



# Columbia Center on Sustainable Investment

A JOINT CENTER OF COLUMBIA LAW SCHOOL  
AND THE EARTH INSTITUTE, COLUMBIA UNIVERSITY



## **Resourcing Green Technologies through Smart Mineral Enterprise Development:**

### **A Case Analysis of Cobalt**

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## Executive Summary<sup>1</sup>

Much has been written in recent years about the urgency to develop new technologies that meet ambitious targets for more efficient energy infrastructure with reduced reliance on fossil fuels. There has also been growing recognition that mineral scarcity can hamper the speed of key technologies being developed. The dominance of China as a global supplier of many technology minerals and the Chinese government's ability to constrain supply has led to a focus on the international trade dimensions of the challenge. The United States, Japan, the European Union and South Korea have all been keenly focused on securing mineral supply for their domestic industries through a range of initiatives. These efforts have included the World Trade Organization dispute resolution mechanism; research investment in alternative and more widely available materials where possible; and considering strategic stockpiles of minerals from internal sources that harken back to Cold War era strategies for material security.

In this report, we argue that a neglected area in addressing the mineral scarcity challenge is the private sector's current trajectory for geological mineral exploration of key minerals and innovative initiatives on material efficiency and recycling where possible. We term this approach Smart Mineral Enterprise Development (SMED) which entails a partnership between public and private entities to consider pathways whereby public sector data sharing on geology can be coupled with research innovations in the private sector both upstream and downstream of mineral supply. Just as smart energy grids harness efficiencies in electricity supply and demand through a dynamic process of communication, SMED processes can do the same for key technological bottlenecks in mineral supply. We focus on cobalt to highlight the bottlenecks; identify alternative supply sources based on current exploration and recycling technologies; propose ways in which the international legal framework could be adapted to promote investments in critical minerals; and consider ways by which the public sector can assist the private sector in developing a SMED process that would bring forth more efficient and effective entrepreneurial activity to meet our green technology needs.

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## 1. Introduction

On December 20, 2017, the United States Geological Survey published its first critical minerals assessment since 1973. The findings were stark and sobering to those concerned about American dependence on foreign-sourced commodities. The report noted that out of the 23 key minerals on which the American economy is most dependent 21 have more than 50% of their demand met from imports<sup>2</sup>. Beryllium and titanium were the notable exceptions. The report raised enough alarm bells that President Trump issued an executive order the very next day to expand critical minerals production by "increasing activity at all levels of the supply chain, including exploration, mining, concentration, separation, alloying, recycling and reprocessing critical minerals."<sup>3</sup> Yet, the mechanisms by which this production could best be facilitated have eluded much discussion.

A lot of these critical minerals highlighted in the survey are needed for the development of renewable energies. Harnessing the supply at the global level is necessary to achieve the Paris Climate Agreement. The Agreement, signed in December 2015, is a landmark global treaty committing all participant countries to reducing carbon emissions and limiting global temperature rise to below two degrees Celsius above pre-industrial levels. This historic agreement cemented the world's commitment to combating climate change and set the stage for exponential growth in the demand for renewable-energy and energy-efficient technologies. To achieve the ambitious goals of the Paris Agreement, worldwide production of sustainable technologies must increase drastically, far beyond current levels. Article 10 of the Agreement highlights the importance of green technology for achieving global climate goals, calling for green tech growth, innovation, enhancement, and transfer:

“1. Parties share a long-term vision on the importance of fully realizing technology development and transfer in order to improve resilience to climate change and to reduce greenhouse gas emissions.

2. Parties, noting the importance of technology for the implementation of mitigation and adaptation actions under this Agreement and recognizing existing technology deployment and dissemination efforts, shall strengthen cooperative action on technology development and transfer.”<sup>4</sup>

And while the Paris agreement recognizes green technology as an essential element in achieving climate goals, research performed on the feasibility of actually developing, building, and

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<sup>2</sup> Klaus J. Schulz, John H. DeYoung, Jr., Dwight C. Bradley, and Robert R. Seal II, U.S. Geological Survey, *Critical Mineral Resources of the United States—An Introduction*. Available at: <https://pubs.usgs.gov/pp/1802/a/pp1802a.pdf>. (Accessed 23 Jan. 2018).

<sup>3</sup> Presidential Executive Order on a Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals. December 20, 2017. Available at: <https://www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/>. (Accessed 23 Jan. 2018).

<sup>4</sup> Paris Agreement, Article 10, entered into force November 4, 2016, United Nations Framework Convention on Climate Change (UNFCCC)

deploying green technology at this scale has been insufficient. In reality, these sustainable technologies are highly material-intensive and will require the mining and refining of a wide range and vast quantities of “technology minerals” from which to produce the technology metals, alloys, and chemical compounds required. This supply does not yet exist, raising serious concerns about where, and how the world will procure enough supply to meet growing demand. If the goals of the Paris Agreement are to be met, the supply of technology minerals must increase drastically.

Technology minerals—defined as the geological sources for the metals, alloys, and chemical compounds used in the production of modern technology—are critical in the production of nearly all green technologies. Technology minerals are used to increase efficiency, decrease weight, prolong battery life, and a myriad of other essential functions. Although often used in trace amounts and abundant in the Earth’s crust, depending on access to these critical materials can be extremely risky due to the paucity of their availability to mining in accessible deposits, and awareness of their importance is largely unknown outside of the mining and tech industries. Thus, this paper distinguishes between physical supply (i.e. what exists on earth in a geological sense) and practical supply (i.e. what is available globally, with consideration for technical, political, and economic influences and consequences). Vast amounts of technology minerals exist in the Earth’s crust in varying concentrations, meaning there is no theoretical risk of physical supply shortage. However, financial, geopolitical, and technical issues render the practical supply of them at risk of shortage. As such, producing and securing a reliable global supply of technology minerals is paramount and the practical scarcity of supply of most of the technology minerals represents a significant obstacle to the future of renewable- and energy-efficient technologies, and their continuous supply is already in jeopardy.

This paper will discuss ways of addressing the tenuous global supply—as an overlooked yet fundamental element to achieving the goals of the Paris Agreement and the future of the green economy. The paper first defines “criticality”, a term used to determine which minerals are most important to the advancement of green technology. Then, based on this determination, we focus on cobalt as a case study of a mineral that is likely to be essential for green technologies and where a supply shortage appears unavoidable. In its central piece, the paper covers various investment solutions to address the supply shortage but in particular hones in on a mechanism that the authors coined as the “Smart Mineral Enterprise Development (SMED)” which entails a partnership between public and private entities whereby public sector data sharing on geology can be coupled with research innovations in the private sector both upstream and downstream of mineral supply.

## 2. Technology Minerals and Criticality for Green Technology

In 2010, the United States Department of Energy (DOE) commissioned the *Critical Materials Strategy* to determine “the extent to which widespread deployment of [renewable energy] technologies may increase worldwide demand for rare earth elements and certain other materials.”<sup>5</sup> Separately, the European Union (EU) created its own criticality report in 2010 (updated in 2014), evaluating 54 raw materials to discern their criticality to the EU economy.<sup>6</sup> Other nations, trade and industry associations, and scientific organizations have created similar measurement tools to evaluate the criticality of raw materials based on economic importance and identified supply risk factors. The goal of these criticality assessments has been to determine which materials are essential to the economic well-being of each nation (or bloc in the case of the EU), and to raise awareness and/or influence legislation that will further secure the national supply of these critical materials.

The Columbia Center on Sustainable Investment (CCSI) has undertaken the following assessment report with a different, two-pronged goal in mind. First, it provides an overview of which minerals should be considered critical in the next decade, and why. Fundamental innovations in renewable energy and sustainability technology, and the raw materials used to produce them, have caused increased supply and demand for certain materials and decreased supply and demand for others. Many technology minerals deemed critical just three years ago are now considered either secure or no longer important, while others considered non-critical in 2014 are now essential to the future of green technology. This report reflects the current state of criticality among the technology minerals.

Second, CCSI performed this research by focusing specifically on the *global* markets for technology minerals rather than analyzing the industry from a national or regional supply security perspective. The economic well-being of specific countries is not considered. This paper does not make suggestions on how countries can create self-reliance; rather it seeks to raise awareness across the public and private sectors of the criticality of key technology minerals in the green technology industry, put forth an analysis of the major players in the production of these minerals, and present recommendations for the future technology mineral marketplace as green technology continues to expand.

To structure this research, CCSI developed a criticality assessment focused specifically on technology minerals used in the production of solar energy, wind energy, electric vehicles (EVs), storage batteries, fuel cells, and carbon capture and sequestration. It is based on the economic importance of the technology minerals to the production of green technology, and the supply risk associated with procuring the necessary quantity of mineral to meet demand. Furthermore, it incorporates the ability for the mineral to be substituted for another material in an end product. The less feasible this substitution is, the higher criticality the technological mineral was considered to be. This assessment is informed by primary interviews with industry experts,

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<sup>5</sup> U.S. Department of Energy, *2010 Critical Materials Summary Strategy*, 2010. Available at: [https://energy.gov/sites/prod/files/edg/news/documents/Critical\\_Materials\\_Summary.pdf](https://energy.gov/sites/prod/files/edg/news/documents/Critical_Materials_Summary.pdf) (Accessed 31 Feb. 2017).

<sup>6</sup> “Report on Critical Raw Materials for the EU – Report of the Ad hoc Working Group on defining critical raw materials”. May 2014.

market analyses and projections of green technologies, and published reports that have sought to measure the relative importance of key raw materials.

Based on our defined methodology for criticality, we have identified **Lithium** and **Cobalt** as having the highest criticality and significance for the future of global green technology. We also identified two rare earth elements, **Neodymium** and **Dysprosium**; the very rare chalcogenide, **Tellurium**; and the rare member of the aluminum family, **Indium**. As essential elements of renewable technologies, these technology minerals are fundamental to the economic growth and stability of all nations, and to the success of the Paris Agreement. Securing consistent, reliable, and sustainable global access to these materials is of increasing concern and importance. Table 1 provides a summary of key characteristics of these minerals.

**Table 1:** Key Technology Minerals with Current and Future Supply Prospects and Uses

<b>Technology Mineral</b>	<b>Current Supply countries</b>	<b>New supply prospects</b>	<b>Key uses in green-tech</b>
Lithium	Chile, Argentina, Australia, China	Bolivia, Canada	Battery storage devices for smart grids
Cobalt	D.R. Congo, Canada, Philippines, Indonesia, Russia	Australia	Battery storage in EVs
Neodymium	China, Australia	Greenland, USA, Brazil, Russia	Magnets in wind power turbines
Dysprosium	China, Australia	Alaska, USA, Greenland, Commonwealth Independent States (CIS) countries including Russia.	Magnets in EVs and wind turbines
Tellurium	Japan, Russia, Sweden, USA	Greenland, CIS countries including Russia.	Solar panels
Indium	China, Republic of Korea, USA, Australia	Greenland, CIS Countries including Russia	Photovoltaic semiconductor and solar panels

Out of these critical metals identified, we will consider cobalt as a focused case study in this report, owing to the most serious set of challenges around its supply, the lack of potential alternatives in the short-term for its usage in battery technologies associated with environmentally conscious power systems. These characteristics of cobalt are explained below.

