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Article

Resource-Efficiency and Critical Raw Materials in Covid-19 and Recovery

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Abstract

This paper shows that Japanese experts have built a resource-efficient Covid-19 response, but are also using the crisis to ramp up Japanese-style collaboration on resource-efficient and sustainable communities. The paper also details why this resource-efficiency is essential in the critical raw materials sector. We suggest that Japan's initiatives could be an important indicator of how to maintain momentum against climate change and other hazards. Japan's measures integrate the UN 2030 Agenda's three pillars of the Paris Agreement, Sustainable Development Goals (SDGs), and the Sendai Framework of Disaster Risk Reduction (SFDRR). The paper also details why this resource-efficiency is essential in the critical raw materials sector, where the challenges are of such enormity that seabed mining may be required to mitigate myriad risks.

Introduction

In Japan, the Covid-19 pandemic has led to an accelerating diffusion of all-hazard, disaster-resilient policy integration. Japan's initiatives centre on maximizing the co-benefits from the deployment of scarce fiscal, material, human and other resource. This paper shows that Japanese experts have not only built a resource-efficient Covid-19 response, but are also using the crisis to ramp up Japanese-style collaboration on resource-efficient and sustainable communities, both in Japan and overseas. The paper also details why this resource-efficiency is essential in the critical raw materials sector. Japan's initiatives could be an important indicator of how to stay on track, at a time when action on the climate challenge risks being derailed. Japan's measures further integrate the UN 2030 Agenda's three pillars of the Paris Agreement, Sustainable Development Goals (SDGs), and the Sendai Framework of Disaster

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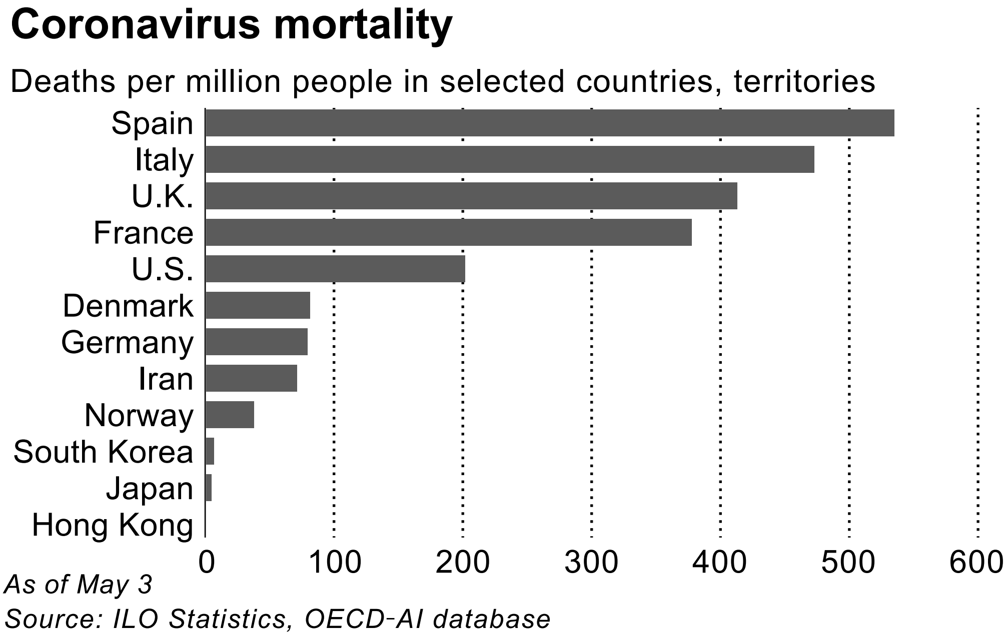
Risk Reduction (SFDRR). The paper also details why this resource-efficiency is essential in the critical raw materials sector. As we see, the challenges are of such enormity that seabed mining may be required to mitigate myriad risks.

Countering Covid-19

In the first half of 2020, Japan waged an apparently successful campaign against Covid-19. In the May 7 *Financial Times* former head of the UN Framework Convention on Climate Change, Christiana Figueres, included Japan among the few countries that “acted in line with the risks.” A number of previous vocal critics of Japan’s response have conceded its success in preventing an outbreak “on the scale seen in many Western countries” (Normille, 2020). One key to Japan’s achievements on Covid-19 is an “expert-led approach” (Du, 2020) : experts implemented countermeasures that maximized the effective use of constrained resources in the midst of a complex institutional environment and still-confusing scientific data on what is best practice. Those lessons apply to Japan’s smart-city decarbonization and other goals as well.

We see evidence of Japan’s success in figure 1, which compares Covid-19 mortality



Coronavirus mortality

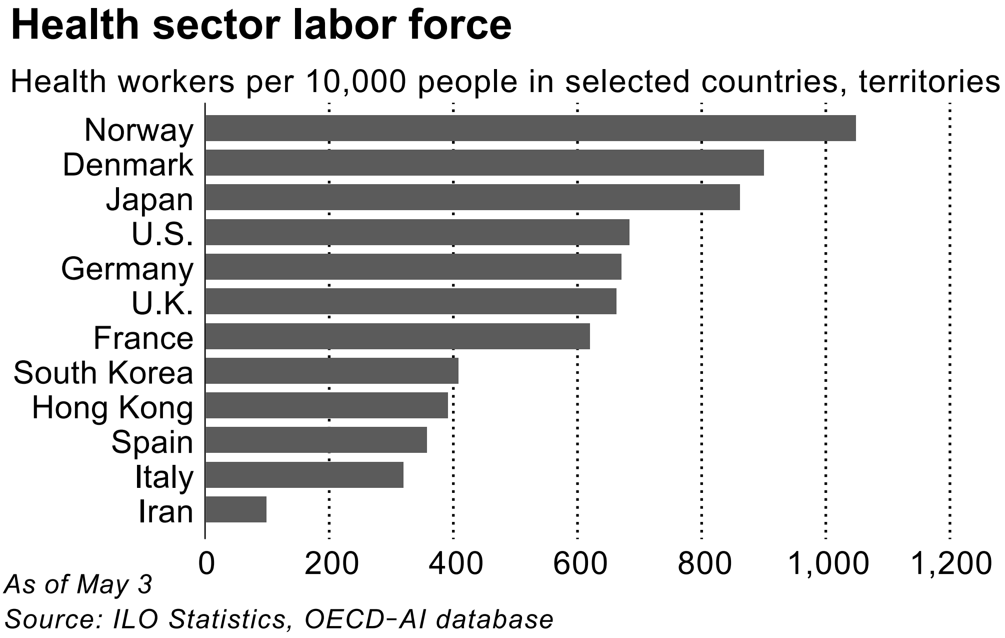
Deaths per million people in selected countries, territories

As of May 3

Source: ILO Statistics, OECD-AI database

Source: Crump, 2020

Figure 1 Comparative Covid-19 Mortality



Health sector labor force

Health workers per 10,000 people in selected countries, territories

As of May 3

Source: ILO Statistics, OECD-AI database

Source: Crump, 2020

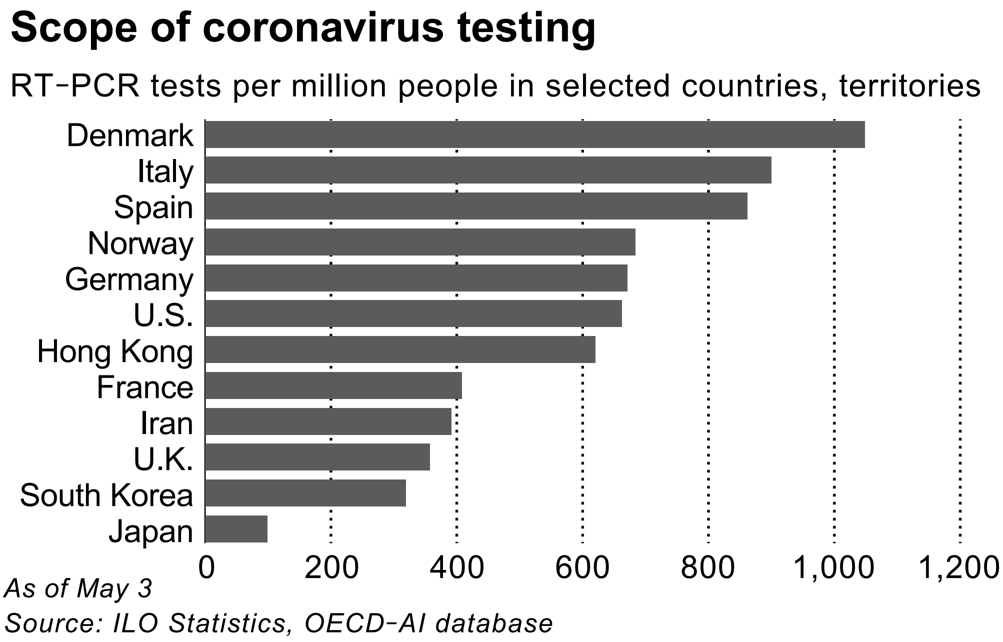
Figure 2 Resources for Combating Covid-19

across several countries as of May 3, 2020. The data indicate that Japan's levels of mortality were quite low as measured by available comparative statistics. Among the countries displayed in the figure, only Hong Kong recorded a lower level of mortality as measured by deaths per million persons.

Figure 2 provides one measure of the relative constraints on Japan's ability cope with Covid-19. The means for pandemic response is a large category, encompassing masks, ventilators, medical staff, and other material and human resources. The figure shows that Japan had comparatively abundant health-sector workers, as one would expect in the world's most aged society. So at first glance, Japan would seem well-endowed with the resources to combat a pandemic such as Covid-19.

But in fact, Japan's health workers are significantly under-trained in contract-tracing and other aspects of pandemic response. Moreover, the health workers also had inadequate supplies of masks, gloves and other "personal protective equipment" (PPE) required for the safe care of suspected and confirmed cases of Covid-19.

Figure 3 further highlights the resource constraint by comparing the rate of Covid-19 testing across several countries including Japan. Japan's current protocol for Covid-19 and other pandemics emphasizes testing, tracing and treatment. The focus is on identifying in-



Source: Crump, 2020

Figure 3 Comparative Covid-19 Testing

fected patients and then testing along with tracing other potentially infected individuals. The approach is very different from widespread testing and is arguably “extremely cost-effective” (Crump, 2020). Rather than devote massive resources to widespread testing and enforced lockdowns, Japanese experts centred their efforts and advice on a “3C” approach. The 3Cs encouraged individuals to avoid: 1) closed spaces with poor ventilation, 2) crowded places with groups of people, and 3) close-contact settings like one-on-one conversations (Feder, 2020).

Providing Integrated Public Goods

While fighting Covid-19, Japanese policymakers invest in a wide range of smart projects to reduce the cost of crucial public goods, including diversifying access to critical raw materials (e.g., cobalt, lithium, rare earths and copper) essential to sustainability (World Bank Group, 2020), further decarbonizing the energy economy, and bolstering multilateral collaboration. Indeed, while most other countries were debating whether to aim at a “green recovery,” Japan was already investing heavily in the governance and technology of decarbonizing and disaster-resilient transformation.

Table 1 COVID-19 Fiscal Stimulus, % GDP (as of May 31, 2020)

Country	Fiscal Stimulus (Amount)	Fiscal Stimulus (% GDP)
Japan	JPY 234.2 trillion (USD 2 trillion)	42.2
US	USD 2.9 trillion	14
Germany	EUR 913 billion	26.9
France	EUR 425 billion	19
China	RMB 3.6 trillion	3.5

Source: Japan Cabinet Secretariat, 2020; IMF, 2020

Table 2 December 2019 Fiscal Stimulus (JPY trillion)

Measure	Public Spending	Total Public/Private
NRP and Disaster Reconstruction	5.8	7
Economic Risk	3.1	7.3
Post 2020 Olympic Games	4.3	11.7
Total	13.2	26

Source: Japan Cabinet Secretariat, 2020

The evidence of Japan's proactive approach included its largely misunderstood fiscal stimulus. Table 1 shows that as of May 31, Japan's Covid-19 fiscal countermeasures exceeded 234 JPY trillion (about USD 2.0 trillion), roughly 42% of GDP. This total is the combined result of two major stimulus packages, both just over JPY 117 trillion, in March and then in May of 2020. In March of 2020, when Japan's first headline-grabbing JPY 117 trillion Covid-19 stimulus was announced, much expert commentary pointed to the fact that it was not new finance. Analysts complained that the JPY 117 trillion stimulus (passed in April) built on Japan's JPY 26 trillion December 2019 fiscal stimulus, displayed in table 2. Their point was that the math of the April stimulus was exaggerated and misleading (Takemoto and Nakagawa, 2020), though the Japanese government did not hide the continuity from December.

Lamentably, such criticism directed at the math of the April Covid-19 stimulus deflected attention from the December 2019 package's content and its role in framing ongoing efforts. To be sure, the December 2019 stimulus had nothing to do with Covid-19 per se. Rather, it focused on decarbonizing, all-hazard resilience in the wake of unprecedented floods, blackouts, and the other shocks Japan endured during 2018 and 2019. This emphasis on content is very important, as in March and April, World Bank and other experts were urging countries to include sustainability goals in their fiscal stimulus packages (Hammer and Hallegate, 2020). By then, Japan was already battling Covid-19 and climate change at the same time thanks to building on the December 2019 stimulus.

Table 2 shows that there were three key pillars in the December 2019 stimulus: National Resilience Plans (NRP) and disaster reconstruction; economic risk countermeasures; and “Post 2020 Olympic Games” legacy investment in Society 5.0, SDGs-inclusive society. The NRP projects emphasize that “coping with climate change is also conducive to disaster prevention.” Hence, investments in more robust communications, water, transport and other critical infrastructure is complemented with Net Zero Energy Buildings. In tandem, the Society 5.0/SDG initiatives explicitly target zero-emissions technology (such as natural refrigerants), energy efficiency, and related decarbonization (Japan Cabinet Secretariat, 2019). Of course, the 2020 Olympic Games have since been postponed to 2021, and in the end may not even be held. But that hardly means the investment in critical infrastructures is wasted, since they increase Tokyo’s holistic resilience and its capacity to accelerate its “Zero Emissions Tokyo Strategy” ambitions to decarbonize (DeWit, Djalante and Shaw, 2020).

We have seen that this initial December 2019 fiscal stimulus was more than quadrupled in the first Covid-19 stimulus (of April 20), which brought additional spending on the National Resilience, SDGs and Society 5.0 detailed above. The expanded package also included JPY 15 trillion for restructuring supply chains to re-shore or at least further diversify (e.g., among ASEAN countries) the production of a host of critical raw materials. Moreover, consistent with the December 2019 approach, the April package ramps up digital transformation, decarbonization, and other measures specifically to reduce the risks of future pandemics. It also emphasizes smart, SDG-style multilateral engagement on overseas water systems, public health and other critical infrastructure via Japan’s aid agencies plus the IMF, the World Bank, the Asian Development Bank, and other multilateral institutions with whom Japan has a record of close collaboration. Indeed, Japan is the largest contributor to the IMF, and its April stimulus included an additional USD100 million “contribution to the IMF’s Catastrophe Containment and Relief Trust as immediately available resources to support the Fund’s capacity to provide grant-based debt service relief for the poorest and most vulnerable countries to combat COVID-19” (Georgieva, 2020).

And then on May 27, the Japanese government announced that it planned to double the stimulus yet again, to the over JPY 234 trillion total shown in table 1. It remains too early to track how that additional fiscal boost, to an unprecedented 42% of GDP, will be used to further enhance all-hazard resilience. The early evidence looks encouraging, but the question deserves a detailed examination at a later date.

The Collaborative Industrial Policy Context

Japan's smart mitigation and adaptation measures are expanding within a larger holistic paradigm of collaborative industrial policy (DeWit, 2019). Japan's "Society 5.0" industrial policy regime predated Covid-19, and indeed was heavily funded in Japan's pre-pandemic, December 2019 stimulus. Society 5.0's policy arms include such critical cyber-physical linkages as digitalization in smart cities, "post 5G" next-generation communications, remote-sensing for disaster risk reduction, 3-D mapping for compact cities, monitoring and controls for integrating variable renewable energy, and other means to bolster evidence-based collaborative governance. Japan's Society 5.0 is also directly linked to the 2030 Agenda's Sustainable Development Goals (SDGs). Indeed, Japan's approach to SDGs initiatives appears to be unique among the developed countries: its multi-level SDGs collaboration deliberately uses the SDGs' 17 goals and 169 targets to focus local government projects on myriad domestic challenges in combination with overseas engagement and contributions. In short, Japan does not see SDGs as external aid but rather as a platform for integrating sustainable domestic and overseas development (Seki, 2019).

As is shown in **Table 3**, Japan has organized a broadly inclusive Local SDGs Public-

Table 3 Japan's Local SDGs Public-Private Collaborative Platform (as of April, 2020)

Member Class	Number
Subnational Governments	453
Central Agencies	13
Private Firms and others	769
Total Membership as of end March, 2020	1,235

Source: SDGs Journal, 2020

Table 4 Japan's Local SDGs Communities and Model Cases (as of April, 2020)

Category and Year	Number
2018 SDG Future Cities	29
2018 SDG Model Cases	10
2019 SDG Future Cities	31
2019 SDG Model Cases	10
Total Cities and Cases	Cities: 60, Model Cases: 20

Source: SDGs Journal, 2020

Private Collaborative Platform. The platform includes 453 local governments in addition to most of the national government's central agencies. It also includes 769 business firms, research institutions, NPOs and other members, bringing the total to 1,235 members as of April 2020.

Table 4 shows the ongoing results of the Japanese Cabinet Office's efforts to disseminate best practice. Since 2018, the Cabinet Office has opened a competition for subnational governments to be designated as SDG Future Cities and for particularly well-integrated initiatives to be designated as Model Cases. As of April of 2020, there are 60 SDG Future Cities and 20 Model Cases, indicative of the prioritization of the program and its widespread impact.

A further important platform context for shaping Japanese action is its Smart City Public-Private Collaborative Platform, whose membership is itemized in table 5. Of particular note is the growing number of local governments, at present 114. The platform is yet another venue via which the 2030 Agenda integration of decarbonizing and inclusive Paris Agreement, SDGs, and SFDRR best practices are shared among multiple stakeholders.

