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Misalignment between national resource inventories and policy actions drives unevenness in the energy transition

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To make projections about the future supply of minerals for the energy transition and set climate targets, it is important to understand inventories of mineral resources as well as national extraction policies. Here, we combine data on mining properties and policies between 2020 and 2023 for 18 countries with substantial resources of energy transition minerals to understand the alignment between the resource inventories and policy actions to make these mineral resources available to market. We find the distribution and near-term production-readiness of energy transition minerals varies across countries. The results show extraction policies align with demand for energy-transition minerals more strongly for countries in the OECD (Organization for Economic Cooperation and Development) compared with their non-OECD counterparts. We suggest these differences between countries could lead to global-scale delays in mitigating climate change and an uneven energy transition structured around national resource endowment, wealth, and inequality.

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In late March 2023, the International Panel on Climate Change (IPCC) issued its sternest warning to date on the need to reduce global emissions, flagging potential intergenerational trauma if world leaders fail to act on climate change[1]. On release of the latest report, the United Nations (UN) Secretary-General stressed the need to "massively fast-track climate efforts by every country and every sector and on every timeframe"[2]. These urgent calls follow similarly robust statements at the Conference of Parties at Sharm El-Sheikh in November 2022[3], and earlier that year a UN Declaration on the right to a clean safe and healthy environment[4]. Since the Paris Agreement in 2015[5], international policy and leading scholars have been unequivocal on the high social cost of fossil fuels and the urgent need for swift structural reforms in the global production and consumption of energy[6–9].

Our research highlights the importance of aligning the policy actions of nation states and the international objective of rapidly increasing the number of production-ready energy transition mineral (ETM) resource projects to meet global demand. This focus imposes a distinction between the urgency of the global energy transition, and the national instruments that determine its feasibility within the timeframes set out under the Paris Agreement. ETMs and their locational complexities form an integral component in characterizing both the material base for developing renewable technologies and the speed at which energy transitions can occur[10]. In this paper we examine the mineral resource inventories[11] and corresponding policy actions across 18 countries with globally significant production and reserves of the highest-demand ETMs (see Methods for country and commodities sampling).

Scholars have noted various geographic[12] and socio-political[13] constraints associated with current global policy aspirations and the location of mineral deposits, arguing that any "rush" to extract ETMs must necessarily include strengthened social and environmental safeguards[14]. The questions pursued in this article relate to the feasibility of a metal-dependent energy transition and the actions of nation states to mobilize their natural resource endowments to meet demand. The IEA estimates an average lead time of 16.5 years to move mining projects from discovery to production, raising serious questions about ETM production in the near-term[15]. Our objective is to assess—at the height of developments in global policy platforms and rhetoric—the type and level of effect given to hastening project-readiness in ETM mining countries.

While arrangements vary, nation states facilitate mineral extraction through laws, decrees, and actions, that enable or inhibit resource development[16–19]. State processes and procedures are moderated by other factors, including capacity to govern, level of corruption or debt, available investment capital, property and resource rights, density and type of resource users, mineral resource characteristics, development ambitions, energy security, community resistance and legal challenges[20–23]. In addition to market forces, the relationship between national resource inventories and the state system of natural resource governance is the primary determinant with respect to the scale and speed of mineral extraction. This relationship, and the practical challenges it poses for meeting ambitious transition timeframes, is frequently overlooked in global policy debates.

Our analysis presents insights into the association between national resource inventories and the status of policies designed to fast-track resource extraction in ETM rich countries in the short-term. The analysis prioritizes 18 countries with a large global share of ETM resources and examines relevant national policy actions between 2020 and 2023. This timeframe captures the period immediately preceding the release of the International Energy Agency's (IEA's) flagship report[24] projecting a rapid multi-fold increase in ETM demand for the energy transition by 2040. This report is an historic point in terms of debate and awareness about the mineral resources required. Our findings show the high levels of variability in the distribution and near-term "production-readiness" of ETM commodities across our sample countries. The findings further illustrate stronger patterns of alignment with global policy objectives among OECD countries compared with their non-OECD counterparts. These areas of alignment relate to both the availability of specific ETMs and the development of national policy mechanisms to expedite or enable future supply. They do not account for the effect of market incentives in stimulating supply. Prices for lithium and cobalt doubled between 2021 and 2022, with commodity prices for copper, nickel and aluminum also rising above 25% in that same period over concerns about growing competition and tightening supply[25] (see Supplement 1 Figure S1). These conditions would appear favorable from the vantage point of enabling metal supply. The corresponding levels of misalignment in non-OECD countries represent a major point of concern given the status of exploration and pre-development for key ETM products considering the unprecedented volumes noted by the IEA. Irrespective of the three transition scenarios furnished by the IEA, Sustainable Development Scenario (SDS), Stated Policies Scenario (SPS) and Net-Zero Emission Scenario (NZE), the requirement for massively upscaling mineral supply appears unavoidable, noting that the NZE projection will require 1.5 times more minerals than the SDS scenario by 2040[26].

Our discussion concludes with four (4) implications that are directly relevant to understanding and framing of the global energy transition. The findings in this research indicate that misalignments may not result in a no-transition scenario, but rather a multitude of other outcomes each with their own underlying risks and opportunities, ranging from wholesale global-scale delays to mitigating climate change, to a more fractious uneven and costly sequence of transition structured around national resource endowment, wealth, and inequality.

Results

The results of the empirical analysis are first organized by national-level resource inventory and policy-action status. These factors provide the necessary foundation for achieving the climate objectives set forth by United Nations and other international-scale initiatives. Resource inventories, when disaggregated by development stage, show the share of materials available for supporting the near-term climate mitigation strategies espoused in global policy forums. Development stage refers to the progress a mineral resource project has reached in building knowledge about the economic feasibility of exploiting and monetizing an orebody. In this study, we focus on development stage based on whether (i) a project will require major additional investment to define its feasibility ("Grassroots & Reserves Development") or (ii) a project has been sufficiently characterized and considered to be construction-ready or "near" construction ready ("Feasibility & Preproduction") (Supplement 1 Table S2). National policy-action status provides a proxy for the readiness of resource-endowed nation-states to "fast-track" ETM projects to enable the mineral and metal supply required to meet the projected demands of the global energy transition. Practically these policies could refer to either the development of new mining projects or the granting of permission to expand existing projects. Policy-actions were categorized to differentiate (i) statements by governments that signaled support or interest in developing their ETM sectors from (ii) policy actions that would result or (iii) had resulted in regulatory changes that would hasten the supply of minerals. These policy actions are labeled "Media Releases & Statements", "Policy Pipeline Instruments", "Legal & Regulatory

