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Critical minerals for green energy transition: A United States perspective

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ABSTRACT

This paper examines the green energy transition objectives from a U.S. viewpoint. It is highly doubtful that targets announced by politicians, climate advocates and green investors will be achieved under-desired time-frames. The lack of a coherent domestic mineral policy, exceedingly long and burdensome permitting timeframes and increasing litigation will result in continuing underinvestment domestic mineral opportunities. As a result, geopolitical risks across necessary critical mineral supply chains are anticipated to escalate as the U.S. de facto strategy will be reliance on foreign sources, both friendly and not.

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Green energy; critical minerals; United States mineral policy; obstacles to mine development

1. Introduction

Political and environmental actors in the Western economies have set ambitious goals for reduction of Green House Gas (GHG) emissions by 2030, a short eight years in the future. The ambitious targets for reductions are almost exclusively the consumption of fossil fuels in electricity production and transportation. Currently, the societally desired replacement for these uses appears to be renewable energy and electric vehicles (EV), at least within Anglophile countries and the European Union, with the more practical long-term solution of nuclear power greatly disfavoured since the 1970s. In the United States (U.S.), the range of proposals and required rapidity of installed wind and solar power generation capacity to meet federal and state-level governmental requirements is enormous, especially considering these sources currently provide only 12% of domestic electricity generation currently [1]. Aspirational goals for replacement of transportation fleets are also of a scale difficult to contemplate, particularly in the US, Canada, and Australia where driving distances for many people are much greater than European or Asian countries. Achievement of these milestones, particularly those targeted for realisation by 2030, are fraught with major problems, of which energy transition advocates seem to give very little realistic thought towards, or rather prefer to ignore. Among these are capital requirements for renewable generation facilities, transmission infrastructure, land use concerns, environmental disruptions, service reliability, consumer affordability, and regulatory permitting.

These obstacles are further intensified by the sourcing and supply chain challenges ahead for the vast quantities of critical minerals needed for both renewable energy generation and the large-scale deployment of EVs. These include enormous volumes of speciality metals, such as lithium, nickel, cobalt, and rare earth elements (REE) which are not currently mined at scale in the U.S. REES have been mined in the U.S. since 1952 at Mountain Pass, California, with intervals of suspension due to environmental/financial problems, as well as ownership changes [2,3]. At the present time, it

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produces light rare earth concentrates which are processed to metals in China (a partially state-controlled Chinese company owns 7.7% of the project). The U.S. government is funding in part the construction of facilities to produce REE intermediates (REE oxides) with 2022 start date [4,5]. Unfortunately, the Mountain Pass deposit contains only light REEs and not the heavy REE elements (Dy, Tb) required for making the preferred highest efficiency magnets.

Even such nominally high production tonnage elements as copper, will be stressed by forecast needs of green energy transition that is defined as all forms of energy production, transport and consumption which do not involve greenhouse gas (GHG) emissions [6].

These realities raise questions as to exactly what U.S. public and private sector policies will be for provision of these resource inputs. Unfortunately, both the experience of the U.S. mining industry over the last four decades, and the continuing lack of a comprehensive national mineral policy for resource development, is not encouraging that these needs will be sourced from domestic resources. The implied policy for the U.S., at both the societal and governmental levels appear to be that the mineral inputs for green energy transition will come principally from foreign sources, regardless of cost, security, or environmental justice. In essence, this is the nation's default mineral policy going forward. It is also ironic that while most environmental activists are rabid in their enthusiasm for an instantaneous transition to a global green energy economy, they adamantly oppose the mining of the critical mineral commodities without which massive-scale energy transformation can never be achieved.

2. The green energy transition

Concern about the impacts of anthropogenic greenhouse gas emissions and related global climate change has increasingly preoccupied environmentalists, politicians, and much of the general public over the past three decades. In 1997, the Kyoto Protocol, operationalising the previous United Nations (U.N.) Framework Convention on Climate Change, committed developed industrialised and industrialising nations to control efforts to limit their GHG emissions [7]. The Protocol established individual country targets for limitation and even reductions.

The Kyoto agreements also provided for periodic reporting on progress by participant countries. Annual reports have been published by the Intergovernmental Panel on Climate Change (IPCC) and periodic major international climate conferences held including the Doha Amendment in 2012, the Paris Agreements of 2015, 2019 U.N. Climate Action Summit, and COP26 in Glasgow, Scotland in 2021 [8]. Under these U.N. auspices, tracking of GHG emissions, climate impacts, monitoring of reduction progress, and the number of participating countries have all expanded. Reduction goals have also been refined and tightened – the IPCC now claims that without new policies to greatly mitigate climate change, its modelling indicates an increase in global mean temperature of 3.7 to 4.8°C, compared to pre-industrial levels, by the year 2100. The IPCC believes the current trajectory of global GHG emissions, both annual and cumulative, will not achieve the targeted U.N. goal of limiting global warming increase to 1.5 to 2.0°C over pre-industrial levels [9].

Weaknesses in the original Kyoto agreement and ensuing amendments, revisions and extensions are numerous. Foremost is that the goals are aspirational – the Convention itself only requests participating countries to voluntarily adopt policies and measures for mitigation. In reality, only the developed economies have made any serious efforts to address reductions to date. Even those, although highly publicised with much government funding, have to date accomplished little towards achievement of the targeted goals. Global GHG emissions continue to grow, particularly in high population industrialising countries such as China, India, and Indonesia [10,11]. These nations' primary focus is economic expansion and climate change is far from a priority among the majority of their populations and leadership ranks. The Western economies to date are carrying the reduction load, a situation that looks to continue for many years to come. It is highly doubtful Western world reductions, no matter the extent, will be able to offset GHG growth in developing countries, and especially when high population growth regions, particularly Africa, are included.