A more recent platform is Japan's Green Infrastructure Public-Private Collaborative Platform. Table 6 shows that its membership as of March 2020 exceeds 400 local governments, central agencies and other stakeholders. The local government membership includes Sendai City (the host city for the Disaster Risk Reduction program), Tokyo, and other influential cases. Moreover, the important role of central agencies is coupled with the participation of business, academe, NPOs and other stakeholders whose collective expertise encompasses water, energy, construction, and other areas crucial to designing and implementing comprehensive green-infrastructure solutions. This emphasis on green-infrastructure not only helps achieve the 2030 Agenda goals of mitigation, adaptation and inclusive sustainability; it also reduces the burden of future costs for maintain traditional "grey infrastructure" such

Table 5　Japan's Smart City Public-Private Collaborative Platform (as of March, 19, 2020)

Member Class	Number
Subnational Governments	114
Central Agencies	11
Businesses, Research Centres, and others	357
Business Associations	2
Total Membership	484

Source: MLIT, 2020a

Table 6 Japan's Green Infrastructure Public-Private Collaborative Platform
(as of March, 19, 2020)

Member Class	Number
Subnational Governments	23
Central Agencies	4
Businesses, Research Centres, and others	150
Individual Memberships	232
Total Membership	409

Source: MLIT, 2020b

as levees (Nakamura, et al, 2019).

One of Japan's key governance platforms for designing, implementing and revising integrated policy is National Resilience (DeWit, Djalante and Shaw, 2020). National Resilience predates the 2030 Agenda's SFDRR, formally adopted in 2015, and closely parallels the latter's content by emphasizing all-hazard disaster preparation, building back better, and "whole of government" inclusive collaboration. National Resilience also encompasses smart communications, sustainable energy systems, resilient water networks, and the other critical infrastructures that are essential to holistic resilience in the modern city. It should be no surprise that Japan is doing this, as it confronts innumerable natural hazards plus severe demographic, fiscal and other challenges. Japan has also historically been the leader on international disaster resilience frameworks, which is why the first international framework is the Yokohama Strategy (1994) and the second the Hyogo Framework (2005-2015). The 2015-2030 Sendai Framework of Disaster Risk Reduction (SFDRR) continues this tradition of Japanese leadership, which emphasizes community involvement and integration with other objectives (de la Poterie and Baudoin, 2015).

National Resilience is also Japan's program for closely linking national and subnational governments in a rapidly expanding portfolio of national and subnational NRPs that have legal precedence over other plans. NRPs are aimed at bolstering the country's resilience to natural disasters and other hazards, before they happen, as well as fostering the capacity to recover from such disasters when they occur. Since 2014, there have been 2 iterations (2014, 2019) of the NRP Basic Plan as well as 6 annual action plans that decide and then monitor the planning cycle and the achievement of Key Performance Indicators (KPI). These KPIs include hard measures, such as monitoring hazards via smart sensors, strengthening back-up power for hospitals and other facilities, reinforcing flood-control systems, and hardening critical communications infrastructure. The KPIs also include soft measures, such

Table 7 Increase in Japan's Local National Resilience Plans (NRPs)

Administrative Level	April 1, 2019	April 1, 2020
Local Government	190	1,445

Source: National Resilience (2020)

Table 8 Sapporo City's 2020 Economic Stimulus-Related Spending (unit: JPY billion)

Disaster-Recovery and Resilience: 20.9	Resilient Schools	9.36
	Emergency Power	0.24
	Flood and Other	11.32
Future-Oriented Investment: 11.1	ICT in Schools	9.54

Source: Sapporo, 2020

as skill-building, risk communication, and measures to break down governance silos. In the 2019 revision of the original 5-year NRP Basic Plan, the number of KPIs had increased to 179. The 2020 update of the NRP action plan is slated to raise the number of KPIs to 268. Moreover, Japanese National Resilience has been funded at roughly JPY 5 trillion per year since FY 2018. The investments finance soft and hard measures in addition to training and international engagement.

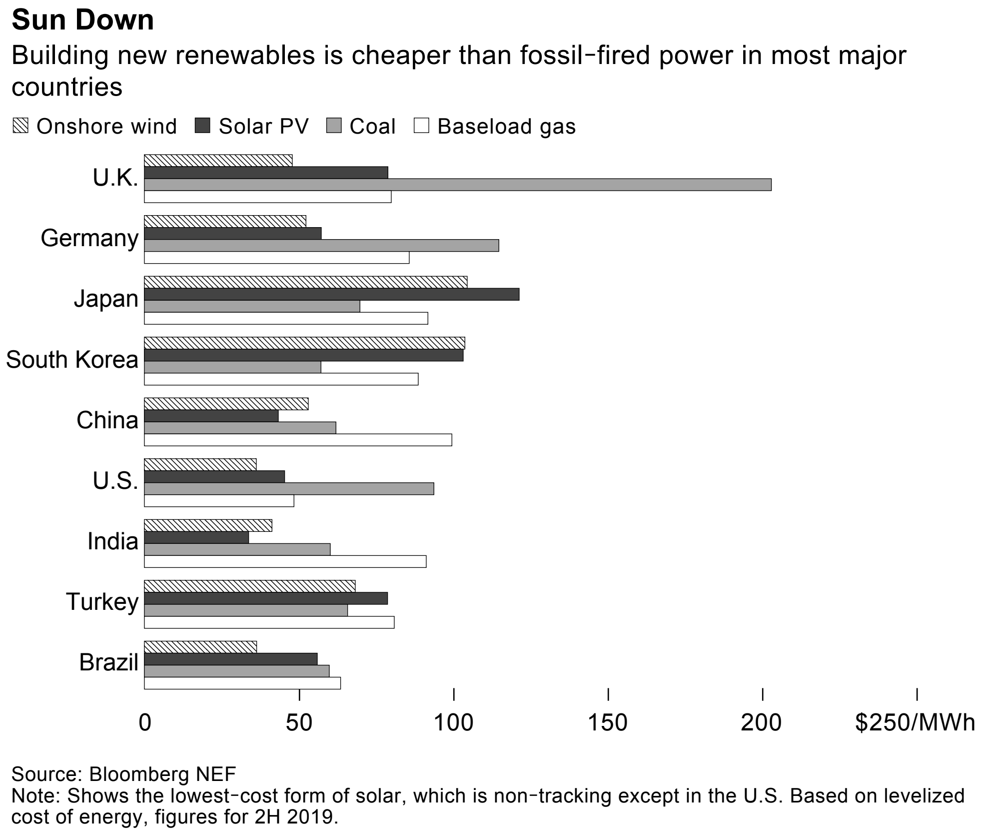
A key test of any such ostensibly collaborative initiative is how well it diffuses and how purposefully engaged the actors are. By April 1 of 2020, all of Japan's 47 prefectures had adopted their own regional versions of the NRP. Moreover, as table 7 shows, 1,445 of Japan's 1,741 cities, special wards, and towns had either adopted their own local versions of the NRP or were formulating plans. This number of local governments doing NRPs was more than seven times the 190 total from a year earlier, April 1 of 2019. That startling 760% rate of increase in one year is testament to the rapid spread of comprehensive risk-awareness in Japan. Recent years of unprecedentedly destructive typhoons, floods and other disasters have led to a consensus on the need for comprehensive planning and integrated counter-measures. Japan's subnational governments now routinely request increased regular budget and special fiscal stimulus spending on NRP, SDGs, Society 5.0 projects and their integration in the smart city. These fiscal and related requests are articulated collectively through such subnational representative organizations as the National Governors' Association, The National Mayors' Association and others.

One example of how the December, 2019 fiscal stimulus is being used at the subnational level is seen in table 8 on Sapporo City. The table shows that Sapporo's 2020 initial spending on economic stimulus, responding to the national government's December stimulus package, focused on close to JPY 19 billion for resilient and smart schools. Resilience schools emphasize enhanced seismic countermeasures in addition to safe water and power supply. Other spending included JPY 11.32 billion on bolstering the city's waterways, transport networks and other critical infrastructure. This emphasis on resilience is no surprise. Like many of Japan's subnational governments, Sapporo is aggressive in building on national policy to pursue integrated solutions to disaster, demographic, fiscal, and myriad other hazards. Sapporo was thus selected as one of the SDGs projects in June of 2018, and followed that up in December 2019 by revising the NRP it had adopted in January of 2016. Sapporo had already been undertaking a Compact City Plan from March of 2016, and had also implemented a Smart City initiative from March of 2017. The Sapporo case is illustrative of the permeation of holistic resilience planning to the local community. This local initiative is stimulated not only by central government financial incentives on a scale found in few other nations but also by silobreaking, comprehensive planning and industrial policy.

Resource-Constraints

Japan's emphasis on the cross-sectoral integration of policies, stakeholders and infrastructures, to maximize resource-efficiency, is important not only for the reasons discussed above, but also because of costs and material constraints in other realms. For example, as noted earlier, there is an emergent consensus that the recovery from Covid-19 must be consistent with the goals of the 2030 Agenda. For many observers, this means emphasizing power generation via solar and wind projects (variable renewable energy, or "VRE") as the centerpiece of a "green recovery." Those VRE investments certainly can help decarbonize power, but they are only part of a larger portfolio of strategic investments for resilient and equitable decarbonization (IEA, 2020a). VRE are also not necessarily the least expensive and most materially efficient means for accelerated decarbonization. These points appear to be particularly relevant in the Japanese case. As shown in figure 4, Japan's costs for VRE are considerably higher than for coal and natural gas, a sharp contrast to the other countries except for South Korea. Moreover, among the countries represented in the figure, including South Korea, Japan's solar and onshore wind costs are the highest.

Figure 4 is also not comprehensive. For one thing, it only compares the cost of new build for power generation facilities themselves while overlooking larger system costs. The latter include power transmission and distribution infrastructure in addition to other ancil-



Sun Down
Building new renewables is cheaper than fossil-fired power in most major countries

Source: Bloomberg NEF
Note: Shows the lowest-cost form of solar, which is non-tracking except in the U.S. Based on levelized cost of energy, figures for 2H 2019.

Source: Fickling, 2020

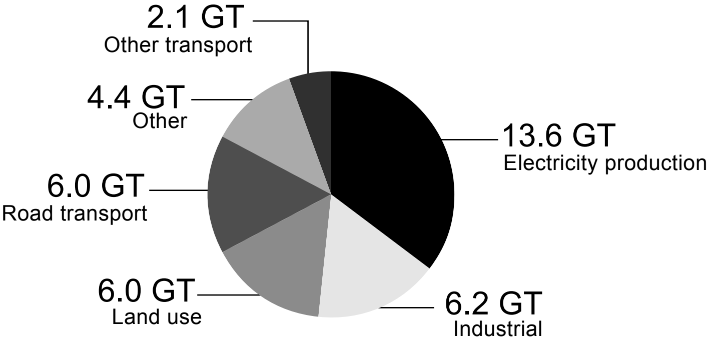
Figure 4 Comparative Renewable Costs, 2019（Units: USD/MWh）

lary costs such as power storage. These costs vary depending on the location of a given VRE or other power-generation project, the proximity of power transmission lines, and other factors. In short, it is misleading to insist that the cost of VRE solar panels and wind turbines are falling, and thus declaring them to be the cheapest option, without paying attention to whether the transmission, storage and other system costs are declining as well（Cox and Xu, 2019; Lesser, 2019; World Economic Forum, 2019）.

Moreover, power generation is only one area where decarbonization is possible, as there are many sectors that release CO2 and other greenhouse gas（GHG）emissions. Figure 5 illustrates some of the details. It shows that total anthropogenic CO2 emissions in 2017 were roughly 37 gigatonnes（Gt）. Roughly 13.6 Gt was from power, while road transport represented a further 6.0 Gt. These two areas are generally the focus of green visions, with their emphasis on VRE and electric cars. But total anthroprogenic CO2 emissions were – as noted – 37 Gt., leaving a further 17 Gt from several other sectors. Industrial CO2 emissions

Glass Half Empty

Completely decarbonizing the electricity and passenger car sectors would still leave about half of global CO2 emissions untouched



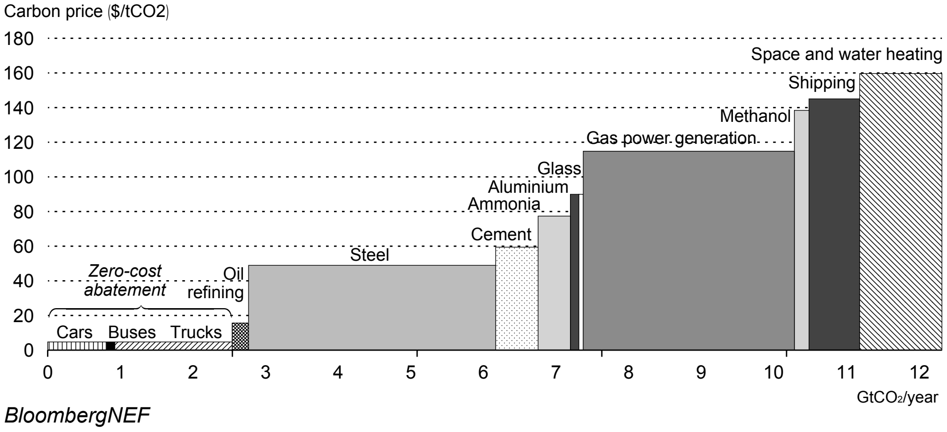
Source: IEA, Global Carbon Project
Note: Most figures are for 2017, land use for 2019. GT=gigatonnes, one billion metric tons. “Other” includes residential buildings, commercial and public services, and energy used in mining coal and refining oil.

Source: Fickling, 2020

Figure 5 CO2 Emissions by Sector (Units: gigatonnes)

were one large sector, at 6.2 Gt, and land use was 6.0 GT.

There are myriad proposals for decarbonizing sectors other than power. One is the use of hydrogen as an energy vehicle in order to displace natural gas and other fuels used for industrial heat (such as in making steel and cement). Figure 6 outlines the abatement costs of this approach, in USD per ton of CO2 and assuming that the cost of hydrogen is USD 1 /kg in 2050. At the time of writing, hydrogen costs roughly USD 3 /ton, and is largely produced by reforming natural gas (IEA, 2019a). So the assumed reductions in generation costs and infrastructures are quite significant. Moreover, Bloomberg New Energy Finance estimates that to meet about 24% of current global energy needs with hydrogen generated through electricity would require 31,320 terawatt-hours (TWh) of power. That figure is enormous, and in fact exceeds the global total of 25,700 TWh of gross electricity generation from all sources (ie, renewable, nuclear, and fossil fuels) in 2017 (IEA, 2019b). Expressed in percentage terms, fossil fuels were 66.8% of gross global power generation in 2017, hydropower 16%, nuclear 10%, wind 4 %, solar 2 %, biofuels and waste 2 %, and geothermal, tidal and others a mere 1 % (IEA, 2019b). Indeed, even by 2019, total power generated by large low-carbon hydro, nuclear, biomass, and VRE was only about 10,000 TWh, of which VRE provided less than 2,100 TWh (IEA, 2020b). Thus any proposal to emphasize



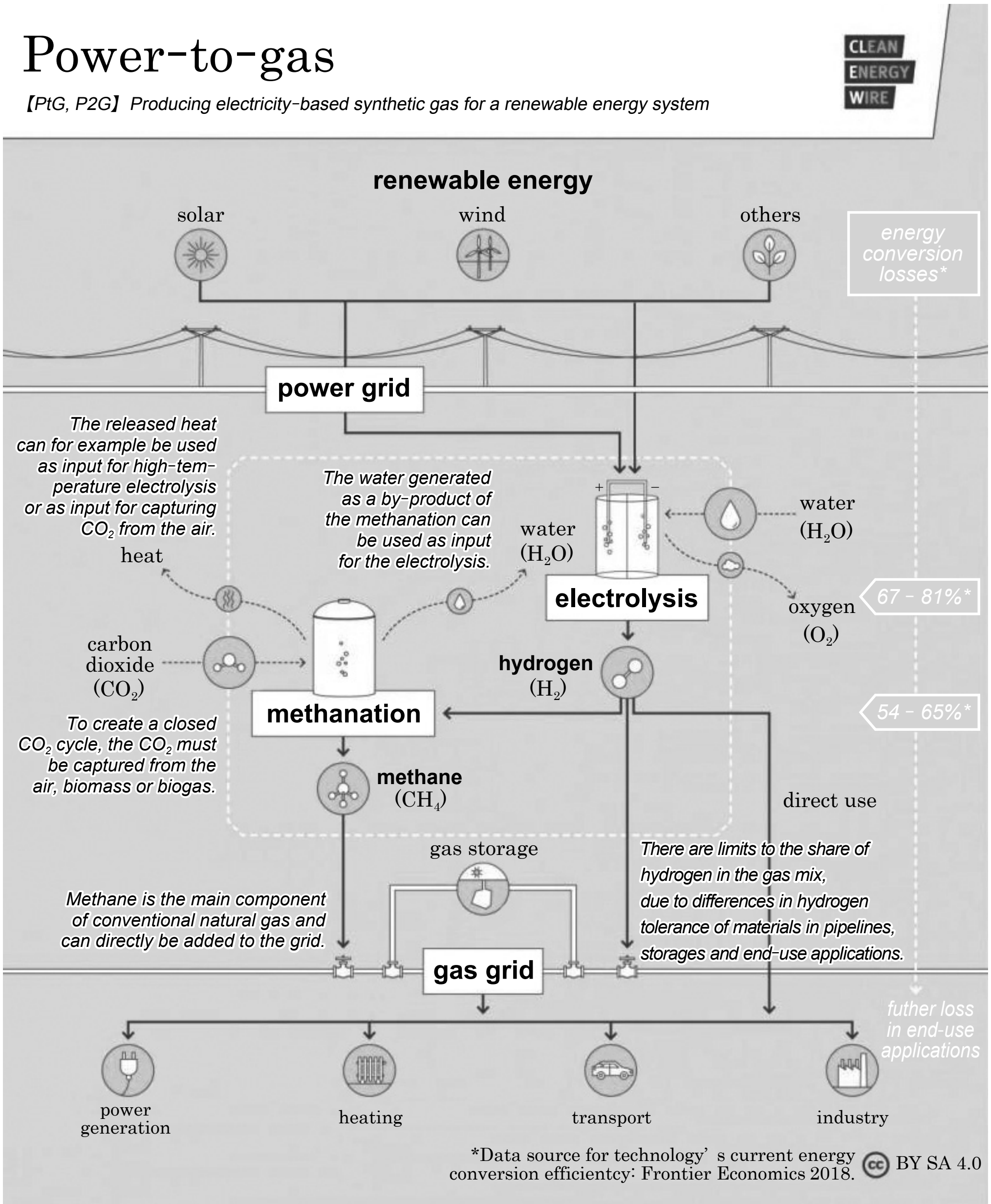
Source: Fickling, 2020

Figure 6　Marginal CO2 Abatement Costs

VRE as the main source of hydrogen has to make a credible case for where the VRE plant can be sited, its cost-effectiveness versus other options (such as the use of nuclear), its comparative material-efficiency (ie, per-unit density of critical raw materials), and other factors.