### 3. Cobalt as a Case Example of Enterprise Deficit

**Cobalt background and uses:** Cobalt is a silver brittle metal that has a high melting point and is of great value due to its adding high wear resistance and strength at high temperatures in its alloys. It is one of three naturally occurring magnetic metals (along with iron and nickel). In addition, it retains its magnetic properties at higher temperatures than any other metal: this makes cobalt the metal with the highest curie point, the point at which a metal loses its permanent magnetic properties. Cobalt was thrust into significance in industry with the creation of aluminum-nickel-cobalt (or AlNiCo) magnets in the 1940s, which were used to replace electromagnets. In the 1970s, samarium-cobalt magnets were designed, which had magnetic energy density values that were previously unachievable.<sup>7</sup> In fact, samarium-cobalt magnets were the first rare earth permanent magnets used by the original equipment manufacturer (OEM) automotive industry; they were superseded by neodymium iron boron magnets in the early 1980s due to the sudden increase then in the price of cobalt.

Cobalt has been used as a “technology enabling” element in alloys and compounds and is used in a wide range of technologies—from energy storage systems and catalytic processes to enabling greater efficiencies in the operation of gas turbines and chemical processes. It has become an integral component to powering electric vehicles, finds its uses in wind and wave generators, and is a catalyst used for the “splitting” of water in solar energy technologies.<sup>8</sup>

In recent years, cobalt demand has been rising due to its usage in rechargeable batteries. In nickel-cadmium (Ni-Cd) batteries, cobalt makes up about 1-5% of the battery by weight. Cobalt usage is about 15% by weight in nickel-metal hybrid batteries, and lithium-ion batteries contain up to 50% cobalt by weight. The use of cobalt in rechargeable batteries has grown by about 13% annually over the last ten years whereas its uses for metallurgical applications has only grown by about 3.4%. Therefore, it is safe to assume that rechargeable batteries will be the main driver for cobalt demand in the future.<sup>9</sup>

**Cobalt supply and demand:** In 2016, cobalt consumption worldwide was estimated to be around 93,950 tonnes.<sup>10</sup> The forecast of demand growth varies from outlet to outlet but all are bullish. By some estimates, cobalt demand is estimated to increase by approximately 30% by 2020, reaching 120,000 tonnes per year.<sup>11</sup> Other estimates provide that by the year 2025, the cobalt consumption will reach about 200,000 tonnes, which is a 90% increase from current levels.<sup>12</sup>

Around 17 kilograms of cobalt is needed per battery. Estimations show that half a million units of the Tesla Model 3 would require around 7,800 tons of new cobalt or roughly 6% of the current

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<sup>7</sup> Terrence Bell, “Cobalt Metal: Properties, Production, and Applications,” *The Balance*. August 19, 2017, <https://www.thebalance.com/metal-profile-cobalt-2340131> (accessed April 31, 2017).

<sup>8</sup> “Why Cobalt?,” *Cobalt Power Group*. 2016, <http://www.cobaltpowergroup.com/why-cobalt/> (accessed April 31, 2017).

<sup>9</sup> “A Brief Cobalt Primer,” *Palisade Research*. 2016, <http://palisade-research.com/wp-content/uploads/2016/10/2016.10.26-Palisade-Research-Cobalt-Final.pdf> (accessed April 8, 2017).

<sup>10</sup> “Cobalt Demand,” *Global Energy Metals Corp.*, <https://www.globalenergymetals.com/cobalt/cobalt-demand/> (accessed November 2017)

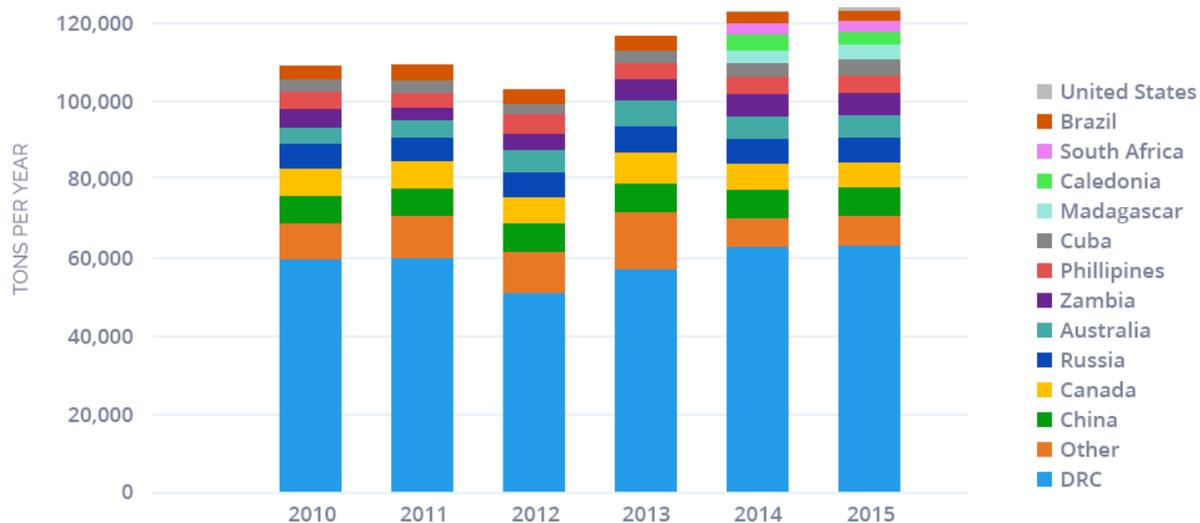
<sup>11</sup> Global Energy Metals Corp., *Cobalt Demand*

<sup>12</sup> “Specialty Minerals and Metals,” *Canaccord Genuity*, Global Equity Research, 25 May 2017

world's annual cobalt production.<sup>13</sup> Japan and South Korea are leaders in battery and cathode technology development and host the headquarters of many electronic giants and their manufacturing units.<sup>14</sup> Asia accounted for about 70.2% of the world's cobalt consumption in 2015, with China alone using 38.5% for its EV production industry.<sup>15</sup> By 2020, numbers are projected to change only slightly, with Asia forecasted to consume 71.1%, and China's demand falling slightly to 38%. As mentioned above, the demand for EVs and growth in battery technology have currently made cobalt the most critical material for storing batteries, EVs and mobile phones.<sup>16</sup>

The supply of cobalt is characterized by a few distinct aspects that contribute to its potential future shortage. For one, the Democratic Republic of Congo, which produces around 60% of the world's supply of cobalt is mired in political strife, conflict, and corruption. The bulk of the remaining cobalt is produced in places such as Russia, China and Canada (see *Figure 1*).

**Figure 1:** Global Cobalt Production



Source: LiCo Energy Metals, Inc.<sup>17</sup>

Second, cobalt, like many critical minerals, is almost entirely (90%) produced as a byproduct of other ore mining operations, and therefore fails to drive investment on its own financial merits. *Figure 2* – the wheel of metal companionability – shows that cobalt is a byproduct of copper, nickel and platinum (the host metals are shown in the inner circle and companion elements in the

<sup>13</sup> Sebastian Gandon, “No cobalt, no Tesla?,” *TechCrunch*. January , 2017, <https://techcrunch.com/2017/01/01/no-cobalt-no-tesla/> (accessed 13 Jun. 2017).

<sup>14</sup> Leo Lewis, “Japan Inc prepares to defend its lead in battery power: Technological advances give Japanese groups an advantage,” *Financial Times*, October 23, 2017. <https://www.ft.com/content/6c821340-a1d8-11e7-8d56-98a09be71849> (accessed November 2017)

<sup>15</sup> Palisade Research, *A Brief Cobalt Primer*.

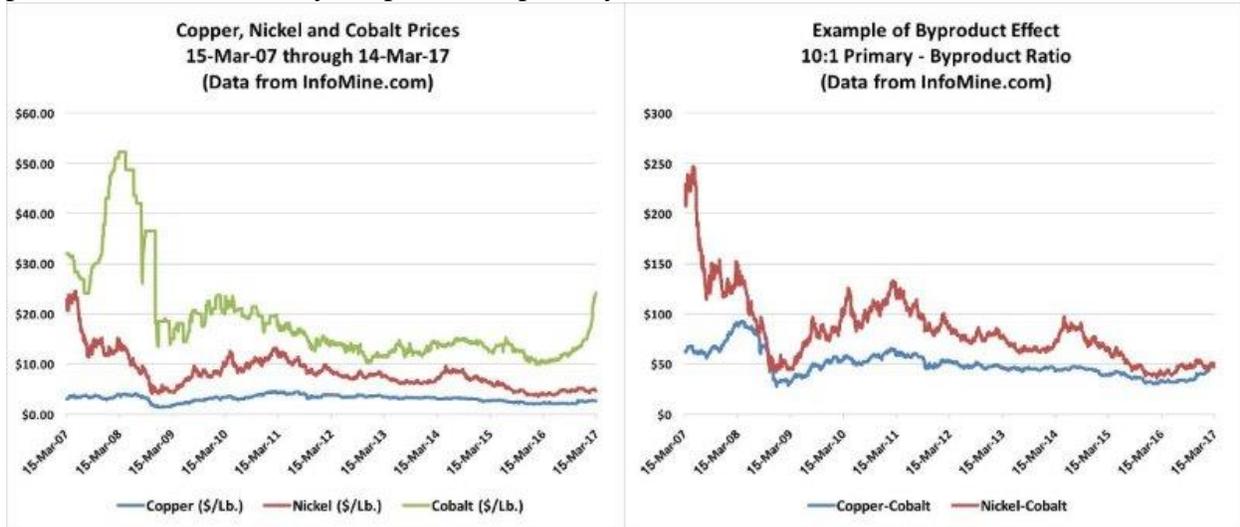
<sup>16</sup> Jack Lifton. Personal Interview. (2017)

<sup>17</sup> “The Importance of Cobalt” LiCo Energy Metals, Inc., 2017. <https://licoenergymetals.com/cobalt/>



**Figure 4** (left): Prices of Copper, Nickel and Cobalt<sup>22</sup>

**Figure 5** (right): Total revenue of a hypothetical copper and nickel mine that produces one pound of cobalt for every ten pounds of primary metal<sup>23</sup>



Up to now, cobalt, while essential to green tech, is considered a nuisance more than a business opportunity by many investors. The processing required to separate cobalt from copper or nickel is immensely complicated and expensive. Rather than invest in this technology, major mining companies prefer to expand their core business (i.e. copper or nickel mining) and focus on short-term profits.

**Box 1:** Interview with Dan Carroll, Manager, Product Development at Freeport Cobalt (Responsible for market/supply & demand analysis for refined cobalt metal and chemicals.)

**1. How does one assess the success of a potential mining project i.e. projects in the prospecting or exploration stages?**

“This is not a simple question to answer. Successful exploration relies on the interpretation of the mine site geology, geochemistry and geophysics along with other factors related to the environment (i.e. water, plant and wildlife), community relations, government regulations, etc. Each exploration project is different.”

**2. How would you describe the exploration and investing space for cobalt right now?**

“Remember, over 85-90% of the cobalt supply is a by-product of copper and nickel mining. Copper and nickel prices (supply/demand) determine how much copper and nickel is mined each year and how much cobalt by-product is brought to the market. The number of primary cobalt mines are limited because they have not been economically feasible. Primary mines must have ore bodies that allow the mine to

<sup>22</sup> Crowd - Corporate Info. Cobalt: The Weak Link In Tesla's Supply Chain | Crowd - Corporate Info, 2017, <https://zsupplychain.com/2017/04/08/cobalt-the-weak-link-in-tesla39s-supply-chain/> (accessed 11 Aug. 2017).

<sup>23</sup> Crowd - Corporate Info. Cobalt: The Weak Link In Tesla's Supply Chain | Crowd - Corporate Info, 2017.

survive operationally when cobalt prices are low. Today, the cobalt prices are high and there is a big risk for those who invest in new (potential) primary cobalt mine sites, especially when you consider it takes 3-4 years to bring the mine to operation. Most of these exploration projects assume the price of cobalt will remain at today's levels or higher than the historical average. This may be a questionable assumption.”

