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Full length article

An integrated supply chain analysis for cobalt and rare earth elements under global electrification and constrained resources

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ABSTRACT

As global electrification becomes more prominent, demand is projected to increase for electric vehicles (EVs), their components (EV batteries, rare earth traction motors), and their raw materials (cobalt, rare earths). To analyze the supply chain constraints associated with these components and raw materials, a system dynamics model was developed to simulate the interactions between the rare earth and cobalt supply chains. Results showed that under current understanding of raw material resources, production of the projected volume of EVs could be inadequate. To meet the aggressive EV volume sale projections set by the International Energy Agency, EV manufacturers will need to implement a large portion of traction motors without rare earths and utilize non-cobalt batteries as much as possible. On the supply side, a much faster ramp-up than what being modeled would be needed to meet much higher demand than current market forecasts.

1. Introduction/literature review

As part of a global effort to reach carbon neutrality by 2050, multiple countries have set ambitious goals for electric vehicle (EV) deployment (IEA 2021, Guterres 2022). Approximately 80-90% of current EVs utilize rare earth permanent magnets in their traction motors (Roskill 2019, Rao and Bagianathan 2021, Sigal 2022). Sintered Nd-Fe-B magnets are used in EV motors due to their favorable characteristics, including high coercivity, thermal properties, and maximum energy product $(BH)_{max}$ range. One of the largest challenges of the Nd-Fe-B supply chain is that most magnet manufacturing takes place in China (92%) making the rest of the world (ROW) reliant on China's output (Smith, Riddle et al. 2022). To alleviate permanent magnet supply chain concerns, major magnet research technologies have flourished including grain boundary diffusion, additive manufacturing, alternative magnets, hydrogen decrepitation and hydrogen disproportionation desorption recombination, and dual alloy (Sugimoto 2011, Coey 2020, Liu, He et al. 2022). One alternative magnet developed by researchers with the Critical Materials Institute (CMI) is a lanthanum-neodymium (La-Nd) magnet as a substitute for sintered Nd-Fe-B magnets. In the La-Nd substitute, lanthanum and cobalt replace some of the neodymium and dysprosium used in the traditional sintered Nd-Fe-B magnet.

China's dominance in the permanent magnet supply chain extends to the world's market for rare earth element (REE) mining and refining. In 2020, China was responsible for over 58% of global REE mining (Smith, Riddle et al. 2022) and 90% of refining (Smith, Riddle et al. 2022). Due to this global reliance on China's REE supplies, global markets can be influenced by the Chinese government and firms through nationwide policymaking or production decisions, respectively (Smith, Riddle et al. 2022). As China pursues consolidation of REE mining companies into a small number of government-owned entities, the criticality of this issue has increased (Smith, Riddle et al. 2022).

In addition to constraints within the permanent magnet supply chain, hinderances exist in the EV battery supply chain as well. Important battery metals such as lithium, cobalt, and nickel have seen increases in demand, and already are experiencing supply chain constraints (Erickson 2021). To combat some of these concerns, auto manufacturers are looking towards battery technologies that do not rely as heavily on cobalt (Lambert 2022, Volkswagen 2022). Volkswagen has already stated its intent to reduce cobalt content in its batteries and is working to develop cobalt-free battery cells (Volkswagen 2022). Tesla has confirmed that over half of its currently produced vehicles are using cobalt-free lithium-iron-phosphate (LFP) batteries (Lambert 2022). Specific cobalt supply chain challenges include a poor political stability

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in mining countries, a concentrated supply market, and cobalt mining as a byproduct of copper and nickel (van den Brink, Kleijn et al. 2020). In 2020, 68% of cobalt was mined in the Democratic Republic of the Congo (DRC) (USGS 2022) which has long been characterized by political instability, causing the country to face widespread poverty and human injustice (Council on Foreign Relations 2022). Additionally, a recent Roskill report found that of the nineteen cobalt mines in the DRC operating in 2020, fifteen were owned or financed by Chinese companies (Searcey, Forsythe et al. 2021). China plays an even larger role in cobalt refining. In 2020, approximately 80% of battery-grade cobalt was produced by China (MiningDotCom 2021).

There have been several studies that utilized system dynamics (SD) to model the REE supply chain. Kifle, Sverdrup et. al modeled the REE supply chain as a simple dynamic system to understand how future demand affects REE resource depletion (Kifle, Sverdrup et al. 2013). Their conclusion was that effective recycling policies should be put in place to create a sustainable REE supply. However, individual REEs were not modeled and represented as an aggregated commodity instead. Keilhacker and Minner developed a more complex SD model to represent the REE supply chain for ~10 years. The major conclusion was that substituting rare earth material in major applications mitigated the greatest supply unavailability. Yet, by only analyzing a short time period, the model did not give an in depth look at the REE supply chain's response to changing REE demand, mine reserve depletion, or long-term price impacts (Keilhacker and Minner 2017). In addition, the effects of global electrification and its increased demand for REEs were neglected in the model with specific applications considered being catalysts, glass polishing, glass additives, metallurgical alloys, phosphor powder, ceramics, Nd-Fe-B magnets, and battery alloys. The model did analyze the effect of hypothetical substitution mechanisms through research and development on the REE supply chain. However, it did not explicitly consider the effect of a specific product of research and development on the supply chain (Keilhacker and Minner 2017).

