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RESEARCH ARTICLE

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Effects of the energy transition on environmental impacts of cobalt supply

A prospective life cycle assessment study on future supply of cobalt

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Abstract

Cobalt is considered a key metal in the energy transition, and demand is expected to increase substantially by 2050. This demand is for an important part because of cobalt use in (electric vehicle) batteries. This study investigated the environmental impacts of the production of cobalt and how these could change in the future. We modeled possible future developments in the cobalt supply chain using four variables: (v1) ore grade, (v2) primary market shares, (v3) secondary market shares, and (v4) energy transition. These variables are driven by two metal-demand scenarios, which we derived from scenarios from the shared socioeconomic pathways, a "business as usual" (BAU) and a "sustainable development" (SD) scenario. We estimated future environmental impacts of cobalt supply by 2050 under these two scenarios using prospective life cycle assessment. We found that the environmental impacts of cobalt production could likely increase and are strongly dependent on the recycling market share and the overall energy transition. The results showed that under the BAU scenario, climate change impacts per unit of cobalt production could increase by 9% by 2050 compared to 2010, while they decreased by 28% under the SD scenario. This comes at a trade-off to other impacts like human toxicity, which could strongly increase in the SD scenario (112% increase) compared to the BAU scenario (71% increase). Furthermore, we found that the energy transition could offset most of the increase of climate change impacts induced by a near doubling in cobalt demand in 2050 between the two scenarios.

KEYWORDS
cobalt, energy transition, future background scenario, industrial ecology, mining, prospective life cycle assessment

1 | INTRODUCTION

Although it is commonly acknowledged that the energy transition will substantially increase the demand for cobalt (Deetman et al., 2018; Sverdrup et al., 2017), it is so far unknown how such a rise of demand will affect the environmental performance of cobalt supply. Cobalt is a key metal for the energy transition as it is for electric vehicles, wind turbines, and other power-generation technologies (Cobalt Institute, 2015). Electric vehicles require batteries and magnets, wind power requires magnets, and other power-generation technologies require superalloys and magnets. The highest demand for cobalt is in electric vehicle batteries, which have seen strong growth in demand over recent decades (Cobalt Institute, 2015).

Deetman et al. (2018) expect a demand increase for cobalt of 10–20 times by 2050 compared to 2010 due to the energy transition. Other researchers also expect a substantial increase in cobalt demand in the coming decades although there is no consensus on magnitude (Junne et al., 2020; Sverdrup et al., 2017; Tisserant & Pauliuk, 2016; Xu et al., 2020).

Different geological sources of cobalt are used for supplying different cobalt-based materials or chemicals to different end-uses. Cobalt is primarily co-mined with two major metals: Copper and nickel. Roughly 60% of cobalt, although exact numbers vary by year, is co-mined with copper, specifically from sediment-hosted copper deposits processed via hydrometallurgy, which is mostly used for battery production (British Geological Survey, 2019; United States Geological Survey, 2017c). About 35–40% of cobalt is coproduced from processing of nickel laterite and nickel sulfide ores, with a growing share being from nickel laterite-based production (British Geological Survey, 2019; United States Geological Survey, 2017c). Nickel laterite ores are mostly mined in open pit mines, whereas nickel sulfide ores are often mined underground. The remaining share comes from minor sources, including pure cobalt and cobalt from platinum group metals production.

Given the increasing importance of cobalt, some studies assessed environmental impacts of products that contain cobalt, such as electric vehicles (Xu et al., 2020). A detailed Life Cycle Assessment (LCA) of cobalt production based on industry data was conducted by the Cobalt Institute (2016), though much of the study remains confidential. The study did however consider cobalt as a coproduct of other metals production and, therefore, the multifunctionality of the metal mining and production processes. Farjana et al. (2019) took a more theoretical approach. Their LCA study is based on data from the ecoinvent database Nuss and Eckelman (2014) and (Wernet et al., 2016). They assessed cobalt production as presented in ecoinvent, disregarding the multifunctional nature of cobalt production. While these studies provide some insight into current impacts, the potential environmental impact of future cobalt production is currently unknown.