**3. How do you think this space will change in the near future?**

“Mining is mining. You only initiate a mining project if it is economically feasible and there is enough long term demand for the metal.”

**4. Are there regions you consider riskier when exploring and developing a cobalt resource? If so, what regions are they and why? If not, why?**

“Again, cobalt supply is mainly a by-product of copper and nickel mining. Mine sites are located in areas where environmental factors, community relations, government regulations, politics, infrastructure, logistics, manpower, available energy, etc. come into play in determining the risk of a new mine site. In 2016, approximately 55% of the mined cobalt came from copper mines in the DRC. These risk factors above come into play in the DRC. Even with these risk factors, copper mining and the supply of cobalt by-product from the DRC has been successful for stakeholders for several years.”

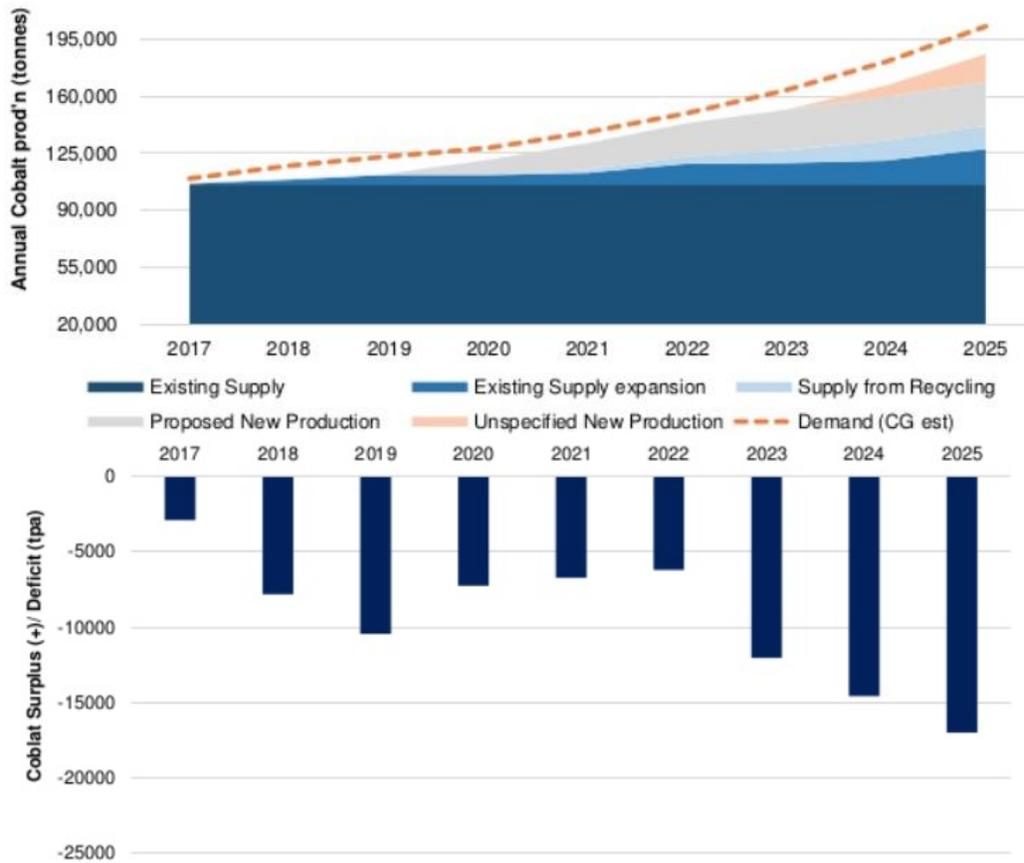
Rio Tinto, one of the largest global mining groups with operations in 35 countries across the world, exemplifies the conundrum of cobalt production. Rio Tinto mines several minerals including aluminum, copper and iron ore. For Rio Tinto, the current market for cobalt is too small, with worldwide production around 100,000 metric tons, to sink heavy investment into processing and production. In contrast, worldwide copper production in 2016 was around 19.4 million metric tons<sup>24</sup>. And even though cobalt demand is expected to grow in the future, the company would rather reinvest profits in its core business—copper—and continue to churn out profits for investors.

As a result of this situation, the likelihood of a serious disjuncture between supply and demand for cobalt based on the aforementioned needs of the battery sector is high (see Figure 6).

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<sup>24</sup> U.S. Geological Survey. *Copper*, USGS Mineral Commodity Summaries 2017.

**Figure 6:** Predictions in future cobalt supply, demand and deficit.<sup>25</sup>



Source: Canaccord Genuity estimates

Only recently, driven by the increase in price, has there been an increased push for cobalt exploration. This exploration is carried out by “junior companies” (i.e. small companies specializing in exploration and developing a mining operation). These companies often find a mineral deposit, and then work as fundraisers trying to rope financiers into investing in the development of a mining facility to reach production. Junior companies often survive through cash injections and salesmanship, but rarely become producers. In the survey below, we give a comprehensive overview of current private investment in cobalt mining.

### ***Cobalt Supply Prospects***

To assess prospects of future supply, we have used a survey to determine the current global distribution of cobalt exploration projects, noting their stage of exploration. To this end, we compiled a database of projects from which a distribution map and a selection of noteworthy projects were produced. The technology minerals sector is highly clandestine and much of the information on supply and demand is not publicly available or is incomplete. Thus to supplement the material that was available online we conducted interviews and a survey of key experts and

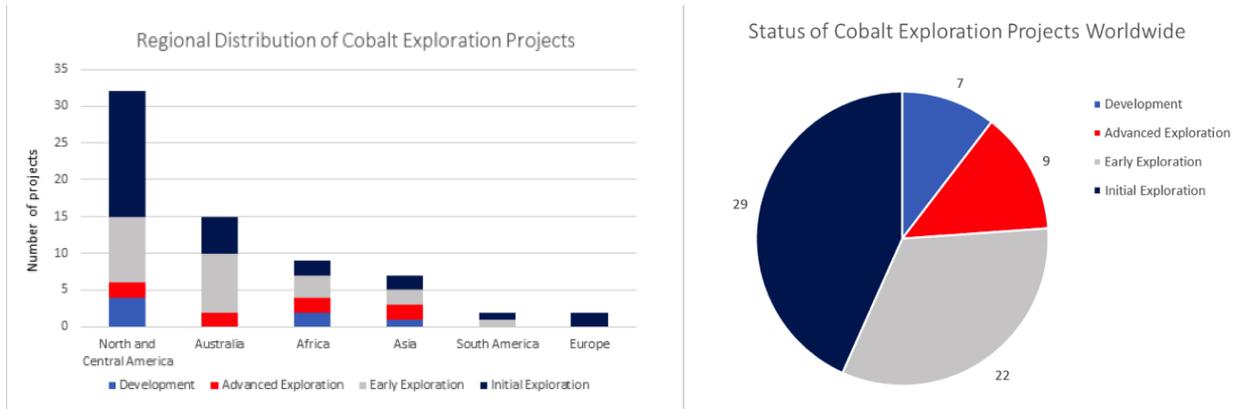
<sup>25</sup> “Specialty Minerals and Metals,” *Canaccord Genuity*, Global Equity Research, 25 May 2017

corporate interests to ensure we had the most current material for this report. Details on the methodology used for this survey can be found in *Appendix A*. The list of the cobalt companies reviewed in the survey can be accessed via an accompanying excel file to this document.

Cobalt exploration and potentially commercially viable projects are concentrated in the Democratic Republic of Congo (DRC), Canada, and Australia. Of the 67 projects surveyed, about 25% are in advanced exploration or development stages. *Figure 7* and *Figure 8* give an overview of the summary results by region and stage of development. *Figure 9* is a spatial map of the identified projects.

**Figure 7:** Distribution stage of cobalt exploration projects;

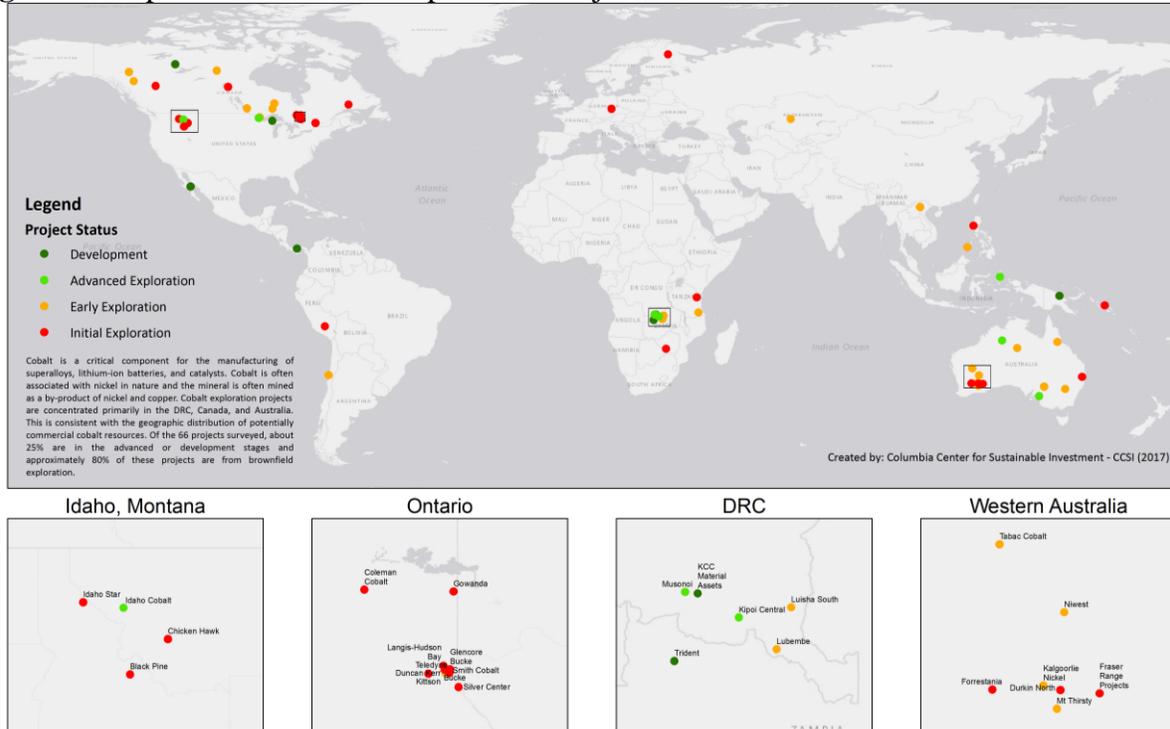
**Figure 8:** Development stage of cobalt exploration projects<sup>26</sup>



Source: Authors

<sup>26</sup> The same analysis was performed for lithium, with the results shown in the *Appendix C*.

**Figure 9: Map of Global Cobalt Exploration Projects Worldwide**



Source: Authors

Following data compilation, analysis, and reconciliation, five projects were determined to be noteworthy. This selection of projects was based on the stage of exploration, media support for project development, corroborated statements on funding for project development in news reports, analyst reports, or company presentations.

Noteworthy cobalt exploration projects include:

1. **Idaho Cobalt:** Wholly owned by eCobalt, this development-stage project was initially planned to come online in 2013, but activities were put on hold due to depressed prices. Given the more favorable price outlook in 2016, the company re-started exploration activities at the site and as of September 2017, the project is fully permitted with an updated feasibility report published on SEDAR on November 10, 2017. Following project development in 2018, the company expects to reach full production in the third quarter of 2018. The project is in Idaho, USA with a projected weighted annual cobalt production of approximately 1,000 tonnes.
2. **KCC Material Assets:** This development-stage project in the Democratic Republic of Congo (DRC) is jointly owned by Katanga Mining Ltd. (KML) (75%), La Generale des Carrieres et des Mines (GCM) and La Societe Immobiliere du Congo (SIMCO) (25%) via Kamoto Copper Company (KCC). Glencore has an 86.33% stake in the project. The project has been plagued by operational, legal, and financial hiccups over the last two years, but it remains one of the world's largest with defined reserves of about 90.9

million tonnes with average cobalt and copper grades<sup>27</sup> of 0.45% and 4.14% respectively.<sup>28</sup> The company published a feasibility report in March 2017 and hopes to reach full capacity early 2018.