In this research, the authors attempt to bridge the gap in the literature by developing a more comprehensive SD model that analyzes both the REE and the cobalt supply chains in response to a global deployment scenario of EVs. To the authors' knowledge, no other work has been previously conducted that connects the REE supply chain with the cobalt supply chain. This work is built upon our previous SD model that analyzed three intertwined commodities and their supply chains: (1) nickel, (2) copper, and (3) cobalt (Nguyen, Eggert et al. 2020) to support global electrification. The main difference is that this work considers a resource constraint for both cobalt and REEs whereas in previous work no constraints were applied. These constraints are necessary to show the impacts of substitution for scarce resources. The authors set out to answer three key research questions:

1. What are the key constraints to EV deployment and does an alternative magnet or non-REE magnet motor technology alleviate the constraints?
2. What individual improvements can be made to the cobalt or REE supply chain (depending on the key constraints) to improve EV sales?
3. If EV deployment is still unfavorable after individual improvements, what are the market conditions that would enable global EV sales goals to be met?

2. Methodology

An SD model was created to simulate market dynamics of magnet substitution and the associated material supply chains. The model was simulated from the years 2005 to 2050 in the software Vensim, version DSS 9.2.3 and Stella Architect, version 3.1.1. Stella Architect was utilized for its intuitive interface capabilities. The years between 2005 and 2019 represent historical information for model validation purposes. The years after 2020 simulate the future and output results and trends of the model. The deployment of CMI technology was set to the year 2027 following internal communication with the CMI principal investigators and leadership team. Where applicable, prior work (Nguyen, Eggert et al. 2020) was cited for similar assumptions and modeling techniques. A comprehensive list of parameters can be found in the supporting document (Table S18, Table S20). A set of scenarios were developed to answer the research questions and can be found in Table 1. Access to the model interface can be obtained upon request.

2.1. Overall model framework

Due to the complex nature of modelling many different rare earth oxides (REOs) and cobalt in the same model, eight individual modules were created to represent and simplify the different aspects of the model. The simplified, overall structure of the model can be seen in Fig. 1. The flow of information of the model is represented in the diagram by colored arrows.

2.2. Permanent magnet demand module

The permanent magnet demand module received input from both the EV demand module and generated demand for other non-EV applications. In this module, five primary commercial magnet technologies were accounted for: Al-Ni-Co, $SmCo_5$, Sm_2Co_{17}, sintered Nd-Fe-B, and bonded Nd-Fe-B. For sintered Nd-Fe-B, a higher Dy content (5%, 4.4%) was considered for EV traction motors and wind turbines, respectively, and a lower Dy content (1%) was considered for all other applications. Only permanent magnets that contained REEs or cobalt were considered. Each commercial technology was assigned a growth rate and an initial value which initialized the demand of the magnet (Benecki, Constantinides et al. 2020) (Table S12, supporting document). Additionally, the demand of the alternative magnet, La-Nd, was calculated by implementing the substitution mechanism described in Section 2.3. Magnet parameters can be found in the supporting document in Table S19 and Table S20.

2.3. Magnet substitution mechanism

Due to variations in density, maximum energy product, remanence, coercivity, and other physical and magnetic properties, a magnet cannot simply be substituted in an application/device with an equivalent mass. The magnetic performance of the system changes with magnet volume. However, traded magnet quantities and raw materials are reported in

Table 1
Scenario names and key assumptions for model analysis

Scenario name	Scenario description and key assumptions
Business as Usual (BAU)	90% of sales to be PM traction motors; N42SH sintered Nd-Fe-B magnet in traction motor
La-Nd Deployment (LaD)	La-Nd magnet substituted for EV traction motors based on cost viability; N42SH sintered Nd-Fe-B magnet in traction motor
Business as Usual N35AH (BAU: N35AH)	90% of sales to be PM traction motors; N35AH sintered Nd-Fe-B magnet in traction motor
La-Nd Deployment N35AH (LaD: N35AH)	La-Nd magnet substituted for EV traction motors based on cost viability; N35AH sintered Nd-Fe-B magnet in traction motor
Reduced Cobalt Content in EV Batteries (RCB)	Cobalt content in EV batteries reduced linearly by 80% for 20 years starting in year 2022
Cobalt Free Sintered Nd-Fe-B EV Magnets	Cobalt removed from sintered Nd-Fe-B EV magnet composition starting in year 2022
Free-market of PM motors and non-PM motors (FMP)	EV sales not constrained by 90% PM traction motor requirement to allow other traction motor technologies when supply of PMs was insufficient to meet demand of EVs
Fast-ramp up cobalt production (FRU) + FMP	A fast-ramp up cobalt production scenario minimizing the time cobalt producers would analyze the market for increasing cobalt demand and the "Free-market of PM motors and non-PM motors" scenario