Figure 7 is reproduced from a study of German options on generating hydrogen and methane for use across a range of applications. The bottom section of the figure thus outlines the potential use of synthetic gases in power generation, heating, transport and industry. The analysis shows that it is technically possible to undertake such a transformation. But at the same time, the study concedes that "Germany may simply not have space for the number of wind turbines and solar panels needed to produce enough synthetic gas to meet demand, particularly given that German citizens are already resisting the construction of renewable energy infrastructure" (Wettengel, 2018). The analysis suggests means of overcoming these constraints, including building offshore wind dedicated to producing hydrogen along with importing synthetic gas produced in North Africa or the Middle East.

The above figures highlight some recent arguments pertaining to the scope for rapid deployment and use of renewables. In the midst of Covid-19, and the emphasis on a "green recovery," many media and academic articles assume the world is well on the way to green energy (almost wholly conceived of as VRE). One example is seen in a June 3, 2020 article in the UK *Guardian*, which asserted that "Renewables surpass coal in US energy generation for first time in 130 years" (Milman, 2020). In addition, a June 11, 2020 article in *Bloomberg News* sought to convey the impression that these trends are global. The articles was titled



Power-to-gas

【PtG, P2G】 Producing electricity-based synthetic gas for a renewable energy system

The released heat can for example be used as input for high-temperature electrolysis or as input for capturing CO_2 from the air.

The water generated as a by-product of the methanation can be used as input for the electrolysis.

To create a closed CO_2 cycle, the CO_2 must be captured from the air, biomass or biogas.

Methane is the main component of conventional natural gas and can directly be added to the grid.

There are limits to the share of hydrogen in the gas mix, due to differences in hydrogen tolerance of materials in pipelines, storages and end-use applications.

*Data source for technology' s current energy conversion efficientcy: Frontier Economics 2018.

Source: Wettengel, 2018

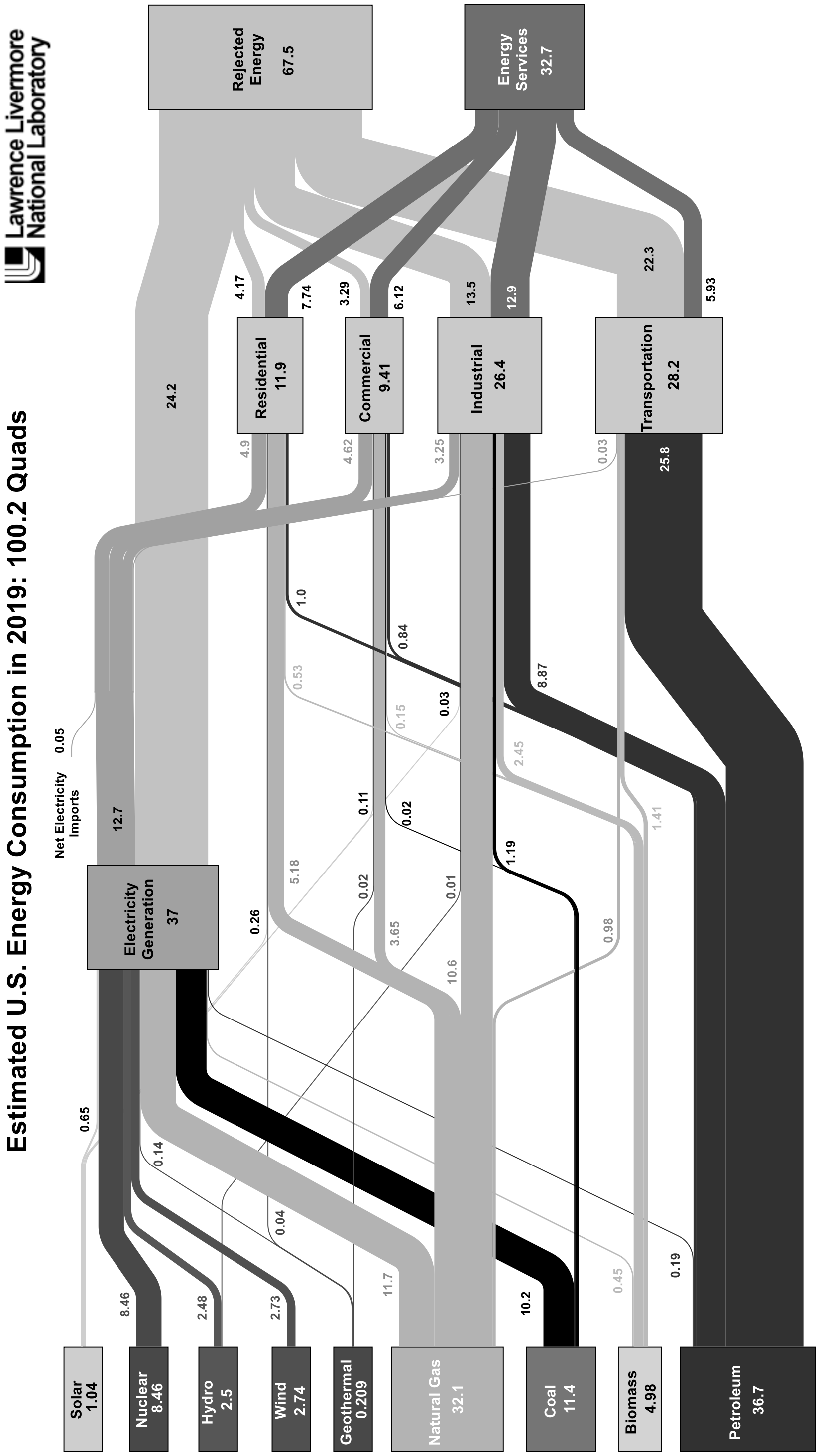
Figure 7 Renewable Energy and Power-to-Gas Pathways

“Renewable Power Will Soon Come Out on Top,” and emphasized net global capacity additions of the various types of power generation between 2010-19 (Bullard, 2020). On this basis, it asserted that VRE solar and wind were set to dominate power systems globally.

The *Guardian* and *Bloomberg* articles are just two of many examples wherein mass media convey the impression that decarbonization of power and other sectors can largely be done by VRE. To be sure, the *Guardian* article is correct in noting that during 2019 coal consumption in the United States fell to its lowest level in 42 years and that renewable energy is likely to exceed coal-fired generation in 2020. But the devil is in the details: the article downplays the fact that cheap natural gas has largely been substituted for coal. Moreover, the article emphasizes VRE among the renewable sources, without analyzing the massive role of hydro. Nor does the article explain that US energy consumption per se is a much larger phenomenon than just electricity, as is evident in **figure 8**.

Figure 8 illustrates the scale of the challenge. It is produced by one of America's leading institutions, Lawrence Livermore National Laboratory (LLNL). LLNL has generated charts on US commodity flows since the mid-1970s, and is regarded as a highly credible source of data. Its estimate of 2019 energy consumption shows, for one thing, that energy is not only electricity. Of about 100 quadrillion British Thermal Units (Quads) of estimated energy consumption in the US during 2019, 37% was used to generate electricity. Of the 100 Quads of total energy consumption for all purposes, VRE solar and wind accounted for only 3.78% of all energy. This level was well under half the 8.46% from nuclear and roughly a third of the 11.4% from coal (which is used for heat and other industrial processes). And these numbers pale when compared to oil and natural gas, both of which are well over 30% of US energy consumption. Hence, one has to keep dramatic increases in any given energy source in perspective. New additions to the low base of VRE lead to misleadingly high numbers for percentage increases, especially in capacity as opposed to actual power output. These numbers can often make continued rapid growth seem inevitable.

This is not to suggest that the renewable energy revolution is a sham. There has clearly been a prodigious deployment of VRE solar, wind, and other comparatively clean (when assessed over the life-cycle) power generation. These deployments have helped reduce GHG emissions and they have led to a dramatic cheapening of unit costs. The real question is whether renewables – and especially VRE solar and wind – are in fact on the way to becoming the majority of power generation in addition to the keystone for all energy supply. A related question is whether VRE is the most cost-effective investment for reducing GHG emissions. Rapid decarbonization is critical to slowing the pace of climate change (not to mention local pollution impacts from fossil fuels). Hence, it is imperative that all aspects be considered in order to maximize the effective use of scarce fiscal, human, material and other resources, including time. If VRE confront a range of challenges, it is prudent to be honest about them and consider what ought to be done. After all, the goal is equitable and sustain-



Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Source: LLNL, 2019

Figure 8 Estimated US Energy Consumption in 2019 able decarbonization rather than merely building as much VRE and other renewables as possible, not matter the impacts.

Land requirements, material density, and a host of other issues give cause to question whether an exponential increase in VRE renewable deployment is likely to continue. Both the *Guardian* and the *Bloomberg* articles ignore the fact that in many regions the easy sites for VRE have largely been exploited. As land located near transmission grids gets used up, it becomes increasingly time-consuming and expensive to plan, site and build generation. Such VRE as onshore wind has also become increasingly difficult to build, even in European countries, due to local opposition (Taraldsen, 2020). In addition, new build that is distant from transmission infrastructure and other assets requires significant investment in transmission and ancillary equipment. All of those system costs require massive amounts of copper, cobalt, lithium, graphite rare earths, and other critical raw materials.

The next sections examine these issues in detail. The purpose here is to explore some of the emergent issues in greening the power economy. The World Bank, The IEA, IRENA and other institutions have recently become quite concerned about materials and related matters, even as they argue for accelerated deployment of decarbonizing solutions. The review of their work will be used to underpin the argument that Japanese-style resource-efficiency crucial for finding sustainable avenues of decarbonization.

The Critical Raw Material Challenge

As noted, recent International Energy Agency (IEA, 2020a) reports on these critical materials warn that ambitious policies on renewables and electric mobility imply cobalt, lithium, nickel and other critical material demand that exceeds current supply. The IEA's concerns parallel those of the Japanese1), the European Union2), the California Business Roundtable3), and a steadily growing number of other actors. Many of these critical materials are used at far greater density, per unit of energy consumption or production, in green

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1) Japan's JOGMEC and other agencies produce a range of materials, as do the carmakers (eg, Toyota), battery suppliers (eg, Panasonic), metal firms (eg Mitsubishi Materials) and other concerns.

2) See, for example, EURACTIV's November 2018 work on "Metals in the circular economy": https://www.euractiv.com/section/circular-economy/special_report/metals-in-the-circular-economy/

3) See "A Closer Look at California's Cobalt Economy," California Business Roundtable, January 2019: https://centerforjobs.org/wp-content/uploads/A-Closer-Look-At-Californias-Cobalt-Economy-2.pdf

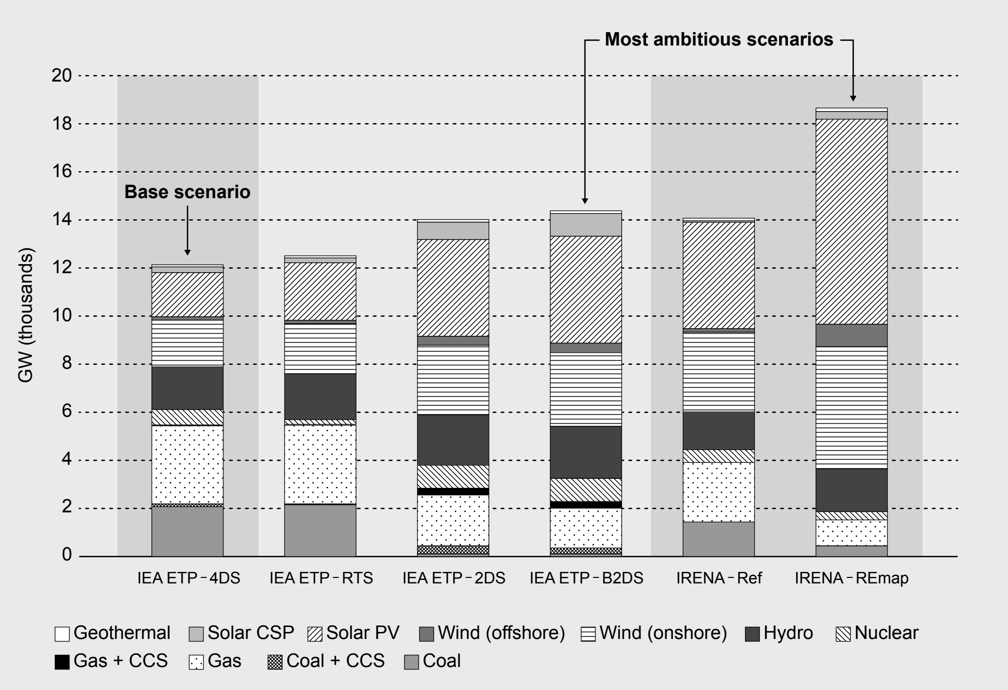
technologies as compared to conventional power systems, automobiles, and the like. And supplies of these materials have other competing sources of demand, including smart phones, jet engines, health care, and multiple other areas. The IEA and other analyses discuss supply constraints, geostrategic risks, human rights concerns, environmental damage (from harvesting and processing critical materials), and other issues.

The World Bank has also been concerned about the supply-demand balance of critical raw materials for several years. Based on its earlier work in this area, on May 11, 2020 it released "Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition" (World Bank Group, 2020). The report sought to examine scenarios of likely demand for cobalt, copper and other materials, their potential GHG impact, and risks for shortages. One important backdrop to the report was the multiple effects of the Covid-19 pandemic, which produced a drop in prices for materials and investment in new supply due to lockdowns. The World Bank sought to assess the likely capacity to satisfy the need for materials in light of this context and the arguments for a green recovery.

Figure 9 is taken from the report, and reflects some of its main analytical assumptions. The figure shows that the report used 6 different IEA and IRENA projections for the power sector to 2050. These projections vary depending on whether the premise was business as usual, increased policy supports for renewables, or very aggressive "most ambitious" proposals for decarbonization via renewables. The report refers to these as "technology-based mitigation strategies." These strategies are not equally comprehensive, as some concern only electricity generation whereas some examine power and storage as well. Collectively, their limitations are evident in the fact that they omit the material-density of power transmission and distribution networks not to mention other energy infrastructure (such as gas grids). They also omit water, transport and other critical infrastructure, which have their own material requirements and are likely to be part of expanding built environments into which clean energy is mixed. Additionally, the scenarios overlook consumption by such products as air-conditioners, automobiles, televisions, data centres, and other devices.

The exclusion of these aspects of the built environment is not unavoidable for want of data. For example, the International Resources Panel collects comprehensive data on the urban material footprint, including in its 2018 report on "The Weight of Cities: Resource Requirements of Future Urbanization" (IRP, 2018). Presumably there is some means of standardizing household consumption and then estimating average material-density under decarbonizing assumptions.

For example, the diffusion of air conditioning is already being modeled. Air condition-



Source: IEA 2016, 2017; IRENA 2019a.
Note: 2DS = 2 - degree scenario, 4DS = 4 - degree scenario, B2DS = beyond 2 - degree scenario,
CCS = cabon capture and storage, CSP = concentrated solar power, ETP = Energy Technology Perspectives,
IRENA = International Renewable Energy Agency, PV = photovoltaic, Ref = reference scenario,
REmap = renewable energy roadmap scenario.

Source: World Bank Group, 2020

Figure 9 Energy Scenarios for 2050

ing is especially crucial to human health in the midst of rising heat and humidity and increasingly frequent heat waves. The current global average is use of air conditioning is 720 hours/yr. Due to climate differences, RAC usage hours per year in China average 545, in Japan 720, but 1,600 in the US. Usage equals or exceeds 1,600 hours/yr in India, Mexico, Brazil, Indonesia and the Middle East (the latter is an astounding 4,672). Because of global climate change, these usage hours are increasing at an estimated 0.7%/yr (leading to a 25% increase by 2050).

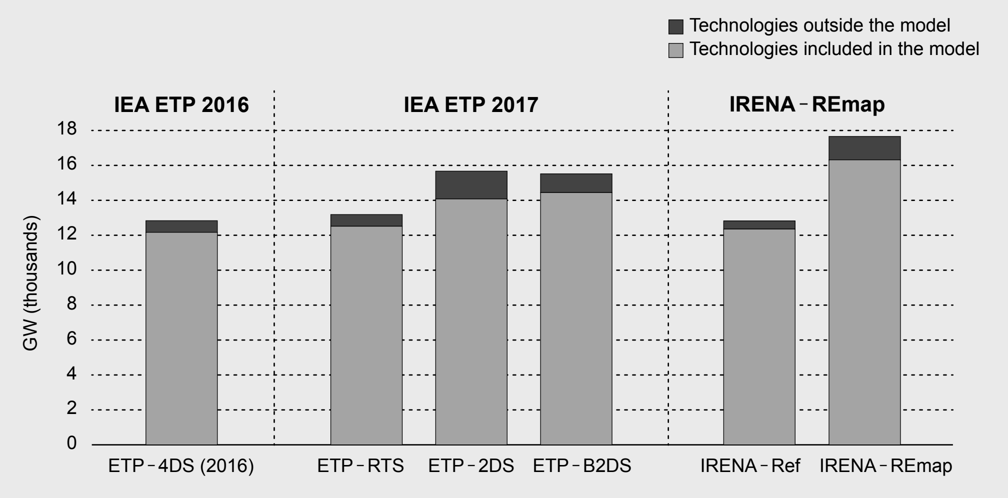
The Rocky Mountain Institute (RMI) and other partners, including many elements of the Indian Government (eg, the Ministry of Power), have organized an initiative to cope with the unsustainable power demand posed by conventional air conditioning in a warming climate. The RMI analysts and their collaborators point out that the global number of room air conditioners (RACs) in 2016 was roughly 1.2 billion (over 400 million in China alone), and that this figure is likely to increase to 4.5 billion by 2050.

The RMI draw on IEA and other data indicating that supplying the power demand for this growth in RAC stock, much of which will be concentrated in growing global megacities, will require roughly USD 1.2 trillion in new generation capacity. This is because the 2016 global RAC power demand of 2,300 TWh will likely more than triple over the same period, reaching 7,700 TWh in 2050 (about 16% of global electricity demand). That 5,400 TWh increase in power demand between 2016 and 2050 would require an astounding addition of 2,000 GW of generation capacity, equivalent to "the current annual electricity consumption of the US, Japan, and Germany combined." And the cumulative GHG emissions (from power demand as well as the effect of refrigerant gases), projected at between 132 GT and 167 GT, would likely exhaust 25-50% of the remaining carbon budget.