3. **Clean TeQ Sunrise:** This is a development-stage Scandium-Cobalt project in New South Wales, Australia. The project is wholly owned by Clean TeQ Holdings through which China's Pengxin International Mining holds a 16.5% stake. As of April 2017, the pilot plant has processed about 20 tonnes of ore, and in August 2017 the company announced an offtake agreement with Beijing Easpring for 20% of cobalt production with the option to convert to life-of-mine supply. The state-owned Beijing Institute of Mining and Metallurgy is a major stakeholder (27%) in Beijing Easpring. Clean TeQ Holdings aims to publish a bankable feasibility study in Q1 of 2018 and commence development activities on site.<sup>29</sup>
4. **NICO:** This is a development-stage project in Canada's Northwest Territories 100% owned by Fortune Minerals Corp. The project is planned to be a vertically integrated primary cobalt mine, with a refinery near Saskatoon, Canada, to refine concentrate to battery-grade. In August 2017, the company announced an update to its 2014 feasibility report, which is currently being done by Hatch Ltd. and Micon International Ltd. and should be published in 2018. The company is currently pursuing offtake agreements and financing opportunities to develop the project.<sup>30</sup>
5. **Northmet:** This is an advanced exploration project in Minnesota, USA wholly owned by Polymet Mining Corp. The company is currently securing permits and financing for project development. While the company is in a relatively weak financial position, the company claims to be taking steps to strengthen its position. Northmet has a fairly sizable reserve base of 249 million tonnes with an average cobalt grade of 0.01%.

Other notable cobalt exploration projects set to come online in the next two years are: Weda Bay in Indonesia jointly owned by Eramet and Tsingshan group; Niwest in Australia owned by GME Resources; Cobre Panama in Panama owned by First Quantum Minerals; Kalgoorlie Nickel in Australia owned by Ardea Resources; Ban Phuc Extension in Vietnam 90% owned by Asian Mineral Resources; and Kipoi Central in the DRC 60% owned by Tiger Resources.

Given that mineral reserves data is constantly changing as new deposits are developed and/or economic conditions become more or less favorable, it is difficult to determine how many mineral reserves remain unexploited. There is also great potential to tap high concentration cobalt reserves once seabed mining becomes economically viable and socially more acceptable.<sup>31</sup> However, the US Geological Survey (USGS) provides an industry-respected baseline estimate from which we can infer results. According to the USGS cobalt mineral survey (2017), world total

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<sup>27</sup> A mineral grade is the concentration or percentage of target mineral in the ore. It is a helpful feature to evaluate the overall quality of a deposit.

<sup>28</sup> Katanga Mining Ltd. NI 43-101 Report, March, 2017: <http://www.katangamining.com/~media/Files/K/Katanga-mining-v2/operations/reportsoperational/technical-report-march-2017.pdf>

<sup>29</sup> Clean TeQ Holdings July 2017 Investor Presentation: <http://www.cleanteq.com/wp-content/uploads/2017/07/Investor-Presentation-July-2017-Final.pdf>

<sup>30</sup> Fortune Minerals Press Release, August 8, 2017: <http://www.fortuneminerals.com/news/press-releases/press-release-details/2017/Fortune-Minerals-Provides-NICO-Project-Update/default.aspx>

<sup>31</sup> International Seabed Authority, "Cobalt Rich Crusts", March 2008: <https://www.isa.org.jm/sites/default/files/files/documents/eng9.pdf>

mine production and reserves of cobalt in 2016 were approximately 123,000 and 7,000,000 tonnes respectively. Based on projected production rates of the advanced exploration projects surveyed by CCSI, an estimated amount of 10,000 – 12,000 tonnes of cobalt will be coming online in the next five years.

As discussed above, several experts forecast a strong long-term battery demand growth. Assuming cobalt production from existing mines remains constant and the addition cobalt from advanced stage projects by 2020 occurs as projected, there is going to be a significant market deficit. Figure 6 shows that this deficit persists even when taking into account increasing output from existing projects and recycling.

### ***Foreseeable Technological Breakthroughs that May Disrupt Cobalt Dependency***

In this context, the most important question is whether there are any replacement technologies that may disrupt cobalt demand. Alternative materials used to replace critical materials must be process-compatible with the materials they replace, meaning they should enable the technology to complete the same task using the same process rather than forcing the technology to be redesigned to fit the new material. As discussed above, currently, cobalt is essential to modern nickel-cadmium, nickel-metal hydride, and lithium-ion batteries used in EVs. Lithium cobalt cathodes have the highest storage capacity efficiency<sup>32</sup> and use significant amounts of cobalt. Other lithium-ion batteries that use less (or zero) cobalt face a number of challenges to industry adoption, including technical feasibility, material scarcity, separation processing capability, and replicability of the unique properties of cobalt (i.e. conductivity and heat strength).<sup>3334</sup> In Volkswagen's recent tender, for example, there is a presumption that cobalt usage per unit battery may decrease over time within an initial usage ratio of nickel:cobalt:manganese at 6:2:2 which could change to 8:1:1 noting the relative scarcity of cobalt and manganese as compared to nickel. However, EV car-makers have explained that this ratio minimizing cobalt will decrease the battery lifespans.<sup>35</sup> Moreover, nickel reserves themselves are also few and far between, being historically dominated by Russia, Canada, Indonesia, the Philippines, and New Caledonia.

Zinc-based batteries represent one of the strongest prospects being explored as a realistic alternative to cobalt-reliant options (illustrated in the table below). Nickel-zinc battery technology has existed since the early 1900s, but is currently being developed for use in EVs by a California-based company EnZinc. EnZinc's battery is expected to be market-ready by 2019.<sup>36</sup> Other companies are pursuing zinc-air battery technology, which oxidizes zinc with oxygen from the air to create low cost, high energy density batteries. Zinc-air batteries have existed for many years, but a recent breakthrough by the University of Sydney and University of Singapore enhancing the ability of zinc-air batteries to recharge effectively has made this battery potentially viable for EVs and other purposes. And because zinc is much more plentiful than cobalt,

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<sup>32</sup> Jack Lifton. Personal Interview. (2017)

<sup>33</sup> AMO Critical Materials Planning Workshop. U.S. Department of Energy. April 18 - 19, 2017.

<sup>34</sup> See Appendix D for an overview of the various battery technologies.

<sup>35</sup> Deign, "The Truth About the Cobalt Crisis: It's Not a Crisis, Yet", October 18, 2017

<sup>36</sup> Carl West, "Carmakers electric dreams depend on supplies of rare minerals", *The Guardian*. July 29, 2017.

<https://www.theguardian.com/environment/2017/jul/29/electric-cars-battery-manufacturing-cobalt-mining> (accessed October 17, 2017).

cheaper, and available in large quantities in many countries throughout the world, zinc-based battery technology is a highly attractive alternative to cobalt-reliant batteries.<sup>37</sup> This technology is however not in use currently and remains unproven. See Table 2 for a comparison of cobalt-based batteries as compared to zinc-based batteries.

**Table 2: Cobalt/Zinc Comparison Table**

<b>Material</b>	<b>Cobalt</b> (in Nickel-cadmium batteries, Nickel-metal hybrid batteries, and Lithium-ion batteries)	<b>Zinc</b> (in Zinc-air batteries and Nickel-zinc batteries)
<b>Properties (Pro)</b>	<ul style="list-style-type: none"> <li>▪ High strength</li> <li>▪ High magnetic strength</li> <li>▪ High energy density</li> </ul>	<ul style="list-style-type: none"> <li>▪ High energy density</li> <li>▪ Accessibility and diversity of source supply</li> <li>▪ Inexpensive</li> <li>▪ No fire risk</li> <li>▪ Lighter weight than Li-ion battery</li> </ul>
<b>Properties (Con)</b>	<ul style="list-style-type: none"> <li>▪ Relatively low discharge current</li> <li>▪ Fire risk</li> <li>▪ Uncertain future supply</li> </ul>	<ul style="list-style-type: none"> <li>▪ Recharging/discharging concerns</li> <li>▪ Unproven technology at mass-market</li> </ul>
<b>Requirements and concerns with Market Entry</b>	<ul style="list-style-type: none"> <li>▪ Ethical supply chain concerns</li> <li>▪ Supply quantity/availability</li> <li>▪ Increasing costs in the future</li> </ul>	<ul style="list-style-type: none"> <li>▪ High availability</li> <li>▪ Low price</li> <li>▪ Stable supply</li> <li>▪ Unproven technology</li> </ul>
<b>Likelihood of Adoption/Use</b>	<ul style="list-style-type: none"> <li>▪ High (currently used)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Medium/High</li> </ul>

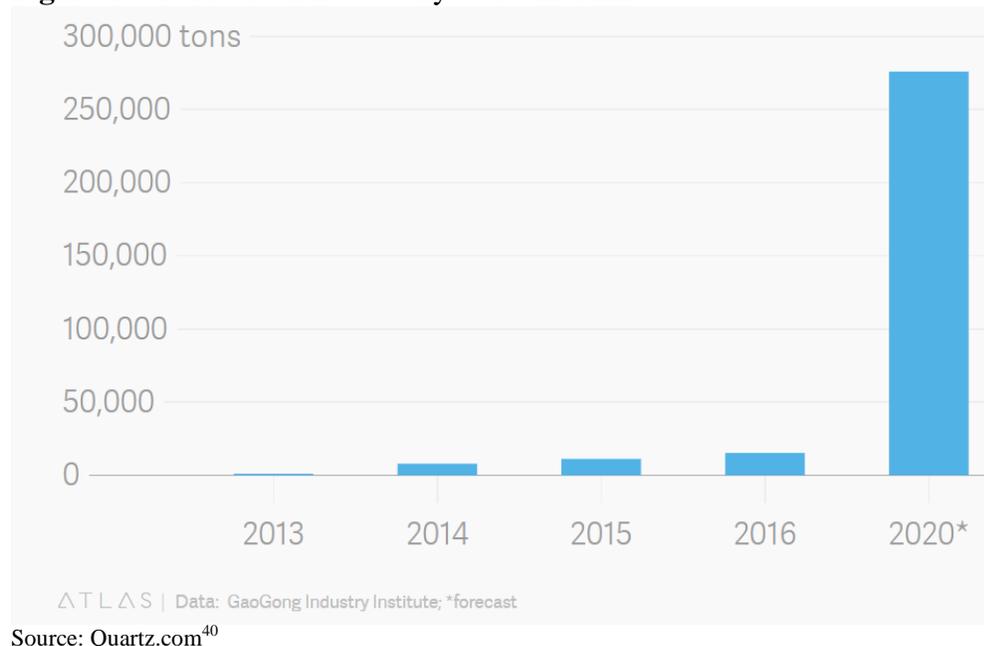
Recycling provides another alternative helping to reduce the dependence of cobalt in batteries. Recycling and repurposing cobalt increases the amount of material available for use, which increases global supply and reduces immediate need for alternative materials and technologies. Currently, cobalt is salvaged from batteries through multiple highly-complex chemical processes which include hazardous materials, extreme temperatures, and high labor intensity. Because processes are not environmentally friendly, strict government regulation is also a hurdle in many countries. In addition, cobalt is often used in small quantities as part of intricate technology products, making it difficult to recover. To date, cobalt recycling is not yet a profitable business model on a large scale. However, because cobalt does not break down during its use, it is fully recyclable. If processing technologies become less expensive cobalt recycling could become economically viable and a consistent source of cobalt for the global market. Given China's early progress on the circular economy<sup>38</sup> and its looming exponential need to recycle battery out of its nascent but booming electric vehicle market (see figure 10), China might hold the promise of

<sup>37</sup> West, "Carmakers electric dreams depend on supplies of rare minerals", July 29, 2017

<sup>38</sup> For complete information on the development and status of the circular economy in China across the economy see: Qi, Jianguo, Jingxing Zhao, Wenjun Li, Xushu Peng, Bin Wu, and Hong Wang. *Development of circular economy in China*. Springer Singapore, 2016.

cobalt recycling technologies.<sup>39</sup>

**Figure 10:** Forecast of EV battery waste in China



Thus, notwithstanding the evolution of battery technology, the complete replacement or eradication of the use of cobalt seems unlikely. There is likely to be some amount of substitution, but the effects on the demand for cobalt are not anticipated to be significant due to the mechanics and the chemistry of batteries.<sup>41</sup> Moreover, while recycling technologies are progressing, they do not eliminate the need to mine additional cobalt supplies for the time being. This working assumption is guiding the central argument of this paper: there is an urgent need to come up with a public private partnership to enable responsible mining of cobalt at a high enough scale to satisfy the needs of green technologies.