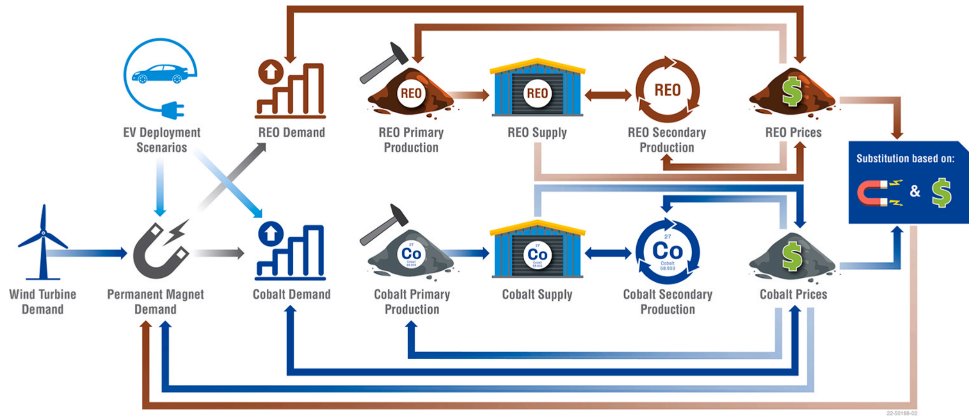

Fig. 1. The general model structure shows the interactions between modules.

mass. For this reason, it is important to have a substitution mechanism based on mass. The model utilized a methodology that calculated an output of a magnet performance ratio that could be multiplied by the substituted mass to yield the mass of the substituting magnet offering the same magnetic performance. More details and information on this mechanism can be found in the supporting document (supporting section 1.1).

2.4. Rare earth oxides and cobalt demand modules

Once the permanent magnet demand was calculated from EVs and other applications, it was used as inputs to the REO and cobalt demand modules. Due to the similarities between the two modules, the description here represents both modules. The modules calculated the theoretical demand of REOs and cobalt utilizing the compositions of the magnets. Additionally, theoretical demand for cobalt and REOs was generated for non-permanent magnet categories by applying a growth rate to an initial value (Table S13, Table S14). Non-magnet cobalt applications included non-EV batteries, EV new batteries, EV replacement batteries, super alloys, hard materials, catalysts, pigments, hard facing alloys, and other applications (Roskill 2018). Non-magnet REO applications included rare earth catalysts, metallurgy, phosphors, and “glass, polishing, & ceramics” (Roskill 2018). Following generation of theoretical demand for REOs and cobalt, an adjusted commodity demand was calculated that accounted for the lead time, and price of each commodity and can be seen in more detail in (Nguyen, Eggert et al. 2020).

2.5. REO and cobalt primary production modules

The cobalt and REO primary production modules were responsible for developing the output of commodities from mining and refining operations. Both modules expand capacity by observing continuous demand growth of each commodity as previously described in (Nguyen, Eggert et al. 2020). To develop actual production from production capacity, supply curves for REEs and cobalt were implemented (Figure S3 and Figure S4, supporting document) that took a normalized commodity price as input. Normalized prices are calculated by dividing the model’s outputted prices by expected prices and are explained in more detail in Section 2.7. Additionally, both modules examined the global mining reserves of the respective commodities. As mentioned earlier, the main difference between this model and previous work was that resources in this paper were constrained. As a particular country’s reserves of a commodity decreased or ran out, the model compensated by adjusting the composition of the mined ore. Additionally, China’s REE production was further analyzed by reserves of the six major REE mining companies. When reserves for a company decreased or ran out, the model adjusted the composition of China’s total orebody to reflect the depletion. Additional information on differences between the cobalt and REO primary production modules and reserve and ore body composition data can be found in the supporting document in supporting section 1.2.

2.6. REO and cobalt secondary production module

The cobalt and REO secondary production modules represented the tracking of end-of-life products and the subsequent recycling through the assignment of values for product lifetime, collection rates, recycling efficiency, and a secondary supply curve (Figure S5, supporting document) to control the potential secondary production of these commodities. Two main differences exist between REE’s and cobalt’s mechanism for secondary supply. First, cobalt utilized a fixed collection rate due to its high recycling rate, whereas REEs utilized the secondary supply curve to control the collection rate. This was done to prevent excessive collection when the economics for recycling is low. Second, cobalt’s supply allocation prioritized EV battery replacement to keep the in-use vehicle fleet operational. The remainder of cobalt supply after meeting maintenance demand was then allocated to the other applications based on demand share. The supply module keeps track of production from both primary and secondary sources. Many different assumptions and input parameters were captured within the secondary production module and can be seen in the supporting document (Table S18).

2.7. REO and cobalt price module

The cobalt and individual REO prices change depending on supply and demand of the individual commodity. The main assumption in this model is rational buying decisions where demand is lower when prices are higher and vice versa. This analysis utilized an assumed demand elasticity to adjust the price based on a ratio between supply and demand. The cobalt demand elasticity was -0.46 (Fally and Sayre 2018), while the REO demand elasticity was -0.5 for LREOs and -0.3 for HREOs (Pothen 2013) to represent an inelastic demand. Cobalt expected price was calculated by taking an average of historical prices from the years 2011 to 2020 (ArgusMedia 2022). REO expected prices were calculated by taking historical data from the available years via subscription (ArgusMedia 2022) while excluding the years 2010 to 2012 to negate the historical price spike. For future expected prices, historical expected prices were inflated by 1.90% per year comprising of the average of the United States, China, and Japan’s historical inflation values for the years 2005 to 2020 (OECD 2021). The price adjustment equation was based on the expected price, demand, and supply. It can be seen in the supporting document and in previous work (Nguyen, Eggert et al. 2020).