In India alone, where RAC penetration is only 7% but sales are already increasing at 15%/yr, the RMI and IEA estimates indicate a more than 20-fold increase in power demand for RAC, from 94 TWh in 2016, to 1,890 TWh in 2050. Seen in per-capita terms, urbanization in India is projected to raise RAC demand from a current global low of 72 kWh to 1,140 kWh. Satisfying that level of demand would require India to install fully one-third of the global 2,000 GW of needed new generation capacity. The RMI is a staunch advocate of renewable energy and efficiency. Hence it is not deliberately bearish in warning that "[w]e cannot solve this magnitude of growth by adding renewables alone." It points out that the in 2017 the total global increase of 94 GW in solar generation capacity was less than that year's RAC incremental demand growth of 100 GW (Campbell, et al., 2018).

It would be useful to update these numbers with some calculations of copper and other material demand scenarios per unit of RACs and other cooling devices. That would add additional empirical realism to the World Bank's data, not to mention the IEA and IRENA scenarios on which it is based.

The World Bank Group's 6 strategies are portrayed from left to right in **figure 9**. The first on the left, 4DS, is a "base scenario," wherein the global community maintains its current trajectory, with minimal improvements in shifting energy system away from fossil fuel sources. The next is RTS, which is slightly more ambitious. It assumes that "all countries will implement their Nationally Determined Contributions (NDCs), as proscribed under the Paris Agreement, resulting in an average temperature increase of 2.7°C by 2100." The 2DS scenario is more ambitious yet, and describes a "50% chance of limiting average future temperature increases to 1.75°C by 2100." The IRENA Ref scenario is similar to the RTS scenario, and "accounts for actions, commitments made under current/planned policies, including NDCs. Rise in temperatures would be at least 2.6°C by 2100." The most aggressive scenario



Source: IEA 2016, 2017; IRENA 2019a.
Note: 2DS = 2 - degree scenario, 4DS = 4 - degree scenario, B2DS = beyond 2 - degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, ETP = Energy Technology Perspectives, GW = gigawatt, Ref = reference scenario, REmap = renewable energy roadmap scenario.

Source: World Bank Group, 2020

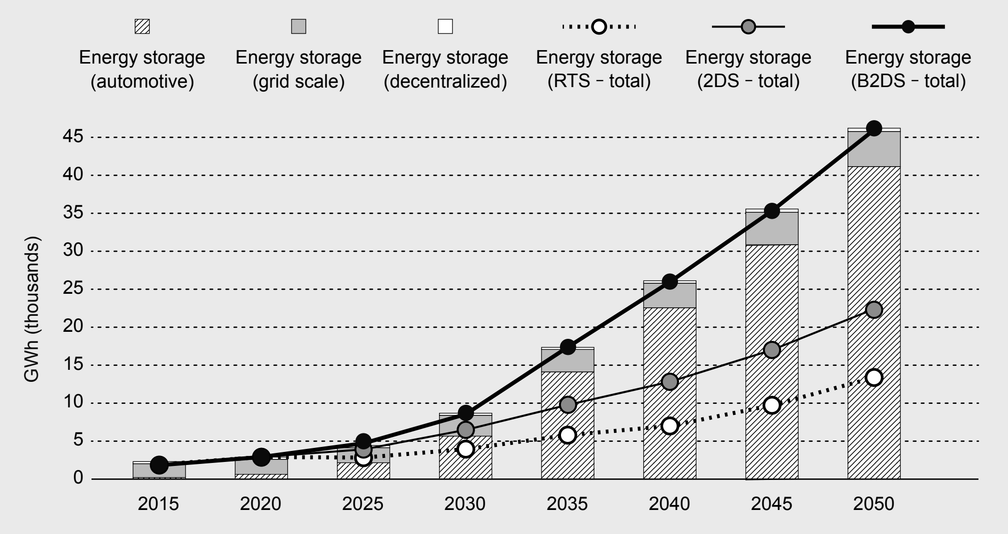
Figure 10 Technologies in the Model

is IRENA Remap, drawn from IRENA's RE roadmap of 2019. This last scenario seeks to limit "the rise in global temperature to "well below" 2°C above preindustrial levels by 2100" (World Bank Group, 2020).

Though the World Bank's analysis is restricted to power, it does detail the essentials of most of the conceivable options for power-generation. This inclusiveness is seen in figure 10, wherein the "technologies outside the model" (oil-fired power, biomass generation, marine power, and a few other minor sources) are shown as a share of those within the model. Barring as yet unforeseen development in power-generation technologies, it would appear that most of the relevant technologies are modeled.

As noted earlier, storage is the only other aspect covered by the models, outside of generation per se. Also, the focus is on battery storage, as opposed to pumped-hydro storage (the majority of current power storage) and storage via power to gas. The IEA Technology Roadmap also notes that pumped hydro storage is both flexible and helps balance variable wind and solar. At 172 GWs, PHS provided 95% of global power storage capacity in 2017 (IEA 2018b). Figure 11 of the World Bank report shows that the vast majority of their modeled storage in power is automotive battery storage.

Table 9 lists up the 17 critical raw materials and other minerals considered in the study. Most countries compile their own lists of critical raw materials, basing them on supply



Source: Based on IEA ETP 2017.
Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, GWh = gigawatt-hours, RTS = reference technology scenario.

Source: World Bank Group, 2020

Figure 11 Storage in the World Bank Scenarios

Table 9 Critical Materials in the World Bank Study

1	**Aluminum**	10	**Manganese**
2	**Chromium**	11	**Molybdenum**
3	**Cobalt**	12	**Neodymium**
4	**Copper**	13	**Nickel**
5	**Graphite**	14	**Silver**
6	**Indium**	15	**Titanium**
7	**Iron**	16	**Vanadium**
8	**Lead**	17	**Zinc**
9	**Lithium**		

Source: World Bank Group, 2020

risk, geopolitical risk, economic importance and other factors. The list of critical raw materials has expanded in recent years, with the EU's triennial assessment raising the number from 14 in 2011, to 20 in 2014, and 27 in 2017 (European Commission, nd). In the World

Bank study, the list is not exhaustive, as it does not include most rare earths, but it does cover some of the main materials used in transition power generation to decarbonizing (or at least low-carbon) options.

Table 10 lists up the same materials displayed in table 9, while also displaying their comparative relevance across sectors (ie, generation technologies, storage, and carbon-capture). Copper is shown to be relevant across all the sectors, with nickel next in ranking, followed by chromium and molybdenum. The data do not compare the material density per unit of power output or per unit of power stored (or unit of CO2 captured). But the cross-

Table 10 The Cross-Sectoral Role of Materials

	Wind	**Solar photovoltaic**	**Concentrated solar power**	**Hydro**	**Geothermal**	**Energy Storage**	**Nuclear**	**Coal**	**Gas**	**Carbon capture and storage**
Aluminum	■	■				■	■	■	■	
Chromium	■			■	■	■	■	■	■	■
Cobalt						■		■	■	■
Copper	■	■	■	■	■	■	■	■	■	■
Graphite						■				
Indium		■					■			
Iron	■					■				
Lead	■	■		■		■	■			
Lithium						■				
Manganese	■			■	■	■		■	■	■
Molybdenum	■	■		■	■		■	■	■	■
Neodymium	■									
Nickel	■	■		■	■	■	■	■	■	■
Silver		■	■				■			
Titanium				■	■		■	■	■	
Vanadium						■	■	■		
Zinc	■	■		■		■	■			
Total	**10**	**8**	**2**	**8**	**6**	**11**	**11**	**9**	**8**	**6**

Source: World Bank Group, 2020

sectoral role is one important measure of possible critical-material challenges.

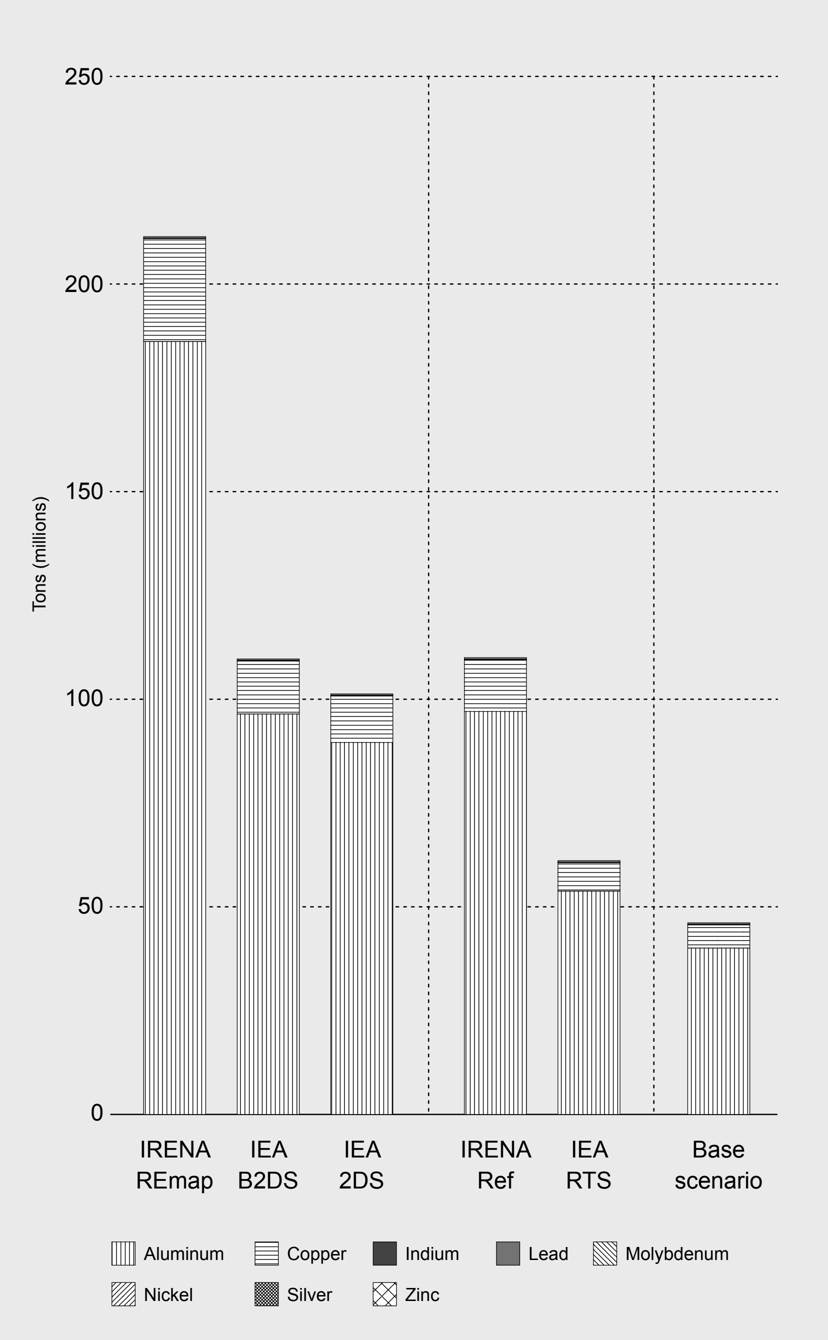
Table 11 offers a generalized assessment of the various technologies' useful lifetimes before replacement. Note that some of the data are questionable. For example, large hydro assets (dams) are generally much more robust and long-lived than the table's 25-year lifetime would suggest. For example, "depending on the component, hydro lifetime ranges between 30 and 80 years with several plants operating for more than 100 years without major overhaul" (Kougias and Schleker, 2019). Hydro turbine makers reportedly list 25 years as the design life of turbines, but only because they are required to. In fact, most exceed that figure by at least two decades (Renewables First, nd). But in any event, the data do give an indication of material requirements, as replacement often entails new volumes of critical raw materials. A lot of cobalt, for example, cannot be recycled for use in batteries due to extremely exacting needs for purity (World Bank Group, 2020).

Figure 12 offers one view of what metal demand looks like for solar through to 2050, depending on the comparative ambition of the scenario. The figure shows that the bulk of the demand – in the million-ton scale (the y-axis) – is for aluminum, followed by copper and then nickel. Other materials (especially silicon and some rare earths) are important, but they

Table 11 Comparative Lifetimes of Technologies

Technology	Assumed life span (years)
Concentrated solar power	**30**
Energy storage (all battery types)	**10**
Geothermal	**30**
Hydroelectricity	**25**
Nuclear	**50**
Solar photovoltaic	**30**
Wind	**20**
Coal	**40**
Coal + carbon capture and storage	**40**
Gas	**30**
Gas + carbon capture and storage	**30**

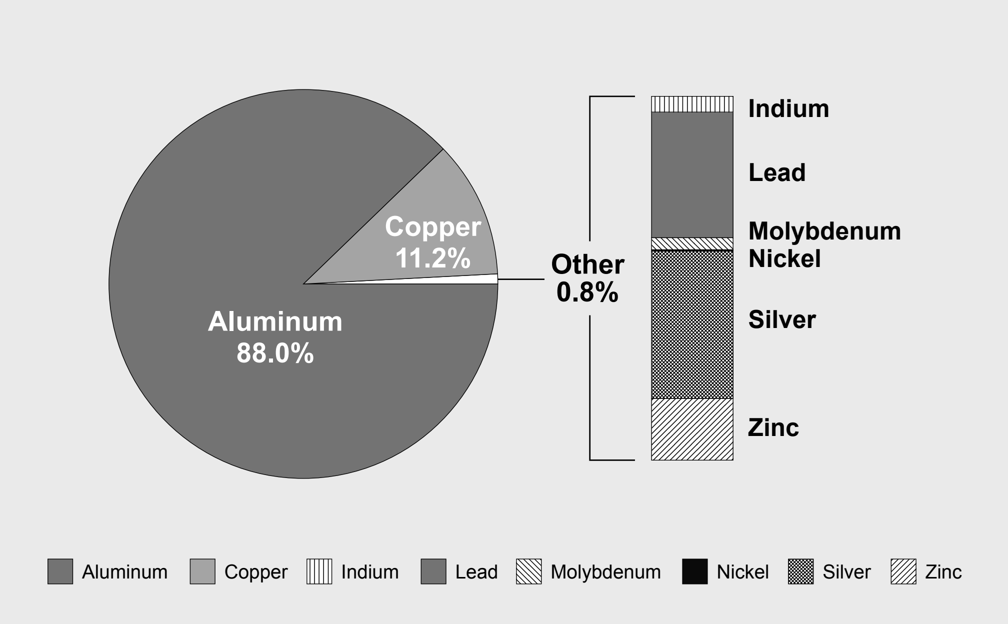
Source: World Bank Group, 2020



Note: 2DS = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, IRENA = International Renewable Energy Agency, Ref = reference scenario, REmap = renewable energy roadmap scenario, RTS = reference technology scenario.

Source: World Bank Group, 2020

Figure 12　Cumulative Mineral Demand for Solar to 2050



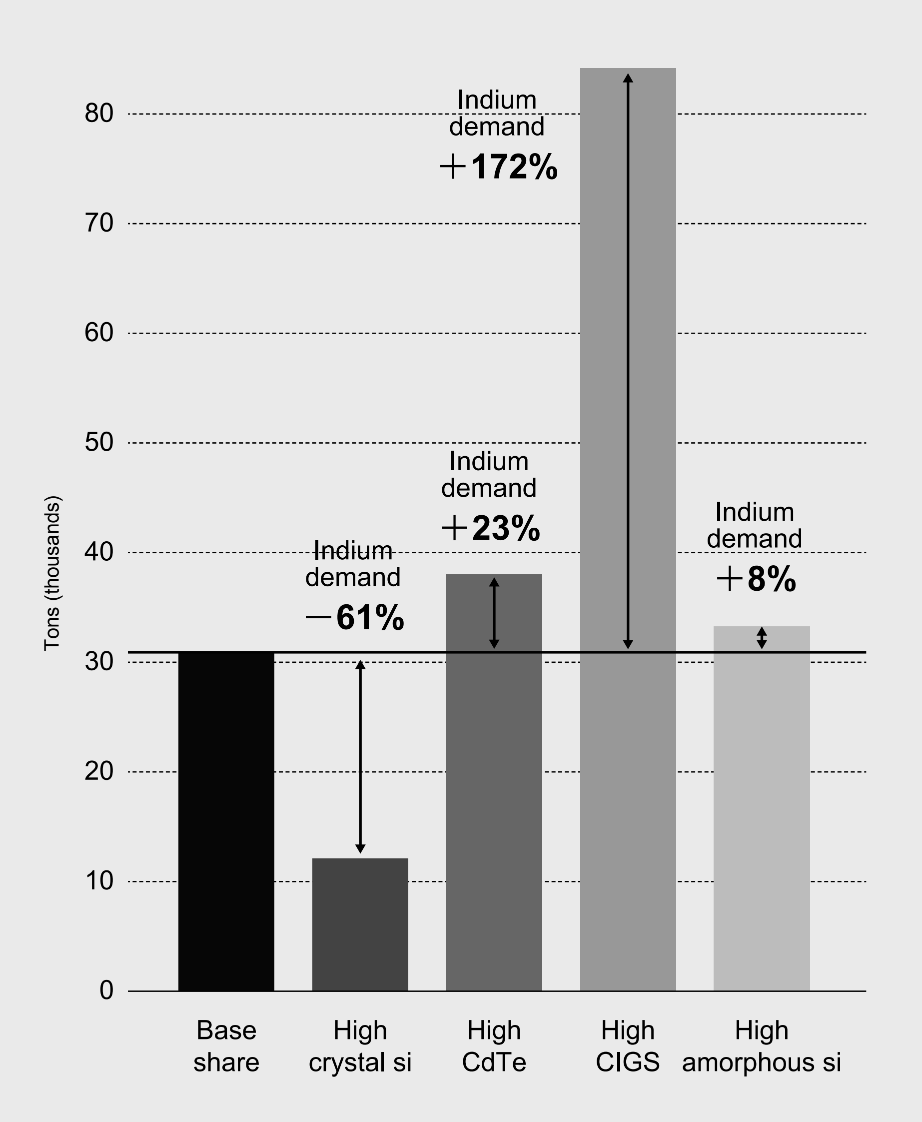
Source: World Bank Group, 2020

Figure 13 Share of Mineral Demand for Solar to 2050

are either not in the table (ie, silicon) or not required in those prodigious mega-ton volumes. It must be noted that material demand varies by over 400% depending on the scenario.

Figure 13 provides a clearer picture of the material demand for solar power through to 2050, using the IEA 2 DS scenario. It indicates that energy-intensive aluminum is 88% of material requirements, and copper 11.2%. The other metals include silver, lead, zinc, indium, molybdenum, and nickel.