## 4. Investment Solutions Moving Forward

Given the supply constraints and that no foreseeable technological breakthrough will significantly reduce global dependency on cobalt, companies are choosing to enter into partnerships and/or purchase ownership in foreign mining operations as a way to secure access to critical materials. Chinese companies recently purchased a controlling stake in the world's largest cobalt mine located in the Democratic Republic of Congo, (and have also entered into agreements in South America to gain access to the lithium reserves there). Germany has done the

<sup>39</sup> Zeng, X. and Li, J., 2015. On the sustainability of cobalt utilization in China. *Resources, Conservation and Recycling*, 104, pp.12-18.

<sup>40</sup> Echo Huang, "China's booming electric vehicle market is about to run into a mountain of battery waste," Quartz.com, September 28, 2017

<sup>41</sup> Battery University, Summary Table of Future Batteries, July 21, 2016, [http://batteryuniversity.com/learn/article/bu\\_218\\_summary\\_table\\_of\\_future\\_batteries](http://batteryuniversity.com/learn/article/bu_218_summary_table_of_future_batteries) (accessed November, 2017)

same in Bolivia, using foreign direct investment as a tool to secure its supply of critical materials needed for its green technology growth.<sup>42</sup> As discussed above, American EV company Tesla has claimed it will source 100% of its cobalt from North America, but skeptics suggest that existing cobalt production from this region of the world will not be enough to supply Tesla's ambitious rollout of 500,000 EVs annually by 2018.<sup>43</sup> The company may soon be forced to renege on this promise and partner with other cobalt miners, or find other ways to obtain cobalt. In September 2017, Volkswagen announced a tendering process for a \$59 billion contract to secure enough cobalt supplies to meet the demand of 150 gigawatt-hours of lithium-ion battery storage by 2025. In October 2017, the firm announced a failure to find a supplier that would guarantee more than four years of cobalt at a fixed price.<sup>44</sup> These examples highlight the need for a more systematic approach to address cobalt supply going forward.

### ***Smart Mineral Enterprise Development for Green Technologies***

As this report has shown, there is a need for a more efficient mechanism for linking triggers of mineral demand with sources of supply. Given the structural constraints in the mining industry and the delays from mine discovery to market delivery of products, a smarter system of mineral enterprise development is needed. We use the word “smart” analogously to how it is used in the context of smart electricity grids which are dynamic systems allowing for rapid feedback loops between demand centers to a devolved set of supply sources. Such a system is geared towards greater resilience and minimal wastage. For smart electricity grids, computer algorithms and digital interfaces can control the flow of information to maximize efficiency. For a smart mineral enterprise development system, there is need for an organizational structure to manage this flow of information.

Without such a “smart” approach, there is major risk associated with the possibility that one country can flood the market and drop prices of critical minerals, running new and junior companies out of business. For example, Chinese industry is organizing its supply chains in a way to ensure that it does not face a shortage of the supply of raw materials. Since China is a centrally planned economy, its strength lies in its government's push for investments in mining both domestically and overseas. China has identified a few critical raw materials to focus on, and uses a hybrid financing-and-government framework to ensure their ample supply. It also has a range of corporate investment vehicles which include buying minority and majority stakes in foreign mining companies from state owned enterprises. All these approaches are ultimately geared towards assuring more direct and efficient connectivity between supply and demand centers.<sup>45</sup>

Resource poor, but high income manufacturing countries that have invested strategically through

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<sup>42</sup> Alex Emery, “Germany's K-Utec signs Bolivian lithium plant contract”, *BNAmericas*, August 18, 2015, <https://www.bnamericas.com/en/news/mining/germanys-k-utec-signs-bolivian-lithium-plant-contract1/> (accessed March 15, 2017).

<sup>43</sup> Gandon, “No cobalt, no Tesla?” January 2017

<sup>44</sup> Jason Deign, “The Truth About the Cobalt Crisis: It's Not a Crisis, Yet”, *Green Tech Media*, October 18, 2017, <https://www.greentechmedia.com/amp/article/the-truth-about-the-cobalt-crisis>. (accessed October 25, 2017)

<sup>45</sup> Jill Shankelman. *Chinese Oil and Mining Companies and the Governance of Resource Wealth*. Washington DC: Woodrow Wilson Center, 2009.

a public-private partnership model in mineral supply chains most notably are Japan and Republic of Korea. Both these countries have engaged public sector entities that assist with mineral supply assurance. In Japan there are two organizations which work closely to ensure mineral supply - one from the geological and scientific side (the Japanese Oil, Gas and Metals National Corporation or JOGMEC) and the other on the finance side (The Japanese Bank for International Cooperation). In the Korean case, there is a state-owned exploration and development company called Korea Resources Corporation (KORES) which has in its stated mission the support of the country's industrial consortia or "chaebols."<sup>46</sup>

In the aforementioned Asian countries, the government works with the financial sector (or in the case of China, controls and dictates actions of the financial sector) to facilitate and ensure capital investment to the technology metals industry.<sup>47</sup> This, in turn, enables increased production by the industry to achieve adequate supply of these critical materials. As a result of these PPPs, the majority of the world's technology metals and materials are produced by entities owned or operated for the benefit of these Asian countries.

Meanwhile, the United States, Canadian, and EU governments do not directly invest in mining or have public-private partnership frameworks in place for such investment. Instead, they rely largely on the private sector to invest unilaterally, based on the belief that the power of the free market will balance the supply and demand needs of their industry. However, the dependence of modern economic systems on critical metals requires us to consider a hybrid approach which combines the innovative impulse of private enterprise with the strategic long-term view that public sector institutions can provide. While the United States has several National Labs and has also supported organizations such as the Critical Materials Institute (CMI) through university and private sector partnerships, the mandate of such efforts is largely limited to research rather than project development.

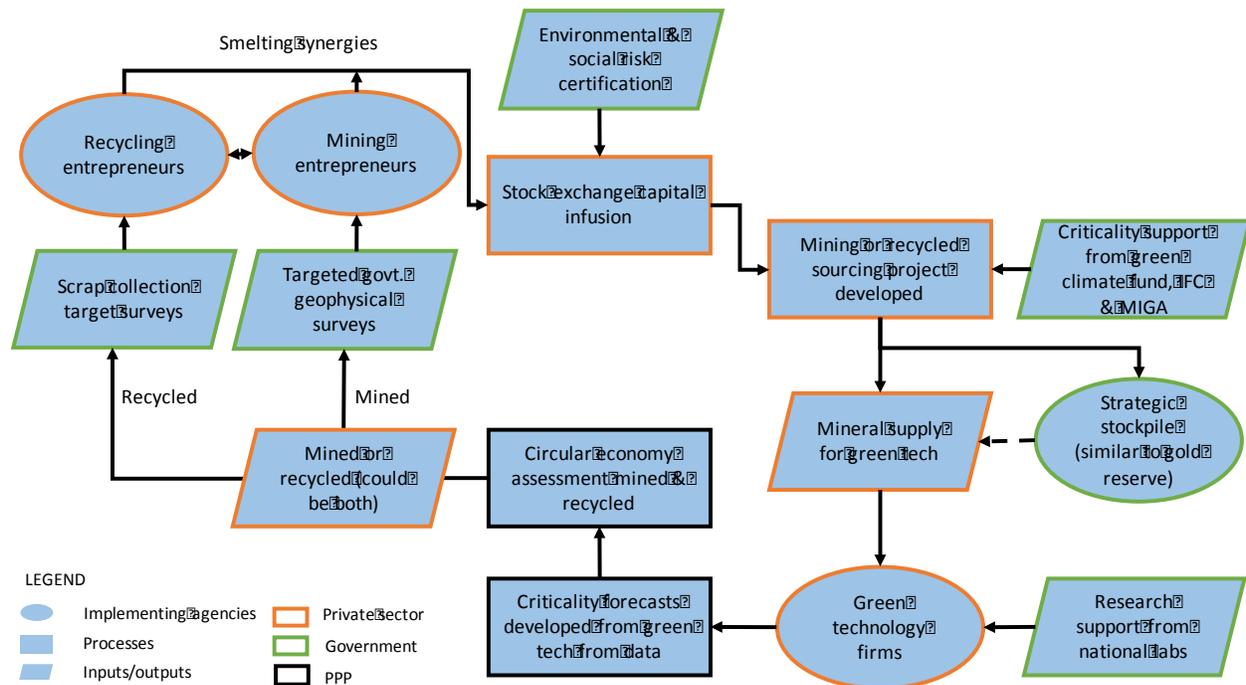
*Figure 11* shows our suggested hybrid or “Smart Mineral Enterprise Development” approach, which can be applied to critical metals planning. The diagram uses flowchart nomenclature with inputs, outputs, decision and process nodes.

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<sup>46</sup> Margaret Armstrong, M., D'Arrigo Rafael, Petter Carlos, and Galli Alain 2016. “How Resource-Poor Countries in Asia Are Securing Stable Long-Term Reserves: Comparing Japan's and South Korea's Approaches.” *Resources Policy* 47: 51–60. <https://doi.org/10.1016/j.resourpol.2015.12.001>.

<sup>47</sup> Shenzhen Jihngang Deep Sea Minerals Technology Development Co., Ltd. Company Profile. 2017

**Figure 11: The Smart Mineral Enterprise Development Framework (SMED)**



The diagram lays out the government and private sector roles as highlighted by the green and orange outlines of the action boxes. The Public-Private Partnerships (PPP), which constitute the backbone of SMED, are noted in black outline. Material service delivery is considered from both mined and recycled sources. The calibration of supply (mined and recycled firm sources) and demand (green technology firms) is maintained through a stockpile. Core to the “smart” element of SMED is the system of communication between supply and demand centers as well as the research and development community. The timing of the signals between technological demand and supply constraints can be much better coordinated to induce entrepreneurial activity in a more proactive way than is usually the case in ad hoc entrepreneurial systems. The SMED approach also considers environmental and social risk safeguards linked to capital markets and stock exchanges to ensure that a more sustainable outcome from junior high risk/high reward firms can also be maintained. This can be undertaken through existing certification schemes that ensure that environmental and social risks are not compromised in the rush to encourage entrepreneurship.