2.8. EV demand module

Finally, the last module was developed for theoretical EV demand over time. The EV demand growth scenario was the Announced Pledges Scenario (APS) developed by the International Energy Agency (IEA) which projects EV sales based on major country announcements such as net zero emissions or other pledges (IEA 2021, International Energy Agency 2021). Following 2030, a 5% growth rate was assumed until 2035 and a 1% growth rate was assumed from 2036 to 2050. The decreasing growth rate was intended to simulate an S-shaped behavior which is accepted as a reasonable production adoption forecast (Bass 1969, He, Wang et al. 2014). This ambitious scenario was chosen to explore an extreme case where EV deployment is high while resources are constrained. A bottom-up approach was used to calculate theoretical cobalt and REO demand from new and replacement EV batteries (cobalt) and traction motors (cobalt, REOs). Four types of vehicles were modeled which included cars, large freight trucks, buses, and vans. Two types of powertrains were modeled which included battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Even though fuel cell electric vehicles were reported by (International Energy Agency 2021), they were not modeled due to their small market share. More information on bottom-up battery and permanent magnet assumptions and calculations can be found in the supporting document in supporting section 1.3.

Lastly, this module output the sales of EVs based on the available supply of cobalt and REOs for both batteries, sintered Nd-Fe-B EV traction motors, and alternative magnet EV traction motors. Typically, non-PM traction motors are less efficient than PM traction motors. To compensate for this, batteries of non-PM traction motor EVs were assumed to be 10% heavier to deliver the same performance (Schultz and Huard 2013). Also, to prevent competition between praseodymium and neodymium in the model, as sintered Nd-Fe-B magnets often use both elements (Ormerod 2020), the sum of the two was used, representing didymium (Nd-Pr) consumption. Didymium is closely aligned with the composition of the input material and is primarily an economic decision since it eliminates an REE separation step (Ormerod 2020). Supply of cobalt and REOs for these applications was allocated based on the dynamic demand share of the application through time. Then, this sale quantity was used to track in-use and end-of-life vehicles. In-use vehicles were tracked to determine the maintenance demand for EV batteries (then converted to cobalt demand) based on the expected lifetime of an EV battery, 15 years (Cagatay 2019, Charluet and Van Barlingen 2021, True Car Advisor 2021). In addition, EV mortality follows a Weibull distribution (Figure S6, supporting document) (Lu 2006, Xu, Yano et al. 2016). Therefore, discarded batteries come from both end-of-life batteries (maintenance) and end-of-life EVs and provide feedstock for secondary supply.

3. Results/discussion

3.1. Model validation

Model results were compared with historical production of both cobalt and REOs for validation. Cobalt's historical validation took place from the years 2010 to 2019 using the United States Geological Survey's (USGS) world refinery production data (USGS 2022). REO's historical validation took place from the years 2010 to 2020 using USGS's mine production data (USGS 2022). A t-test was performed to mathematically validate a negligible difference between the historical data and the model results. For both cobalt and REOs, the differences between the historical and model results were not statistically significant at an alpha value of 95%. A complete summary of the results can be found in the supporting document (Table S17).

3.2. Key constraints, impacts of new magnet technology, and sensitivity analysis

The "Business as Usual" (BAU) scenario modeled the cobalt and REE supply chains with the current understanding of EV technologies and mineral resources. In this scenario, EV sales were constrained by the assumption that 90% of EVs sold would have REE permanent magnet traction motors (Roskill 2019), and the permanent magnet was an N42SH sintered Nd-Fe-B magnet. The results showed a maximum value of EV sales of ~15.9 million vehicles in 2034 (as opposed to ~70 million EVs in 2050 in the IEA APS scenario) before a subsequent decline in EV sales due to a lack of cobalt supply for permanent magnet motor production from the years 2020 to 2034. The key constraint to EV sales in this scenario was the availability of traction motors. Even though only a very small amount of cobalt was needed in the sintered Nd-Fe-B composition (1%), it proved to be a key limiting factor of EV sales. Most of the cobalt supply that went to EV and non-EV batteries was subsequently hindered by a lack of reserves with DRC and ROW cobalt reserves nearing depletion in 2036 and 2038, respectively.