The weaknesses of these international diplomatic efforts to reduce GHG are amplified by the control/reduction strategies now being utilised by participating nations. Heavily influenced by environmental and social activists, these focus almost exclusively on renewable electrical energy generation (including wind and solar power; hydropower is deemed a renewable source but for most developed countries is a mature technology with limited opportunities for expansion). The most benign method for large-scale power generation, nuclear energy, is essentially being ignored in Western World economies, with exception of France. This situation may be undergoing some modification with the recent acceptance by the European Union Parliament of nuclear energy and natural gas as components of the EU's 'green energy tax taxonomy', allowing these generation sources to be considered as 'sustainable investments'. [12]. Nevertheless, renewables are predicted by advocates to be the largest source of power globally by 2050, at 73% of the total compared to 25% in 2020. They claim wind and solar will increase their share of global renewables generation to 85% by 2050 from 34% in 2020 [13].

2.1. U.S. green energy transition goals

Within the U.S., milepost goals for climate change mitigation GHG reductions are established and promoted at both the federal and state levels. At the national level, President Biden and his administration target a 50–52% reduction in US greenhouse gas pollution from 2005 levels by the end of 2030. A further goal is achieving 100% carbon pollution-free electricity generation by 2035, and net zero emissions from the national economy as a whole no later than 2050 [14]. These objectives are supposedly consistent with the IPCC's promoted global warming limitation of 1.5°C [9]. Over the past decade, the core Federal strategies to meet these targets has revolved around the Clean Energy Plan initiated by the Obama administration in 2016. This is augmented by the Biden administration's often cited ambitious target that 50% of all new U.S. vehicle sales by 2030 will be EVs [15]. Such Federal objectives are always subject to change however, by legislative or court-directed actions. On 30 June 2022, the U.S. Supreme Court reversed the 2022 ruling by the Washington DC U.S. Court of Appeals, which struck down the U.S. Environmental Protection Agency's (EPA) Affordable Clean Energy Rule (ACER) [16]. Previously, the ACER had eliminated the authority for individual States, and imposed an EPA-directed one-size-fits-all nationwide control mandate. Full EPA control under ACER would have had devastating effects on states and U.S. fossil-fuel electricity generation, with many industry experts predicting deterioration of grid reliability and power shortages. The implications of this recent Court reversal will take time to worked out but do have potential to slow down renewable energy development is the U.S. The extent of the impact will be determined by cumulative regulatory actions of the individual States, which in turn will reflect the progressive versus conservative divide rampant in the US today.

At the state level are a variety of regulatory actions directed to expand renewable generation. The most frequently used mechanism is to legislatively impose Renewable Portfolio Standards (RPS) which direct that a specified percentage of the electricity consumed in the state must be provided by renewable energy by a certain date (a variant is Clean Energy Standard (CES) which allows inclusion of nuclear power). While RSP promoters claim adoption will diversify energy resources, promote domestic energy production, and encourage economic development, an underlying objective is to force utilities and merchant generators to shutdown fossil fuel plants and rely on solar and wind generation. Regulated public utilities are typically very happy to construct new wind farms and solar installations as this enlarges the capital base from which they earn a fixed return as set by regulators. Consumers, however, are saddled with increased power bills. Table 1 provides examples of the more aggressive state RPS/CES plans for major public, and consumer owned utilities (2020 average retail price (U.S. cents/kWh) also shown [17]):

At present 32 of the 50 US states have RSP plans in place. Details vary but one constant is that, once in place, requirements tend to be accelerated with each new legislative session. The pressure

Table 1. State electricity profiles [17].

State	Average retail price (cents/kWh)	PRS/CES plans
California:	18.0	60% renewable by 2030, 100% carbon-free by 2045
Colorado:	10.3	30% by 2020 (achieved),100% by 2050-proposed move to 2035
Maryland:	11.2	50% renewable by 2030
New Mexico:	9.3	80% renewable by 2040, 100% carbon-free by 2045
New York:	14.9	70% renewable by 2030, 100% carbon-free by 2040
Oregon:	8.8	25% renewable by 2025, 50% renewable by 2040
Washington:	8.3	100% carbon-free by 2045

these standards put on expansion of renewable generation, and follow-on requirement for massive increases in demand for unprecedented tonnages of critical minerals is obvious.

3. Critical material needs for green energy transition

While climate change and green energy advocates are long on enthusiasm and favour putative strategies for quickly reordering how electrical power is generated across the globe, they historically show little concern, or even understanding, of the material inputs which will be required to achieve renewable energy goals. These include the vast quantities of traditional construction materials (steel, cement, fibreglass, copper, etc.) needed for wind farms and extensive solar energy arrays, and critical materials (lithium, nickel, cobalt, rare earth elements) which, while smaller in absolute tonnages, are huge relative to the capacity of the resource industry to supply them economically and securely.

According to the U.S. National Renewable Energy Laboratory (NREL), wind turbines are predominantly made of steel (66–79% of total turbine mass); fibreglass, resin or plastic (11–16%); iron or cast iron (5–17%); copper (1%), depending on manufacturer and model [18]. Added to this is the immense volume of concrete needed for the turbine support base, which can be on the order of 2,000 to 4,000 metric tons (mt). With turbine hub heights of 70 to 120 metres for 1.5-to-3.0-megawatt (MW) nameplate capacity [19], the overall weight of these input materials is on the order of 400 mt for onshore and 3,000 mt for offshore units [20]. Multiplied by the enormous number of turbines required to provide a significant portion of U.S. electrical generation, the amounts of needed resource materials are staggering. Capacity Factors for wind turbines are relatively very low, on the order of 25–30% reflecting the time they actually generate electricity compared to 70–85% for coal plants and 92% for nuclear facilities. This means the number of wind units has to be essentially tripled to achieve rated nameplate capacity [21].

Wind and solar energy also have the fundamental drawback of low energy density compared to conventional coal, gas, and especially nuclear sources. Consequently, renewable energy systems require many more times the amount of critical minerals needed for construction on a per unit of output capacity basis. Figure 1 provides comparisons of the material inputs required by generation type [22]. As shown, a typical EV will require approximately six times the mineral inputs of an internal combustion engine (ICE) vehicle. Per this analysis by the International Energy Agency (IEA), EVs require over 200 kg of minerals including two times the amount of copper as well the many significant minerals required in battery manufacture. From a power generation perspective, an onshore wind plant requires nine times the required materials compared to a typical natural gas-fired plant (even more for an offshore wind facility).

