Will critical minerals constrain future 1.5 °C target?
This study explored the annual mineral demand from 2000 to 2050 in line with 1.5 °C targets under various SSPs. The shortage of minerals to meet their demand is assessed by comparing total cumulative mineral demand to the present mineral production capacity. Our results, together with de Koning et al (2018), indicate the mineral of Te, Se, and Dy in nearly all scenarios may face physical shortage based on present mineral reserve, i.e. the cumulative Dy demand during 2021–2050 reached 9–58 kt, equals to running out 3%–18% of the global economic reserve (314 kt), highlighting the potential constraints in the further development of wind and solar to meet the 1.5 °C target. Further exploration and attention on efficient production for those three minerals should be given.

Despite adequate mineral reserve, the mineral production may face scalability constraints due to the long period of preparation (5–15 years) (Prior et al 2012) for capacity expansion and limitation in host metals (critical minerals as by-products), which is measured by the average mineral demand to the present total production capacity in figures 4 and 5. It is found only Cd, Se and Nd can be supplied with current production capacity. However, the rest three minerals (i.e. Dy, In, and Te) should expand their production capacities quickly for wind and solar power growth worldwide. There are two specific concerns
Figure 4. Balance assessment between mineral production capacity and future demand of wind-related metals for achieving 1.5 °C targets. In each of the two subfigures, the left panel indicates the mineral’s production capacity, and the right panel shows the mineral demand for achieving 1.5 °C targets under different SSPs in 2030, 2040 and 2050. The average value of mineral demand is demonstrated using a red star.

That desire further notice: the future deployment of wind power may be constrained by the rare earth production capacity limitation in China and the shortage of Dy in the global minerals (Lee and Wen 2018), thus mines outside China and the substitution of Dy in wind turbine is very important for 1.5 °C targets. While solar power faces severer constraints from the physical shortage of Te and Se as well as the limited scalability in In production, suggesting the innovation of novel solar cells without those critical minerals in meeting energy needs as well as climate targets is very urgent.
Figure 5. Balance assessment between mineral production capacity and future demand of PV-related metals for achieving 1.5 °C targets. In each of the four subfigures, the left panel indicates the mineral’s production capacity, and the right panel shows the mineral demand for achieving 1.5 °C targets under different SSPs in 2030, 2040 and 2050. The average value of mineral demand is demonstrated using a red star.

4. Discussion

4.1. Results validation and sensitivity analysis
There are several previous studies (e.g. Stamp et al 2014, Månberger and Stenqvist 2018, Takuma et al 2018) have projected the demand for energy-related materials. On the basis of those work, this study introduced more detailed analysis related to the changes of mineral supply chain along its life cycle in different SSPs with key parameters like lifetime, recycling rate, material intensity and technology mix (i.e. share of PM wind turbines and thin-film PVs). We performed a sensitivity analysis to capture the impacts of those parameters, in which AIM/CGE-SSP2 scenario was selected as a proxy with the development of around 11 ‘sensitivity analysis’ scenarios in the section S5 of the support information. As figure S7 shows, for Nd, compared with the base case, a 5% lifetime extension can result in a 0.68% reduction in metal demand from virgin ores, a 1.42% reduction in total demand, and a 16.53% reduction in metal recycling. As for the recycling rate, a 5% improvement can cause a 0.24% reduction in metal demand from virgin ores and cause a 5.01% increase in recycling. Thus, it is found that material intensity and technology mix are two key parameters, i.e. a 5% increase in material intensity and new energy infrastructure (PM wind turbines and thin-film solar PVs) market share will result in a 5% increase in metal direct demand and metals from virgin ores, indicating the importance of the innovation in material substitution and energy technologies in future low-carbon transition. Meanwhile, further cautions should be paid for the application of future critical metal demand results, particularly on the assumptions of material intensity and technology mix. Meanwhile, we further compare our results with those publications to validate our results in section S6 of the supporting information. As shown in table S9 of the supporting information, it is found our estimation is in line with most studies with acceptable differences.

4.2. Incorporating mineral availability into IAMs
Given the importance of prediction of long-term climate change pathways, the IAMs have emerged as a modeling backbone of the IPCC reports (IPCC 2022) and other fundamental studies (Bednar et al 2021) due to their great potential in exploring inter-linkages between climate, energy, land-use, and economic development (Pauliuk et al 2017). Our study
has recognized that mineral resources have been key constraints on low-carbon energy development and further the achievability of climate targets. However, our analysis through the applications of six widely-used IAMs is mainly limited to the direct link to demand projection of various critical minerals, while the analysis of mineral price changes and their interactions with low-carbon technologies competitiveness is yet conducted.

This work, as one preliminary and explorative study, demonstrate the potential impacts of critical minerals on future climate mitigation pathways. Among various IAMs, the MEDEAS (Capellán-Pérez et al 2020) has tried to incorporate the mineral system into the IAM framework, highlighting a large amount of interrelated energetic, material, and economic investments will be required to build, operate and interconnect energy infrastructures. Meanwhile, other studies (Deetman et al 2018, Boubault and Maïzi 2019, Kalt et al 2022) also introduced IAMs into such analysis. Still, all those studies mentioned above can help to provide the trends of future critical mineral demand under different climate and energy scenarios but fail to capture more dynamics related to the interdependence between material, energy, and climate systems.