Also depicted in Fig. 2a was a "La-Nd Deployment" (LaD) scenario which showed the non-impact of CMI's La-Nd magnet on EV sales. Due to the quantity of cobalt in the magnet, at no point does the magnet become economically favorable for substitution with the default magnet, an N42SH sintered Nd-Fe-B magnet. To test alternative scenarios, a simulation was performed that utilized an N35AH grade sintered Nd-Fe-B magnet as the default magnet for EV traction motors (BAU: N35AH and LaD: N35AH scenarios). Fig. 2b shows that when this magnet was the default, the La-Nd magnet had a much greater impact on EV sales yielding a maximum increase in EV sales of ~3.3 million in 2036. Cumulatively, the total EV sales over the course of the simulation for the LaD: N35AH scenario was 170 million EVs compared to 147 million EVs in the BAU: N35AH. Additionally, an average decrease in Dy prices of 37% from the year of deployment (2027) to the end of the simulation and a maximum decrease of 74% was observed.

3.3. Scenarios to increase EV sales

Since cobalt was identified as the primary constraint in the previous section, different scenarios were individually developed that attempted to increase EV sales by reducing the cobalt content required in EVs. First, a "Reduced Cobalt Content in EV Batteries" (RCB) scenario was tested to reduce cobalt content in EV batteries by 80% over 20 years starting in 2022. The results showed (Fig. 3) a maximum of EV sales of ~21 million EVs in year 2035 with an approximate increase of ~5 million vehicles in the year 2035 compared to the BAU scenario. The decrease in cobalt for EV batteries increases the cobalt supply for the magnet sector in this scenario compared to BAU. This illustrates how reducing competing demand for certain applications is important to increase supply for other applications. However, towards the end of the simulation, the constraint in this scenario remains cobalt in sintered Nd-Fe-B magnet motors. Therefore, the benefit of reduced cobalt in EV batteries was not effective to increasing the model's output of EV sales.

Based on the previous scenarios, it is important to understand the role of cobalt free NdFeB magnets used in EVs. A "Cobalt Free Sintered Nd-Fe-B EV Magnets" (CFS) scenario was created that set the content of cobalt in sintered Nd-Fe-B magnets to zero in EVs starting in year 2022. The results showed a maximum of EV sales of ~25 million EVs in 2046 (Fig. 3) compared to the BAU result of ~16 million EVs in 2034. Starting from 2037, sales would stay relatively constant until 2046 at 23 million EVs/year, which is a major improvement compared to BAU. However, this shows that another constraint occurred. EV traction motors were again the limiting component when compared to theoretical sales. Within the EV traction motors, the initial limiting factor starting in 2005 was cobalt until the year 2022, followed by didymium from 2022 to 2046, and concluded with dysprosium from 2046 to the end of the simulation. Part of the reason for a didymium shortage rather than a Dy shortage had to do with the magnet grade requirement for different applications. All modeled sintered Nd-Fe-B magnets required didymium, however, only the EV and wind turbine sintered Nd-Fe-B magnets required elevated Dy content.