The SMED approach can be actualized through a range of existing organizations that are assigned specific tasks within the framework with the goal to connect green technology firms with mineral enterprises through a series of efficiency and risk management steps. We have developed this framework with the anticipation of a rise in recycling technologies and noted the importance of a circular economy approach to resource planning. A strategic stockpile of key metals that is managed at a global scale through international agreement would also allow for greater resilience in the system when there is over supply of some metals that can be saved for

future shortages. During the Cold War, countries regularly kept metal stockpiles. This has been studied and investigated by the U.S. National Academy of Sciences.<sup>48</sup>

The Intergovernmental Forum on Mining Metals and Sustainable Development (IGF) could potentially be a coordinating body for this effort. This forum, which was originally motivated by the Canadian government to improve governance of mining countries in order to minimize risk for Canadian miners, now has a membership of over 60 mining countries. It could be further empowered through an international protocol which allows for the sharing of valuable geological and scrap availability data. Existing certification systems such as those developed by the OECD could be harnessed for the environmental and social risk certification component of the framework (see *Box 2*).

**Box 2:** Responsible Cobalt Initiative for DRC

The Chinese Chamber of Commerce for Metals, Minerals & Chemicals Importers & Exporters (CCCMC) in partnership and cooperation with the Organization for Economic Cooperation and Development (OECD) Due Diligence Guidance, launched the Responsible Cobalt Initiative (RCI) that provides member companies with steps to take to identify and address potential adverse impacts associated with their activities or relationships. RCI was launched in response to human rights abuses and egregious health and safety conditions in some artisanal cobalt mines in the Democratic Republic of the Congo. As a priority, the RCI intends to tackle issues of the worst forms of child labor.

Launched in November 2016, the RCI strives to bring about a collective response to social and environmental risks in the cobalt supply chain. The initiative promotes the responsible sourcing and use of cobalt in all forms and aims to improve the lives of children and adults who mine cobalt in the Democratic Republic of the Congo.

Members of the initiative pledge to follow OECD Due Diligence Guidance on Responsible Supply Chains of Minerals from Conflict-Affected and High-Risk Areas, which calls for companies to trace how cobalt is being extracted, transported, manufactured and sold. The OECD provides clear, practical guidance for companies to ensure they do not contribute to conflict or human rights abuses through their mining activities through a five-step risk-based due diligence process. This applies to all companies in the mineral supply chain that could potentially use minerals from conflict affected or high-risk areas, including pre-production exploration activities. Its members currently include Apple Inc., Beijing Easpring Material Technology Co.,Ltd., HP Inc., Huawei Device Co.,Ltd., L&F, Samsung SDI, Sony Corporation, Tianjin B&M Science and Technology Joint-Stock Co., Ltd., Zhejiang Huayou Cobalt Co., Ltd., and First Cobalt Corp. Companies will work together, in coordination with the Government of the Democratic Republic of the Congo, to develop and begin implementation of an action plan during the next 12 months.<sup>49</sup>

<sup>48</sup> Refer to National Research Council, *Managing Materials for a Twenty First Century Military*. Washington DC; National Academies Press (2008). Chapter available online: <https://www.nap.edu/read/12028/chapter/10>

<sup>49</sup> Chinese Chamber of Commerce for Metals, Minerals & Chemicals (CCCMC) *Importers & Exporters (2017). Facing challenges, sharing responsibility, joining hands and achieving win-win.* <http://www.cccmc.org.cn/docs/2016-11/20161121141502674021.pdf> (accessed 2 Jun. 2017); Anon, (2017). <https://www.juniorminingnetwork.com/junior-miner->

A prototype for such a public-private partnership for more effective interface between mineral suppliers and manufacturers of batteries has recently been established by the World Economic Forum (*Box 3*). *Box 3* also features the effort of the Cobalt Institute, a non-profit trade institution seeking more coordination, knowledge and sustainability in the cobalt industry.

**Box 3: Global Battery Alliance Initiative: An Example of a Public-Private Enterprise Effort; and The Cobalt Institute: An Example Of Coordination Mechanism Across The Cobalt Value Chain**

**The Global Battery Alliance Initiative** is a new initiative that was publicly launched in September 2017. The alliance was formed with the vision to develop an inclusive, innovative and sustainable battery value chain to power the Fourth Industrial Revolution. Its mission is to catalyze, accelerate and scale up public-private action to achieve this vision. The main objectives are to: 1) Mobilize a global alliance of principals supporting the vision, 2) Catalyze action towards specific pillars of work under the alliance that addresses social, environmental and innovation challenges, and 3) Build a global movement to replicate these learnings in other global value chains.

The working model proposed by the alliance is one of a global catalyst and accelerator.

- The alliance accelerates or catalyzes actions towards specific pillars of work.
- This action is facilitated through partnerships on a country or cross-country level.
- The partnerships involve and leverage several critical local stakeholders.
- Comparable initiatives developed by the World Economic Forum include the Tropical Forest Alliance 2020, the Water Resources Group 2030, and the Grow Africa Partnership

A few of the emerging areas the alliance seeks to work on are:

- Responsible sourcing of raw materials, addressing challenges such as child labour, health and safety hazards in the battery value chain.
- Moving towards a circular economy for batteries, to address the principal challenges of battery recycling and life cycle sustainability across all chemistries and regions.
- Unlocking innovation across the value chain, for example by using emerging technologies (e.g. blockchain) to support a more traceable, smart and innovative value chain.
- Working towards supportive policy principles and approaches across relevant countries, country groupings (e.g. G20) and regions

**The Cobalt Institute**

The Cobalt Institute (CI) is a non-profit trade association composed of producers, users, recyclers, and traders of cobalt, promoting the sustainable and responsible production and use of cobalt. They act as a knowledge centre for governments, agencies, industry, the media and the public, and represent the voice of the cobalt industry on cobalt related health, safety, and environmental issues. They promote co-operation between members, especially on issues of the environment and human health, and provide a mechanism for the development of independent

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[news/press-releases/first-cobalt/33478-first-cobalt-corp-adopts-responsible-cobalt-initiative-for-drc-projects.html](https://www.weforum.org/news/press-releases/first-cobalt/33478-first-cobalt-corp-adopts-responsible-cobalt-initiative-for-drc-projects.html) (accessed 18 Jun. 2017).

information concerning the resources, production and safe use of cobalt.<sup>50</sup>

### ***The International Legal Framework and SMED***

The international legal framework could also support the implementation of SMED in different ways. International trade and investments are governed by the World Trade Organization (WTO), Free Trade Agreements (FTAs), and Bilateral and Multilateral Investment Treaties (BITs). This framework supersedes the domestic legal frameworks. Following intense treaty-signing activity during the 1990s, the number of investment treaties and agreements jumped from under 400 in 1990 to over 3,300 in 2015.<sup>51</sup> There are several ways in which the framework could be adapted to support the implementation of SMED.

#### Trade:

There is an ongoing negotiation at the WTO to eliminate tariffs for “environmental goods.” In January 2016, the Asia-Pacific Economic Cooperation (APEC) promoting free trade in Asia-Pacific took the lead and signed such an agreement that includes a list of 54 goods linked to renewable energies and energy efficiencies.<sup>52</sup> If critical minerals qualify as environmental goods, WTO and related free trade agreements would ensure that trade barriers do not stand as an obstacle to the implementation of SMED. Moreover, WTO has been criticized for banning green subsidies as it does for any specific subsidy.<sup>53</sup> There are suggestions that these subsidies should be “non-actionable” (not subject to countervailing measures) given their potential to contribute to the improvement of public welfare.<sup>54</sup> In case the WTO reinstates green subsidies as being non-actionable, these should encompass those involved in the implementation of SMED.

Another recent development that could encompass green technology mineral promotion and information exchange among trading partners to support SMED is Europe’s chapter on Trade and Sustainable Development (TSD) that the EU intends to include in its FTAs. A recent FTA signed with Singapore includes the following relevant articles:

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<sup>50</sup> Adapted from the Cobalt Institute website: <https://www.cobaltinstitute.org/>

<sup>51</sup> Jesse Coleman and Lise Johnson, “International Investment Law and the Extractive Industries Sector,” *Columbia Center on Sustainable Investment*. January 12, 2016. [http://ccsi.columbia.edu/files/2016/01/2016-01-12\\_Investment-Law-and-Extractives\\_Briefing-Note\\_1.pdf](http://ccsi.columbia.edu/files/2016/01/2016-01-12_Investment-Law-and-Extractives_Briefing-Note_1.pdf). (accessed November 5, 2017)

<sup>52</sup> Asia Pacific Economic Cooperation website, APEC Cuts Environmental Goods Tariffs – Singapore, 28 January 2016, available at: [https://www.apec.org/Press/News-Releases/2016/0128\\_EG](https://www.apec.org/Press/News-Releases/2016/0128_EG) (accessed November 5, 2017)

<sup>53</sup> According to the WTO a subsidy is every government intervention that grants benefits to specific recipients rather than the public at large. Subsidies are either prohibited (export and local content subsidies), or ‘actionable’. A third category that included environmental subsidies was classified as ‘non-actionable’ over a five-year period up to 1 January 2000 (Art. 31 of the Agreement on Subsidies and Countervailing Measures (SCM)). Actionable subsidies are ‘countervailable’, either through unilateral or through multilateral action (dispute before a Panel). The agreement on non-actionable subsidies was not renewed post 2000. (Source: Mavroidis, Petros C., and De Melo, Jaime, “Climate Change Policies and the WTO: Greening the GATT Revisited”, pp. 225-238 in Scott Barrett, Carlo Carraro, and Jaime de Melo (eds.), *Towards a Workable and Effective Climate Regime*, CEPR and FERDI: London, UK. 2015)

<sup>54</sup> Petros C. Mavroidis and Jaime De Melo, “Climate Change Policies and the WTO: Greening the GATT Revisited”, pp. 225-238 in Scott Barrett, Carlo Carraro, and Jaime de Melo (eds.), *Towards a Workable and Effective Climate Regime*, CEPR and FERDI: London, UK. 2015

*Article 13.1: ...“The Parties recognise that economic development, social development and environmental protection are interdependent and mutually reinforcing components of sustainable development. They underline the benefit of cooperation on trade-related social and environmental issues as part of a global approach to trade and sustainable development.”<sup>55</sup> ...,*

*and*

*Article 13.10: “Cooperation on Environmental Aspects in the Context of Trade and Sustainable Development:*

*The Parties recognise the importance of working together on trade-related aspects of environmental policies in order to achieve the objectives of this Agreement. The Parties may initiate cooperative activities of mutual benefit in areas including but not limited to:*

- (a) exchange of views on the positive and negative impacts of this Agreement on environmental aspects of sustainable development and ways to enhance, prevent or mitigate them, taking into account sustainability impact assessments carried out by either or both Parties;*
- (b) cooperation in international fora addressing environmental aspects of trade and sustainable development, including in particular at the WTO, under the United Nations Environment Programme and under multilateral environmental agreements;*
- (c) cooperation with a view to promoting the ratification and effective implementation of multilateral environmental agreements with relevance to trade;*
- (d) information exchange and cooperation on private and public certification and labelling schemes including eco-labelling, and green public procurement;*
- (e) exchange of views on the trade impact of environmental regulations, norms and standards;*
- (f) cooperation on trade-related aspects of the current and future international climate change regime, including ways to address adverse effects of trade on climate, as well as means to promote low-carbon technologies and energy efficiency;*
- (g) cooperation on trade related aspects of multilateral environmental agreements, including customs cooperation;*
- (h) sustainable forest management to encourage effective measures for certification of sustainably produced timber;*
- (i) exchange of views on the relationship between multilateral environmental agreements and international trade rules;*
- (j) exchange of views on the liberalisation of environmental goods and services; and*
- (k) exchange of views regarding conservation and management of the living marine*

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<sup>55</sup> Singapore- Europe free trade agreement, chapter thirteen trade and sustainable development.  
[http://trade.ec.europa.eu/doclib/docs/2013/september/tradoc\\_151766.pdf](http://trade.ec.europa.eu/doclib/docs/2013/september/tradoc_151766.pdf). (accessed November 5 2017).

