August 2020

Metals Dependence of the Third Industrial Revolution

Modern human history is marked by recurring periods of multifaceted innovations leading to an acceleration in industrial production and efficiency gains. Coined by the economic historian Arnold Toynbee, we now refer to these periods as Industrial Revolutions. As Jeremy Rifkin notes [i], each of these economic paradigm shifts relied on three fundamental elements: an energy source, an innovative communication medium, and a novel transportation and logistics mechanism. In the 19th century, the First Industrial Revolution was concomitant with factories powered by the Watt steam engine, the telegraph, and national railroad systems. In the 20th century, the Second Industrial Revolution relied on the infrastructure of coal powered, centralized electricity, cheap oil, the telephone, and the internal combustion vehicle. Today, we are in the early stages of the Third Industrial Revolution, reliant on carbon neutral electricity generation, fiber optic communications, electric mobility, and a democratized logistics system made efficient by the Internet of Things.

Advances in materials sciences and natural resource production and utilization played a critical role in each of the Industrial Revolutions. The First Industrial Revolution saw the crucible steel technique, increased coal production, and low sulfur coke fired blast furnaces for iron production while the Second Industrial Revolution saw the Cowper stove for iron production, the Bessemer steel process, and the utilization of oil in industrial processes and the Burton refining process. The Third Industrial Revolution will distinguish itself by both the breadth and intensity of metals and minerals demand required to enable the related advances in energy generation, communications, and transportation. While previous Industrial Revolutions relied on consumable raw materials such as coal and petroleum, the Third Industrial Revolution's carbon neutrality mandate directs demand towards raw materials that can be considered an asset. Critically, shortages in requisite metals and mineral supplies could impact the potential speed and scale with which these new technologies will be deployed.

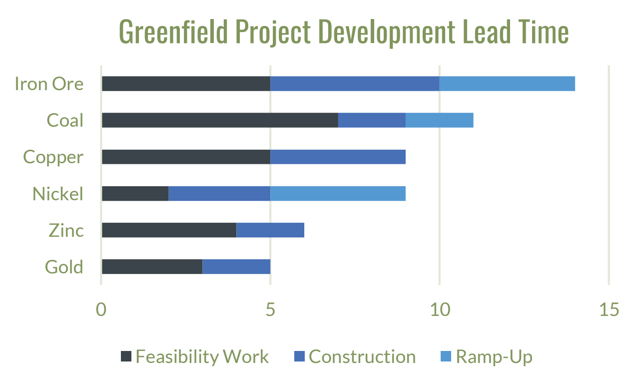

Figure 1: Source: CRU

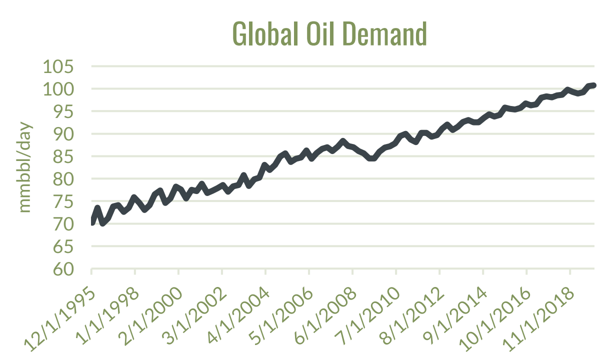

Figure 2: Source: Bloomberg; IEA

Rather than internationally transporting hydrocarbons for local power generation, the focus is now on local, carbon-neutral generation and transportation of free electrons for immediate use or to be stored in batteries. Previously, fossil fuels were utilized due to superior energy density, lack of viable alternatives and convenience. However, the plethora of evidence of anthropomorphic climate change has made fossil fuels decidedly inconvenient. Technological advances in oil extraction, particularly hydrofracking, significantly shortened the supply reaction function due to fluctuations in oil demand. Given the long lead times for project development, metals and minerals supply cannot react quickly to price fluctuations (Figure 1). Over the past decades, oil consumption rose in a remarkably linear fashion as consumers consistently required renewed supplies (Figure 2). In the Third Industrial Revolution, establishing the fixed assets necessary for renewable power generation will frontload demand for metals and recycling will ensure that subsequent demand is met with both primary and secondary supply (Figure 3). This will have two significant impacts on market dynamics: 1) consumers will be less likely to search for substitutes and 2) producers will be less likely to commit capital to expanding production to satiate demand they view as ultimately transitory. This will cause significant raw material shortfalls in the early years of this paradigm shift.