Figure 14 drills down further to examine the implications of solar technologies. The IEA 2 DS scenario can be achieved via a number of subtechnology options. The demand for indium varies according to the option. The least demand for indium arises from high crystalline silicon ("High crystal si"). But this substitution presents its own issues, as the silicon must be very high-grade with minimal impurities. The source for this silicon is high-grade quartz, whose supply is constrained and whose processing is energy-intensive (Chandrasekharam and Pathegama, 2019). The figure shows that there are alternatives to this, but that they involve higher reliance on the rare earth indium. Among the many issues that indium presents is the fact that its production is about 800 tonnes per year and generally as a by-product of zinc mining. To increase the supply of indium entails a range of challenges, including opening new mines and increasing the rate of recycling. These challenges



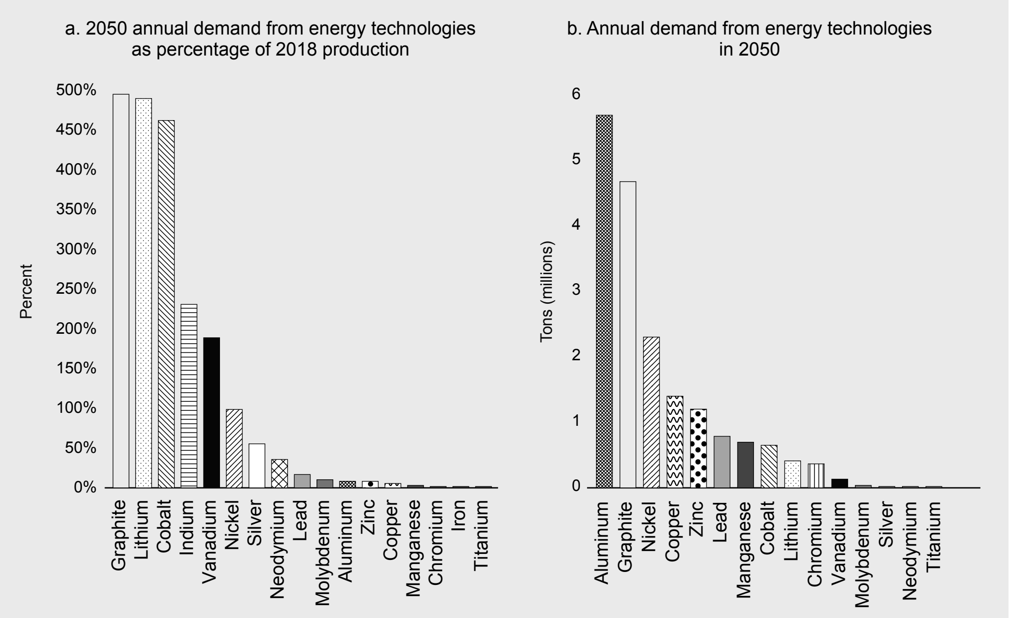
Note: CIGS = copper indium gallium selenide, crystal si = crystalline silicon

Source: World Bank Group, 2020

Figure 14　Indium Demand in Solar, Cumulative to 2050

are not necessarily insurmountable（Ylä-Mella and Pongrácz, 2016），but they do almost certainly imply price increases for the raw or recycled material.

Figure 15 affords another perspective on the shift in material demand. It shows that the IEA 2 DS scenario – not especially ambitious, as noted earlier – likely entails a quintupling of aluminum demand. Aluminum is a very energy-intensive product, but its supply is



Source: World Bank Group, 2020

Figure 15 Increased Material Demand, Cumulative to 2050 vs 2018

not constrained (Brough and Jouhara, 2020). Aluminum is produced through the refining of alumina from bauxite, and the latter material's reserves are currently assessed at 30.4 billion tonnes (Natural Resources Canada, 2019). That abundance contrasts with lithium, cobalt, indium and other materials, which in **figure 15** are projected to require very high rates of increased supply. And these results, it must be recalled, are based on quite conservative assumptions coupled with leaving aside the larger system requirements to link power-generation options to consumers.

Table 12 presents the World Bank Group's data from **figure 15** in a format that shows the projected demand increase versus 2018 production volumes, and then the percentage of 2018 production volumes (in tons) expected to meet demand. Despite the massive volumes of additional aluminum required, it is actually only 9 % of 2018 production. That contrasts with lithium, where annual demand in 2050 is projected to be a quintupling of current supply.

Figure 16 shows that even with restricted assumptions and scoping, the annual demand for materials is set to ratchet up and continue. Of course, the demand varies considerably by scenario. But even the highest projected increase in demand is likely to considerably understate calculable reality.

Table 13 presents the World Bank Group's categorization of challenges in light of the above. The table separates the materials into 4 different quadrants. It shows that quadrant

Table 12 2018 Mineral Production and Projected 2050 Demand

Mineral	2018 annual production (Tons, thousands) [a]	2050 projected annual demand from energy technologies (Tons, thousands)	2050 projected annual demand from energy technologies as percent of 2018 annual production
Aluminum	60,000	5,583	9%
Chromium	36,000	366	1%
Cobalt	140	644	460%
Copper	21,000	1,378	7%
Graphite	930	4,590	494%
Indium	0.75	1.73	231%
Iron	1,200,000	7,584	1%
Lead	4,400	781	18%
Lithium	85	415	488%
Manganese	18,000	694	4%
Molybdenum	300	33	11%
Neodymium	23 [b]	8.4	37%
Nickel	2,300	2,268	99%
Silver	27	15	56%
Titanium	6,100	3.44	0%
Vanadium	73	138	189%

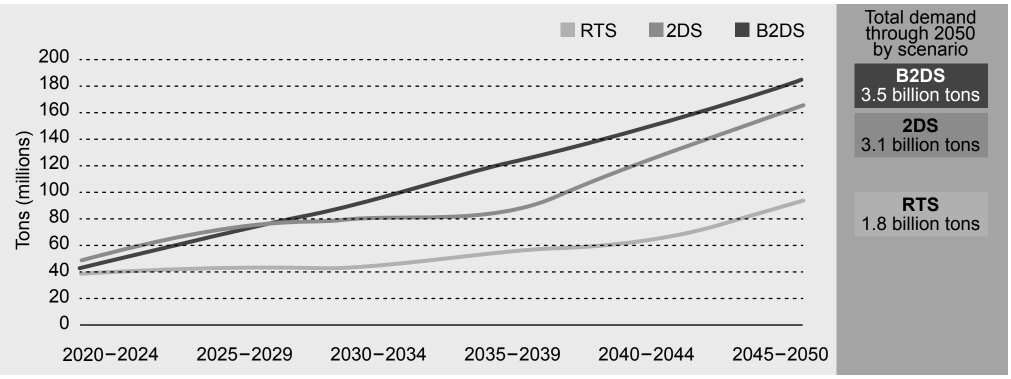
a. Data for 2018 annual production sourced from the U.S. Geological Survey.

b. Data sourced from Deetman et al. (2018).

Source: World Bank Group, 2020

1 is only medium-impact in terms of demand due to the focus on demand from energy technologies only and the elimination of supply risks and other issues from the scope of the study. By comparison, the quadrant 4 material copper is a cross-cutting technology that the study believes will not be significantly impacted. Yet this conclusion rests on the limited focus of the World Bank Group's scoping plus the elimination of water and other challenges from consideration. It is understandable to try and keep a study manageable by constraining the number of variables to be considered. But it risks understating the problems, especially if they are dynamic and inter-related. For example, copper production depends on water availability. In turn, demand may be further increased by the declining availability of water, due to the need for more piping and other elements in water treatment and desalination (Wood Mackenzie, 2020).

Figure 17 provides a different perspective on comparative material demand for power



Note: "Minerals" refers to the 17 minerals included in this analysis plus steel, but excluding concrete. Steel has been included because of the size of demand for the alloy from energy technologies. Average annual demand is the mean demand for minerals across the time periods given. The higher mineral demand under the 2DS than the B2DS before 2030 can be explained by the higher overall generation capacity projected by the IEA to be needed in the 2DS compared with the B2DS. This is especially true of solar photovoltaic in the 2DS in these time periods. Subsequently, the plateau in mineral demand in the 2DS is caused by a relatively slower penetration of renewable generation, followed by a rapid increase in storage capacity from 2035 onward. 2SD = 2-degree scenario, B2DS = beyond 2-degree scenario, IEA = International Energy Agency, RTS = reference technology scenario.

Source: World Bank Group, 2020

Figure 16 Projected Annual Demand for Minerals to 2050

generation. The figure is from a May 2020 IEA report titled "Clean energy progress after the Covid-19 crisis will need reliable supplies of critical minerals" (IEA, 2020a). The IEA figure ranks the material density of the various power generation technologies in kilogram per megawatt (kg/MW) of generating capacity. Its data show that the copper intensity of offshore wind is much higher than onshore wind, a very important fact given that local opposition to onshore wind is making the latter a preferred choice. The IEA's figure also includes the role of silicon in solar, an item which was left out of the World Bank Group's scoping study.

The IEA's data also show that the material density of gas and coal-fired generation is very low. But these fossil fuel generation technologies are also very high in GHG emissions. So the figure is only meant to illustrate that the transition to VRE decarbonization has higher critical material costs.

An important aspect of the IEA study is that the material density's measure is for rated capacity as opposed to actual power output. The significance of this is due to the intermittence of VRE, as depending on location and other pertinent factors a given capacity rating may actually generate only 10 to 50% of power. Among VRE, solar's capacity factor has not changed considerably, at roughly 10-20% (IEA, 2018b). In Japan, the power actually generated by intermittent VRE projects was only 12% (solar) or 20% (wind) of their total

Table 13 Implication of Energy Transition for Material Demand

Quadrant	Category	Implication
Quadrant 1	**Medium-impact minerals**	Quadrant 1 minerals may appear to be less of a priority, but that may not necessarily be the case. Some of these minerals may be critical to key subtechnologies, and although some substitution may be possible, they may be strategically important to the clean energy transition. Since these minerals may not face the hign levels of demand faced by quadrant 2 minerals, nor the stable conditions faced by quadrants 3 and 4, less priority may be given to these minerals, but in turn, this may result in potentially increasing their criticality, if supply constraints exist.
Quadrant 2	**High-impact minerals**	Demand for minerals in quadrant 2 is much higher, but it is much more concentrated in certain technologies or subtechnologies. Demand growth could be substantial, but potentially more varied if shifts in policy, market conditions, or other key factors cause different types of technology or subtechnoiogy to be deployed at greater, or lesser, levels.
Quadrant 3	**High-impact, cross-cutting minerals**	Quadrant 3 minerals encounter the dual challenge of meeting high levels of demand from a broad range of technologies. They do not face the same challenges of technology choice as quadrant 2 minerals, but they face higher levels of relative demand than quadrant 4 minerals. Demand pressures are thus likely to be highest and most stable in these minerals.
Quadrant 4	**Cross-cutting minerals**	Quadrant 4 represents stable and steady levels of demand. Minerals in this area are not so dependent on shifts in energy technology, and greater levels of climate ambition are likely to lead to increases in these minerals across the board. Demand growth is therefore likely to be predictable and steady.

Source: World Bank Group, 2020

capacity in 2015[4]. The particularly significance of the link between material density and capacity factors is that critical raw materials should perhaps be best used in the configurations that deliver the most decarbonizing effect. That argument would seem especially relevant if the supply and demand balance of critical raw materials is under stress via the pressure to accelerate the transition to decarbonizing energy.

A similar phenomenon is seen in figure 18, which compares critical materials in conventional and electric vehicles. The figure shows that electric cars have a much higher foot-

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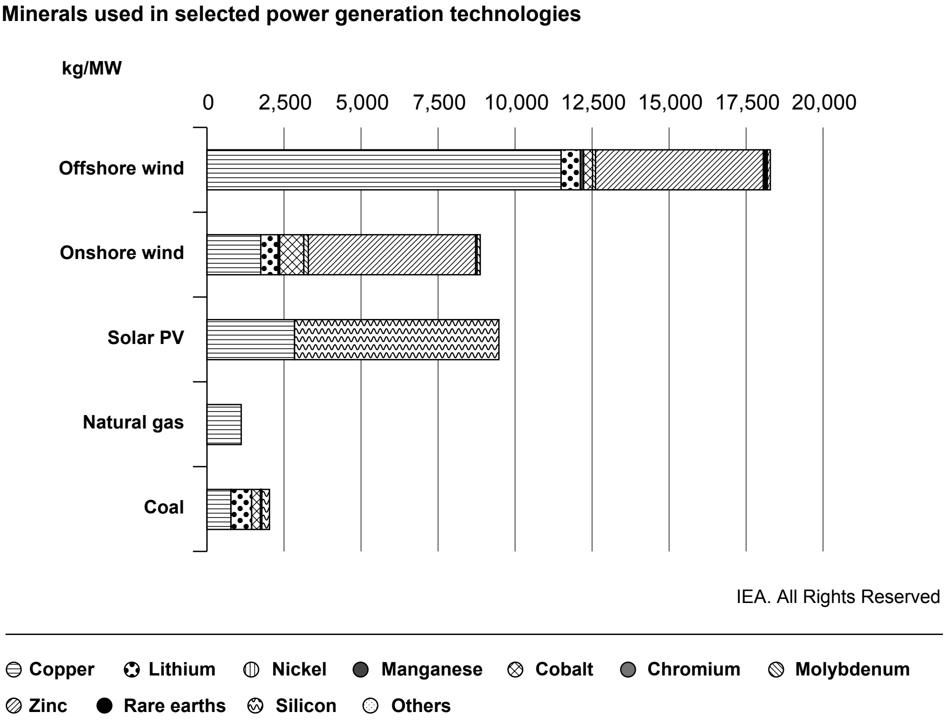
4) The US EIA undertakes comparative studies on average generation capacity factors（meaning the percentage of energy output versus rated capacity）. Its survey of output between 2008-2012 indicates that Japan's aggregate figure for both solar and wind is 15 percent, far less than the 27 percent recorded for the United States, the 26 percent seen in Canada, and the 18 percent figure for China（EIA, 2015）.

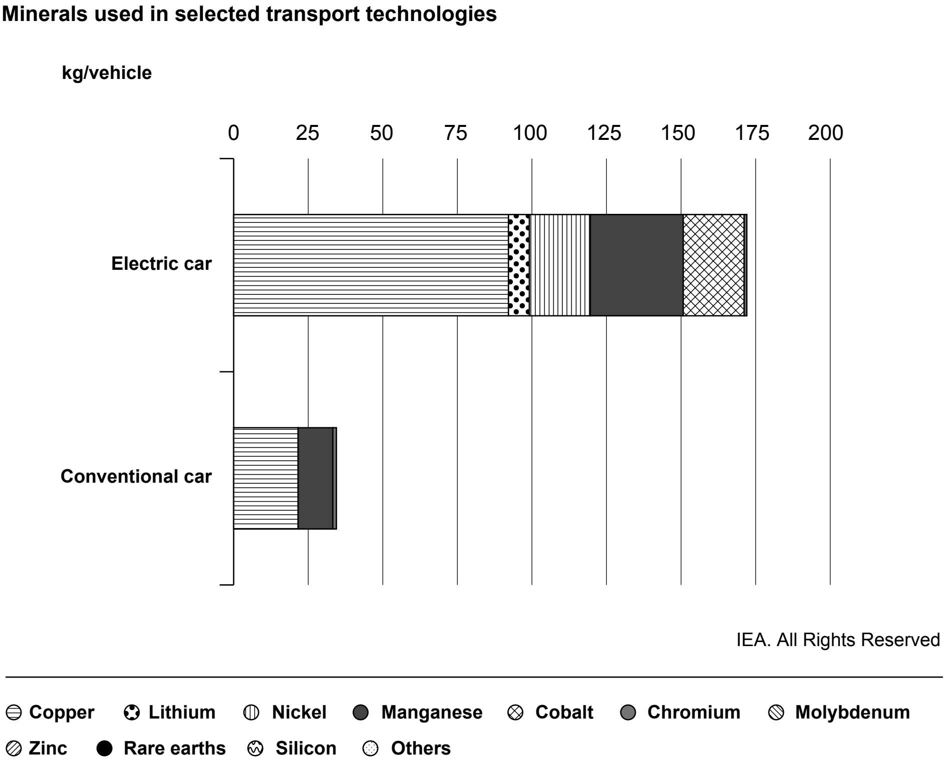


Source: IEA, 2020a

Figure 17 Comparative Assessment of Mineral Demand for Power Generation (units: kg/MW)

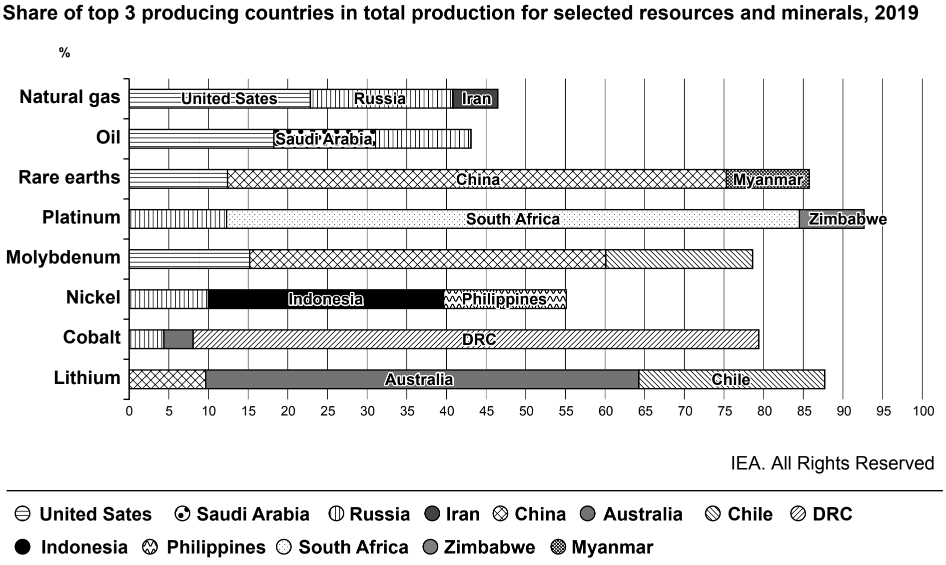
print (kg/vehicle) than conventional cars. The point is not, of course, that electric cars are bad for the environment. But it is important to recognize their material demands in addition to other devices. That recognition might help convince consumers to buy smaller cars (whose battery requirements are lower) or support alternatives such as public transport.