*resources.*”<sup>56</sup>

Existing TSD chapters in EU trade agreements include a comprehensive set of binding provisions, rooted in multilateral standards, notably the International Labour Organisation (ILO) conventions and Multilateral Environmental Agreements (MEAs). The institutional structure operationalizing EU TSD chapters grants civil society a key advisory role. Civil society groups participate in the monitoring of the FTA implementation through platforms on the side of each FTA partner and through Joint Platforms bringing together civil society organisations from both FTA partners. TSD provisions are binding and subject to a different dispute settlement mechanism, as it grants an explicit role to civil society and international organizations. This mechanism does not include sanctions and enforcement has been limited, which is an area that is currently being reviewed.<sup>57</sup> Such mechanism could provide a useful framework for countries to cooperate in order to promote the implementation of SMED at the international level.

#### Investment:

BITs could also be adapted to support the implementation of SMED. BITs are signed between states and impose obligations and restrictions on countries regarding their treatment of foreign investors. BITs protect investors from government action that would harm the right and interests of foreign investors that seek to invest or who have invested in a host country. When a state signs a treaty, “a state’s ability to adopt, revise, repeal, and enforce laws and policies that affect foreign investors or investments is made subject to the state’s obligations under that treaty.”<sup>58</sup> A breach of these obligations due to the promulgation of a law that would negatively affect an investment can trigger an arbitration procedure whereby a foreign investor covered by the BIT takes the state to arbitration in an international tribunal. A BIT supporting critical mineral development could include a chapter focused on critical minerals that makes the investment conditional on the implementation of a specified SMED process that allocates the implementation responsibility to the state. Furthermore, the chapter could include protections for the investor such as uncompensated nationalization, denial of justice and export restrictions. This would be particularly relevant to the implementation of SMED at the global level since export restrictions could disrupt the supply of critical minerals.

It should be noted BITs have often been used abusively by foreign investors that have been taking governments to court for imposing environmental and social protection mechanisms. Many of these investor-state disputes are related to extractive industry investments (E.g.<sup>59</sup>

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<sup>56</sup> Singapore- Europe Free Trade Agreement, Chapter Thirteen Trade and Sustainable Development (Article 13.10)

<sup>57</sup> Non-paper of the Commission services. Trade and Sustainable Development (TSD) chapters in EU Free Trade Agreements (FTAs). [http://trade.ec.europa.eu/doclib/docs/2017/july/tradoc\\_155686.pdf](http://trade.ec.europa.eu/doclib/docs/2017/july/tradoc_155686.pdf). (accessed November 5 2017).

<sup>58</sup> Coleman and Johnson, “International Investment Law and the Extractive Industries Sector”. Columbia Center on Sustainable Investment. January 12, 2016.

<sup>59</sup> Among the other cases concerning investments in the extractive industries sector, the following types of government actions have been challenged by investors: – Termination of contracts with investors (e.g. Occidental Petroleum Corporation and Occidental Exploration and Production Company v. Ecuador 2012); – Revocation/ termination of permits authorizing investors’ operations (e.g. The Renco Group, Inc. v. Peru; Gold Reserve Inc. v. Venezuela); – Decisions not to grant permits (e.g. Pac Rim Cayman LLC v. El Salvador; Clayton and Bilcon of Delaware Inc. v. Canada); – Changes to fiscal regimes (including changes in interpretations of and enforcement strategies for existing laws and regulations) (e.g. Occidental Exploration and Production Company v. Ecuador 2004; Perenco Ecuador Limited v. Ecuador); – Requirements to purchase local goods and services/invest in

Glamis Gold, Ltd. vs United States and Lone Pine Resources Inc. vs Canada for more stringent environmental regulations”)<sup>60</sup>.

As such, much care should be taken to draft SMED related investor protection clauses and governments should “carefully define the scope and content of these agreements in order to protect their ability to regulate in the public interest.”<sup>61</sup> Thus suggesting how BITs could be used in favor of SMED is a delicate exercise. If investments in critical minerals ought to be protected by BITs in particular, the state’s right to legislate to limit the social and environmental harm of an investment in critical minerals should be equally protected. The right to arbitration should not be granted if a foreign investor is in breach of the IFC performance standards for instance. To further limit the potential for abuse of BITs by investors, it is recommended that the dispute settlement can only be triggered by a state complaint, as is currently the case under the WTO and trade chapters of the FTAs.

Beyond the existing legal framework governing investment and trade, a recent development in the field of international environmental governance could be used for implementing the SMED approach: in June 2017 world leaders agreed to collaborate on putting forth a Global Pact for the Environment. The proposal foresees a universal, international umbrella binding document synthesizing and harmonizing the principles outlined in the Rio Declaration, the Earth Charter, the World Charter for Nature, and other instruments shaping environmental governance.<sup>62</sup> This Global Pact for the Environment could promote the principles of SMED while ensuring that any critical mineral exploitation would comply with the international environmental and social standards.

## 6. Conclusion and Further Research

While there has been increasing focus on critical materials for green technologies, the relationship between public and private sectors to spur appropriate investments to meet the lurking supply crunch has thus far been neglected. Using the example of cobalt, which is a key input to a variety of green technology products with limited substitutability, we show that the private sector, mainly composed of mining entrepreneurs, is currently not investing sufficiently in exploration and development to bring enough projects on stream to satisfy the demand necessary for the energy transition. This is because the incentive mechanisms are not supporting timely private sector investments in that space. Given the public good nature of green technologies, there is a strong case for government intervention to support the transition. While in many countries policies are in place to support and subsidize the roll-out of renewable

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research and development (e.g., *Mobil Investments Canada, Inc. v. Canada*)”, etc. (source: Coleman and Johnson, “International Investment Law and the Extractive Industries Sector”. Columbia Center on Sustainable Investment. January 12, 2016)

<sup>60</sup> Coleman and Johnson, “International Investment Law and the Extractive Industries Sector”. Columbia Center on Sustainable Investment. January 12, 2016.

<sup>61</sup> Coleman and Johnson, “International Investment Law and the Extractive Industries Sector”. Columbia Center on Sustainable Investment. January 12, 2016.

<sup>62</sup> “French initiative to create global environment pact deserves support, says Secretary-General”. *UN News Centre*. 17, September, 2017, Available at <http://www.un.org/sustainabledevelopment/blog/2017/09/french-initiative-to-create-global-environment-pact-deserves-support-says-secretary-general/>. (accessed November 2017)

energies and green transport solutions, these interventions will fall short if not paired with policies that help guarantee the supply of key inputs, such as cobalt. Several Asian countries are utilizing PPP frameworks in critical materials mining with great success, but no such system exists in the US, within the EU, or at an international level. We therefore propose a framework which enables the public sector and research community to play an essential role in facilitating an efficient and “smart” system for managing enterprise development, which mimics the efficiency of an eponymous “Smart Grid” system for energy. Stock exchanges, which host small mining and recycling companies, must also be more actively engaged in this process to monitor any environmental and social risks of listed companies.

Forecasts of supply and demand are highly malleable and more refined models are needed to link technological developments, geological discoveries and consumer choice. This should be an area of further research governments should be more involved in primary data recording and acquisition. So far the criticality of minerals is being highlighted at national or regional levels, similar to the latest list of critical metals published by the U.S. Geological Survey on February 16, 2018.<sup>63</sup> While such lists are useful, there is a need for a more global approach to this phenomenon to address global environmental concerns such as climate change. The international governance system could help with the promotion of investments in critical minerals. While we are conscious of continuous alternative material research in all criticality cases, our broader goal is the development of a system that supports any new material needs of ever-changing technologies that supports the energy transition. Ultimately, international treaties such as the Paris Agreement, which set targets for particular environmental goals, will need to pay more attention to material needs and mechanisms for ensuring any embedded targets can be met.

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<sup>63</sup> Draft List of Critical Minerals – Federal Register, February 16, 2018:  
<https://www.federalregister.gov/documents/2018/02/16/2018-03219/draft-list-of-critical-minerals>

## Appendix A: Survey Methodology

### *Data compilation*

We drew up a list of publicly-traded mining and exploration companies on stock exchanges in Canada, Australia, USA, Europe, Tokyo, and Hong Kong. These exchanges were selected for the similarity in their listing rules to allow for greater uniformity in the sort of company data collected. Also, given the deposit types of naturally occurring cobalt compounds, the selection was constrained to companies with some combination of nickel, copper, and occasionally gold as the primary mineral, with secondary targets for cobalt.

Next, we collected technical data on cobalt projects. This data comprised of: the size and location of the mineral resource and reserve; the grade or concentration of the target mineral; and the status of exploration at the project site. The sources for this data include NI 43-101 technical reports, announcements on the Australian Stock Exchange (ASX), news and media reports, and descriptions on company websites. The survey required technical data that is compliant with JORC 2012 and NI 43-101 standards as a minimum (see box 4 for more information on the mineral investment process). It was important that all the information collected on the companies and projects are publicly available to allow for easier verification and data reconciliation. In total, 67 projects were surveyed. The database structure used for the survey was:

1. Exchange (name of stock exchange on which the company is listed)
2. Company (name of company)
3. HQ Location
4. HQ Region
5. Project (name of project)
6. Ownership (% ownership of project for company listed)
7. Country
8. State
9. Latitudinal and longitudinal data (for mapping purposes)
10. Status (stage of project exploration)
11. Deposit or Exploration type
12. Grade (in %) and tonnage (in million or thousand M.tonnes) for Proven & Probable Reserves (P&P)
13. Grade (in %) and tonnage (in million or thousand M.tonnes)for Indicated & Measured Resources (I & M)
14. Grade (in %) and tonnage (in million or thousand M.tonnes) for Inferred Resources
15. NI 43-101 report (yes/no)
16. Notes relevant to project or company
17. Additional financial information

A column on exploration type was included to note which projects were brownfield or greenfield exploration for further analysis.

### *Data Analysis and Reconciliation*

To begin the spatial distribution analysis, location data for each project was collected and plotted. Oftentimes, this data was given as longitudinal and latitudinal data included in project

descriptions on company websites, presentations, or in technical reports. Where longitudinal and latitudinal data was not provided, as in initial or early exploration projects where no technical reports had been prepared, a central location point was inferred from project descriptions. As an example, a project described as 100 km southwest (SW) of a town or city was estimated to be at any point 100 km SW of said city, and within 50km radius of said point. This was done so as to allow projects in initial and early exploration stages to be plotted regardless of exactness of the locational data.

In determining a project's stage of exploration, the following key was developed with guidance from the Generalized Model of Resource Development (see *Appendix B*):

- **Initial Exploration:** At most, land staked and property claims filed, reconnaissance and data compilation underway.
- **Early Exploration:** At least inferred resources have been defined. Anomaly surveys underway. Might include a scoping report, pre-feasibility report, or preliminary economic assessment.
- **Advanced Exploration:** At most, proven and probable reserves have been defined. Might include a scoping, pre-feasibility, or feasibility report.
- **Development:** At least proven and probable reserves have been defined. Company announcements and news reports of permitting, construction, offtake agreements, and other development activities at project site.

It was important that information reported on company websites were consistent with company announcements on security or stock exchanges, report publications in security exchange databases such as SEDAR, and news in the media.