Multiplying the much-increased weights of renewable energy generation critical mineral requirements per unit of power output by the enormous number of wind and solar installations required indicates cumulative mineral/metal demand of unprecedent scale. Given the widescale anti-mining attitudes of society and other technical and policy obstacles to the discovery/extraction of such mineral volumes, the achievement of touted 2030 and 2050 GHG reduction goals looks extremely unlikely.

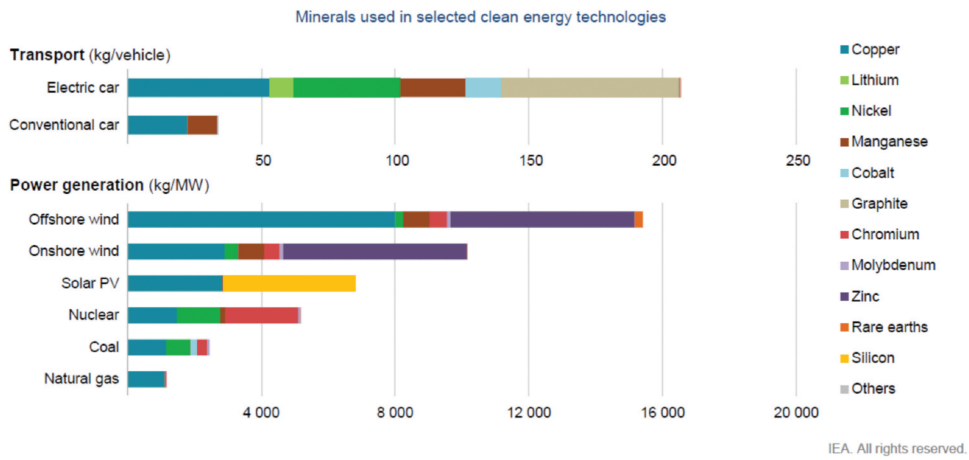

Figure 1. Materials used in selected green energy technologies [22].

A more recent IEA report builds on this, noting that critical material supply chains will be under mounting pressure as EV production drastically increases to meet net-zero ambitions [23]. According to the IEA, annual demand for EV batteries will grow from around the current 340 GWh to over 3500 GWh by 2030. This will require that global battery and critical mineral supply chains expand by a factor of 10 to meet projected 2030 demand. A historically staggering number of hundreds of new mines in IEA's opinion will have to be constructed meet this 2030 battery metals demand – on the order of 50 more lithium mines, 60 more nickel mines and 17 more cobalt mines by that date [23]. Even without the numerous environmental and social roadblocks to building new mines, global expansion of this scale and timeframe is wholly unrealistic.

In the following, we examine these obstacles to future critical mineral supply in detail. Our purpose is educational, noting a general lack of basic knowledge about the realities of mineral development and production among politicians, environmental activists, and the general public. The 'inconvenient truth' is that if U.S. society desires massively expanded wind and solar energy and EV adoption, the public will have to accept greatly expanded exploration and mining activities.

4. Scarcity drivers for critical materials required for green energy transition

Obstacles to producing the necessary volumes of critical minerals to meet green energy goals by end of the decade are numerous. They primarily focus on factors retarding the ability of mining companies to find and bring into production operations of scale, cost efficiency, and product quality to meet mineral demand. For most of the critical minerals, downstream processing capability has to be considered as well, with the transformation of ores and concentrates to useable intermediate and finished forms which is often more challenging and costly than the resource extraction itself. Many of the most impeding scarcity drivers for critical minerals, however, are social in nature, rather than technical. These consist of regulatory barriers and environmental and/ or social opposition to the development and mining of new mineral deposits. While our discussion is focused on the U.S. mining situation, much of it increasingly applies to other countries as well.

4.1. Time required to permit new or expanded mines

The most significant contributor to critical mineral vulnerability in the U.S. is the arduous permitting requirements at federal, state, and local levels. On average, for mining companies to explore mineral opportunities in the U.S., it may take two or more years to obtain the majority of

Table 2. Example mining project permitting timelines [24].

	Time required to receive	
Jurisdiction	Exploration permits	Mining permits
U.S.	2+ years	7–10 years
Western Australia	1–2 months	2 years (maximum)
Ontario, Canada	6–18 months	2–3 years (maximum)

required permits to conduct initial field exploration activities. Once discovered, permission approvals for deposit delineation may add another 2–3 years. However, an actual mining permit to construct mine and processing facilities, and commence operations, may require an additional 7 to 10 years to secure. By comparison, permitting timelines in many other countries, for example, Australia and Canada, may be on the order of 1 to 2 months and 2 years, respectively (Table 2).

As an illustrative example of the time consuming mine permitting process in the U.S., we describe the continuing experience of Lithium Americas and its Thacker Pass project [25]. Thacker Pass, located in northwest Nevada is currently the largest known lithium deposit in the U.S. provides a representative example of the time required to explore, evaluate, and obtain required permits and authorisations. Figure 2 displays a summary timeline for Thacker Pass. In the 1970s and 1980s, Chevron Corporation initiated exploration programs in the area for uranium, leading to the outline of a lithium deposit. During the 1990s, claims in the area lapsed, with the cessation of exploration activities until 2007 when exploration plans were submitted to federal and state agencies, focusing on lithium. In addition to exploration and technical study work necessary to evaluate the economic viability of the project, over the course of the next nine years, Lithium Nevada (which later merged with Western Lithium to form Lithium Americas in 2016) completed numerous environmental and social studies critical to support subsequent Environmental Impact Statement (EIS) and other permit applications. In 2017, Lithium Americas commenced further exploration programs to further define the scope of the project. The following year, a 43–101 report and prefeasibility study were published, summarising the technical aspects of the project and viability of the reserves to be profitably mined. In 2020, a draft EIS that detailed the impact of the