4.3. The importance of other mineral supply constraints on climate targets

Our analysis highlighted the resource availability and production capacity of critical minerals would become a major constraint of the global low-carbon transition. Indeed, critical minerals are a finite, non-renewable resource found in the Earth’s crust (Ober 2017). Some consider depletion to be unavoidable given the fixed resource stock and continuous demand (Cohen 2007, Gordon et al 2007, Ragnarsdóttir 2008). For some energy-related minerals such as cobalt, nickel, and cadmium, geological scarcity might be a major concern. However, new technologies and innovation can offset the cost-increasing effects of depletion (Tilton and Lagos 2007, Turner 2008), which are not captured in this work. Thus, the technical factors and their impacts on physical scarcity should be further studied.

Aside from resource perspective, the production of critical minerals is also energy-intensive and carbon-intensive, the factors of which should also be valued and captured by IAMs. For example, researchers have assembled extensive information on the cradle-to-gate environmental burdens of 63 minerals and found that the major industrial metals (e.g. iron, manganese) are at the lower end of the environmental impacts scale (Nuss and Eckelman 2014). Other work has warned that producing a kilogram of nickel requires more energy and causes more GHG emissions than copper, iron, and aluminum (Van der Voet et al 2019). Meanwhile, mining critical minerals will cause a series of local environmental threats (Holland et al 2019), which is absent from our analysis. For example, rare earths extraction may result in chemical pollution and radioactive waste that threatens rural groundwater aquifers as well as rivers and streams (Sovacool et al 2020). The tantalum and nickel mining in Brazil drives extensive deforestation in Amazon (Sonter et al 2017), and the mining of cobalt in DR Congo causes the heavy metal contamination in Amazon (Sonter et al 2017). This would be considered negative feedback to achieve sustainable development goals. In this way, the mineral constraints for climate mitigation will become severer than our results indicated. This calls for a regional-specific analysis of mineral production as well as holistic assessment of the corresponding economic, environmental, and social impacts on those local suppliers.

4.4. Key strategies to mitigate mineral constraints on low-carbon transition

How can we mitigate such pressing metal constraints on the global energy system transition? From a systematic perspective, our work has clarified this challenge and its corresponding metal-related strategies, as shown in table 2. From the mineral supply side, we urge to expand geological exploration to increase the resource base, and improve their mining and processing technologies to harvest more metal resources. However, it is worth pointing out that this set of strategies may cause severe environmental impacts associated with metal extraction and production. To overcome the resulting environmental inequality, cooperative mechanisms are needed to actively share the burden between both the production and the consumption sides.

To identify the key strategies and their priorities, this work further performed the sensitivity analysis of key parameters and details can be found in section S5 of SI. In our model, material intensity and market share of new technology can directly impulse the mineral demand, indicating that material reduction will play an important role in mitigating mineral constraints. This also indicates that the end-of-life options (i.e. recycling rate improvement) will have limited impacts on reducing mineral demand, compared to other demand-side options. Thus, combining material efficiency strategies (Allwood et al 2011, Ciacchi et al 2016) into MEC nexus is key demand-side measure to alleviate the contradiction between supply and demand of critical metals. CE aims to decouple growth from the consumption of finite resources, including various strategies, such as recycling, re-manufacturing, and reuse, to ensure the high value of products, components, and materials throughout the
whole lifecycle. Meanwhile, strategies to reduce the amount of material required by energy technologies during the in-use stage, call for technical innovations and the design for material efficiency. These can help to deliver more renewable services and prolong the lifetime and efficiency of renewable energy technologies during the in-use stage. Consequently, less new infrastructure would be required, and critical materials could be saved, which calls for more research and development efforts.

5. Conclusion

The systems of mineral cycle, energy transition, and climate change are strongly interlinked. This study aimed to explore such a nexus with three-fold efforts: Firstly, a novel MEC nexus framework was proposed with the introduction of various quantitative approaches such as IAMs and the stock-driven model. Secondly, for the holistic analysis of critical mineral constraints in achieving global 1.5 °C targets, six state-of-the-art IAM models were applied to obtain future development of wind and solar power and its corresponding annual requirement of six types of minerals (i.e. Nd, Dy, Cd, Te, Se, In). Thirdly, different settings of factors in material system, and technology energy were combined under different SSPs for such analysis. We find more stringent climate targets and more sustainable SSP call for higher mineral demand which are within the physical mineral storage Luckily. However, geo-political constraint, production capacity expansion below expectation, and limited economic mineral reserve may derail humanity from a more sustainable trajectory towards 1.5 °C target. This study proposes to incorporate the mineral sector to IAM models, taking the availability of mineral to energy transition and the offset effect to carbon emissions into account, as well as factors like uneven geo-distribution of minerals, environmental pollution, geopolitical, and uncertainty of technology evolution, etc.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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