The environmental impacts of metal production can be influenced by different factors, such as ore grades, market shares between different production technologies, technological efficiency improvements, and the source of the energy supplied to production. The ore grade, that is, the ratio of contained metal to total ore mass, influences the amount of ore that needs to be processed to produce one unit of metal. Ore grade is a well-known factor influencing environmental impacts of copper and nickel production (Calvo et al., 2016; Chapman & Roberts, 1983; Harpprecht et al., 2021; Norgate & Rankin, 2000; Northey et al., 2014; van der Voet et al., 2018). Market shares can be divided into production from virgin resources, known as primary production, and recycling, known as secondary production. The environmental performance of cobalt production (both primary and secondary) strongly depends on the production route, applied methods, and technologies (Harpprecht et al., 2021; Li et al., 2017; Norgate et al., 2007; van der Voet et al., 2018; Yang et al., 2014). Secondary production adds to these differences through large differences in production methods like pyrometallurgical and hydrometallurgical production (Harpprecht et al., 2021; van der Voet et al., 2018). While technological improvements were considered by Harprecht et al. (2021), the influence on environmental impacts was minor. A more external factor to production is the electricity supply. As revealed by previous studies, the electricity supply could considerably reduce GHG emissions of copper and nickel production (Harpprecht et al., 2021; Norgate et al., 2007; Norgate & Rankin, 2000, 2002) as well as of cobalt production (Cobalt Institute, 2016; Farjana et al., 2019). Harpprecht et al. (2021) also considered technological improvements to production, but this was found to have only a minor influence on environmental performance. Each of these variables could be affected by changes in demand, in part due to the energy transition. In addition, these variables depend on each other. These variables should thus be considered in conjunction, taking a systematic approach considering interdependencies. So far, this has not been studied for cobalt production.

Previous studies modeled most of these variables or scenarios for such variables, either for cobalt itself or for metals related to cobalt production. While scenarios for ore grade decline of copper and nickel have been addressed by Harpprecht et al. (2021) and Northey et al. (2014), none currently exists for cobalt ore grades. Future market share projections for different cobalt-production routes have also not been explored yet, although future demand has been estimated, for example, by Deetman et al. (2018). Additionally, estimates for cobalt use by category and recycling rates exist (Harper et al., 2012; Sun et al., 2019). Finally, for future developments of electricity supply, LCI background datasets are available for future scenarios of electricity production (Mendoza Beltran et al., 2018).

An approach to consider scenarios for interlinked systems in LCA is the use of background scenarios. Background scenarios can be incorporated into a background database to create a future version of supply systems. This keeps interlinkages between systems and thus allows for environmental assessments of future, interdependent systems. Mendoza Beltran et al. (2018) developed a method to generate LCI databases that represent future scenarios for global electricity production from the integrated assessment model (IAM) of IMAGE (Stehfest et al., 2014). These scenarios are based on the shared socioeconomic pathways (SSPs) scenarios (O'Neill et al., 2014). From these future scenarios, they mapped production efficiencies, emissions, as well as market shares of electricity production technologies onto the ecoinvent database. Harpprecht et al. (2021) have built further on the approach of Mendoza Beltran et al. (2018) and developed background scenarios for metals production (copper, nickel, zinc, and lead).

The use of future backgrounds is ideally suited for prospective LCA, which was previously defined as an "...approach [that] studies future technological systems and their environmental implications" (Cucurachi et al., 2018). The further development of future background databases is considered an important development in making more accurate and reliable predictions of future environmental impacts in LCA (van der Giesen et al., 2020).

In this study, we aim to gain insight into the potential future environmental impacts of cobalt production. We develop background scenarios for key variables in the cobalt supply chain using metal demand as the driver, while adhering to the overall storylines of the SSP scenarios. We use the LCA results to identify production hotspots and conduct a sensitivity analysis for important variables. Furthermore, we calculate the potential total impact of cobalt production by considering cobalt demand increases. Finally, we compare our results to previous studies for cobalt production. The results are intended to be used as background scenarios of cobalt production in future prospective LCA studies.

2 | METHODS

This study presents a prospective LCA that models four key variables for cobalt production between 2010 and 2050 in five-year time steps:

1. "Ore grade," leading to changes in energy and resource requirements
2. "Primary production," market shares of primary production routes
3. "Secondary production," market share of secondary production, that is, recycling
4. "Energy transition," changes in the electricity supply

The modeling has been done in alignment with two SSP scenarios (O'Neill et al., 2014), which drive the changes in the earlier-mentioned variables:

1. SSP2 "business as usual" is a scenario that is considered a likely pathway in terms of difficulty in mitigating and adapting to climate change.
2. SSP2-450 "sustainable development" assumes a successful reduction in emissions to limit global warming to 2°C by the end of the century.

The modeled variables were used as changes in the background LCA model for the supply of cobalt, which is described subsequently.

2.1 | Background LCA model of cobalt production

As shown in Figure 1, we represent the supply chain of cobalt through the three principal primary production routes and two methods of recycling. We based our model on the ecoinvent v3.6 cut-off database (Wernet et al., 2016). The three primary production routes were based on existing processes in ecoinvent: Hydrometallurgical production of copper, production of nickel sulfide, and production of ferronickel from nickel laterite, which are also shown in SI-1. For the production of nickel from nickel laterite, we developed an additional process "cobalt production from nickel laterite" to represent the refining of cobalt. Secondary production of cobalt is based on the original ecoinvent processes.