Lastly, a "Free market of PM and non-PM motors" (FMP) scenario

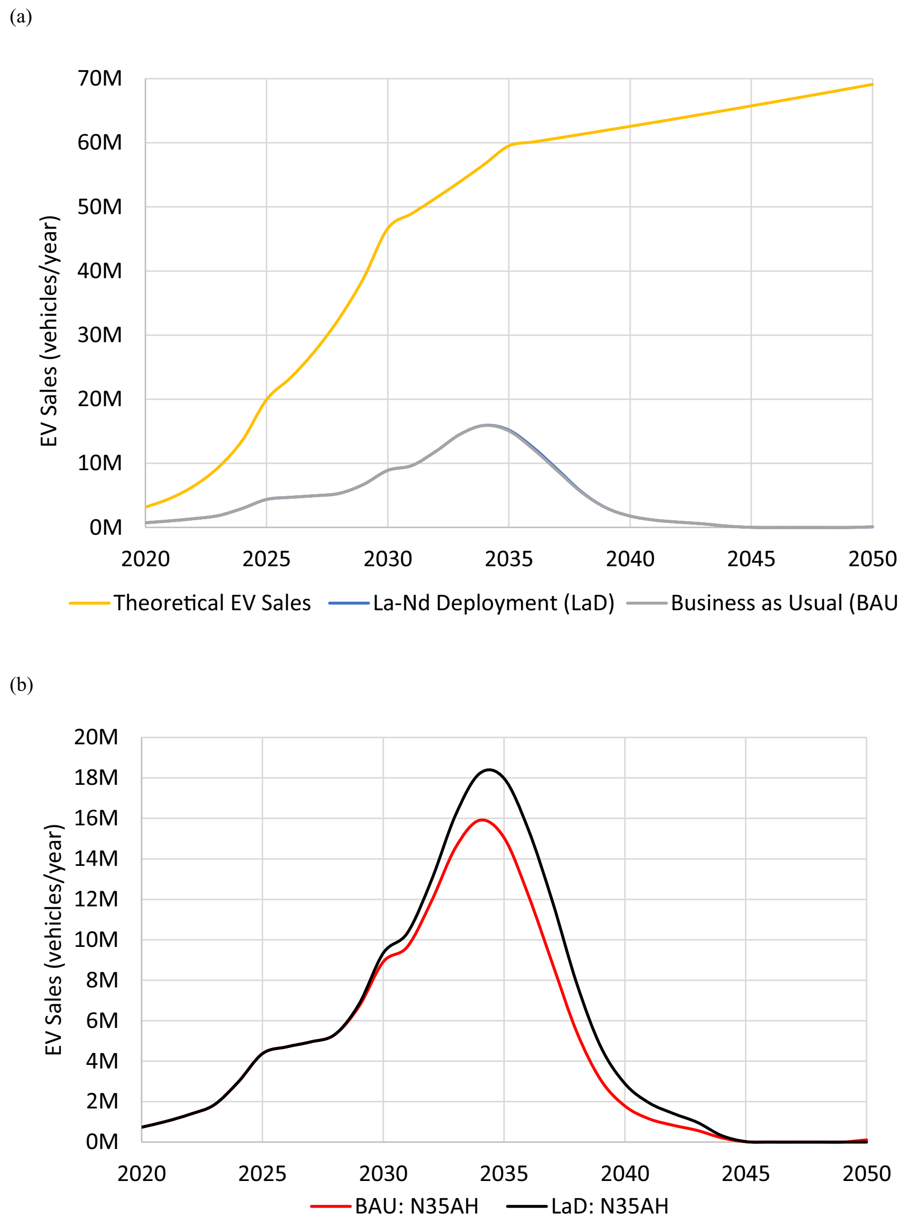

Fig. 2. (a) Annual EV sales of the BAU and LaD scenario compared to theoretical EV sales using an N42SH grade Nd-Fe-B magnet and (b) Annual EV sales of the BAU: 35AH and LaD: 35AH scenario using an N35AH grade Nd-Fe-B magnet as the base case magnet.

was developed that modeled the same parameters as the BAU scenario without restricting EV sales to the requirement of 90% rare earth permanent magnet motor constraint. Instead, the model allowed a free market between non-permanent magnet motors (induction motors, switched reluctance motors, etc.) and permanent magnet motors. When there wasn't enough PM motor supply, alternative motor technologies were used instead. Although non-PM motor EVs require a bigger battery and subsequently more cobalt, the results showed a major improvement compared to the BAU with a maximum value of EV sales of ~54 million vehicles in year 2034. In this scenario, because the constraint of PM motor was removed, the only remaining constraint was the EV battery due to cobalt supply. The corroboration of this result also has some evidence in the current marketplace with EV manufacturers such as Tesla, BMW, Toyota, Volkswagen, and Nissan either utilizing non-rare earth motor technologies or reducing rare earth content in their motors (Carney 2021, Edmonson 2021, Onstad 2021), however, today the interior permanent magnet (IPM) is still the most electrically efficient solution for EV traction motor systems. EV sales in this scenario are worse than other scenarios after 2040 because more cobalt was used in previous years to support high EV sales before reaching the peak of ~55 million in 2034.

3.4. *Scenarios required to achieve theoretical EV sales*

As seen in Fig. 3, it was clear that by only deploying one potential scenario at a time, the model's output of EV sales was not going to approximate the theoretical sales of EVs. To address this issue, multiple scenarios were integrated to test the potential to meet the theoretical EV sales (Fig. 4). A scenario was implemented that incorporates the FMP scenario and a fast ramp-up (FRU) scenario which accelerates cobalt production capacity in response to increasing cobalt demand. The FRU scenario was implemented by minimizing the time cobalt producers would analyze the market for increasing cobalt demand before expanding capacity, representing potential contractual mechanisms to help guarantee sustained demand. This scenario combination seemed to be the most similar to the theoretical EV sales before the constraint of

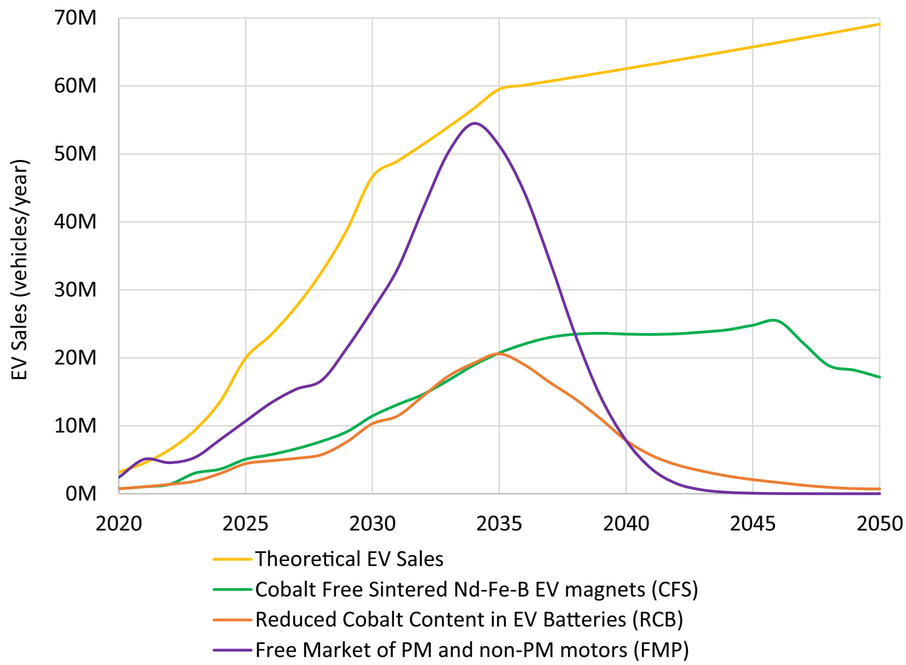

Fig. 3. Cobalt scenarios and their impact on the amount of EV sales.