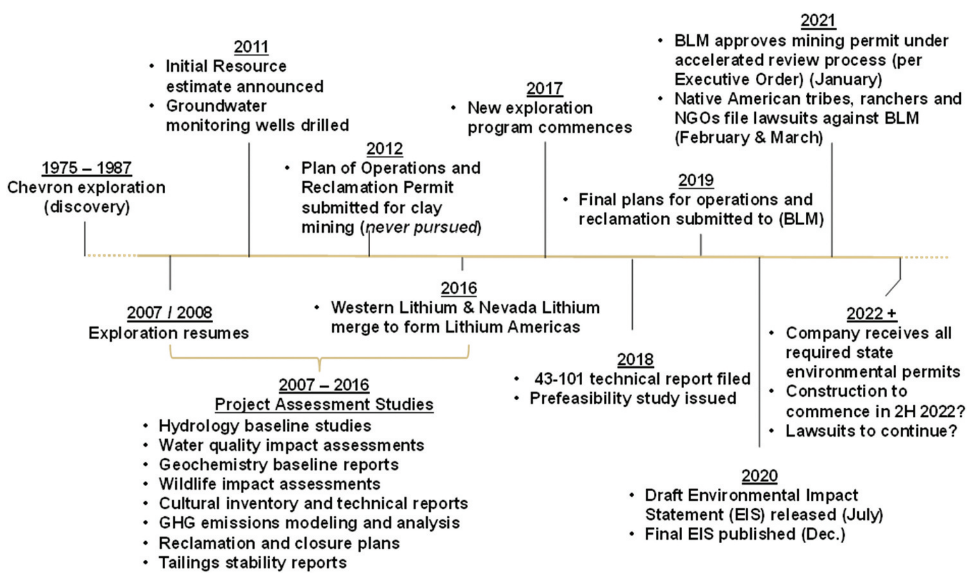

Figure 2. Thacker pass, NV – high level milestones [25].

Table 3. Permits required for thacker pass lithium mine [26].

Permit	Regulatory Agency
Mine Plan of Operations/Record of Decision	United States Department of the Interior, Bureau of Land Management (BLM)
Surface Disturbance Permit and Air Quality Permit to Construct/Permit to Operate	Nevada Division of Environmental Protection, Bureau of Air Pollution Control (BAPC)
Water Pollution Control Permit	Nevada Division of Environmental Protection, Bureau of Mining Regulation Reclamation (BMRR)
Permit to Appropriate Water	Nevada Division of Water Resources (NDWR)
Industrial Artificial Pond Permit	Nevada Department of Wildlife (NDOW)
Explosive Permit	United States Department of the Treasury, Bureau of Alcohol, Tobacco, Firearms, and Explosives (ATF)
General Discharge Permit (Stormwater)	Nevada Division of Environmental Protection, Bureau of Water Pollution Control (BWPC)
Highway Encroachment Permit	Nevada Department of Transportation (NDOT)
Hazardous Materials Storage Permit	Nevada Department of Motor Vehicles and Public Safety, Fire Marshall Division; Fire Protection Licensing Bureau, HAZMAT Office.
Hazardous Waste Identification Number	United States Environmental Protection Agency (EPA)
Liquefied Petroleum Gas License	Nevada Division of Environmental Protection, Bureau of Health Protection Services (BHPS)
Class III Solid Waste Landfill	Nevada Division of Environmental Protection; Bureau of Waste Management (BWM)
Portable Water System Permit	Nevada Division of Environmental Protection, Bureau of Safe Drinking Water (BSDW)
Certificate of Public Convenience and Necessity for Power Generation	Public Utilities Commissions of Nevada (PUCN)
Dam Safety Permit	Nevada Division of Water Resources (NDWR)
Energy Projects Fund	Nevada Department of Wildlife (NDOW)
Septic System Permit	Nevada Division of Environmental Protection, Bureau of Water Pollution Control (BWPC)
Working in Waterways	Nevada Division of Environmental Protection, Bureau of Water Pollution Control (BWPC)
Conditional Use Permit	Humboldt Country Planning Department
Building Permit	Humboldt Country Building Department

project on the surrounding environment. Following a period for the public to comment, the final EIS was published later in 2020.

Following an Executive Order signed by former President Trump, the U.S. Department of Interior issued mandates to streamline the process for EIS reviews to be completed within 12 months of submittal. Subsequently, the Bureau of Land Management (BLM) approved the mining permit for Thacker Pass in January 2021. In February and March 2021, Native American Tribes and local ranchers and other NGOs filed lawsuits against the BLM. While a federal judge denied the tribal request to halt development of the mine, in March 2021, significant opposition continues. In early 2022, Lithium Americas announced it had received all of the necessary federal, state and local permits and that construction of the mine will commence later in the year. Table 3 displays the permits Lithium Americas has been required to receive prior to building the mine.

As this example demonstrates, the required exploration, evaluation and approval process requires many years. It has taken approximately 15 years from when exploration activities resumed in the Thacker Pass area to when Lithium Americas announced plans for mine construction, which itself is expected to take another two years at a minimum, barring any further lawsuits. Even under an expedited Federal review process, which could simply be revoked under future presidential administrations, advancing U.S. mineral opportunities to reality will not be an overnight process.

4.2. *Litigation by social and environmental activists to block mine development*

From the long permitting delays caused by their litigation strategies, one has to conclude that the goal of environmental and activists is first and foremost to stop mining projects, not make them more environmentally acceptable or compliant. No mining at all is the objective, although sometimes social activists may target the more understandable outcome of increased economic benefits. The logic of most major environmental organisations is unexplainable, where one side of an NGO is furiously advocating renewable energy expansion, and across the hall another staff unit is demanding a total halt to mining. The complete disconnect and irony seems completely missed by these green enthusiasts.