The market for cobalt was modeled by adding the three primary production routes to the existing "market for cobalt" process. The two original sources of cobalt to the market were maintained, their market shares were fixed at 1.5% independent of other variables, and other variables were not considered for these flows.

Cobalt is produced from the three production routes along with copper or nickel products. As these production systems produce multiple products, assigning impacts to any individual product requires the use of allocation to resolve the multifunctional nature of the production systems. A revenue-based allocation was conducted based on the ten-year (2006–2015) global average price and production data of the metals from the United States Geological Survey (2014, 2017a, 2017b, 2018). This led to an allocation factor of 19.1% for cobalt from copper and 4% for cobalt from nickel. Our allocation approach is explained in more detail in SI-1; we also calculate and discuss mass-based allocation in our sensitivity analysis given later.

As functional unit, we used 1 kg of cobalt metal. Four different origins were compared: Each of the three primary production routes, and finally, the "market for cobalt" considering market shares of the three main routes and recycling.

2.2 | Scenarios

We modeled the future changes in cobalt production based on implementations of the policy scenarios "business as usual" and "sustainable development." We used these scenarios as a representation of two policy directions.

As the production of cobalt is strongly related to the production of copper and nickel, we applied the primary copper and nickel demand from the Yale Major Metals (YMM) scenarios by Elshkaki et al. (2018). From the YMM scenarios, we matched the "Market World" to our "business as usual" scenario and the "Equitability World" to our "sustainable development" scenario. Demand for cobalt in various products was previously modeled in