### ***Limitations of survey***

Three factors constrain the survey of projects:

1. **Time limitations:** Project or company announcements that have not been updated after three fiscal quarters (nine months) are excluded in the final ranking of companies. This is to ensure public information on the projects are current. As an example, Metorex, a company traded on the Hong Kong stock exchange, claims their Musonoi project in the DRC is in the advanced exploration stage with a relatively sizable resource base. However, the company's latest publicly available annual report is from 2010 and the last project update on their website is from 2014. As a result, the project was not included in final rankings for advanced cobalt projects.
2. **Company type:** Only publicly-traded companies were surveyed due to greater transparency and availability of information on these companies. Security and stock exchanges mandate companies adhere to certain rules. As a result, private companies with lithium and cobalt exploration projects were excluded. We also only included companies traded on exchanges in the United States, Canada, Australia, and Europe in the final analysis due to greater uniformity in listing rules on their respective exchanges.
3. **Regional project density:** The survey required a minimum of two exploration projects in a geographic region to be noted as significant. As an example, Birimian Limited's Goulmina project in Mali was not charted as it is the only lithium exploration project in the MENA and African regions with JORC-compliant resources.

#### **Box 4: Mineral Investment Process**

Investing in a mining project involves analyzing a unique mix of geological, technical, economic, social, and environmental risks at nearly every stage of the project. As with any other investment, it is important investors do their due diligence when deciding on a project. The process for assessing the potential success of a mining project rests primarily on three factors: the technical components of the project, the knowledge and expertise of the project directors, and the region in which the project is located<sup>64</sup>. These three factors are known colloquially in the mining industry as the three Ps – project, people, and place – and they factor in many of the risks associated with developing a mining deposit.

A robust mineral deposit is the foundation on which a good project is built, and the defining metrics of a mineral deposit are its grade, tonnage, and metallurgy. The grade of a deposit is the percentage or concentration of valuable mineral in the ore, while tonnage refers to the volumetric size of the deposit. A deposit with above average grade and tonnage has a higher chance of making it to production, all things being equal. In addition to the tonnage and grade, the technical viability of the metallurgical methods proposed should also be assessed, as incorrect metallurgical analyses can lead to cost overruns and can betray a lack of specialized knowledge in the team.

This geological and technical information is typically sourced from technical reports or official resource estimates, which are published by companies at certain project milestones. When assessing a project, it is important that the exploration results and mineral estimates published by the company are compliant with standardized mineral reporting rules and guidelines such as the JORC Code (2012), NI 43-101, and SAMREC. Resource estimates not compliant with reporting standards are not reliable and will incur more risk for the investor if used as the basis for analyses.

Finally, one should assess the category of the mineral deposit. As discussed above, project risk varies with the resource classification and stage of development. A mineral deposit is classified as a resource when primarily geological risks have been considered, and as a reserve when economic risks (factoring in legal, political, social and environmental circumstances) have been considered in addition. The geological risk associated with the project reduces with more tests and delineation, while economic risk reduces with studies analyzing the effects that commodity price, costs, and other economic parameters have on the viability of developing the project.

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<sup>64</sup> David Talbot: Interview (April, 2017)

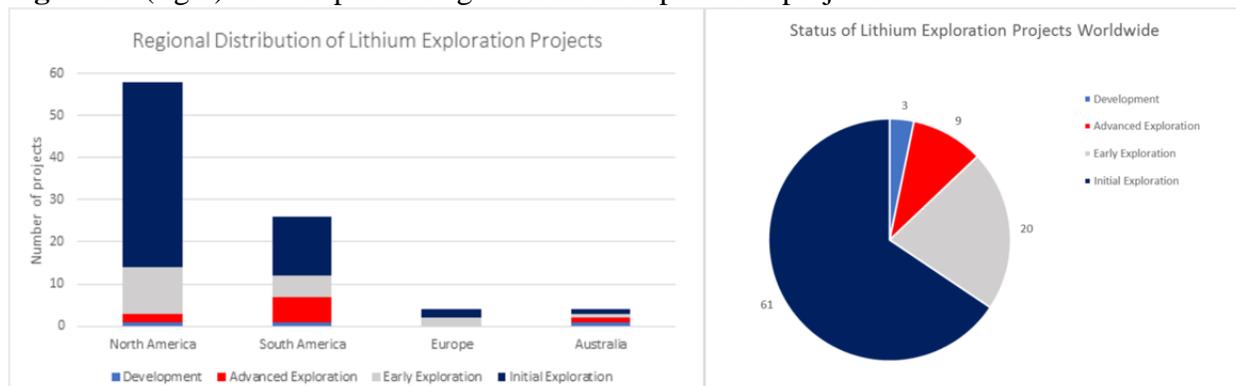
## **Appendix B: Cobalt Companies Examined For Analysis**

Access excel file online for this information.

## Appendix C: Lithium survey results

**Figure 12** (left): Distribution stage of lithium exploration projects;

**Figure 13** (right): Development stage of lithium exploration projects



The spatial analysis shows that lithium exploration projects are largely concentrated in North and South America. Of the 92 lithium exploration projects surveyed, 12 projects are in the advanced exploration to development stages and are concentrated in Argentina, Canada, and Western Australia. The clear majority of lithium exploration projects are in the initial exploration stages where even inferred mineral resources have not been defined.

### Noteworthy Lithium Exploration Projects:

1. **Greenbushes Expansion:** Jointly owned by Albemarle (49%) and Tianqi Lithium (51%) via Talison Lithium, the company announced plans to double production at their Greenbushes mine by early 2019. Already the world's largest lithium mine, yearly capacity at Greenbushes will reach 1.34 million tonnes of lithium concentrate, approximately 180,000 tonnes of lithium carbonate, by 2019 according to the company. Greenbushes is an open-pit spodumene mine located in Western Australia.
2. **Pilgangoora:** The development-stage project is in the Pilgangoora area in Western Australia. Wholly-owned by Altura Mining, the project is planned to be an open-pit spodumene mine commencing production in the first quarter of 2018. As of September 2017, Altura Mining has completed preliminary offtake agreements for 100% of production with Optimum Nano and Lionergy, two major Chinese battery-grade lithium manufacturers.<sup>65</sup> Construction of the project is fully funded and at 50% completion.<sup>66</sup>
3. **Cauchari-Olaroz:** This development-stage project located in Argentina is operated as a 50/50 joint venture between Lithium Americas and the Sociedad Quimica y Minera de Chile (SQM). Lithium Americas entered a financing deal with GFL International Co. Ltd.<sup>67</sup> and BCP Innovation Pte Ltd.<sup>68</sup> to fund Lithium Americas' share of capital costs. The project is planned to be completed in early 2019 with a production capacity of

<sup>65</sup> OptimumNano is a wholly-owned subsidiary of Shaanxi J&R Optimum Energy listed on the Shenzhen Stock Exchange. Lionergy owns a vertically integrated lithium exploration, development, sales and distribution for lithium-ion batteries.

<sup>66</sup> Altura Mining Investor Update 2017: <https://alturamining.com/wp-content/uploads/2017/08/1710794.pdf>

<sup>67</sup> GFL International Co. Ltd. Is a wholly-owned subsidiary of Jiangxi Gangfeng Lithium Co. Ltd

<sup>68</sup> BCP Innovation Pte Ltd. is a wholly-owned subsidiary of Bangchak Corporation Public Company Ltd.

25,000 tonnes of lithium carbonate annually.

4. **Whabouchi:** Whabouchi Lithium is a development-stage hard rock project located in Quebec, Canada. As of September 2017, the company has met feed production targets for the Phase 1 Plant in Shawinigan, Quebec. The company aims to be a fully integrated lithium producer processing lithium concentrate into battery-grade lithium compounds at their Shawinigan plant through a patented process. The project has an open-pit mineral profile of 20 million tonnes of proven and probable reserves at an average grade of 1.53% and is projected to expand to an underground mine. Commercial production is expected by early to mid 2018.
5. **Sonora Lithium:** Jointly owned by Bacanora Minerals (70%) and Cadence Minerals (30%), the lithium-clay project is located about 190km north of Hermosillo, Mexico and is in the advanced exploration stage. In June 2017 the company entered an offtake contract with Hanwa Co. Ltd.<sup>69</sup> for 70% to 100% of planned production in Phase 1, conditional on an initial 10% equity interest in Bacanora.

Other advanced projects expected to come online in the next two years are: Jadar in Serbia by Rio Tinto; Planta Salar in Chile owned by Rockwood Lithium; Salar de Centenario in Argentina owned by Eramet; Sal de Vida in Argentina owned by Galaxy Resources Ltd.; Sal de Los Angeles in Argentina owned by Lithium X Energy Corp.; Tres Quebradas in Argentina owned by Neo Lithium Corp.; Authier in Canada owned by Sayona Mining, and further expansion at Albemarle's Silver Peak mine in the USA.

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<sup>69</sup> Hanwa Co. Ltd. is a major Japanese battery chemical trading company. Project source: Corporate Presentation June 2017 <http://www.bacanoraminerals.com/cms/wp-content/uploads/2017/06/Corporate-Presentation-June-2017-08.06.17.pdf>

## Appendix D: Summary Table of Potential Future Battery Technologies<sup>70</sup>

Chemistry	Lithium-air	Lithium-metal	Solid-state Lithium	Lithium-sulfur Li-S	Sodium-iron Na-ion
Type	Air cathode with lithium anode	Lithium anode; graphite cathode	Lithium anode; polymer separator	Lithium anode; sulfur cathode	Carbon anode; diverse cathodes
Voltage per cell	1.70–3.20V	3.60V	3.60V	2.10V	3.6V
Specific Energy	13kWh/kg (theoretical)	300Wh/kg	300Wh/kg (est.)	500Wh/kg or less	90Wh/kg
Charging	Unknown	Rapid charge	Rapid charge	0.2C (5h)	Unknown
Discharging	Low power; inferior when cold	High power band	Poor conductivity when cold	High power (2,500W/kg)	Unknown
Cycle life	50 cycles in labs	2,500	100, prototypes	50, disputed	50 typical
Packaging	Not defined	Not defined	Prismatic	Not defined	Not defined
Safety	Unknown	Needs improvement	Needs improvement	Protection circuit required	Safe; shipment by air possible
History	Started in 1970s; renewed interest in the 2000s. R&D by IBM MIT, UC, etc.	Produced in the 1980s by Moli Energy; caused safety recall	Similar to Li-polymer that started in 1970	New technology; R&D by Oxis Energy, Bosch and others.	Ignored in the 1980s in favor of lithium; has renewed interest
Failure modes	Lithium peroxide film stops electron movement with use. Air impurity causes damage.	Dendrite growth causes electric short with usage	Dendrite growth causes electric short; poor low temperature performance	Sulfur degrades with cycling; unstable when hot, poor conductivity	Little research in this area
Applications	Not defined; potential for EV	EV, industrial and portable uses	EES, wheeled mobility; also talk about EV	Solar-powered airplane flight in August 2008	Energy storage
Comments	Borrowed from “breathing” zinc-air and fuel cell concept	Good capacity, fast charge and high power keep interest high	Similar to lithium-metal; may be ready by 2020; EVs in 2025	May succeed Li-ion due to lower cost and higher capacity	Low cost in par with lead acid. Can be fully discharged.

<sup>70</sup> Battery University, *Summary Table of Future Batteries*, July 21, 2016, [http://batteryuniversity.com/learn/article/bu\\_218\\_summary\\_table\\_of\\_future\\_batteries](http://batteryuniversity.com/learn/article/bu_218_summary_table_of_future_batteries) (accessed November, 2017)



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