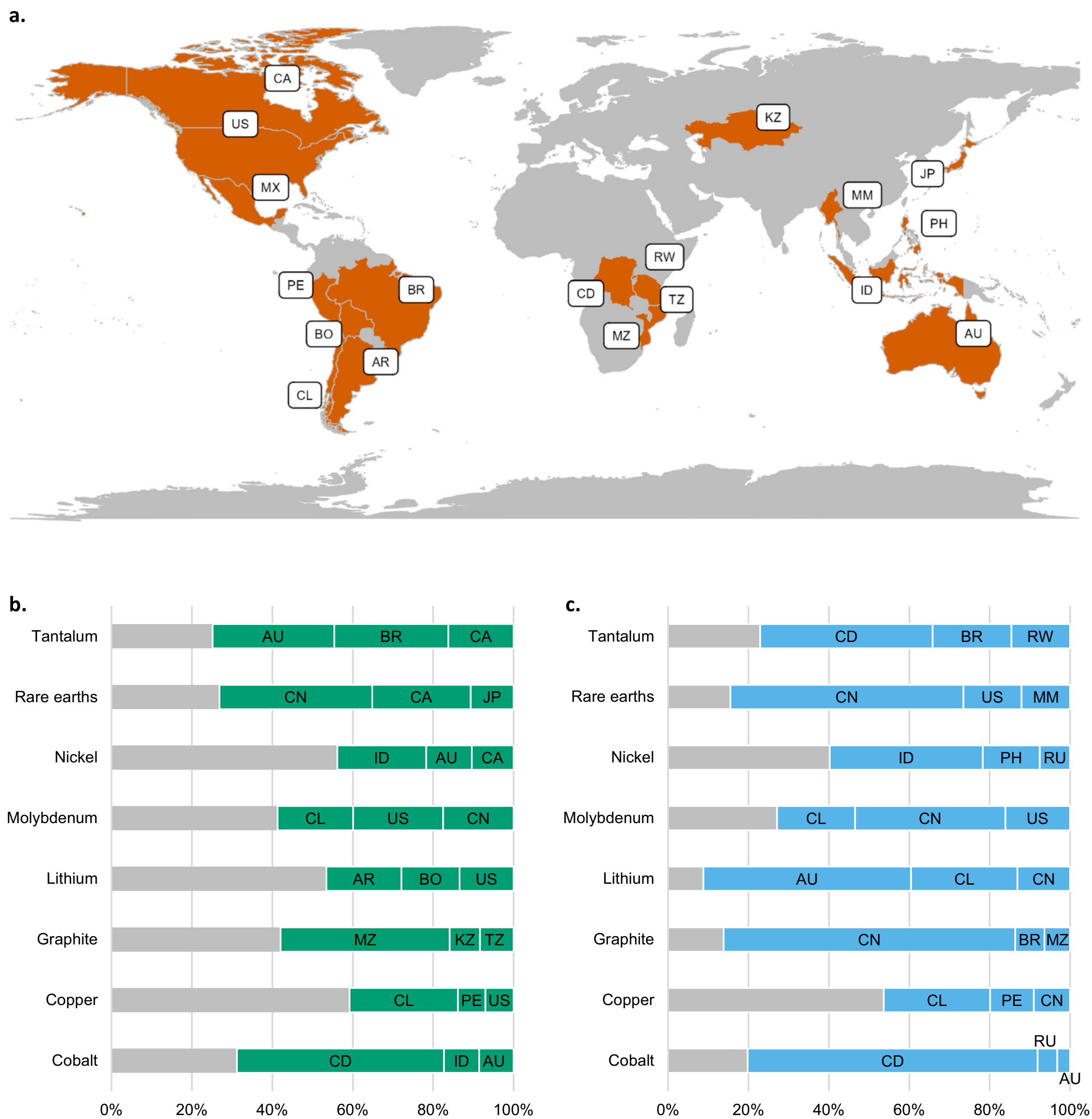

Fig. 1 Overview of key ETM countries. a Map showing key ETM countries selected for the analysis (AR Argentina, AU Australia, BO Bolivia, BR Brazil, CA Canada, CL Chile, CD Democratic Republic of Congo, ID Indonesia, JP Japan, KZ Kazakhstan, MX Mexico, MZ Mozambique, MM Myanmar, PE Peru, PH the Philippines, RW Rwanda, TZ Tanzania, US United States). **b** Top 3 countries by global share of ETM reserves and resources. **c** Top 3 ETM producing countries.

Instruments" respectively. These distinctions are used as temporal indicators for supply or production-readiness.

To explore the readiness question, we identified 18 countries (see Fig. 1) with the largest share of global production and or reserves and resources of ETMs. The set of key ETM countries span six continents ranging from developed, industrialized and well-established mining countries (Australia, Canada, and the US) to emerging economies with large mining sectors (Brazil, Indonesia) to developing countries relatively new to mining (Mozambique, Tanzania).

Across the sample of countries (Fig. 2a), Australia, Brazil, Canada, and the US have the highest diversity of minerals. In other countries, reserves and resources are established for a relatively smaller set of minerals. For example, Japan has reserves of REE and nickel, while Rwanda has reserves of tin and tungsten. Conversely, Peru is known for its large reserves and resources of copper, but not for other minerals. In terms of development stage (Fig. 2b), most countries in the set have a large portion of mining properties in the "Grassroots & Reserves Development" (i.e., very early) stage of development, with relatively few properties in the stage of "Feasibility & Preproduction" (i.e., construction-ready, or near to).

Policy actions ($n = 67$) were analyzed using a hierarchy based on their direct effect on enabling supply in the short-term (i.e., in the next 5 years). The hierarchy ranges from media statements (lowest) to laws and executive orders (highest) and covers announcements or enactments made in the period January 2000–April 2023 (see Fig. 3 and Methods). Only one policy