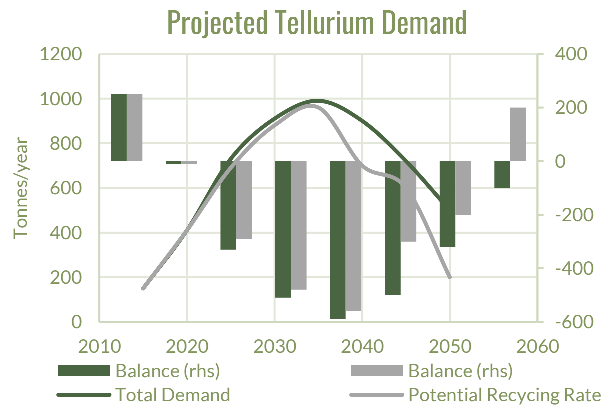

Figure 3: Source: VAM Research. Market balance scenarios with and without recycling

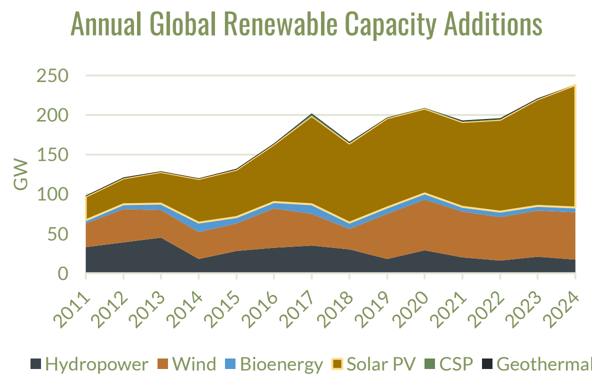

Figure 4: Source: EIA

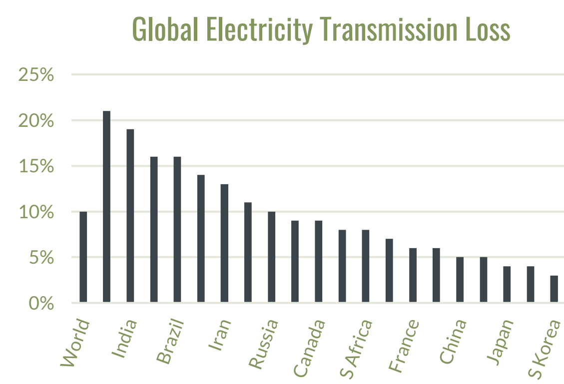

Figure 5: Sources: World Bank; IEA

Installing renewable and carbon-neutral power generation facilities will have the most profound impact on metals demand from copper to rare earth elements. Governments and consumers around the world recognize the existential threat of climate change. Thus, the expansion of renewable power generation is not solely reliant on free market economics but also mandated by government policy borne from the Paris Accord and consumers that understand the long-term benefits versus the short-term costs (Figure 4). Each subcomponent necessary to achieve a sustainably powered Internet of Energy [ii] is metals intensive. Solar and wind power generation facilities will require additional supplies of aluminum, copper, silver, indium, tellurium, dysprosium, neodymium, selenium, germanium, and gallium. [iii] Electricity distribution expansions and upgrades, necessary for the requisite efficiency gains and two way flow of residential net producers, will require additional production of copper, aluminum and, eventually, lanthanum, cerium, samarium, neodymium, dysprosium, yttrium and praseodymium for high temperature superconductors (Figure 5).