Unlike many of the critical minerals, good potential to decrease import dependency and make significant contributions to global supply does exist in the U.S. The problem is again the obstacle of environmental and social opposition, just as described previously for the Thacker Pass lithium project. The largest new potential U.S. copper project is Resolution located in a historical mining district in Arizona. To date the Rio Tinto-BHP joint venture partners have spent over $2 billion on exploration, technical evaluation, and development over a nearly 20-year period. These outlays also involve extensive permitting and accommodating social opposition. Slow progress is being made on the multiple litigations placed as obstacles to ever binging this mine, which would be the largest copper operation in North America, into production, however strong opposition by social/environmental justice activists continues. It remains uncertain whether Resolution will ever be put into production. It is far from alone – also in Arizona is the Rosemont Project, now called Copper World owned by Hudbay Minerals. It would be a surface mine complex which faces intense opposition by environmental organisations who are determined that it never be built. Together these two new mines could produce almost a third of current U.S. primary copper demand. Opposition via permitting obstacles will continue to delay, if not stop, these major contributors to satisfying green energy metal demands.

4.3. Declining ore grades and production at existing mines

To recover the huge upfront capital costs, required to explore, study, and build a mine, operating plans will most typically begin in the highest quality part of a deposit. As such, ore grades will decline over a mine's life. Using copper as an example, Figure 3 displays average reserve copper ore grades for domestic operating mines in the U.S [27]. Since 2000, ore grades have declined and continue to trend lower. Lower grades translate into mining companies needing to mine and process more ore (and higher unit costs) to recover the same amount of critical minerals. Declining grades, combined with fewer new copper mines being permitted and built in the U.S., has resulted in domestic copper mine production remaining fairly constant over the last 40 years, however, providing a decreasing share of overall global supply (Figure 4). With copper imports now nearly 50%, declining ore grades of remaining domestic reserves at all-time lows and the expected

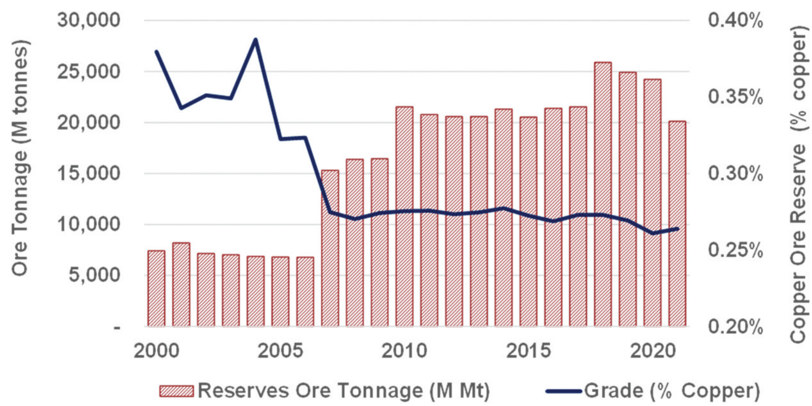

Figure 3. U.S. leading copper mines (reserve grades & ore tonnage) [27].

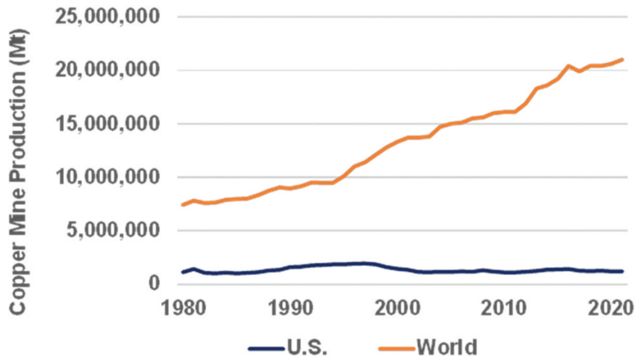

Figure 4. U.S. & global copper mine production [28].

skyrocketing demand coming from the requirements for green energy transition, it is perplexing why copper is not included in the latest version of the U.S. Critical Minerals list.

The U.S. presently consumes around two million tonnes of copper annually, with nearly half of this amount sourced from imports. While the U.S. does have very high recycling rates for copper, this currently supplies less than 40% of annual consumption. The balance of which is made up of primary mined ore and processed metal [29]. As with other critical minerals, the U.S. will remain import reliant for copper needs for the foreseeable future.

4.4. Time requirements for greenfield exploration discoveries

As many major oil companies learned the hard way during the resource diversification heyday during the 1970s and 1980s, mineral exploration and discovery is a risky and time-consuming endeavour. It is nothing like petroleum exploration where a single successful well can indicate commercial discovery and economic benefit, with a prospective project moving to production stage in a matter of months. Greenfield mineral deposits typically involve years if not decades from beginning of an exploration program until a new mine actually commencing production. And the odds are long; statistical studies are few for many daunting data reasons, but those the authors are aware of suggest well over a 1,000 geological ‘ideas’ or prospects are needed to generate one successful mine [30–33]. Further, mineralisation prospects often have very long lives, repeatedly taken up for evaluation by successive exploration companies before moving to success or final abandonment. As with any commodity, mineral prices, and supply–demand balances dictate the level of geological interest and exploration investment. Cyclical supply/demand patterns can generate great attention and financial promotion of a mineral deposit over a short interval, followed by long periods of dormancy. The bottom line is that any expectation that brand new discoveries of critical mineral deposits leading to near-term production sufficient to meet 2030–2035 GHG objectives has very limited validity in practice. Further, even if the U.S. government opts to significantly fund critical mineral exploration in efforts to speed up the process little will be achieved in view of the realities of the mineral exploration process.

4.5. Lack of a coherent mineral policy in the United States

For well over 100 years, there have been numerous attempts at the national level to pass legislation for a comprehensive minerals policy in the U.S. These have fallen short due to a lack of prioritisation and budgetary reasons. As such, policies have been limited to Congressional Acts for the stockpiling of minerals deemed strategic and more recently, through Presidential Executive Orders of which can be rescinded during subsequent administrations.

4.5.1. Strategic mineral stockpiles

Following the first World War, leading scientists stressed the need for a national minerals plan that sought to establish policies to ensure adequate supplies of raw materials be available for all industrialised nations at the time. Under the view that 'American individualism' had propelled the U.S. to become a dominant global power, this more cross-border approach proved unpopular, and Congress failed to enact this policy. Following the invasion of Poland by Germany in 1939, the U.S. Congress passed the Strategic Materials Act that created a national stockpile of strategic materials with a total budget of $100 M, with only $500 K per year allocated for domestic exploration purposes [34].