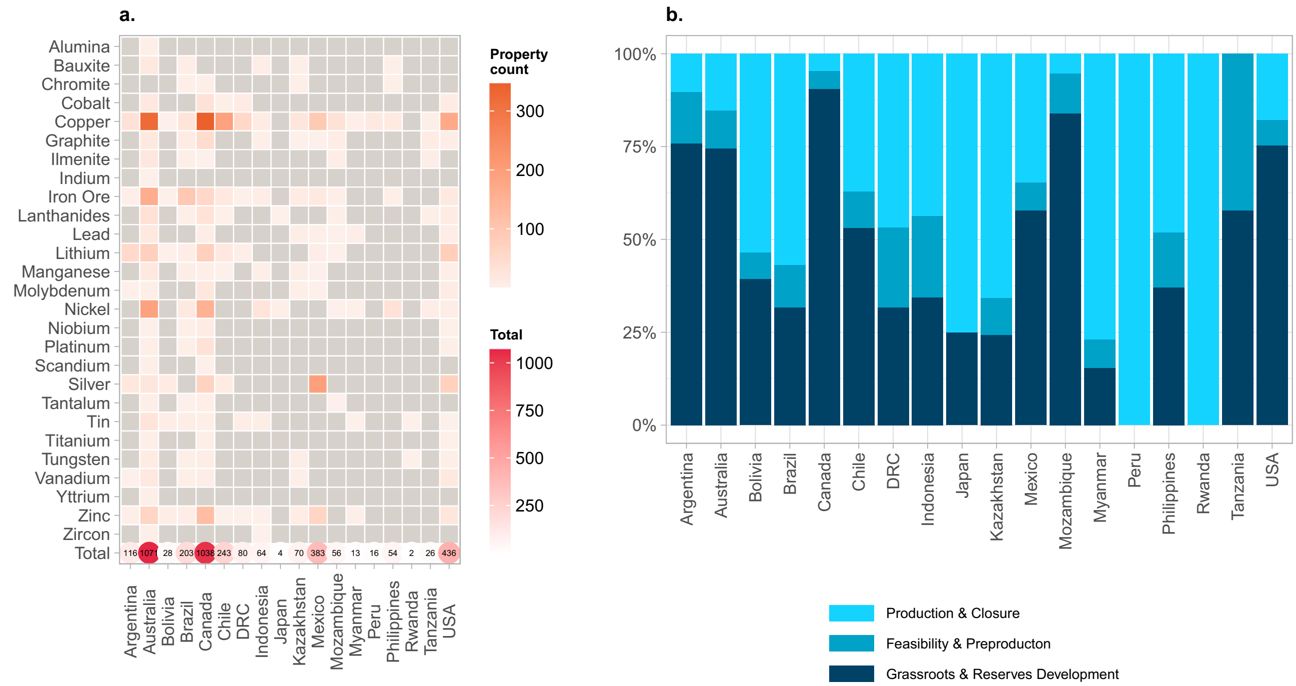

Fig. 2 Overview of ETM resource inventories in key ETM countries. a Distribution of ETM properties across selected countries by mineral and **b** Share of ETM properties by development stage in selected countries.

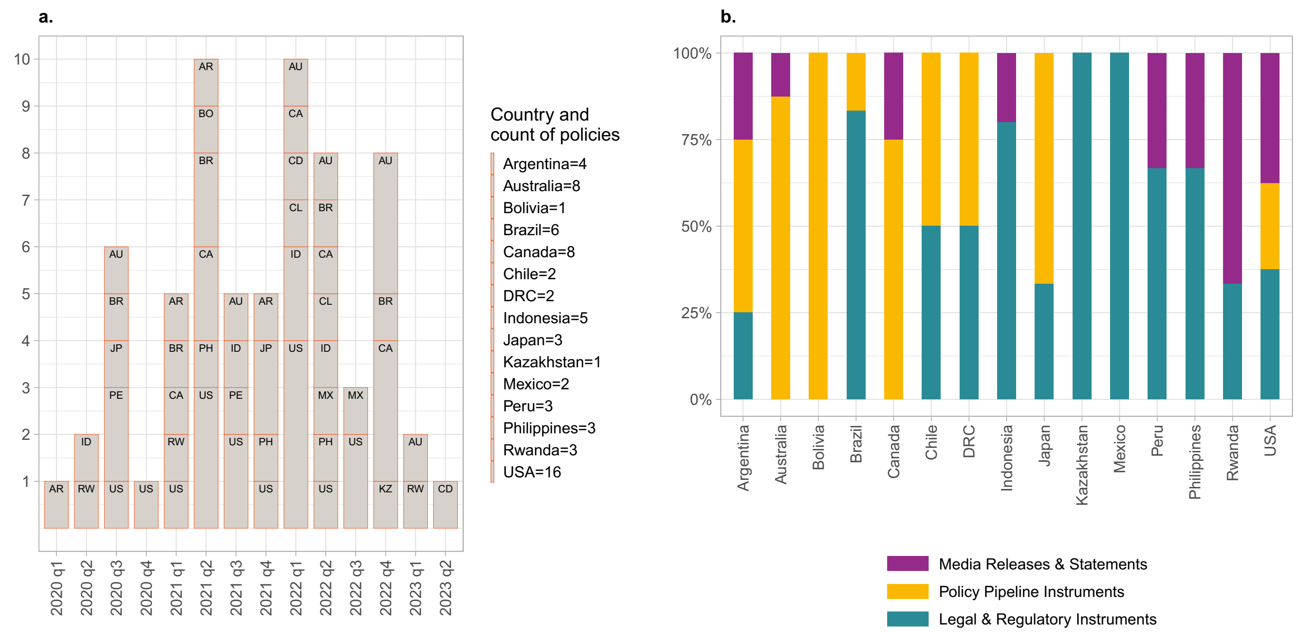

Fig. 3 Overview of national policy actions across key ETM countries. a Policy documents announced or adopted in selected countries between 01.01.2020 and 30.04.2023. **b** Share of policy documents by type.

action[27] in our document sample made explicit reference to the expansion of existing assets, indicating a strong bias in the policy discourse globally for discovering and developing new mineral deposits. Our analysis identified three groups (clusters) of countries considering their ETM resource inventories, economic and political characteristics. The value of utilizing clusters is to assist scholars and policy makers in more accurately defining the jurisdictional, material, and geographical conditions that will influence energy transition schedules and strategies.

Groups of ETM countries. A cluster analysis resulted in three groups of countries (Fig. 4). Key differences between the clusters are attributed to the economic and political characteristics and the different structure of ETM mining properties by stage. Parallel coordinates plots presented below demonstrate how individual countries sit across all variables in each cluster.

The distribution of resource inventories across the three clusters is relevant not only for understanding the presence or absence of country-scale factors relevant for resourcing the