Grid level energy storage technologies, necessary due to the fluctuations in electricity generation potential during each nychthemeron, will require additional sources of copper, tin, vanadium[iv], lithium, cobalt and manganese. The magnitude of materials demand changes will be large. The World Bank[iii] estimates that to achieve the IEA's 2-degree scenario[v], solar power generation excluding distribution infrastructure alone will require an additional, cumulative 160 million tons of aluminum and 20 million tons of copper, equal to 10x and 1.2x current annual production, respectively. In the minor metals and rare earth elements, the impact is even more profound. By 2030, annual tellurium demand for production of cadmium telluride (CdTe) photovoltaics will be 220% current production and, by 2030, annual vanadium demand for vanadium flow redox batteries (VFRB) is expected to be 2x current levels.

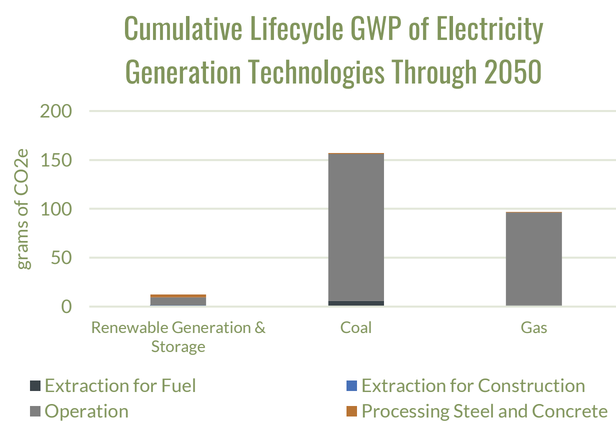

Figure 6: Sources: World Bank; GWP: Global Warming Potential

Innovations in communications, the second pillar of the Third Industrial Revolution and a large contributor to the zero marginal cost phenomenon[vi], will also have a large impact on raw material demand. In addition to the economic benefit, global expansion of fiber optic internet connectivity and 5G wireless communications significantly advance the UN's Sustainable Development Goals of quality education, reduced inequalities, and efficient infrastructure.[vii] The Internet of Things will significantly increase consumer appliance energy efficiency, but will require supplementary installed bandwidth. As with new energy infrastructure, this advance in the global communications network will require additional supplies of metals and minerals such as germanium for fiber optic cables; tin for consumer electric solder materials; ruthenium for data storage (Figure 7); iridium to produce lithium tantalite; and indium and gallium for integrated circuits and discrete field effect transistors.