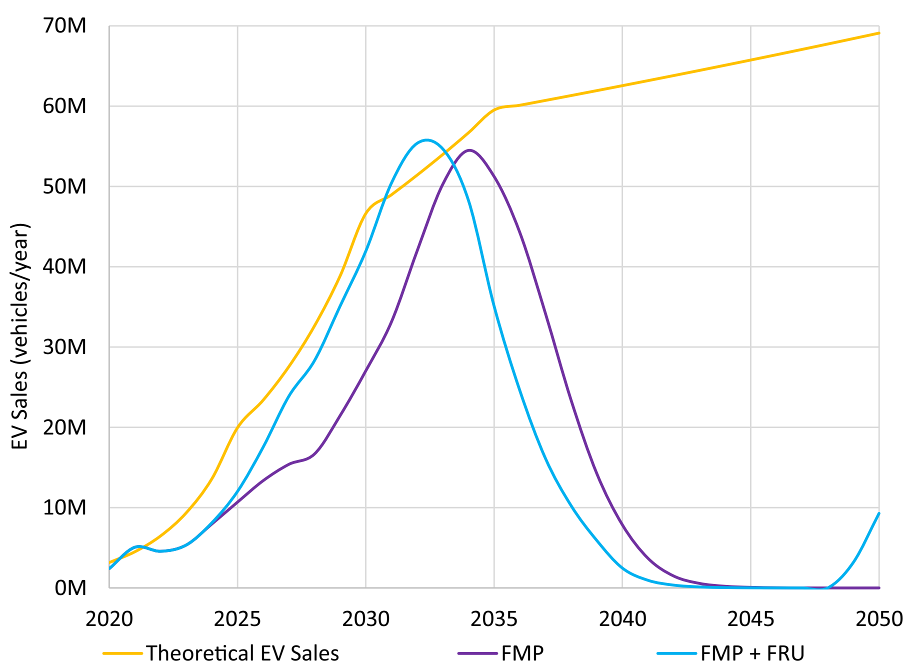

Fig. 4. Scenarios developed for the model to meet theoretical EV sales.

cobalt reserves proved to be the limiting factor to continued EV sales growth. Based on the results of the model, to replicate theoretical EV sales, EV manufacturers will need to implement non-PM traction motors and non-cobalt batteries into their vehicles to increase EV sales, and cobalt production will need higher capacity expansion than the current rate to meet fast changing market demands in the coming years.

A complete summary of all the scenarios, their key assumptions, and key results can been in Table 2. The last column shows cumulative sales over the entire simulation period. Cumulative EV sales were an important metric, as a maximum sales value at an instance in time did not always result in the greatest quantity of vehicles sold over the simulation period. The reason was due to increasing EV maintenance demand from increased in-use EVs by increasing EV sales. When increased maintenance demand occurred earlier in the simulation, the amount of cobalt available for new EV batteries was subsequently decreased preventing additional sales.

3.5. Analysis implications

Based on the results of the analysis, there are several key takeaways based on a constrained cobalt and REE resource assumption that could be utilized by stakeholders of the relevant supply chains.

First, the model highlighted the importance of utilizing alternative EV traction motor technologies in order to realize the ambitious goals set

Table 2
Summary table of the various scenarios and the key results

Scenario name	Scenario description and key assumptions	Maximum EV sales quantity (million EVs per year)	Year of maximum EV sales	Cumulative EV sales over entire simulation: 2005 - 2050 (million EVs)
Business as Usual (BAU)	90% of sales to be PM traction motors; N42SH sintered Nd-Fe-B magnet in traction motor	16	2034	148
La-Nd Deployment (LaD)	La-Nd magnet substituted for EV traction motors based on cost viability; N42SH sintered Nd-Fe-B magnet in traction motor	16	2034	148
Business as Usual N35AH (BAU: N35AH)	90% of sales to be PM traction motors; N35AH sintered Nd-Fe-B magnet in traction motor	16	2034	148
La-Nd Deployment N35AH (LaD: N35AH)	La-Nd magnet substituted for EV traction motors based on cost viability; N35AH sintered Nd-Fe-B magnet in traction motor	18	2034	170
Reduced Cobalt Content in EV Batteries (RCB)	Cobalt content in EV batteries reduced linearly by 80% for 20 years starting in year 2022	21	2035	224
Cobalt Free Sintered Nd-Fe-B EV Magnets	Cobalt removed from sintered Nd-Fe-B EV magnet composition starting in year 2022	25	2046	473
Free-market of PM motors and non-PM motors (FMP)	EV sales not constrained by 90% PM traction motor requirement to allow other traction motor technologies when supply of PMs was insufficient to meet demand of EVs	54	2034	499
Fast-ramp up cobalt production (FRU) + FMP	A fast-ramp up cobalt production scenario minimizing the time cobalt producers would analyze the market for increasing cobalt demand and the “Free-market of PM motors and non-PM motors” scenario	55	2032	504