Figure 19 is also drawn from the IEA study. It hints at the geopolitical implications of energy transition (along with other infrastructural aspects of decarbonization), by listing the top 3 producers of a given commodity. Natural gas and oil production are of course concentrated in the United States, Saudi Arabia, and Russia. But critical raw materials also tend to be concentrated among a few suppliers. The Democratic Republic of the Congo (DRC) is especially dominant in cobalt, a cause of much concern because of political instability, environmental damage, child-labour, and other factors. As to rare earths, China is the supplier for 62.9%. China's role has become a source of increasing concern in recent years, due to the accelerating importance of these materials and the fraught relationship between China and many other major consumers of these materials (such as Japan, the EU counties, and the United States).



Source: IEA, 2020a

Figure 18 Comparative Assessment of Mineral Demand for Transport (units: kg/vehicle)



Source: IEA, 2020a

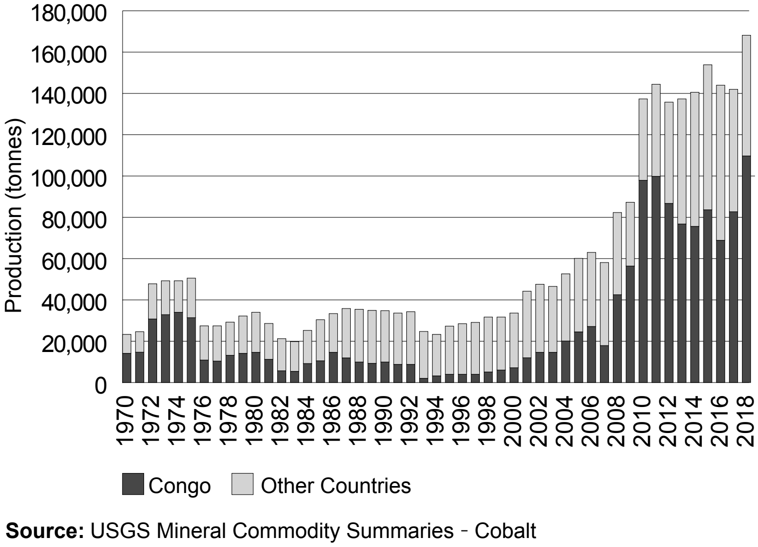
Figure 19 Geographical Concentration of Mineral Supply

The IEA's report on critical materials is a warning on two fronts. One is that the argument for accelerated decarbonization as a counter-measure to the economic effects of Covid-19 entails material issues that need to be assessed. Rapid deployment of VRE has implications, for example, for cobalt. The IEA points out, concerning cobalt, that "rapid growth has put strains on supply, as witnessed by the five-fold increase in cobalt prices between 2016 and early 2018. Although supply has responded, the volatility of prices in recent years has been a wake-up call for companies and governments in terms of the importance of reliable mineral supplies for clean energy transitions" (IEA, 2020a). A second factor is that the pandemic has had significant impacts on mining activity along with investment. The IEA's warning in this regard is worth quoting at length:

> "The impacts of investment cuts vary by mineral. But some, especially copper and nickel, could soon feel strains when demand recovers. Demand and supply of copper and nickel were delicately balanced before the pandemic, and there were expectations that supply imbalances might emerge in the coming years.
>
> Short-term pressures have weakened with the contraction in demand caused by the Covid-19 crisis. But both minerals could see demand grow rapidly as the world emerges from the crisis and boosts efforts to accelerate energy transitions, especially if many governments put renewables and batteries at the heart of their economic stimulus packages" (IEA, 2020a).

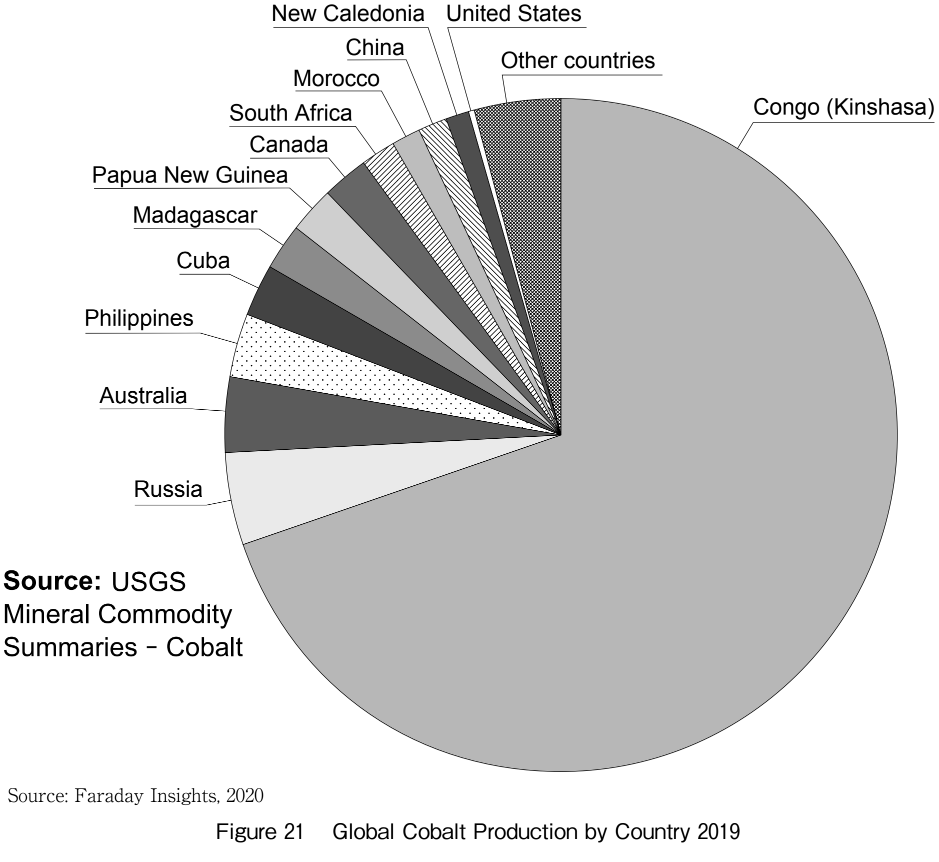
The IEA's concerns are well-grounded, as we see in **figure 20**. The figure displays the growth in cobalt production from 1970 to 2018 and the DRC share (in the figure, "Congo"). The increase in supply is particularly striking after 2008. The main driver for this is demand from batteries for electric vehicles, which represented 55% of global cobalt consumption in 2019 (Faraday Insights, 2020). This assessment seems credible, as the German Mineral Resources Agency expects batteries to account for 62% of cobalt demand of 225,000 tons in 2026 (Siegel, 2019).

Figure 21 affords an additional perspective on the cobalt problem. It shows that the DRC share of production exceeds 60% in 2019. Even as other countries' shares expand, the DRC's production has remained the majority share for well over a decade (see **figure 20**). Analysts expect increased production from other areas and recycling to reduce the pressure on DRC supplies. But at the same time, we have already seen that it is difficult to get investment into production.



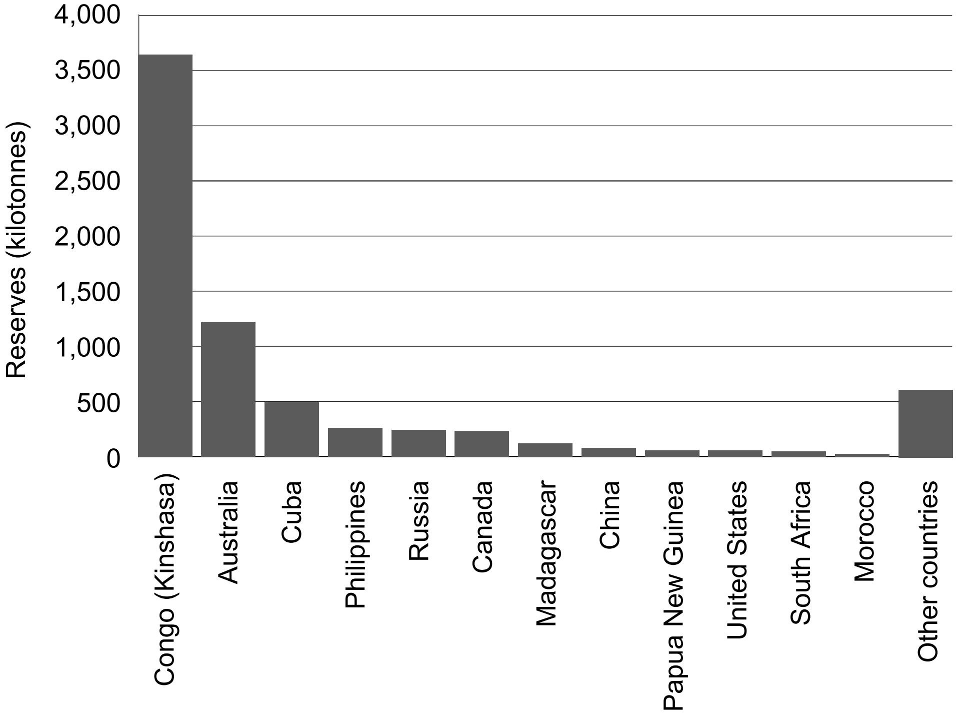
Source: Faraday Insights, 2020

Figure 20 Global Cobalt Production 1970-2018



Source: Faraday Insights, 2020

Figure 21 Global Cobalt Production by Country 2019



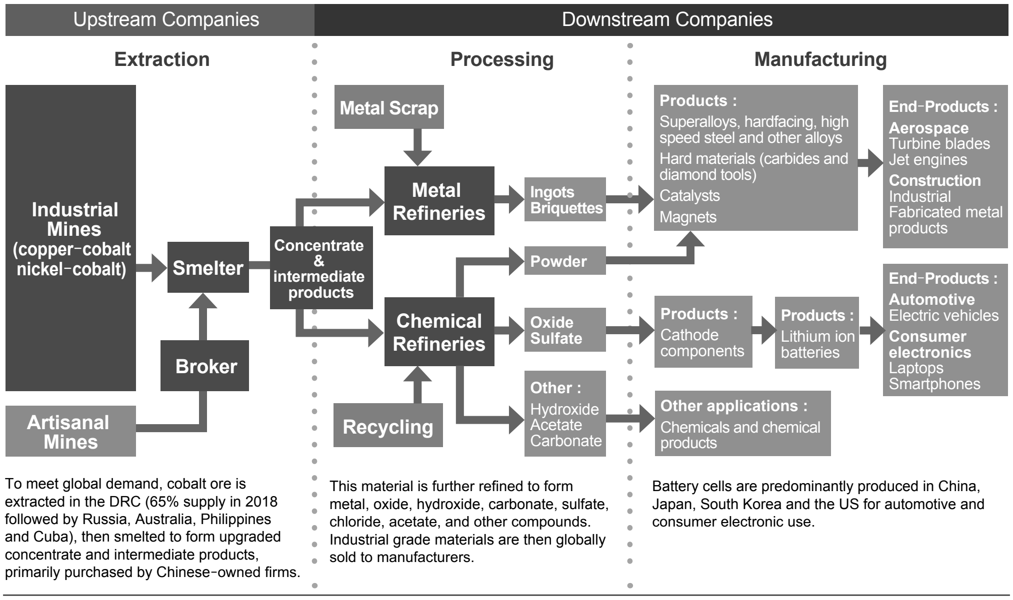
Source: USGS Mineral Commodity Summaries - Cobalt

Source: Faraday Insights, 2020

Figure 22 Global Cobalt Reserves by Country, 2019

Moreover, figure 22 shows that the DRC share of total global reserves of 7 million tons is over half, at 3.6 million tons. Reserves are not the only factor, as potentially recoverable resources are also important (dependingon price, technology, and other factors). Total global terrestrial resources are thought to be 25 million tons (USGS, 2020). But in the short term, it would appear that the DRC will remain the main locus of production. One reason is that cobalt mining is generally not for cobalt per se, but rather with it as a byproduct of mining for nickel or other metals. Another reason is that opening up new mining capacity is generally quite costly and time-consuming. In developed countries, there is often a great deal of opposition to expanded mining (Martine, 2020).

Figure 23 affords a perspective on the global cobalt supply chain, from extraction, to processing, and then to manufacturing of alloys and the products they are used in. The left of the figure shows that most mines are not for cobalt per se, but rather industrial mines wherein cobalt is a by-product. Artisanal mines are largely in the DRC, where cobalt is mined deliberately and often at great costs to human rights. The far right of the figure



Source: BMI, CRU International Ltd, British Geological Survey

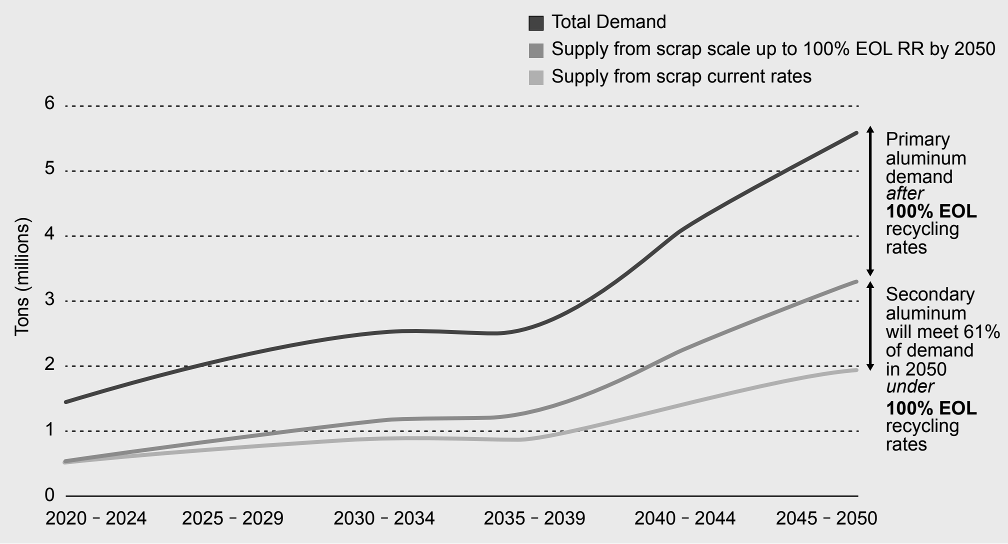
Source: Faraday Insights, 2020

Figure 23 Global Cobalt Supply Chain

shows that the majority of manufacturing tales place in East Asia, centring on batteries for automobiles and electronic devices. As noted earlier, it is especially difficult to recycle cobalt for battery use, due to high purity requirements in that application.

Recycling is generally seen as the key means of reducing critical raw material demand. The is a large literature on the “circular economy” that seeks to recycle as much material as possible. Some of this emphasis is well-grounded. As we see in figure 24, recycling aluminum can dramatically reduce the amount of new material required. One reason is that aluminum is infinitely recyclable. Another is that recycled aluminum is about 90% less energy-intensive than virgin aluminum (Green, 2007). It thus makes economic sense to recycle aluminum. The figure shows that 100% end of life (EOL) recycling of aluminum would allow 61% of required supply to be satisfied by secondary (ie, recycled) material rather than primary, and energy-intensive material.

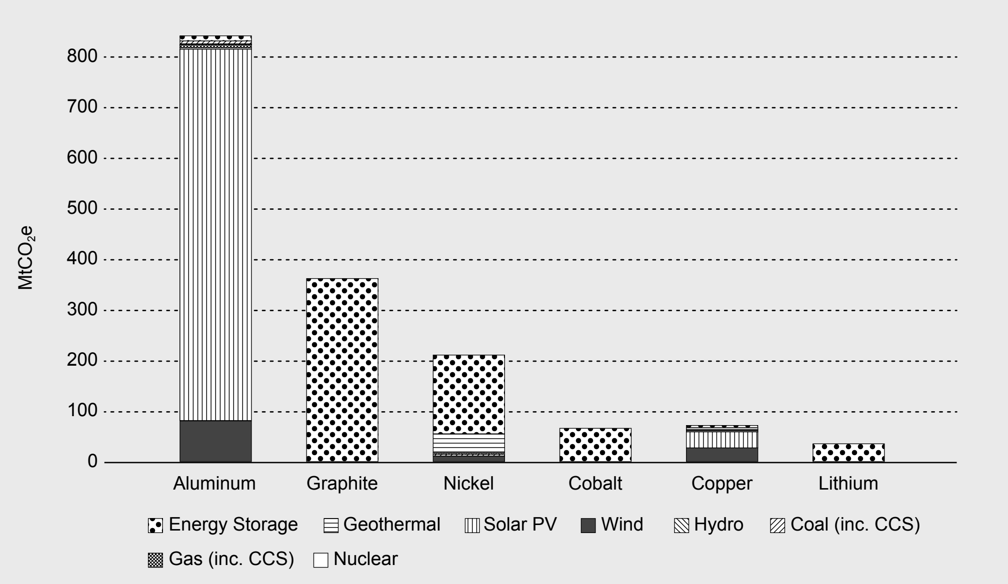
Similarly, figure 25 suggests that greater recycling and repurposing of materials might not be enough to reduce the GHG cost of using VRE and other energy generation. In the World Bank’s assessment, the largest contributor to GHGs is producing aluminum, largely used in the VREs solar and wind. The next highest is graphite used in battery storage, and third the nickel used in storage and wind (primarily). The data indicate that under the IEA



Note: EOL recycling rates are assumed to increase annually to meet 100 percent EOL by 2050. This means that secondary aluminum meets an increasing amount of aluminum demand over time.
EOL = end of life, RR = recycling rates.

Source: World Bank Group, 2020

Figure 24 Recycling Aluminum for Energy Savings



Note: CCS = carbon capture and storage, MtCO$_2$e = million tons of carbon dioxide equivalent.