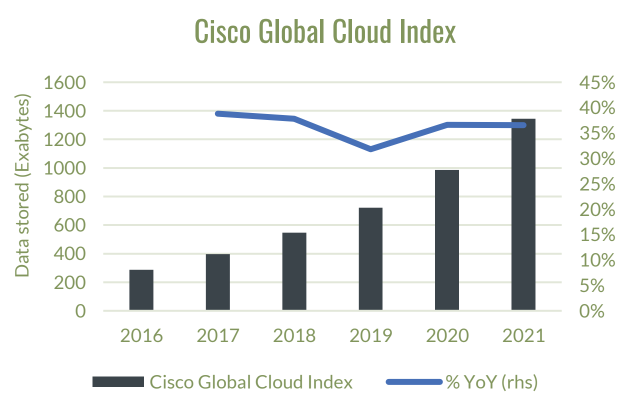

Figure 7: Sources: Cisco; Bloomberg

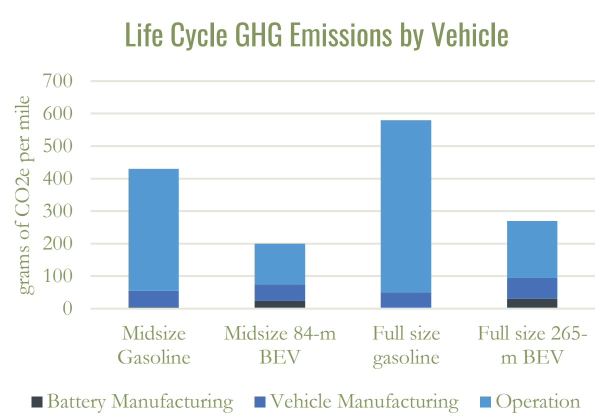

Figure 8: Sources: World Bank; IEA

Advances in logistics and transportation, the third component of the Third Industrial Revolution, present a unique set of challenges in terms of material demands as technological solutions have size and weight constraints. While a VFRB may prove the most cost-efficient solution for grid level storage, its average specific energy of 20 Wh/kg versus lithium ion's 100 – 200 Wh/kg make it ill-suited for mobile applications. The most prominent example of mobility innovation is the electric vehicles. In its early stages, debate surrounded the comparative mine and well to wheel environmental impact of EVs versus internal combustion engine (ICE) vehicles. Since that time, numerous studies have supported the finding that EVs have a far smaller overall environmental impact than ICE vehicles (Figure 8).[viii] However, if global society is to meet the EV deployment goals set by the Paris Accord (Figure 9), there must be a significant increase in the availability of certain metals and minerals. In response to rising prices, battery manufacturers have made significant progress in substituting cobalt out of nickel-manganese-cobalt (NMC) without significantly destabilizing the cathodes. However, the associated increase in nickel sulfate loadings has set up the nickel market for significant deficit beginning in 2021 (Figure 10). This evolution in cathode material concentrations highlights an important aspect of the Third Industrial Revolutions reliance on metals: because renewable power generation and storage rely on specific, atomic electrochemical properties, the range of acceptable substitutes is limited. It is far easier to manipulate the molecular bonds of a hydrocarbon chain than it is to reconfigure the valence electrons of a metal or mineral.

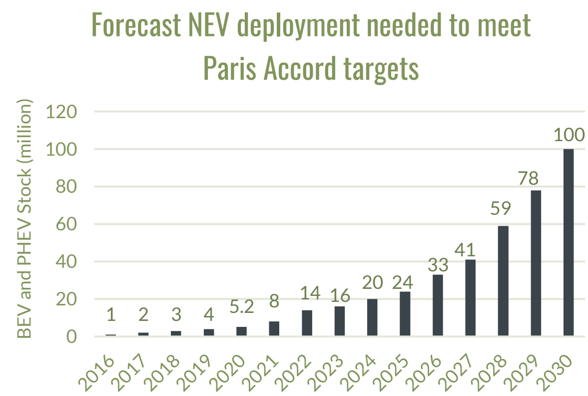

Figure 9: Sources: Adamas Research

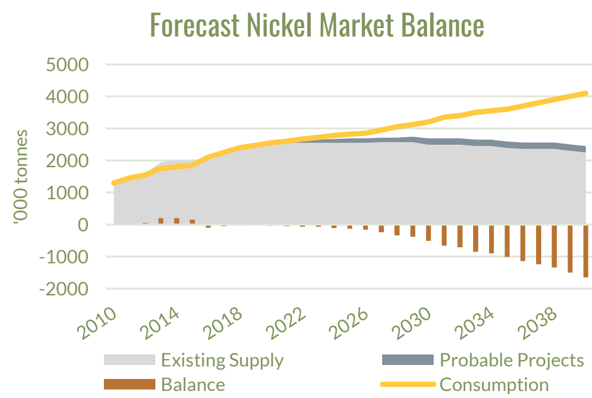

Figure 10: Source: CRU; VAM Research

In addition to material needs of an EV's power source, other EV components and charging infrastructure will present a challenge to supply the necessary metals and minerals. Copper demand from this application alone is forecast to reach 17% of current global production by 2035 (Figure). Production of dysprosium (Dy) and neodymium (Nd), necessary for the permanent magnets of electric induction motors, will have to increase 50% and 110%, respectively, to achieve the drastic reduction in emissions that EVs will achieve over internal combustion vehicles (Figure 11). Evolutions in lightweight chassis construction will significantly alter aluminum demand.