In 1946, Congress reaffirmed commitments to building a national stockpile when it amended the previous Act emphasising the importance of lessening country's dependence on foreign sources through the development of domestic sources of strategic minerals. At the time, a target of over $2B was set for the stockpile which was progressively increased to over $8B in 1950 to cover three years of supply under the Defense Production Act of 1950. This Act gave the President broad powers to encourage development of mineral resources and their production during times of war. Through the use of direct federal subsidies, purchase commitments and loan guarantees, domestic mining of strategic minerals was incentivised. The initial time frame for the duration of the mineral stockpile was intended to cover was five years of domestic demand, but later reduced to three in 1958 and then to one year in 1972.

In 1951, the focus of mineral stockpiles shifted to emphasise obtaining strategic minerals 'at the least cost possible for equivalent values', resulting in domestic production no longer being a priority over lower-cost foreign sources. In 1954 and in 1974, Congress passed Acts that allowed for the trade in farm surpluses and weapons, respectively for foreign strategic minerals. At its height during the beginning of the Cold War, the strategic mineral stockpile was valued at nearly $42 billion in today's dollars. That value has plummeted to less than $900 million as of last year following decades of congressionally authorised selloffs to private sector customers, using the proceeds to fund other programs [35].

4.5.2. Attempts, but failure at mineral policy

In terms of broader policy, the Mining and Minerals Policy Act of 1970 established national goals of fostering and encouraging private enterprise in the development of domestic mining. However, well intentioned, this Act proved ineffective as the Department of Interior denied they had the broad authority to implement the policy and the executive branch of government provided little attention [36]. In 1980, Congress passed the National Materials and Minerals Policy, Research and Development Act that reaffirmed the goals expressed in the 1970 Act. Seeking to address the need for a comprehensive mineral policy, this Act mandated the Department of Interior (through the U.S. Geological Survey (USGS)) and U.S. Bureau of Mines (BOM) collect, evaluate data related to mineral occurrence, production, and demand to be used for domestic mining companies. During subsequent years, however, as budget deficits climbed, many of the programs needed to carry out these provisions were cut [36]. Since 2010, several bills have been introduced that would use a variety of policy options and approaches – from streamlining the permitting framework for REEs and other mining and processing projects on federal land, to the additions of selected critical materials to the National Defense Stockpile.

4.5.3. Recent reliance on executive orders

Under both the Trump and Biden administrations, the nation's vulnerability to the supply of critical minerals have garnered attention. However, similar to current trends in Washington, with partisan gridlock in both Congress and Senate chambers, stop-gap, executive orders issued by the President have been the sole route to bring into focus these vulnerabilities. In 2017, President Trump issued Executive Order 13,817, which was the first to identify critical minerals, their roles in the national economy and commitment to the reduction of vulnerability to supply disruption. The Order called for identifying new sources, increasing activity through the supply chain (from exploration, mining, processing, and recycling) and to streamline associated permitting processes. Following the Order, the USGS published a list of 35 critical minerals of which the U.S. is 100% import reliant on 14 and lacking primary domestic production for another 22. Under the current administration, President Biden issued Executive Order 14,017 with provisions to identifying production and processing locations for critical minerals and updating associated standards. In February 2022, the USGS released it most updated list of commodities critical to the U.S. economy and national security. The current list expands on the 2018 version, identifying 50 mineral commodities. The increase in commodities listed is driven by splitting the rare earth elements and platinum group elements into individual entries rather than including them as 'mineral groups'. In addition, the 2022 list of critical minerals adds nickel and zinc to the list while removing helium, potash, rhenium, and strontium [37]. Presidential Executive Orders remain in force until they are cancelled, revoked, deemed unlawful, or expire on their terms. At any time, a president may revoke, modify, or make exceptions to any previous Executive Order. In addition, Congress can pass a new law to override an executive order, subject to a presidential veto. Given the time and expense required to explore for and develop facilities to extract and process critical minerals, a national mineral policy implemented via these orders is relatively useless.

4.5.4. A critical need left unfulfilled

As stated, 35 years ago, '*The United States is in need of an effective strategic mineral policy. Without one, U.S. national security is threatened, and foreign policy is rendered confusing and hypocritical . . . it is essential that stronger legislation be enacted by Congress as soon as possible and, . . . both Congress and the President commit themselves to such a policy*' [36]. Outside of the recent presidential Executive Orders, lack of coordinated commitments by these branches of governments continue to propagate the offshoring of critical mineral supply, exacerbating threats to national security and economic well-being. In response to the more recent directives, governmental agencies such as the Department of Defense (DOD) and Department of Energy (DOE) have provided funding to universities and selected private entities over the past decade for research in certain critical minerals, primarily REEs, as reliance on foreign sources has become belatedly recognised. These grants focus, however, almost entirely on research into low probability of commercial success (i.e. long-shot) potential domestic resources of REEs, such as acid rock drainage from former mining operations, coal mine waste, power plant ash, and on the development of processing facilities for the mid-stream processing of REE concentrates into oxide and carbonates. Almost zero support is being provided to foster exploration and development of viable new domestic REE mineral resources. Ironically, there have further been suggestions by agency officials that perhaps the U.S. government should provide funding support of REE mining companies who are working to find potentially commercial mineral deposits *outside* the US and ignore domestic resources entirely [38–41].

In an attempt to shore up domestic supply chains, in March 2022, the Biden administration announced plans to use the 1950 Defense Production Act to ramp up the mining and processing of key minerals used in batteries for renewable energy and EVs. The U.S. Defense Production Act allows the president to respond to a national emergency by requiring that companies prioritise federal contracts for whatever goods or materials it deems necessary [42]. Under this guidance, companies 'could' receive funding for feasibility studies to extract lithium, nickel, cobalt, graphite, and manganese. Concerns arise, however, as to how the Act will actually assist mining companies in increasing supply, processing needs and overcoming permitting delays. First, while companies may obtain assistance for the study of potential domestic projects under the Act, it does not appear that the U.S. government will help with actual capital expenses or financing guarantees associated with building mining operations. Second, the significant risks associated with many critical minerals lie in the processing of intermediate products, for example, oxide and hydroxide forms in the case of lithium, as inputs to battery supply chains. Approximately 60% of this processing activity occurs in China. These capabilities did not come about overnight; the Chinese have been working for over a decade on refining processes to transform lithium containing ores into the exacting and precise materials required by battery manufacturers for eventual use in EVs and other critical electrical equipment used in industry and by consumers. Building the required processing infrastructure and expertise within the U.S. will require similar time frames.