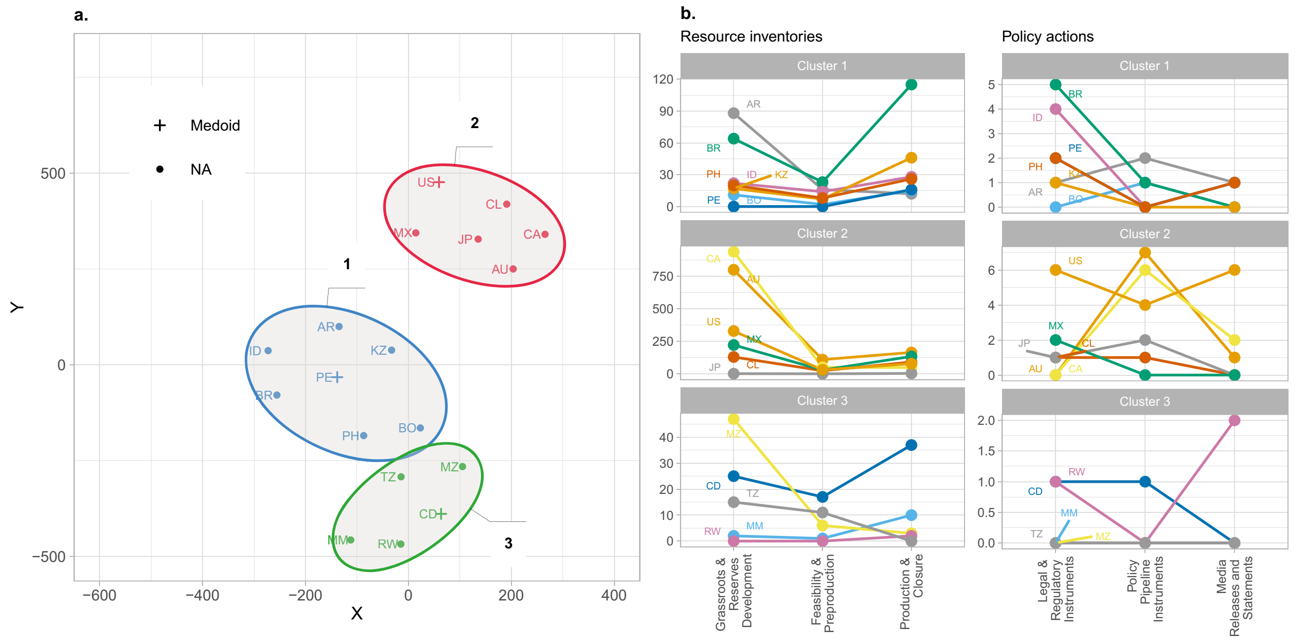

Fig. 4 Cluster structure and alignment of resource inventories and policies. **a** Cluster membership and country-medoids. **b** Distribution of resource inventories and policy actions across three clusters.

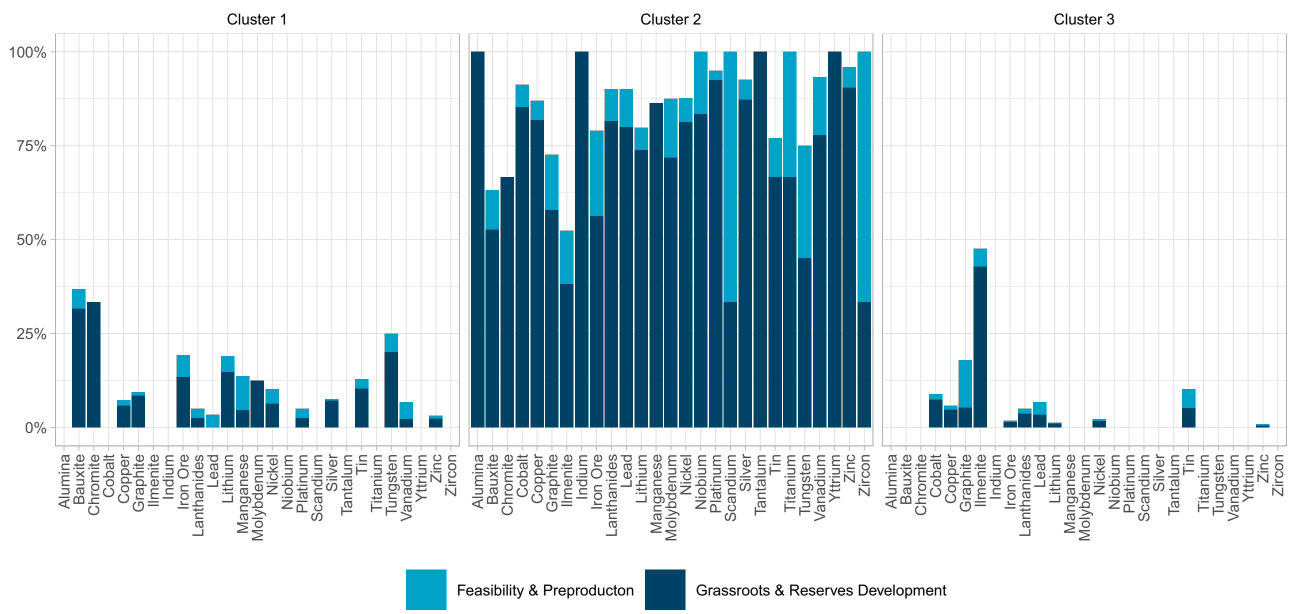

Fig. 5 Distribution of resource inventories across three clusters by early development stages. Share of ETM projects in Feasibility & Preproduction and Grassroots & Reserves Development stages across the three clusters.

climate change mitigations proposed in global policy forums[28], but also for delivering these resources within the sensitive timeframes expressed by the IPCC. As Fig. 5 shows, over 85% of ETM projects ($n = 2655$) in the early stages (Grassroots & Reserves Development and Feasibility & Preproduction) are concentrated in Cluster 2, followed by 9.5% ($n = 292$) in Cluster 1 and 4% ($n = 124$) in Cluster 3.

Cluster 1. Non-OECD countries with established mining economies. Cluster 1 is best described as nation states with established mining economies and a diverse ETM reserves and resources base. Membership includes Argentina, Brazil, Bolivia, Indonesia, Kazakhstan, Peru, and The Philippines. These are non-OECD countries with medium to very high rankings in both the United Nation's Human Development Index (HDI) and the Resources Governance Index (RGI). In recent years, resource projects in these countries have been associated with heightened conditions of social and political risk, owing to increasing concerns over resource nationalism (e.g., Indonesia[29–31]), anti-mining sentiment or frequent protest (The Philippines[32,33], Peru[34,35]), internal security (Kazakhstan[36]), the requirement to recognize Indigenous Peoples (Bolivia[37]) and environmental damage (Brazil[38–40]).

In terms of the respective ETM inventories of these countries, the largest share of projects is in the "Production & Closure" stages; that is, already operating or no longer operating. These development stages outweigh project propositions in the earlier stages indicating relatively low levels of investment in mineral exploration or pre-development. This finding holds for most of the countries in Cluster 1, except for Argentina, which has few projects in "Production & Closure" and an emerging lithium sector.

The balance of policy-actions for this group suggests a relatively high number of new policy initiatives at the upper end of the policy hierarchy (i.e., new and proposed instruments), with fewer actions at the lower range (i.e., public announcements). Despite the social and political risks identified for Cluster 1, the archival review of policy documents in the target timeframe revealed few examples of public strategy, national plans, or public consultation documents and announcements aimed at hastening mineral supply by bringing new projects into production or supporting the rapid expansion of existing mines.

The correlation matrix (Supplement 2) for this cluster indicates a strong positive relationship between projects in "Grassroots & Reserves Development" stage and "Policy pipeline instruments" (0.83 for counts and 0.49 for shares) and between ETM projects in "Feasibility & Preproduction" stage and "Legal & regulatory instruments" (0.69 for counts and 0.47 for shares). The correlation between policy action and development stage indicates a pattern in which projects at a greater stage of maturity can be expected to receive higher levels of administrative support to proceed apace.

Conversely, this cluster showed a strong negative relationship between the share of projects in "Grassroots & Reserves Development" stage and shares of "Media releases and statements", indicating lower levels of effort and investment in early-stage exploration in these countries.

Cluster 2. OECD countries with established mining economies. Countries in Cluster 2 are OECD countries with very high HDI and RGI rankings and established mining economies. These countries are described as "safe jurisdictions", that is, they are primarily liberal democracies with low levels of social and political risk[14]. The membership of Cluster 2 is: Australia, Canada, Chile, Japan, Mexico, and the United States of America (USA).