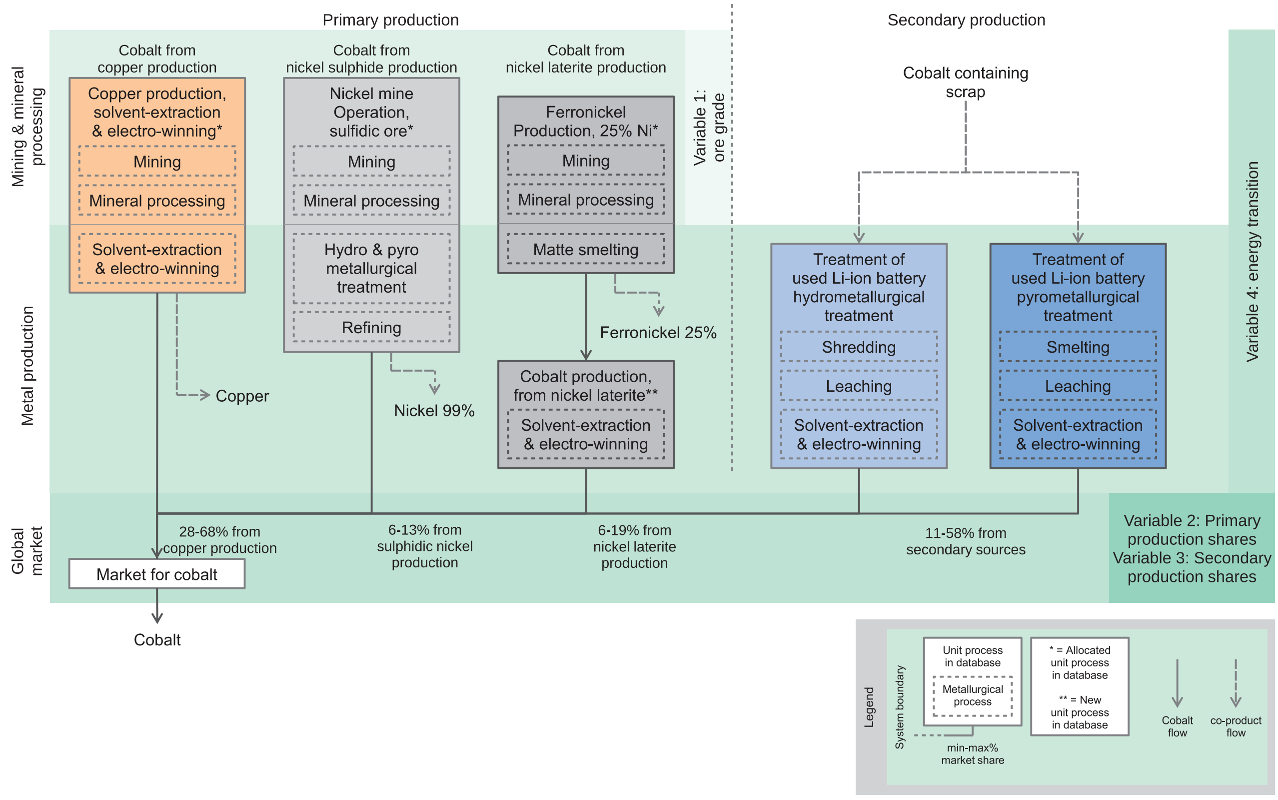

FIGURE 1 Overview of the modeled LCI supply routes based on ecoinvent. Each of the three main primary supply routes and two secondary supply routes and their link to the “Market for Cobalt” process are shown. The market shares refer to the modeled minimum and maximum market shares. All processes affected by a variable are shown within dotted lines

the IMAGE IAM (Stehfest et al., 2014) implementation of the SSP scenarios by Deetman et al. (2018). We used these estimates as the demand for cobalt. Finally, we used electricity-production scenarios from Mendoza Beltran et al. (2018) based on the IMAGE implementation of the SSPs.

2.3 | Variable 1: Ore grade

We used mined ore grade as a proxy for change in ore grade (Figure 2a). Considering the dependence of cobalt production on copper and nickel production, we used their respective future developments of ore grade as a proxy for future cobalt ore quality. A decline in ore quality means a higher energy and materials requirement to produce the same amount of metal.

Based on cumulative future demand of copper and nickel from Elshkaki et al. (2018), we modeled ore grade change through a regression model. Basing the model on cumulative demand allows us to distinguish between different metal-demand scenarios. With the demand in each year, we derived the ore grade in each year for each demand scenario.

Next, we used the results from the ore grade regression model as inputs for another regression model based on data from Calvo et al. (2016). This model estimates electricity and diesel requirements for mining based on ore grade, for open pit mining for copper and nickel laterite, and underground for nickel sulfide mining.

Energy requirements during the refining step of cobalt production do not seem to depend strongly on changes in ore grade (Sverdrup et al., 2017). This relationship diminishes as once a mineral concentrate is produced or the metal has been chemically extracted, the original ore has no direct bearing on downstream processing anymore. We thus assumed refining energy requirement to remain at 3.77 kWh/kg as an average of various sources (Åkre, 2008; Elsherief, 2003; Mulaudzi & Kotze, 2013, p. 14; United States Geological Survey, 2011).

Finally, we linked the energy and ore grade models to exchanges in the LCA unit processes. We did this by identifying each exchange as part of a category, like “mining,” or “refining.” For the production of tailings during mining, tailings were linked to ore grade, for example, a decline in ore grade from 1% to 0.95%, and therefore a relative decline of 5%, means a relative increase in tailings of 1/0.95 (i.e., 5.26% or from 100 to 105.26 kg). For the exchange of diesel use, diesel was linked directly to the modeled diesel requirement. For the exchange of electricity, it was linked directly to the modeled electricity requirement. Additionally, the static amount of electricity (3.77 kWh/kg) required was also included on top to represent refining.