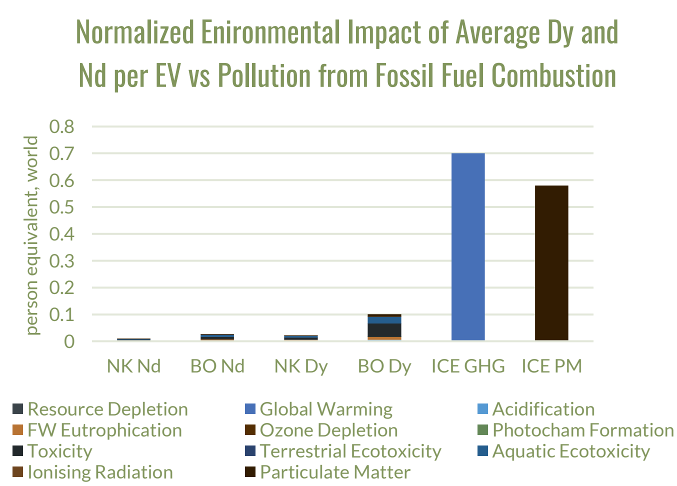

Figure 11: Sources: Schreiber et. Al.; NK: Norra Kärr mine, BO: Bayan Obo mine, EV: electric vehicle, ICE: internal combustion engine, GHG: green house gas, PM: particulate matter

Though the environmental, economic, and social benefits of the end use of these materials is evident, increasing extraction and processing of these metals could have a negative environmental impact. However, these metals and minerals are necessary to achieve the leap forward in eliminating the environmental impact of fossil fuels and ensuring their availability is critical. With the current composition of US electricity generation, a full sized, 265 mile battery electric (BEV) vehicle's lifecycle emissions are 53% less than a comparative gasoline vehicle (Figure 8). As renewable electricity generation is installed, this disparity increases significantly. Lifecycle emissions of a solar generation facility are less than 5% of a coal fired plant of comparative capacity (Figure 5). The extraction of dysprosium and neodymium for electric vehicles have a fraction of the environmental impact of fossil fuel production and use (Figure 11). [ix]

Despite the gains versus fossil fuels, the impact of extraction and processing metals for new technologies can be mitigated by both government regulations and price incentives. In response to the rise of illegal rare earth element mines, China enacted several reforms meant to shutter these illegal mines and funded a broad environmental cleanup effort. [x] These reforms were necessary and critical to attenuate the environmental damage, but the result is a looming dysprosium and neodymium shortage that could threaten the pace of wind turbine and EV deployment needed to meet climate change goals. As with all metal and mineral extraction processes, environmentally responsible rare earth mining is inherently higher cost and will require a higher price for the materials produced. The long lead time associated with developing new supply projects means that these higher prices must occur before the increased demand becomes apparent. Indeed, from 2004 to 2006, a mere .5% cumulative copper deficit coincided with a 150% price increase (Figure 13). The prospect of future supply shortfalls underpinned the rally. This dynamic is even more stark in the minor and esoteric metals, exemplified by rhodium's recent 600% rally alongside a mere 4% supply shortfall. Vital to the goals of the Third Industrial Revolution, the anticipatory nature of metals and minerals prices ensure that the decarbonization of electricity generation does not simply shift emissions upstream. [xi]