forth in the APS scenario from IEA. Alternative EV traction motors technologies could include non-permanent magnet motors such as induction or switched reluctance motors, or they could include permanent magnet motors that don’t rely as heavily on rare earth elements or cobalt. Supply constraints of both cobalt and the key sintered Nd-Fe-B magnet elements (Nd, Pr, Dy) prevented EV sales from meeting the goals of the APS scenario evidenced by the BAU scenario (cobalt) and the “Cobalt Free Sintered Nd-Fe-B EV Magnets” scenario (REEs). The largest challenge with addressing this issue is that the current state of technology favors RE permanent magnets in EV traction motors due to their improved performance over non-RE motors and non-PM motors.

Second, in addition to concerns with EV traction motor availability, the results indicated that in order to meet the early deployment targets set forth by the APS scenario, EVs will need to be dependent on non-cobalt battery technologies. Significant gaps between the APS scenario and model results for EV sales indicate that cobalt supply will be insufficient requiring additional technologies to supplement deployment.

Third, in conjunction with the inability to meet early deployment quantities of EVs, the model showed that under a constrained cobalt resource assumption, cobalt availability would be a major concern moving forward. This indicates the importance of continued cobalt resource exploration, improvement of economic feasibility of extraction, and finding unconventional sources.

3.6. Limitations of the model

There are several limitations to the simulation model developed. The first limitation involved the allocation of supply to specific applications for both rare earths and cobalt. Demand share was assumed to be the driver for allocating supply of a commodity to an application without consideration for different application’s willingness to pay. The only caveat being that for cobalt, maintenance demand for replacement EV batteries was given priority for cobalt supply and the remainder of cobalt supply was allocated based on demand share. The second limitation was using single price for a commodity regardless of applications. In this sense, cobalt for EV batteries has the same value as cobalt for pigments. Certain markets may have a higher willingness to pay for cobalt than other markets depending on product specifications/grades. The third limitation of the model was that the La-Nd magnet was assumed to be a drop-in replacement for a sintered Nd-Fe-B magnet in EVs through the use of the methodology described in Section 2.3 and in the supporting document, section 1.1. However, in practice, this was only an approximation of the magnet mass required to replicate performance. Detailed engineering and finite element analysis would be performed to determine the appropriate mass of magnet required for a specific EV application. The final limitation was the assumptions utilized for generating cobalt and REO demand from EV deployment. EVs were assumed to the have the same traction motor magnet mass even though different makes and models may contain varying quantities of magnet, and EVs were assumed to have the same magnet composition. Related to cobalt, EVs were assumed to have the same cobalt content in the battery, regardless of make and model.

3.7. Next steps/future work

Planned future work for this model includes the development of cumulative availability curves for both cobalt and rare earths to integrate these curves through resource to reserve conversion. The implementation of a cumulative availability curve utilizes the cost required to extract a resource with the quantity of resource contained. By using this information, the dynamic price computed in the model could be used in conjunction with the cumulative availability curve to determine which resources are economically viable to extract. Necessary data would include cumulative availability curves for individual countries or if possible, individual deposits. These data would be used in conjunction with model’s dynamic price outputs to convert resources to reserves.

4. Conclusion

The model discussed in this research provided a macro-level look at the supply chains of both cobalt and rare earths in response to global EV deployment. Global EV sales, price trends, and global cobalt and REO reserves were assessed by the model to show potential bottlenecks and challenges moving forward. Multiple scenarios were analyzed including permanent magnet substitution for EV traction motors, reduced reliance on permanent magnet traction motors, reduced EV battery mass, reduced cobalt content in EV batteries, removal of cobalt from EV traction motors, and increased cobalt production capacity expansion in response to increasing cobalt demand. The main conclusions showed that permanent magnet EV traction motors could be the key constrained component due to both cobalt and REE supply constraints. With deployment of CMI’s La-Nd magnet under an N35AH magnet assumption, EV sales saw a maximum increase in yearly EV sales of ~3.3 million occurring in 2034 with an average decrease in Dy prices of 37% and a maximum decrease of 74%. If the constraint of EV traction motors is alleviated, EV batteries face a similar issue with a lack of cobalt supply available under the modeled constrained resources. This indicates the importance of non-cobalt battery technologies such as lithium iron phosphate batteries and is corroborated by recent announcements by auto manufacturers (Lambert 2022, Volkswagen 2022). Lastly, it was shown that under the BAU scenario cobalt reserves based on their current 2021 values could reach near complete depletion by ~2040.

CRediT authorship contribution statement

Michael H. Severson: Methodology, Software, Validation, Investigation, Writing – original draft, Writing – review & editing. **Ruby T. Nguyen:** Conceptualization, Methodology, Software, Visualization, Resources, Supervision, Project administration, Funding acquisition. **John Ormerod:** Methodology, Resources, Investigation. **Sophie Williams:** Writing – original draft, Investigation.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106761.

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