4.6. Absence of knowledgeable governmental agency to advise policy decision makers

Across the globe, the majority of countries have governmental technical organisations to assess domestic mineral resources, provide support to industry in mineral development, and serve as informed advisors to politicians and other governmental divisions. In the U.S., the USGS tracks global supply and domestic demand for mineral commodities. It also provides geological research and mapping in support of mineral development. This agency, however, does not currently have the capabilities to research, evaluate or support either the technical or commercial aspects of operating or new mineral production [24]. It is primary staffed with geologists, and not engineers and mineral economists. As such, the USGS is unable to provide the information the Executive and Congressional branches need to make realistic decisions regarding which mining developments have the best attributes for technical/economic production, which process technologies appear to have the best chance of commercial success, and the viability of public or private ventures promoted to solve the nation's critical minerals supply problems. In short, a source of reliable advice on which mineral projects should receive governmental support and encouragement.

Until the mid-1990s, the U.S. did have a government organisation which did have these capabilities and was well equipped to advise political decision makers. The U.S. Bureau of Mines was established in 1910, with the priority to reduce the high number of deaths due to mining accidents [43,44]. In 1913, the Bureau's scope was expanded to include the collection, analysis, and dissemination of economic data within the mining industry and to conduct scientific investigations concerning mining, economic development in the mining, quarrying, and metallurgical industries. Over the years, its research was well respected by industry and as a nonbiased data source that provided needed information and accurate advice in the hand of politicians for making mineral-related policies and investments. Unfortunately, the Clinton administration cut all funding for the Bureau in 1996 in response to demands of the environmental lobby. The agency's experienced and knowledgeable professional staff was disbanded. As a result of the closure, the U.S. is the only major industrialised economy without an agency dedicated to advancing domestic mineral opportunities through production, further strengthening the trend of U.S. reliance on foreign sources [24].

4.7. Need to development new/improved process technologies

Many of the elements now designated as critical minerals have historically represented minor metals with specialised applications. Demand for many have been a fraction of the need for major metals such as copper and iron. For some elements on the critical minerals list, downstream processing capability has to be considered as well, as transformation of ores and concentrates to useable intermediate and finished forms is often more challenging and costly than the resource extraction itself. Complex metallurgical chemistry is most always required to liberate or separate the elements desired, and since expanded use of these materials is relatively new compared to the long-established smelting and refining of major metals such as copper, nickel and zinc, many touted processing techniques for critical minerals very much remain in the experimental stage. Echoing themes above, advancing practical processing technologies will be fraught with trial and error and will not occur under desired energy transition timelines.

4.8. Magnitude/Availability of required exploration/mine development financing

The scale of the capital investment by the global mining industry needed over the next three decades just to keep up with mineral demand for historical usage is enormous. The greatly expanded tonnages reflect demand generated by world population growth, increased intensity of use in the developing world, and the much greater additive needs of the green energy transition. Where this capital will come from and how or whether it will be effectively deployed are major questions for which politicians, investment bankers and mining executives currently have no answers. A fact to keep in mind is that the major mining companies will not undertake exploration/production of critical minerals except as byproducts at existing operations (the one exception at present is lithium in which Rio Tinto is making investments). On the other hand, major banks are reluctant to lend to mining project development due to their current focus on ESG policies as part of their current business strategies. Consequently, primary financing of critical mineral development will likely have to come from private equity, with its attendant requirements for higher returns on investment, hence higher metal prices. We also note that based on experience, at least half of capital invested in junior critical mineral explorers will be misallocated, consumed by financial promoters with poor projects having remote chances of success. Finally, the slow and outdated development process demonstrated by the Thacker Pass venture is a primary reason many mining firms and investors avoid the U.S. minerals industry. Delays in permitting have caused mineral investment dollars for projects in the U.S. to deteriorate over the past 20 years – for example falling from 21% of the global total in 1993 to 8% in 2013 [45].

4.9. Shortage of geological and mining professionals and skilled mine operators

Growing mining workforce shortages are of growing concern in the Western World for two decades now, as older professionals and blue-collar workers retire, and new entrants have significantly decreased. Without sufficient workforce, the development of the many new mines needed to provide critical minerals for the green energy transition will be impossible.

5. Summarized findings

At the National, State and Local level, reductions for GHG emissions and renewable portfolio and clean energy standards provide well-publicised mandates, with achievement timelines varying from as short as 2030 to midcentury. On the basis of the supply of necessary critical minerals to support such targets, it is extremely doubtful that targeted timelines will be achieved. Attempts to establish domestic supplies of these minerals will continue to be hampered by the lack of a formal mineral policy, extensive permitting requirements, litigation, and minimal financing which greatly exacerbate the fundamental time requirements necessary to explore, study and construct mining operations. As such, the U.S. will increasingly be exposed to geopolitical risks surrounding the supply chains of critical minerals. Clean energy transition timelines will further be impacted as critical mineral prices climb in response to global demand pressure.

6. Concluding observations

We have discussed the provision of critical minerals required for attainment of GHG reduction goals from a U.S. perspective. More specifically, we have examined the critical obstacles which block provision of supply of these elements, especially in the enormous quantities which will be needed for transition to a green electrical energy economy in the politically desired timeframe. For the U.S., we offer the following the observations regarding the critical minerals supply situation over the next couple decades.