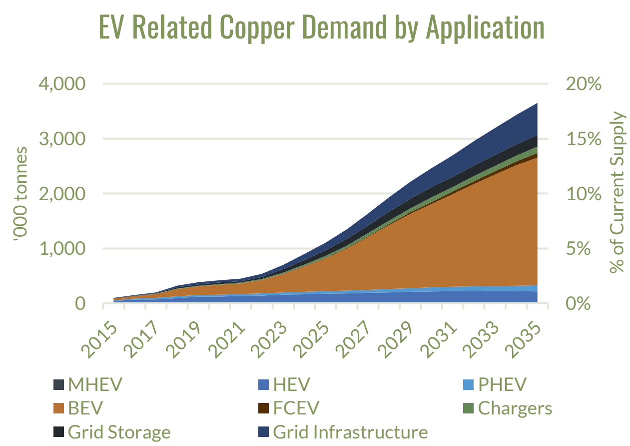

Figure 12: Source: CRU

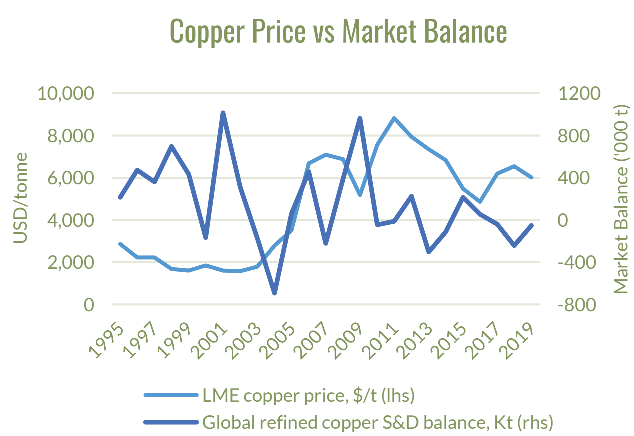

Figure 13: Source: CRU, Bloomberg

The three pillars of the Third Industrial Revolution will be deeply metals intensive with frontloaded demand due to installation of necessary fixed assets. The resulting environmental, societal, and economic impacts will be unequivocally beneficial, but specific metals and minerals prices must rise in anticipation to ensure both sufficient and responsibly sourced supply. Technological developments must be continuously monitored to assess their impact on specific metals and minerals fundamentals. To date, existing inventories built during China's economic moderation have satiated demand and capital expenditures have focused on developing communications, transport and clean energy infrastructure rather than ensuring the supply of required inputs (Figure 14). This is unsustainable. With proper oversight and social cognizance that was notoriously lacking when oil majors expanded internationally, the demand created by the Third Industrial Revolution could benefit several underserved yet resource rich communities.[xii] With preemptive price appreciation and responsible sourcing powered by renewable energy, the metals and minerals needed for technological advancement will not only be secured, but will be done so in harmony with the ideals of the Third Industrial Revolution.

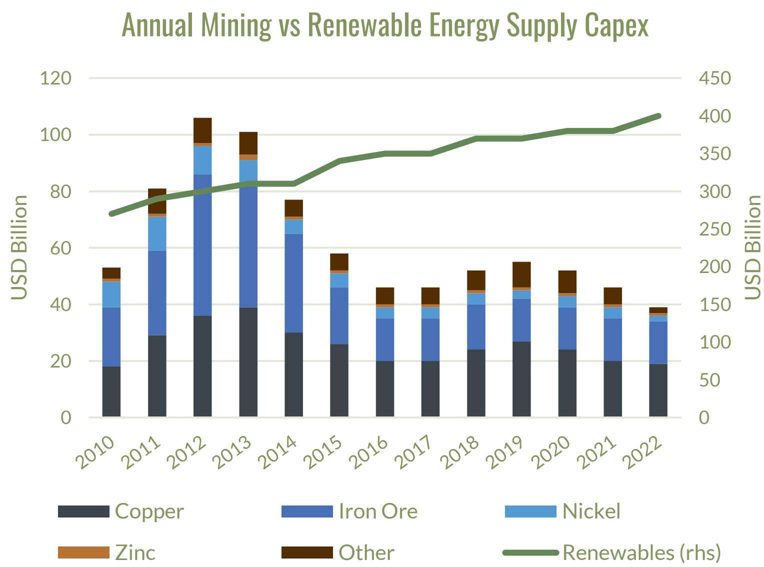

Figure 14: Source: S&P Global, Goldman Sachs, VAM Research

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[i] https://magazine.wharton.upenn.edu/issues/summer-2015/welcome-to-the-third-industrial-revolution/

[ii] Nguyen, D., Thao, N.G., Tran, H. (2019). The Prospective of the Internet of Energy. *3rd International Workshop on MEMS and Sensor Systems (IWMS 2019).* Pp. 35 - 37

[iii] https://www.worldbank.org/en/topic/extractiveindustries/brief/climate-smart-mining-minerals-for-climate-action#:~:text=A%20new%20World%20Bank%20Group,demand%20for%20clean%20energy%20technologies.

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[vii] https://sustainabledevelopment.un.org/

[viii] https://www.ucsusa.org/sites/default/files/attach/2015/11/Cleaner-Cars-from-Cradle-to-Grave-full-report.pdf

[ix] Schreiber, A., Marx, J., Zapp, P. (2016). *Environmental Impacts of Rare Earth Mining and Separation Based on Eudialyte: A New European Way. Resources* (5, 32)

[x] https://e360.yale.edu/features/china-wrestles-with-the-toxic-aftermath-of-rare-earth-mining

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