Across Cluster 2, Australia and Canada have the largest resource inventories with respect to the total number of ETM projects at "Grassroots & Reserves Development" and "Feasibility & Preproduction". Similarly, the US contains a relatively large number of ETM projects across development stages. Japan has a long-established presence in the mining industry through off-shore investments and refineries and has the least diverse resource inventory compared to other nations in Cluster 2.

In terms of policy actions, Cluster 2 recorded a higher share of "Policy pipeline instruments" with smaller shares for "Legal and regulatory instruments" and "Media releases and statements". This is attributed to the democratic form of governance across the cluster whereby new actions move through a defined policy development process that involves gauging public sentiment and interest before investing in consolidating actions in policy mechanisms further up the hierarchy[41,42].

The results show a strong positive relationship (Supplement 2) between "Policy pipeline instruments" and projects in "Feasibility & Preproduction" stages (0.77 for counts) and "Grassroots & Reserves Development" (0.87 for counts). A negative relationship exists between projects in "Grassroots & Reserves Development" stage and "Legal and regulatory instruments" (−0.3).

The findings for Cluster 2 suggest a modest level of alignment between production-ready projects and the corresponding policy action required to move projects to the active mining stage of development. In other words, the policy actions in Cluster 2 can be taken as a measure of confidence in the pace of project development in these countries. The negative relationship between the earliest stage of project development and the highest level of policy action indicates that countries in Cluster 2 have not proceeded to institute new laws to stimulate investment in ETM exploration.

Cluster 3. Non-OECD countries with strong exploration potential. The membership of Cluster 3 is the Democratic Republic of Congo (DRC), Mozambique, Myanmar, Rwanda, and Tanzania. Countries in this cluster have fewer reported projects across all stages of project development compared to Clusters 1 and 2. Cluster 3 countries have consistently medium to low rankings for both HDI and RGI. As a group, Cluster 3 ranks poorly on security, social and political risk measures. Myanmar is in a longstanding state of internal conflict[43], and Rwanda experienced a brutal civil conflict almost 30 years ago[44]. Mozambique and the DRC have also experienced severe and protracted periods of internal conflict[45,46]. Tanzania and the DRC are established mining jurisdictions with active investments from leading global mining corporations such as Barrick and Glencore and are also well-known hot-spots for artisanal small-scale mining[47]. Metal mining in Mozambique is less well-established but has recently hosted major industry players Vale and Rio Tinto. The system of governance across Cluster 3 is considerably more diffuse when compared to both Clusters 1 and 2.

Few countries in Cluster 3 publicized policy actions in the three-year period evaluated in this research. In total, the group averaged less than 1 document for each category. Rwanda reported the largest number of media releases across the Cluster.

Focusing on correlation by counts (Supplement 2), there is a strong positive relationship between projects in "Feasibility & Preproduction" stage and "Policy pipeline instruments". Correlation matrix by shares indicates that there is a strong negative relationship between "Media releases and statements" and projects in early development (−0.93 for "Grassroots & Reserves Development" and −0.76 for "Feasibility & Preproduction"). This result could be taken as confirming a general absence of transparency with respect to notification of new projects or public mechanisms for supporting processes consistent with public consultation and free prior and informed consent (FPIC). Equally, these results can be understood as marking a distinction between the status and role of the media in different jurisdictions. A positive relationship is observed between "Legal and regulatory instruments" and projects in "Feasibility & Preproduction" stage (0.51). As with Clusters 1 and 2, this finding suggests general support by states for accelerating construction and production-ready projects within their respective resource inventories.

Discussion

Combining national resource inventories and domestic policy actions provides a useful guide for understanding the immediate future status of alignment between globally established targets for mitigating climate change and the socio-technical[48] readiness of particularly mineral rich countries to mobilize their material base to achieve these objectives. Our findings indicate major points of misalignment between global climate targets and the policy actions of nation states with the resource inventories that will be most pertinent to giving effect to a rapid energy transition. Drawing on eight years of research, the IPCC's 2023 report details the devastating consequences of failing to change course on climate change, including destruction of homes, loss of livelihoods, mass migration, and social conflict. All 193 parties to the Paris Agreement have made public pledges through at least a first nationally determined contribution (NDC) to emissions reduction. The World Resources Institute calculates that NDC actions would reduce the world's GHG emissions by only 7% from 2019 levels by 2030, well below the 43% required to limit temperature rise to 1.5 degrees Celsius and avoid irreversible impacts on the climate and the availability of planetary resources for future generations[49]. On this basis, any policy misalignment, particularly any temporal misalignment between globally mandated targets and country-level action, would have severe consequences[50]. Price data for the period observed indicates no notable effect between favorable market values for metal goods and enabling policies to furnish supply. Our findings show that, at minimum, describing the status or process of transition in terms of a "rapid switch" is both misleading and counterproductive to understanding how climate targets might finally be realized[51–55]. We note that this does not include considerations relating to the complexities associated with global supply chains which will necessarily impact on mitigation strategies once resources are mobilized from their source[56–58].

While it is common practice to utilize nation states as a basis for comparison[59–61], this can be problematic[62]. Nations exhibit considerable diversity in their legal and political systems, their development status, history, and demography[63]. This difficulty notwithstanding, given their critical role in mobilizing ETMs, we use nation states as the foundation for defining the spatial and political constraints around the mineral resource inventories required to fuel the global energy transition. Any miscalculation within or across nations in terms of where, when, and how ETM extraction occurs raises key concerns about the speed at which minerals and metals can be mobilized for the urgent purpose of mitigating climate change.

National resource inventories. From a resource inventories perspective, countries in Cluster 1 are critical to the future supply of ETMs. These countries are established mining jurisdictions with the balance of their known inventories in active operation. Compared with Cluster 2, Cluster 1 countries have fewer ETM projects in the exploration phase, signaling lower levels of confidence by investors in either the jurisdiction or the prospects for resource discovery[64]. Fast-tracking actions by states in this context would need to take the form of expediting the resource development life-cycle, circumventing aspects of it for new projects or providing bureaucratic support to enable project expansions to extract more resource from existing mines. By way of example, Argentina's Resolution 47/2020[65] seeks improved effectiveness, efficiency, speed, and flexibility for developers in the project approval process; Indonesia's Presidential Regulation 55/2022[66] enables the Ministry of Energy to delegate decision-making to provinces to speed up project permitting; and Peru's Supreme Decree N 020-2020-EM[67] reduces the time required for prior consultation with local communities in exploration and project development.