6.1. Critical materials supply will not meet green energy transition goals

Realistically, it is highly doubtful that the supply of the vast quantities of critical minerals necessary to meet U.N./U.S. green energy transition targets will be achieved, at least in volumes necessary to accomplish the timeframes demanded by climate change activists, politicians, and green energy investors. As a representative example, global automobile sales are expected to approach 125 M units by 2030 (a nearly 45% increase from 2021) [46]. If the world is to build towards a '*Net Zero Carbon by 2050*' scenario, it is estimated that this will require nearly 60% of 2030 automobile sales to be electric. However, considering the current lithium supply chain, this would require mine supplies to be approximately 5-times higher than the approximate 100 K mt mined last year. As demonstrated by the Thacker Pass mine, when one contemplates the actual time needed for companies to actually explore, study and model potential resources, to obtain permits, the extensive efforts to solidify buy-in from local communities and stakeholder, the raising of capital funds and then to the actual construction of a mine, this level of expansion (all within less than 8 years) is extremely unlikely. Further, this high-level calculation ignores the requirements in electronic and medical devices as well as the building requirements for the lithium to be needed in actual EV charging stations. As the world operates today and Congress will eventually discover, it is much easier to make proclamations such as, '*The U.S. Government will end gas-powered vehicle purchases by 2035*' than to fulfil that proclamation. This is particularly true when environmental advocates support such green initiatives while concurrently blocking the mining of critical minerals required for the transition.

6.2. Critical materials price will significantly increase green energy costs

The inability of the global resource industries to quickly increase production to meet expanded demand for many materials crucial to green energy development will undoubtedly drive-up capital costs. Wind and solar generation's much higher requirements for these minerals and other elements per unit of energy capacity will cause supply–demand imbalances rarely seen in the mining sector. Cost increases at both the upstream extraction end and at the component processing/fabrication phase of supply chains will limit the economic feasibility and advancement of green energy development. If wide-scale development of renewable energy is eventually mandated, even ignoring issues of economic competitiveness, capital requirements will be much higher than promoters have as yet considered. Assuming political entities, the environmental lobby, and society as a whole eventually recognise that expanded mineral extraction is an unavoidable necessity to achieve climate change goals, these cost challenges may eventually be addressed. However, changes in environmental activist and social attitudes to actually encourage domestic mineral extraction will take much longer than the timelines currently envisioned for the green energy transition.

6.3. The U.S. government will continue to have no formal mineral policy

At a national level, the continuation of sharply divided political views of the U.S. populace will continue to block any consensus on a clear policy to foster domestic mineral production. Regardless of efforts by knowledgeable professionals to encourage the establishment of at least some form of policy, governmental entities will rely on stop-gap measures, such as executive orders. However, without stable investing and operating environments, mining and exploration companies will continue to ignore large portions of geologically favourable prospective lands within the U.S., diverting exploration and development investment capital towards foreign, more politically favorable jurisdictions.

6.4. The De Facto U.S. supply strategy for critical minerals is 'Other countries'

The U.S. government's continuing default policy for sourcing of critical minerals will be to rely on foreign suppliers rather than instead of domestic resources. Be it 'Off-Shoring', 'Near-Shoring', 'Friend-Shoring', etc., (but never 'On-Shoring'), U.S. policy makers and consumers appear to have decided that the nation's critical mineral needs will come from other countries instead of new domestic resources, regardless of the numerous economic, social, and environmental impacts or national security considerations. Obviously, there are a number of critical minerals for which the U.S. will have to remain import reliant, as geological existence of these, in the demanded quantities, is simply not within the current confines of the U.S.

However, geologic knowledge is always advancing and avoiding domestic mineral exploration and mine development because it is socially unacceptable will continue to be bad long-term policy for the U.S. Intermediate and final processing of some critical minerals, which are absolutely necessary and complex, such as with REEs and lithium, may eventually be encouraged through some form of formal policy, and Federal funding support. As with mining, the political, environmental, and general public appear to be very comfortable outsourcing the environmentally challenging intermediate processing of critical minerals to China. To the authors this seems an extremely myopic and somewhat selfish attitude and smacks of old-style resource imperialism. In the context of Green Energy, the implications of an 'anywhere-but-here' approach for the bulk of U.S. critical minerals need were summarised in a recent Foreign Policy post [47]:

> *The dirty secret of the green revolution is that its that are produced using some of the world's dirtiest technologies. What's more, the accelerated shift to batteries now threatens to replicate one of the most destructive dynamics in global economic history: the systematic extraction of raw commodities from the global south in a way that made developed countries unimaginably rich while leaving a trail of environmental degradation, human rights violations, and semipermanent underdevelopment all across the developing world.*

6.5. The vast disconnect between environmental advocates and critical minerals reality appears likely to continue

It is hard to understand the logic of social, political, and environment activists, particularly in the U.S., whom on one hand demand the immediate transition away from fossil fuels, while on the other insist that no mining of the critical minerals indispensable to enable such transition. Or alternatively, to rely on other nations to provide such materials without regard to economic, social, and environmental costs. Realistically, we see no change in this attitude across the American public for the foreseeable future as the evils of mining have been beaten into US citizens for now decades, mainly via the elementary, secondary, and higher education institutions. News media has also contributed greatly, often demonstrating appalling lack of understanding of modern mineral resource extraction and the necessity of such for modern civilisation. The majority of US-based environmental advocacy organisations of course are adamant that extraction of domestic mineral resources should not occur or be greatly constrained. This anti-mining attitude in the face of reality that, given continuing major global population growth and pressing desire to replace fossil fuels with renewable sourced electrical power, is shared by elites beyond US borders, was succinctly capsulised by U.N. Secretary General António Guterres at last year's COP26 [48]:

> "*Fast forward three years, and there's still little or no acknowledgement from climate crisis actors for the need for rapidly growing metal and mineral extraction. The nescience of climateers when it comes to mining remains striking and helps explain the applause for (United Nations) Secretary General António Guterres at the opening of the COP26 summit for these words:*
>
> *It is time to say enough! [. . .] enough of burning and drilling and mining our way deeper. We are digging our own graves.*

Again, the authors have great difficulty understanding the logic of this apparently widely held belief that the mineral products needed for GHG mitigation via renewable energy will appear without mining them, as if by magic.

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