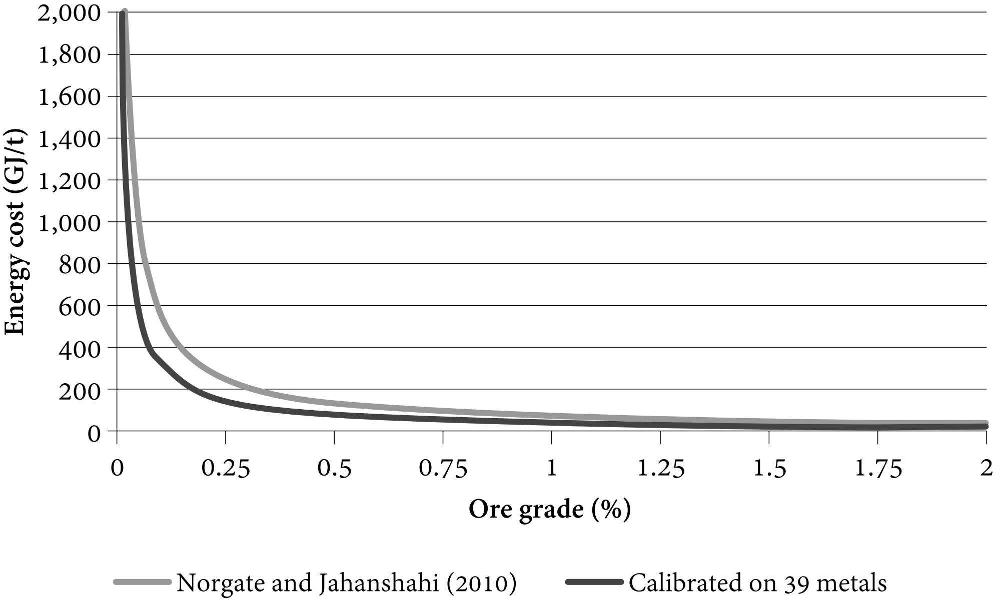
Source: World Bank Group, 2020

Figure 25 Recycling Aluminum and Other Materials for GHG Reduction

2 DS scenario, the production and operation of VRE and storage represent 6 % of coal and gas generation. That difference is, to be sure, large. But overall, the emissions up to 2050 represent 16 Gt of CO2 equivalent, which is equal to the combined emissions of China and the United States in 2018. The World Bank concedes that these numbers do not take into account transporting the minerals.

And one might add that the data do not account for increased energy, water and other costs to extract materials from declining ore grades. For example, recent data for copper suggest that required energy inputs per unit of output have increased significantly in recent years (Palacios, 2019). One 2017 study of Chilean copper production warned that "electricity demand for Chile's copper production is expected to increase by 53.5 % between 2015 and 2026, although the planned increase in copper production over that period is only 7.5%" (AT Mineral Processing, 2017).

One of the key drivers of rising energy demand in mining is the declining quality of ore grades. **Figure 26** puts these two realities in context by presenting the relationship between ore grade (eg, the percent of copper in an ore body being mined) and energy cost, with 2010 data for copper and a generalized calibration for 39 other metals. Energy is required at all stages of production, from extraction through to processing and then shipment.

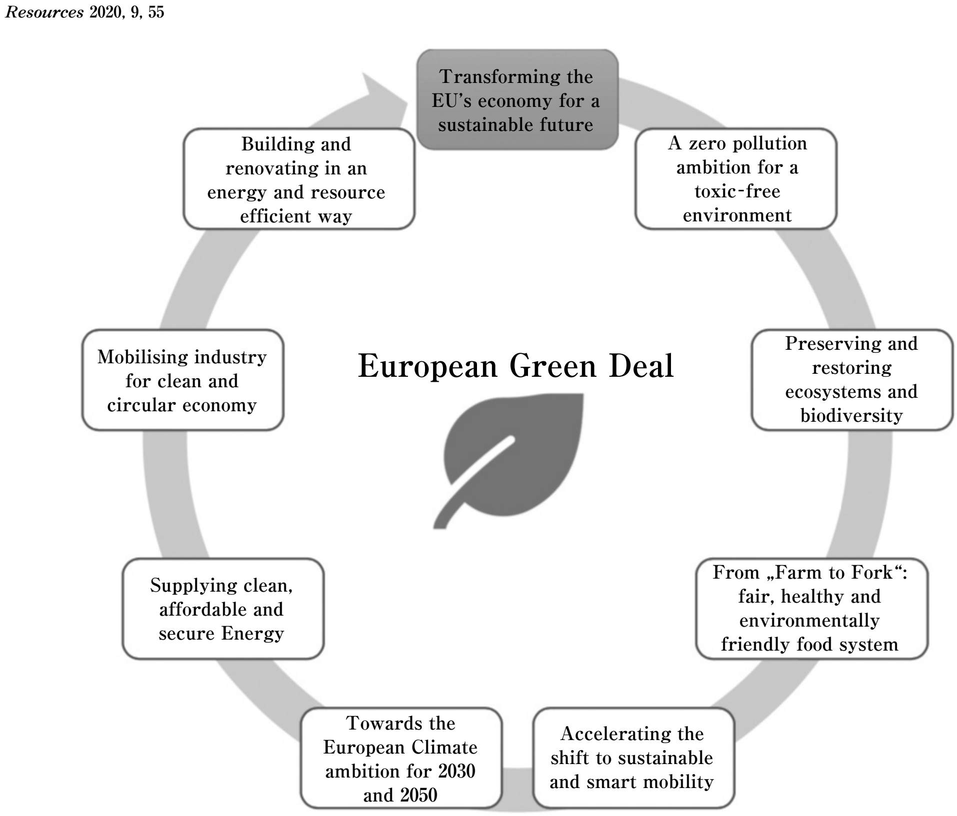


Source: Fizaine and Court, 2014

Figure 26 Ore Grades and the Energy Cost of Extraction

Increasing amounts of water used in these functions also contribute to rising energy demand. The figure indicates that as ore grades decline to the 0.5% level (mined material as a share of total material mass) the energy costs (gigajoules per tonne) increase dramatically and then skyrocket when they pass the 0.25% level.

This serious problem in ramping up the extraction of copper and other metals has been understood and quantified for many years by resource experts. One example is seen in the United Nations Environmental Programmes's International Resource Panel (UNEP) 2014 study "Decoupling 2 : Technologies, Opportunities and Policy Options." The UNEP agreed with the standard argument that technological innovation can help locate new resources as well as make some additional amount economically recoverable. But it warned that "this very rarely avoids the need for more energy, water and resource inputs to extract the same quantity of a natural resource. The tendency to process lower grades of ore to meet increasing demand is leading to a higher energy requirement per kilogram of metals, and conse-



Source: Smol, et al., 2020.

Figure 27 EU Green Deal Elements

quently to increased production costs” (UNEP, 2014).

These factors reviewed above all help to explain why the EU is stressing critical raw materials in its Green Deal. **Figure 27** outlines the ambit of the EU Green Deal, showing that it encompasses energy, food, transport and a wide array of areas.

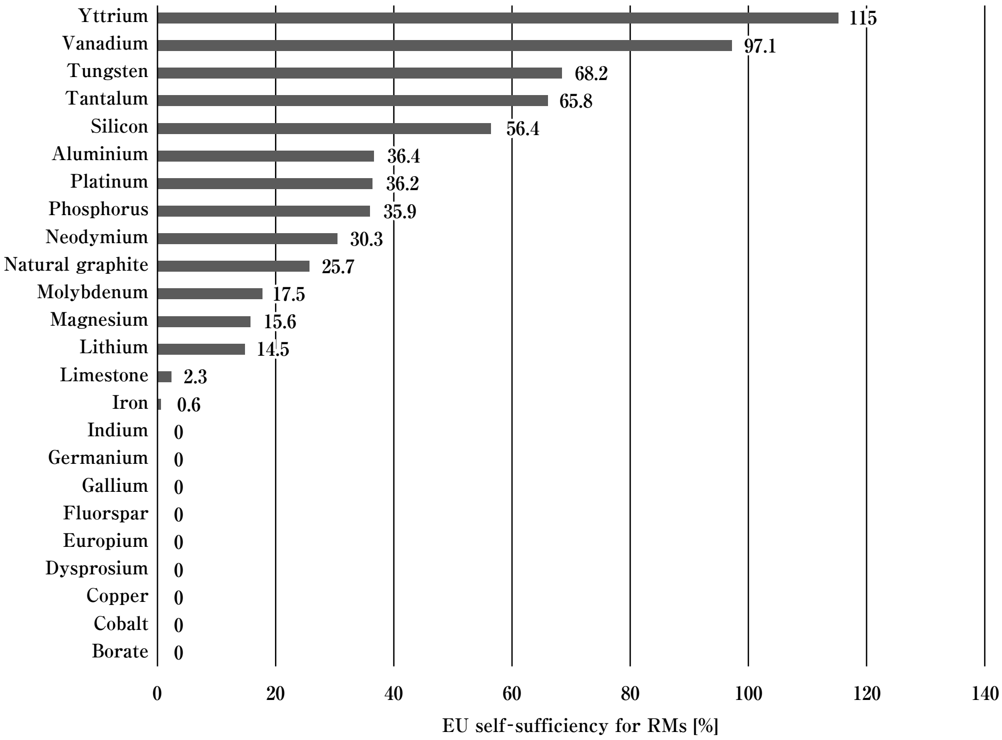
Figure 28 outlines the strategy for getting to circularity. It shows that recycling and reuse are only part of a larger whole. Along with those come greater self-sufficiency in raw materials, seen in the upper right-hand of the figure. The EU has in fact undertaken a concentrated industrial policy to achieve more critical raw material self-sufficiency.

Figure 29 shows why there is a great deal of concern in the EU, especially with regard to cobalt and other materials discussed above. We can see from the table that the EU has managed to achieve considerable self-sufficiency with respect to materials like yttrium , vanadium and others. Recycling and other policies have helped achieve these high levels. However, there is virtually no self-sufficiency in the EU for indium, copper, cobalt and the other materials reviewed in the World Bank Group study. The vulnerability is clear, in light of the massive material requirements and the geopolitical uncertainties. One could add that the potential for dramatic cost increases in materials could severely impact “green recovery” plans.

Figure 30 underscores the EU’s vulnerability. Even after end of life (EOL) recycling, the EU’s self-sufficiency for indium, copper, and cobalt remains virtually zero. The data suggest that it is rather easier to design circular economy approaches, as plans, than it is to ac-

Source: Smol, et al., 2020.

Figure 28 EU Green Deal Circular Economy Supply Chains



Share of Secondary RMs in the Demand for Mineral Resources

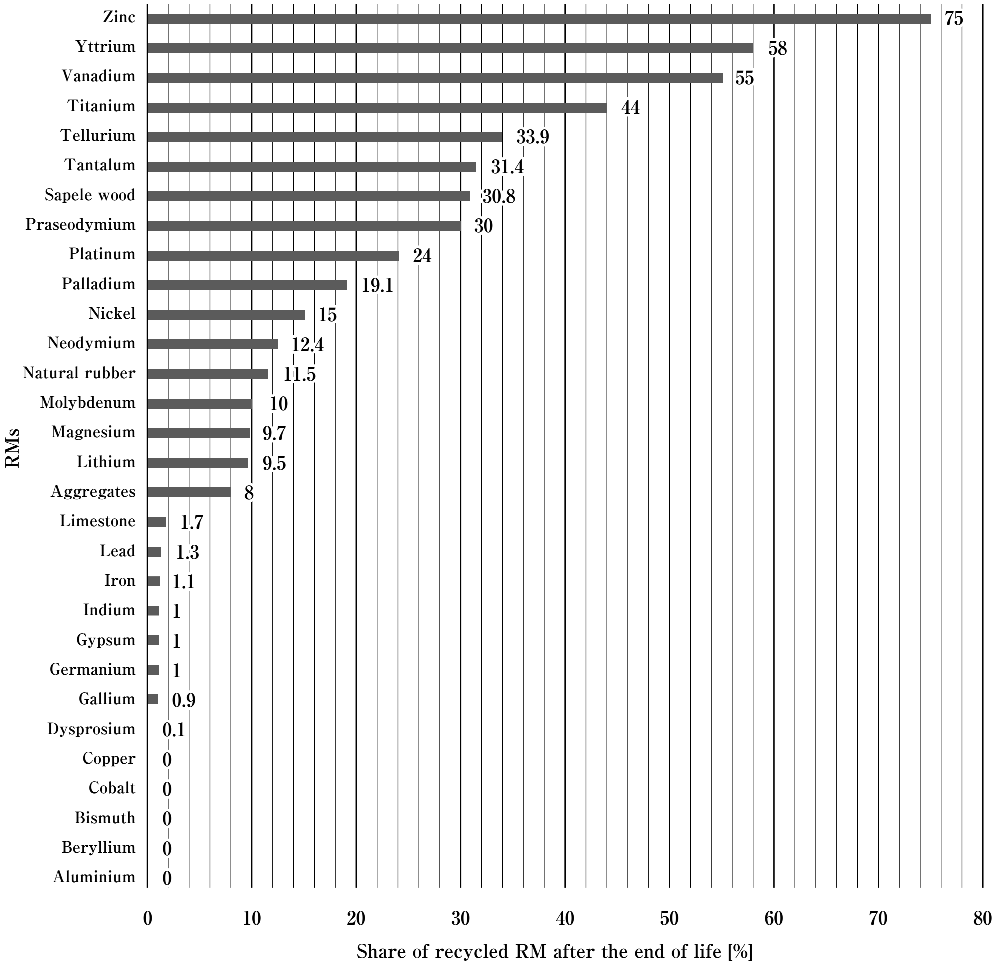
Source: Smol, et al., 2020.

Figure 29 EU Raw Material Self-Sufficiency

tually implement them. The myriad challenges include not just cost and compliance (by business and the public), but also the difficulty of extracting important critical raw materials from amalgams.

Figure 31 illustrates a wide discrepancy among the EU countries concerning material consumption. This variation suggests that there is considerable room for reducing consumption, particularly among the Nordic countries. Many arguments related to critical raw materials indeed assume that reduced consumption is key. But that solution cannot apply globally, as the vast majority of the human population has far lower levels of material consumption than EU countries, North America and East Asia (such as Japan, Singapore, South Korea, and coastal Chinese megacities). Most scenarios on critical materials overlook this global context, which makes the modeling much easier but also renders the results quite suspect.

Figure 32 is a 2019 publication from the EU Science Hub, one that seeks to generalize a sense of crisis concerning critical raw materials. We have seen that the EU seeks to pursue a Green Deal, which implies a higher density of critical raw materials. Recycling and con-



Source: Smol, et al., 2020.

Figure 30 EU Share of Recycled Raw Materials After End of Life

servation can help reduce risks, but only partially. The Science Hub initiative aims to illustrate this. Figure 32 thus lists how raw materials play their roles in a wide variety of devices and applications in energy, defence, and other spheres.

The EU Science Hub was concerned to measure increased demand for various critical materials, versus current global supply, based on the EU's target of 32% renewable energy by 2030. The 2030 targets include reaching 88 GW of wind, 45.4 GW of solar, and 10 million electric vehicles. Hence, the EU experts, meeting in Brussels from the 14th to 22nd of 2019, launched in tandem an interactive feature. The interactive is displayed in figure 33. On the left-hand side, it itemizes 9 critical raw materials, complete with clickable access to each material's import dependence (ie, the EU's dependence), the country or countries of origin,

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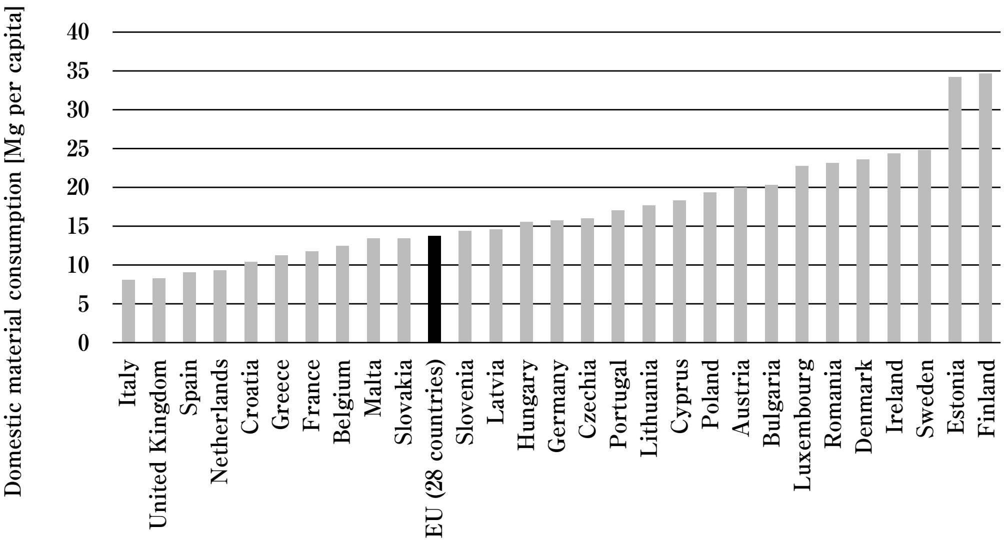
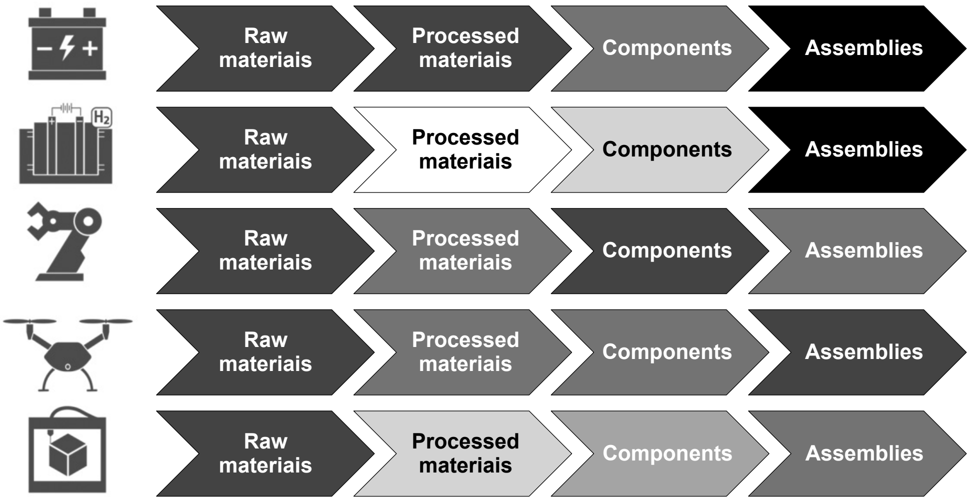


Source: Smol, et al., 2020.