An important characteristic of the resource inventories in Cluster 1 countries is that the process of resource development for large, globally significant projects, typically involves companies headquartered in Cluster 2 countries. The implication of this is that critical decisions relating to investment, safeguarding or the resolution of major disputes are made off-shore, and frequently with enormous cost and delay. For example, the legal action that has followed the catastrophic tailings facility failure at the Samarco iron ore mine in Brazil in 2015 that killed 19 people and devastated an entire river system. More than 200,000 people, including businesses, churches, municipalities, utility companies, and an Indigenous community, are pursuing a class action against one beneficial owner in the English court system. The beneficial owner contested the action, arguing that loss and damages were being paid out in Brazil, and that the action would be duplicative of those in Brazil's judicial system. Despite the corporation's objections, a trial date for the multi-million-dollar civil suit has been set for 2024, which if it proceeds, would be the largest ever heard in the English courts[68,69]. At the same time, criminal proceedings are ongoing.

From a project phase perspective, there are notable differences across the three clusters. Relative to the number of active projects, Cluster 1's pipeline of new projects is remarkably low, and compared with Cluster 2 countries, Cluster 1's new project pipeline appears stunted, with little early phase activity. Accelerating production of ETMs in Cluster 1 in the near-term would need to rely, almost exclusively, on expansion at existing projects. Cluster 2 countries have the highest number of early-stage projects in the overall set. This indicates stronger exploration spending and resource characterization across the clusters. The high number of projects in the operational phase of the mine life cycle is notably higher, particularly compared with Cluster 3. The level of investment in early and construction stage projects suggests that markets, and by extension corporations, are determinably more confident with the inventories and conditions in "safe" Cluster 2 countries.

Procedural certainty. The states represented in Cluster 2 have ratified key instruments of international law, conferring a complex set of procedural and property rights to First Nations peoples. Recent research shows extensive overlaps between the interests of First Nations people and the resource inventories of these countries[70]. These may be safe jurisdictions from the vantage point of ease of doing business, but the locations where these resources occur within these countries are subject to procedural uncertainty as processes for securing FPIC unfold. New procedures require time, effort, and resources to navigate. On the face of it, these procedures may induce greater procedural misalignment if we assume that Cluster 2 is better positioned to hasten project development.

An example of procedural uncertainty is captured in the pre-development history of the Resolution Copper project in Arizona, the US[71]. The project contains an estimated 27 million tonnes of reserves and would be the largest operating copper mine, in North America, run over an estimated 60 years, and produce 25% of future US copper demand each year. Despite the compelling case for development from a national interest perspective, the proponent faces strong opposition from a group of First Nations peoples over concerns that the project would destroy the sacred Oak Flat, a culturally significant site for Apache tribes[72].

Global indicators. Cluster 3 countries have the least number of projects across development status categories. While they are non-OECD members like countries in Cluster 1, Cluster 3 countries are notable for their relatively poor performance against global development measures for quality of life, economic health, and governance. The resource inventories reported for countries in Cluster 3 contain globally significant quantities of cobalt, natural graphite, ilmenite, and tin and in conjunction with commodities extracted from jurisdictions from Clusters 1 and 2 will be critical to meeting projected demand for ETMs.

By human development status, countries in Cluster 3 appear least able to identify the resources, formulate policy instruments to enable timely exploitation, or attract the necessary investment to advance quickly. Of the countries across the overall sample, Cluster 3 is likely to be in the weakest bargaining position for attracting foreign investment or safeguarding the social and environmental rights of local landholders[73]. These countries mostly feature in the bottom quartile and lower half of countries on the RGI. The general paucity of knowledge about how countries in Cluster 3 are strategizing or negotiating the liberation of their resource inventories as Cluster 2 nations take a greater interest in their resource endowments is a major gap in terms of understanding the material and temporal constraints to reaching global mitigation targets.

Implications. In the context of the energy transition, with its unparalleled demand for mined materials, alignment is critical if we are to reach the ambitious targets that have been agreed to in the international arena. While there is variation between different ETMs in terms of their characteristics and availability, the important consideration is the extent to which one or multiple mineral resources can be substituted or be made redundant when supply is not forthcoming. This is important given that new clean energy technologies will emerge and each step change in technology will require different combinations of multiple ETMS (or bundles). Our analysis reveals a series of concerning misalignments, between resource inventories, within and across countries, policy actions to enable resource extraction, and project and production readiness.

An important question for policy makers and analysts relates to how misalignments should be framed and understood. There is, for instance, an obvious core-periphery association[74–76] to be made between the three clusters with Cluster 2 representing the core, followed by Cluster 1 and Cluster 3 as closer and further markers on the periphery. From this vantage point, it is unsurprising that Cluster 2 countries present the highest levels of alignment with global policy targets. It is likewise, unsurprising, that these nations stand to benefit the most from the commercial extraction from Cluster 2 resource inventories, enabling them to build their own climate resilience, while reaping minerals from Clusters 1 and 3 respectively. Cluster 3, with the strongest markers of traditional peripheral states, show few points of alignment in terms of policy actions or efforts to make public the status of their ETM resource inventories. The absence of information in Cluster 3 should be treated with caution, and not taken to infer too much about the intentions of member countries or the development status of ETM projects in these locations.

Our analysis shows that alignment with global policy targets is not evident in the policy actions or the resource inventories we analyzed across the 18 countries sampled for our study. On this assessment, we consider the following four (4) implications for the energy transition as having greatest significance.

1. Policy misalignments between global and national-level actors imply elevated social costs associated with delays in the exploitation and supply of ETM critical for the implementation and achievement of globally defined targets to combat the most adverse effects of climate change. If delays to urgent mitigative action are considered to impose further impacts to climate, or stress future resource demand, timeframes and impacts need to be thoroughly re-defined and re-assessed[77].
2. The strongest proposition for rapidly exploiting national ETM inventories is from large operating resource projects in Clusters 1 and 2. The expansion of already very large facilities imposes the least immediate cost in terms of policy action and capital outlay. However, the potential social and environmental ramifications need to be carefully evaluated and incorporated into energy transition discourse. Our research revealed little evidence to suggest that global or national-level actors are openly considering the role of existing operations, or the rights and safeguard mechanisms required to ensure that when driving project limits beyond their present conditions, imposing social, human rights and environmental impacts is not granted as a foregone conclusion[78]. While ramping up production at existing facilities may be regarded as the strongest proposition, it should be thought of as a highly-contingent solution given concerns about the resource sector's ability to construct and responsibility manage its waste, and other social and environmental impacts[78–81].
3. A similar potential exists for re-processing or re-mining economically exhausted resource projects[82]. This proposition involves a higher level of capital investment and technological innovation than presently exists. As above, working with low-grade assets, whether previously closed, or in their waste stream, carries obvious social and environmental risks that need to be carefully considered given their long-range historical consequences[83].
4. Finally, more nuanced energy transition and demand scenarios are needed to account for where alignments and alliances are forming most strongly. Our findings indicate that misalignment both in the core and the periphery could result in either major delays in the extraction of resources from Clusters 1 and 3, or an ability to harness national inventories in these same jurisdictions to build internal resilience to climate change. Likewise, Cluster 2 highlights tensions between procedural rights for mining-affected people, and the need to proceed at pace to satisfy global demand for more minerals.

The results from this study suggest a need to re-define timeframes and differentiate geographies of transition to properly account for disparities in economic power, the status of development in defining and mobilizing resource inventories, and the level of actionable alignment across nation states in achieving global mitigation targets.

Methods

Country selection. The focus of the analysis in this paper (Fig. 6) is on key ETM countries—a sample of countries with a large share of global resources and production of ETMs. To identify these countries, we focused on ETMs where demand is projected to be fast-growing. One criterion used was that demand for these minerals driven by low-carbon energy technologies in 2040 is expected to be at least double the demand from these technologies seen in 2020 and be higher than 10% of current annual production (IEA 2022). This criterion was applied on the basis that future demand forecasts were a motivating factor for countries with inventories of those commodities to use state policy mechanisms to fast-track mining projects. These minerals (based on the most conservative demand projections from the IEA's SPS) include lithium (258%), graphite (107%), cobalt (83%), nickel (47%), copper (47%), molybdenum (14%), REE (8%), and tantalum (8%).

We then identified the top three (3) producing countries of these commodities using US Geological Survey's Mineral Commodity Summaries[84] and the top three (3) countries with the largest reserves and resources of those commodities based on the S&P Capital IQ Metals & Mining Properties database[85]. After identifying 20 countries, we eliminated Russia and China from the list due to the geopolitical trend towards greater supply independence from these countries (see also Limitations). Countries ($n = 18$) included in the analysis are Argentina, Australia, Bolivia, Brazil, Canada, Chile, DRC, Indonesia, Japan, Kazakhstan, Mexico, Mozambique, Myanmar, Peru, Philippines, Rwanda, Tanzania, and USA. These choices were current in February 2023, however, the data on future mineral demand and reserves and resources are constantly updated, and other countries might need to be considered in future as this knowledge continues to evolve.

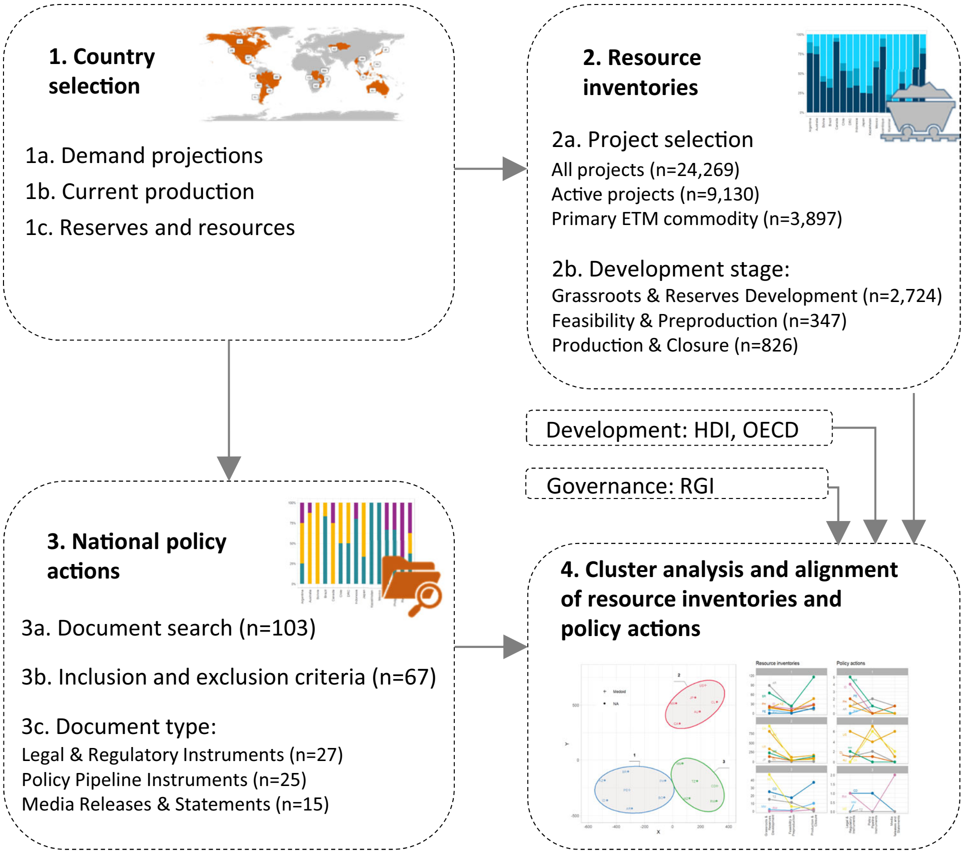

Fig. 6 Methodological sequence. **1** Country selection: **1a** ETM demand projections from energy transition technologies using data from IEA; **1b** Global mineral production data from USGS; **1c** Global mineral reserves and resources data reported by the S&P; **2** Resource inventories: **2a** Project selection using data from S&P; **2b** Mineral property grouping based on development stage; **3** National policy actions: **3a** Document search; **3b** Application of inclusion and exclusion criteria; **3c** Document grouping based on document type; **4** Cluster analysis and alignment of resource inventories and policies.

Data. We collected quantitative and qualitative data to characterize our country sample. Four (4) primary dimensions were used: resource inventories, policy actions, level of development, and quality of governance. To characterize resource inventories, data on mining properties were extracted from the S&P Capital IQ Pro platform on 22 March 2023. Data was extracted for all mining properties for selected countries. The initial dataset contains 24,269 mining properties. First, we excluded inactive properties ($n = 15{,}079$) and projects in rehabilitation ($n = 60$). After excluding these properties, the dataset contains 9,130 entries. Second, we identified mining properties with ETMs listed as primary commodity (Supplement 1 Table S3). A list of 29 ETMs developed by Owen et al.[70] was used to identify these properties. These reflect sets or "bundles" of metals most associated with the renewable energy technologies proposed for supporting climate change mitigation. Our focus on primary commodities means gold mining projects with copper or cobalt as by-product were not considered an ETM property. The resulting 3,897 ETM projects were then grouped according to their development stage: "Grassroots & Reserves Development", "Feasibility & Preproduction", and "Production & Closure".

The mining policy dataset was built by reviewing policies and regulatory requirements intended to hasten or accelerate the supply of ETMs in the sampled countries. Information was gathered from publicly available sources: reports, government sources, professional intelligence, company reports, news coverage, industry news, events, and academia. To ensure the approach captured recent and relevant initiatives, 12 rounds of discussions were conducted with representatives of international advocacy and policy organizations. This step enabled the research team to identify developments not readily available through online searches. We identified 103 policies and regulatory requirements that focused specifically on mining and ETMs as defined above. Each document was further assessed for relevance and included in our analysis if it satisfied the following criteria: (i) was adopted or announced between 1 January 2020 and 30 April 2023; (ii) was adopted or announced at federal or national-level; and (iii) seeks to create an enabling environment to accelerate ETM extraction. Documents were excluded if they represented: (i) sub- or supra-national-level policies and announcements; (ii) international partnerships and alliances; (iii) generalist initiatives (e.g., for infrastructure, foreign investment, or geoscience strategies), or (iv) were adopted before 2020. In total, this process of data collection resulted in 67 documents.