Figure 31 Domestic Material Consumption per capita in the EU (28) in 2018

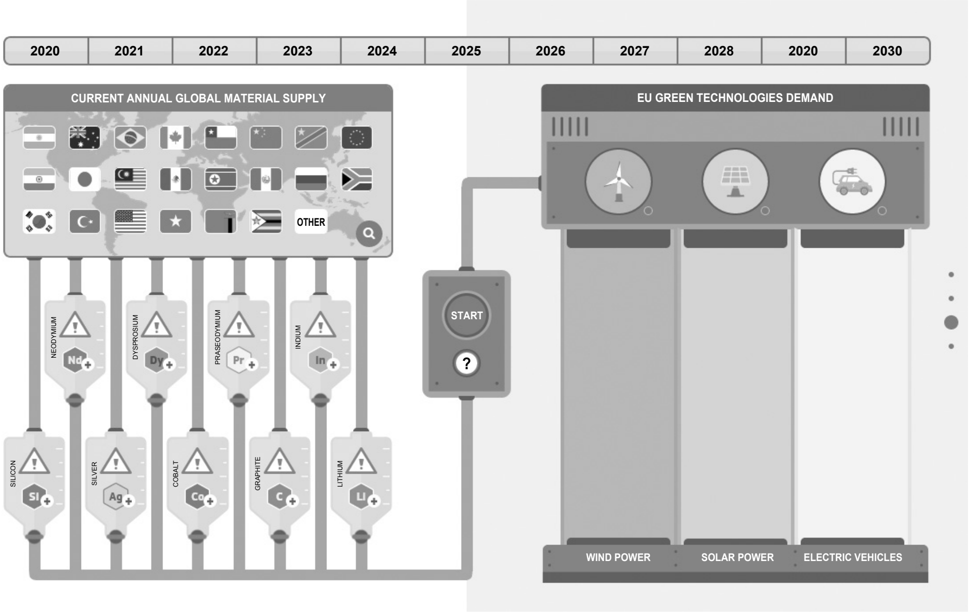


Supply risks identified for Europe in the supply chains of Li-ion batteries, fuel cells, robotics, drones and 3D printing

©EU 2019

Source: EU Science Hub, 2019

Figure 32 EU Supply Risks



©EU 2019

Source: EU Science Hub, 2019

Figure 33 EU Critical Raw Material Supply Risks

the current global supply, the range of uses (ie, cobalt is used in jet engines and other devices), and the relative share used in “green technologies” (VRE and electric vehicles). The interactive’s upper menu allows the user to select a given year and other aspects of the EU’s efforts to achieve its 2030 green targets by VRE (wind and solar) and electric vehicles. The interactive then calculates possible materials shortages stemming from projected demand for “Green Technologies” (right-hand side of the figure).

As we see in figure 34, even if one calculates only the amounts needed for the EU to reach 32% RE by 2030, the planetary supply runs into shortages on some non-substitutable items in short order. The figure shows that a simple run of the interactive alerts the user to an impending shortage of dysprosium in 2021, should the EU Green Deal proceed according to plan in deployments of wind. The interactive reveals that total global supply of dysprosium is 1,355 tonnes, one of the rarest of the rare earth metals, and crucial for magnets in a range of industries and applications. Fully 95% of the EU’s dysprosium is imported from China, and – in global terms – 72% of dysprosium is used by “non-green” industries, for magnets, leaving only 28% of supply for wind and electric vehicles. Subsequent runs show that lithium and other materials also soon become insufficient in subsequent years.

These results probably under-estimate the crisis. For one thing, the EU aims at a

In this scenario for **2021**, the EU will not be able to meet the demand for **wind power**, because the **current** annual global supply of key raw materials needed will be insufficient.

Source: EU Science Hub, 2019

Figure 34 EU Critical Raw Material Supply Risk for Dysprosium

32.5% increase in energy efficiency, which implies the use of a lot of digital equipment and other devices that consume critical raw materials. To include these elements in the interactive might hasten the onset of shortages.

In addition, the sobering results are just for the EU. The EU's 513 million residents are only 6.7% of the global total of 7.7 billion people. That means generalizing the EU's green energy ambitions would rapidly worsen the critical raw material challenge.

Moreover, the EU has special advantages compared to much of the rest of the world. Most low- and middle-income countries will have to grow their energy consumption in order to provide clean water, education, and the other public goods central to SDGs and the other elements of the 2030 Agenda. But in the EU, overall energy consumption is flattening and it has an international power grid to balance VRE with large hydro generation and pumped storage in Norway and Switzerland. There is also plenteous low-carbon nuclear power in Sweden and France, together with other baseload and low-carbon assets (biomass and biogas) that help back up VRE. Other countries aiming to depend on VRE would have to over-build and add in massive storage capacity, putting additional pressure of critical raw materials.

For example, consider that the average per-capita stock of copper in the developed world is 140-300 kilograms (kg) as compared to 30-40 kg in less-developed, lower-income countries (UNEP, 2010). These developed countries are generally the high-income countries, which account for 17% of the global population of 7.6 billion. The stock of copper in high-income developed countries is embodied in electricity grids, electric motors, plumbing, and a myriad other items in daily use. The high-income countries are being joined by many more billions in a wave of urbanization that could add about 2 billion new city dwellers over the next 15 to 20 years. The material implications of this urbanization are evident in the case of China. Recent estimates of per-capita copper stock in China indicate that it rose from 7 kg in 1990 to 60 kg in 2015, an eight-fold increase (Soulier, 2018).

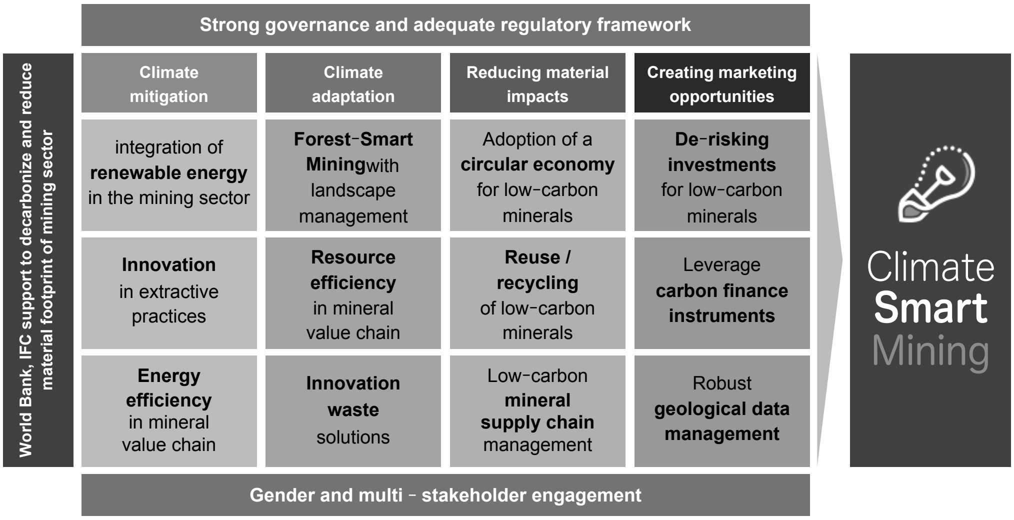
Most of the rest of the world lacks the EU's capacity to balance various types of low-carbon power. So achieving 100% renewable energy globally, especially as a green response to Covid-19, would require an astoundingly inefficient (and critical material intensive) build-out of wind and solar plus battery storage, rapid construction of EU-style international grids, and other emergency measures.

Thus a global acceleration of VRE deployment, to meet pledges of 100% renewable energy by 2030/2050 or whenever, would be a great many times more material-intensive than illustrated in the EU's interactive tools.

Against this backdrop, it is rather dismaying that the World Bank left the environment and related implications of material demand to the last section of its report. It recognizes that most additional extraction of materials will happen in developing countries, in large part because so many of the resources are there. But as we see in figure 35, its proposal for climate-smart mining entirely disregards the water and other stresses of increased mining. Since ore grades are declining, the amount of overburden to be dealt with is increasing. That results in greater energy, water and other use, with corresponding impacts on the environment and human health – precisely the items that "climate-smart mining" is ostensibly aimed at protecting.

The World Bank Group report is worth quoting at length on these omissions:

> "Beyond specific climate-related risks, other environmental and social risks of increased mineral extraction also need to be considered throughout the supply chain. These have not been addressed in this analysis given the focus on GHG emissions.
>
> From a broader environmental perspective, for example, the water intensiveness of the mining sector and the impact of deforestation need to be integrated in how these minerals will need to be produced to sustainably supply clean energy technologies.



Strong governance and adequate regulatory framework

World Bank, IFC support to decarbonize and reduce material footprint of mining sector

Climate mitigation	Climate adaptation	Reducing material impacts	Creating marketing opportunities
integration of **renewable energy** in the mining sector	**Forest-Smart Mining**with landscape management	Adoption of a **circular economy** for low-carbon minerals	**De-risking investments** for low-carbon minerals
Innovation in extractive practices	**Resource efficiency** in mineral value chain	**Reuse / recycling** of low-carbon minerals	Leverage **carbon finance instruments**
Energy efficiency in mineral value chain	**Innovation waste** solutions	Low-carbon **mineral supply chain** management	Robust **geological data management**

Gender and multi - stakeholder engagement

“Climate-Smart Mining: Minerals for Climate Action” (Brief), Extractive Industries, World Bank, https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action.

Source: World Bank Group, 2020

Figure 35 Climate-Smart Mining

From a social perspective, understanding issues such as the impact of mining upon local communities is vital to ensure that the transition to a clean energy system is beneficial for all. Given how critical minerals are to the low-carbon transition, a failure to address these wider environmental and social risks could facilitate a backlash against renewable electricity generation and energy storage technologies needed to mitigate GHG emissions” (World Bank Group, 2020).

It is precisely these concerns that led Michael Moore and Jeff Gibbs to highlight environmental consequences in their 2020 documentary, “Planet of the Humans.” The documentary is a warning about VRE and other renewable energies, insisting that they are not as environmentally friendly as reputed. The documentary attracted a great deal of criticism from fervent supporters of a VRE-led green shift or Green New Deal. Whatever its errors, the film certainly did correctly highlight the environmental and human rights implications of cobalt, as illustrated in figure 36. The documentary showed that critical raw materials do not only have environmental damage, but also severe implications for human rights. Cobalt is especially problematic in this respect, because artisanal mining produces about 30% of the DRC’s supply which in turn is about 70% of global supply. Thousands of children are exploited in these artisanal mines (Sanderson, 2019). Figure 36 is one visualization of that political-

Michael Moore Presents: Planet of the Humans | Full Documentary | Directed by Jeff Gibbs

Source: https://planetofthehumans.com

Figure 36 Cobalt in The Planet of the Humans

ly uncomfortable reality.

The Moore/Gibbs film could be faulted for not adequately pursuing the question of how to implement 2030 Agenda goals in developing countries when the bulk of the materials they supply are used inefficiently in developed countries. We have seen that critical raw material resources are constrained, and in many cases difficult to recycle and repurpose. So it seems imperative to ask whether it is environmentally just that resource-efficiency not be first and foremost in proposals for greening. Many green enthusiasts in developed countries celebrate the diffusion of small-scale VRE without bothering to ask whether the low capacity factors and requirement for additional storage, transmission and other infrastructure imposes costs on the regions where the critical raw materials are extracted.

Yet it seems quite clear that the more rapidly the rollout of materially inefficient decarbonization in the developed world, the greater the risk of leaving the developing world with worsened environmental damage. And that damage might be exacerbated by even more constrained choices on clean development. That is because the critical materials used inefficiently in developed countries will almost certainly not be available in sufficient quantities and reasonable prices for low-income developing countries. There is, in short, the patent risk of a truly historic and possibly irremediable injustice. This prospect, plus the lack of attention to it, is a bitter irony considering the developed world green activists' emphasis on environmental justice in their own cities and countries.

These uncomfortable realities have evidently led many analysts to confine the scope of their studies, leaving the larger issues to be mentioned – if at all – near the end of their work. That failure to take on the larger implications has left an enormous analytical hole. But recent work on the critical material challenge has advanced the proposition that the environmentally sustainable alternative is deep-sea mining. The firm DeepGreen Metals commissioned a very thorough study on this issue. One result is displayed in table 14. The study compared the impacts for mining nickel, manganese, cobalt and copper from terrestrial sources and the sea floor. The focus was on the material needs of 1 billion electric cars, and not the much larger needs of decarbonizing the built environment. All the same, the work is

Table 14 Comparing Terrestrial and Sea Floor Mining

Environmental, social and economic impacts

Cradle-to-gate production of nickel sulfate,
manganese sulfate, cobalt sulfate and copper cathode
Serving size **1 billion electric cars**

	Land	**Nodules**	**% change**
Climate change			
GWP-CO_2 equivalent emissions, Gt	1.5	0.4	**−70%**
Stored carbon at risk, Gt	9.3	0.6	**−94%**
Nonliving resources			
Ore use, Gt	25	6	**−75%**
Land use, km^2	156,000	9,800	**−94%**
Incl. Forest use, km^2	66,000	5,200	**−92%**
Seabed use, km^2	2,000	508,000	**+99.6%**
Water use, km^3	45	5	**−89%**
Primary and secondary energy extracted, PJ	24,500	25,300	**+3%**
Waste streams			
Solid waste, Gt	64	0	**−100%**
Terrestrial ecotoxicity, 1,4-DCB equivalent Mt	33	0.5	**−98%**
Freshwater ecotoxicity, 1,4-DCB equivalent Gt	21	0.1	**−99%**
Eutrophication potential, PO4 equivalent Mt	80	0.6	**−99%**
Human & wildlife health			
Human toxicity, 1,4-DCB equivalent Mt	37,000	286	**−99%**
SOx and NOx emissions, Mt	180	18	**−90%**
Human lives at risk, number	1,800	47	**−97%**
Megafauna wildlife at risk, trillion organisms	47	3	**−93%**
Biomass at risk, Mt	568	42	**−93%**
Biodiversity loss risk	Present	Present	
Economic impact			
Nickel sulfate production cost, USD per tonne Ni	14,500	7,700	**−47%**
Jobs created (non-artisanal) worker-years	600,000	150,000	**−75%**

Source: Paulikas, et al., 2020

instructive because it compares the sources of the materials. This work is without precedent, as these has been no previous estimation of the comparative impacts. As we see from the table, the results suggest that mining sea-floor nodules rather than terrestrial sources has considerably lower emissions, land use, water use, waste and even biodiversity impacts.

There is no scope in this paper to delve at greater depth into the question of whether terrestrial or marine mining is more sustainable. Suffice it to say that because of mounting critical material demand, geopolitical risks, and other factors, many countries already seek to mine the sea floor. These countries include Germany, China, South Korea, Brazil, Russia, Japan, and others. Many are particularly interested in cobalt. As a recent article on the issue noted, “they have exploration contracts for cobalt-rich ferromanganese crusts. Cobalt is a vital component in batteries, including car batteries. It is a rare mineral and considered dangerous to mine on land” (Abbany, 2020). The marine resource base also greatly dwarfs the terrestrial resource base. We saw earlier that the USGS assessed terrestrial cobalt resources at 25 million tons. Its surveys indicate that more than “120 million tons of cobalt resources have been identified in manganese nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans” (USGS, 2020).

Conclusion

We have seen that many critical materials are used at far greater density, per unit of energy consumption or production, in green technologies as compared to conventional power systems, automobiles, and the like. And supplies of these materials have other competing sources of demand, including smart phones, jet engines, health care, and multiple other areas. The IEA and other analyses do not adequately discuss supply constraints, geostrategic risks, human rights concerns, environmental damage (from harvesting and processing critical materials), and other issues. These challenges are all central to sustainable development and the circular economy. The emerging facts suggest that any credible, rapid shift to sustainable energy and efficiency will require prioritizing the use of constrained critical materials. Doing that will almost certainly require Japanese-style comprehensive governance.

The first imperative is to reduce undue reliance on any particular material via substitution. The Japanese did this in the wake of 2010, when rare earth price rose and Chinese policies on rare earths indicated increased risks of export bans against Japan. In response, the Japanese invested heavily in alternatives. These strategic investments resulted in such innovations as new magnet technologies that greatly reduce the role of neodymium.

Yet substitution has its limits, because of the enormous projected increase in demand for nearly all these materials. One example is seen in the effort to use nickel to reduce reliance on cobalt in electric vehicle batteries. In collaboration with Panasonic, the US automaker Tesla has been at the forefront of this initiative. Indeed, Tesla's goal is to entirely eliminate the role of cobalt in electric-vehicle (EV) batteries, and it is achieving notable success in this objective. However, the initiative has encountered something of a "whack a mole" phenomenon. This is because supplies of nickel are increasingly constrained, posing a challenge to large-scale substitution of cobalt in the high energy-density batteries required for electrified transport. Global demand for nickel in EV batteries is projected to increase from 3% of all sources of demand (such as stainless steel, non-ferrous alloys, and other products) in 2018 to 12% by 2023, as global automakers are expected to introduce over 200 new EV models. But the volatility of prices for nickel have been a drag on investment in increased mining capacity. In consequence, metals analysts warn that "[t]here is no new nickel in the pipeline" even as other specialists highlight the time required to find alternatives (Hoyle, 2019).

Because options for substituting critical materials appear limited, and perhaps very problematic, increased attention to strategic, spatially-smart use of these scarce materials is required. The circular economy literature features some new work that attempts to examine the spatial issue across countries. This literature seeks to promote circularity (and carbon neutrality) within the far-flung supply chains that link prominent critical-material producers and exporters, such as Australia, to consumer countries within the global resource network. This macro-level perspective on circularity and critical materials is important, but surely needs to be supplemented with a micro-level focus that starts from cities.

We have also seen that compact and resource-efficient community has long been an element of National Spatial Planning and other policy regimes, and is incorporated in Japan's National Resilience and Society 5.0 industrial policies. Japan's comprehensive approach to circularity places the objective within multiple other goals, and matches that with integrated institutions and ample public finance. This approach seeks to maximize the co-benefits for a very broad range of stakeholders, giving the paradigm enduring political legitimacy. The paradigm is also the focus of Japanese official development assistance, which has increased significantly in the midst of the Covid-19 crisis (IMF, 2020). In this respect, it is important to note that the Overseas Development Institute ranks Japan first in the category of "global cooperation," which measures support for multilateral institutions, tackling climate change by mitigation and adaptation, and combatting the spread of infectious diseases (ODI, 2019).

This paper has argued that Covid-19 has led Japan to accelerate its diffusion of all-hazard, disaster-resilient, and silobreaking policy integration. I have outlined the fiscal and organizational evidence. Sapporo provides one example of the productive use of the fiscal stimulus within Japan's larger context of 2030-Agenda oriented platform institutions. But myriad other examples could just as easily have been adduced to illustrate Japan's inclusion of coping with Covid-19 while building on a larger, pre-existing industrial policy of holistic and transformative resilience. In short, the evidence shows that Japan is already emphasizing mitigation and adaptation in its countermeasures to Covid-19. Attention to this fact could not only help Japan maximize the beneficial impact of its investment, but also help other countries learn how to do holistic, silobreaking policymaking and project implementation. Against the backdrop of extreme material challenges, Japanese resource-efficiency is an important model to learn from.

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