After reviewing each document in detail, policy actions were grouped according to document type: "Legal & Regulatory Instruments", "Policy Pipeline Instruments", and "Media Releases & Statements". These categorizations formed a 'policy hierarchy'. The "Legal & Regulatory Instruments" type sits at the top of this hierarchy. It includes documents with force: laws; acts, ordinances, statutes; government decrees; and executive orders. Laws, acts, ordinances, and statutes represent sources of law, and other documents have executive power. Type "Policy Pipeline Instruments" includes bills; consultation documents; discussion papers, reports; and strategies, plans and programs. These are proposed initiatives that can be taken as indicating a future direction by the state. Type "Media Releases and Statements" includes media releases and statements from official sources. These statements contain less certainly as to purpose and carry far less force than the other two policy types established in the hierarchy. Electioneering was accounted for in media releases and statements, reinforcing their position at the bottom of the hierarchy (Supplement 1 Table S4).

To characterize level of development and quality of governance, we used HDI[86], membership in OECD (https://www.oecd.org/about/members-and-partners/), and the RGI[87]. These variables act as proxies for the country's quality of governance and ability to handle procedural elements and investment effectively.

Empirical approach and analyzes. The empirical approach included two steps. First, we applied cluster analysis to identify groups of countries that had the greatest potential to accelerate ETM mining projects. Country-level data used for the cluster analysis included economic and political characteristics and resource inventories. Second, we analyzed the resource profiles of these clusters in relation to the policy actions designed to accelerate ETM projects. All statistical analyzes and visualizations were performed using R, version 4.1.0[88]. The R package 'cluster'[89] was used to perform the cluster analysis.

The first set of variables included country features related to the level of economic development and governance; these were HDI, OECD membership, and RGI. Summary of categorical variables is provided in Table 1.

Continuous variables used in the cluster analysis characterize resource inventories of selected countries. Table 2 provides a summary of continuous variables used in the cluster analysis.

Cluster analysis aims to group a set of units in a way that units in the same group are more similar to each other than to those in other groups. Our cluster analysis emphasizes two important features for understanding national-scale alignment with global initiatives the (i) extent and development status of national resource inventories for ETMs, (ii) the economic and political characteristics of nations themselves. These factors serve as an important step for determining the causal pathways that lead to hastening or accelerating project approvals and other 'mining enabling' policies.

Cluster analysis identified the existence of three defined clusters (see Supplement 2 for details on Gower distance and detection of cluster structure using silhouette coefficients). We used Gower distance as the dissimilarity matrix coefficient and given the presence of both continuous and categorical variables, we used PAM (Partitioning Around Medoids) algorithm of clustering that minimizes the distance between medoids. A log transformation was applied to counts of minerals and policies because of positive skewness. Variables characterizing country's level of economic development were ratio-scaled and treated as ordinal. The iterative procedure included the following steps: choice of random medoides, assignment of each entry to its closest medoid using the Gower distance, selection of the lowest average distance, and re-assigning to clusters or termination of the algorithm. PAM provides numerous benefits over k-means method: more robust for a small dataset, less influenced by outliers and extremes, and it prevents loss of knowledge for categorical variables.

Table 1 Summary and sources of categorical variables used in the cluster analysis.

Variable	Categories	*N*	%
Human Development Index (HDI)	Very high	7	38.89
	High	4	22.22
	Medium	3	16.67
	Low	4	22.22
OECD membership	OECD	6	33.33
	Non-OECD	12	66.67
Resource Governance Index (RGI)	Very high	6	33.33
	High	9	50.00
	Medium	1	5.56
	Low	2	11.11

Limitations. The research contains several limitations which highlight the necessity for future research and development by scholars and policy leaders. Our focus is on large-scale projects identified in the S&P Capital IQ Pro platform. This dataset does not report on alluvial deposits of artisanal and small-scale mining (ASM) properties. For the scale of production required for most ETMs, meeting demand would not be achievable through ASM.

At a country level, China, India, and Russia are important exclusions with respect to accurately capturing cooperative trends between the strategizing of national resource inventories and policy alignment with global targets. This exclusion was unavoidable on the sources available, both with respect to the low level of public reporting and incompleteness of resource inventories within the S&P Capital IQ Pro platform in these jurisdictions and state announcements on the utilization of these assets. While, in the case of India, for example, it would be possible to gather a greater level of detail about policy actions, the level of incompleteness in terms of records for resource inventories would be analytically prohibitive. See Supplement 1 Figure S-5 for the resource inventory status of China, India, and Russia in comparison to selected countries.

Our research does not take a complete stock of resource inventories and policy actions by all nation states. The sample considered but did not include a comparison of sub-national policy actions (in mostly liberal democracies) or supra-national policies (such as the Critical Raw Materials Act from the European Union). Emergent trade blocs and strategic partnerships were not considered as these involve countries but are not comparable units. Moreover, some blocs are disproportionately active in the policy arena (such as the European Union) while holding comparatively little value in terms of future supply inventories (i.e., from BRICS or ASEAN). The inclusion of sub- and supra-national instruments was not necessary for analyzing misalignment between global and national-scale actions for responding to climate change targets at supply. The trends we have identified indicate a clear potential for delays to occur and for these delays to have major consequences for climate change and its associated impacts. Importantly, the research does not attempt to re-define transition timeframes or proffer new projections on possible impact scenarios that may follow delays or unevenness across countries as they exploit their ETM resource inventories or invest in building national resilience measures.

Table 2 Summary of continuous variables used in the cluster analysis.

Variable	*N*	Mean	St Dev	Min	Max
Count of active ETM properties in stage Grassroots & Reserves Development	18	151.30	275.46030	0	936
Count of active ETM properties in stage Feasibility & Preproduction	18	19.28	26.06960	0	109
Count of active ETM properties in stage Production & Closure	18	45.89	49.75574	0	164

Similarly, the research does not describe a future diffuse or heterogenous shape for the transition despite the research showing that a single homogenous global movement toward an energy transition is extremely unlikely.

Data availability

The dataset of resource inventories and policy actions analyzed during this study is available in the University of Queensland's eSpace[90] https://doi.org/10.48610/a831967. The datasets used to generate figures can be downloaded from Figshare[91] https://doi.org/10.6084/m9.figshare.24494617.v1.

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J.O.: conceptualization; data curation; formal analysis, funding acquisition; investigation; methodology; supervision; validation; writing—original draft; writing—review and editing. D.K.: conceptualization; formal analysis, funding acquisition; investigation; methodology; project administration; supervision; validation; writing—original draft; writing—review and editing. W.S.: data curation; investigation. J.L.: conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing—original draft; writing—review and editing.

Competing interests

The authors declare no competing interests.

Additional information

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