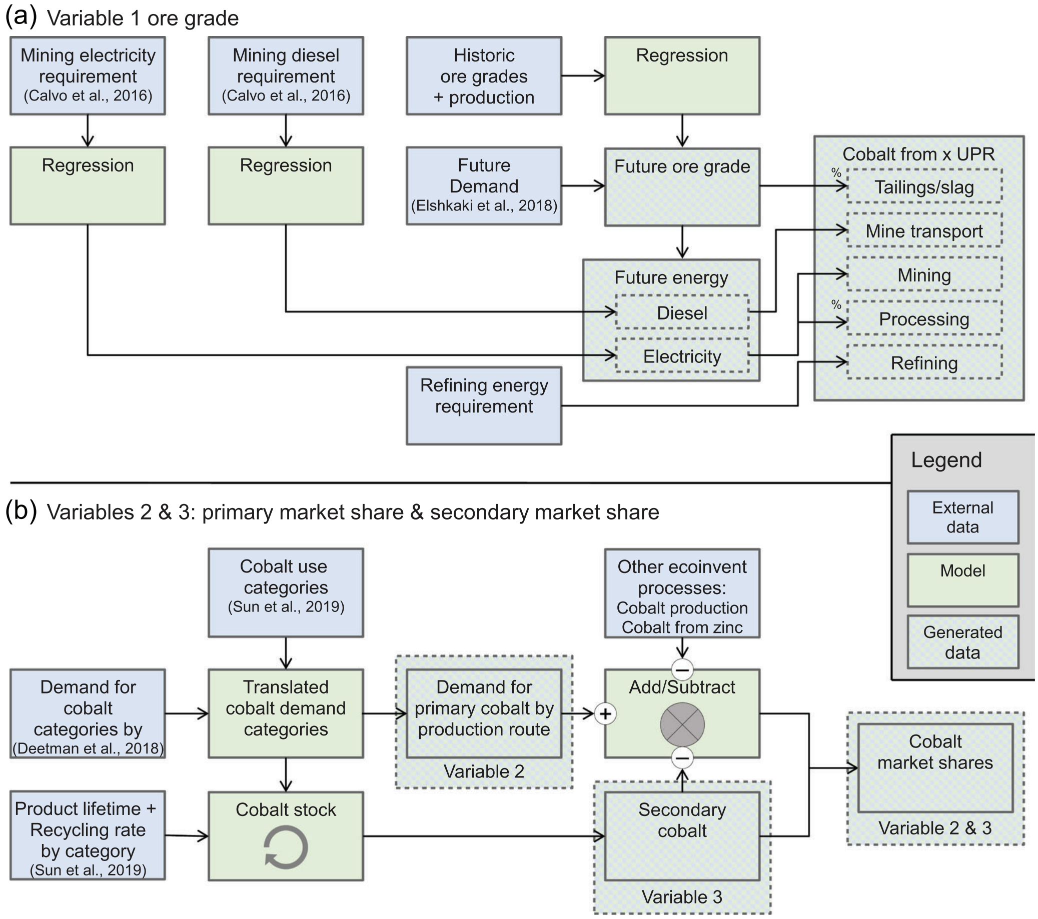

FIGURE 2 Overview of variables 1–3. (a) Variable 1. Based on historic ore grade and future demand, we modeled future ore grade, which we combined with mining electricity and diesel requirement to model future energy requirement. We used this to alter each exchange in a cobalt production process. (b) Variables 2 and 3. We converted demand for cobalt to different demand categories to both model primary demand routes (variable 2) and model cobalt stock with additional product lifetime and recycling rates data (variable 3). By combining primary and secondary cobalt supply, we finally modeled the combined market shares

Next, other exchanges were linked. For this, we mapped each exchange to two major production phases, "mining/processing" or "refining." Each exchange mapped to "mining/processing" was linked relatively to a change in electricity requirement, for example, a relative increase in electricity requirement of 5% (from 1 to 1.05 kWh/kg) means a relative increase in "conveyor belt" of 5%, which would be used for transport at the mine and processing site. The recovery rate of cobalt was assumed at a fixed percentage for each source of cobalt. The implementation of this variable is explained in more detail in SI-1.

2.4 | Variables 2 and 3: Primary and secondary production

Each separate production route for producing cobalt has differences due to the use of different materials and technologies. The model is shown in Figure 2b. This leads to differences in their environmental performances. Variable 2 describes future market shares of different primary production routes, while variable 3 describes the secondary market shares.

Variables 2 and 3 are closely linked as cobalt consumption has a lagged effect on the amount of recycled cobalt available; as such, we modeled them together, while their effects could be assessed separately with our model. Tisserant and Pauliuk (2016) suggest that to better understand future environmental impacts of cobalt production, demand in end-use categories should be modeled in combination with a database like ecoinvent. We used the future demand estimates for cobalt from Deetman et al. (2018). Although not all cobalt demand is covered in these categories, this is the only source with this level of detail. This demand is separated into different categories of material use, for which absolute quantities and market shares differ between the categories in the two scenarios.

Next, we required product lifetime and recycling rates to estimate potential quantities of recycled cobalt. We translated these use categories from Deetman et al. (2018) and Sun et al. (2019), which provide estimates for such recycling data. This process is described in SI-1. Then, the cobalt demand in the new categories was used to derive the market shares of the different primary production routes (variable 2). The demand per category was further used together with lifetimes and recycling rates in a simple stock model. The stock model was used to find the production of secondary cobalt (variable 3) and is further described in SI-1. To combine variables 2 and 3, we subtract the supply of cobalt from secondary sources, as well as the supply of cobalt from the two unmodified ecoinvent processes (cobalt production, and cobalt from zinc) from the total demand to determine the market shares of primary production routes.

The resulting market shares for each of the production routes were linked to the LCA unit process of "market for cobalt."

2.5 | Variable 4: Energy transition

The final variable "energy transition" was included based on the study of Mendoza Beltran et al. (2018), which combined future scenarios from the IMAGE model (Stehfest et al., 2014) with the ecoinvent database to yield future scenario LCI databases. These future scenario LCI databases differ from the ecoinvent database in a number of aspects, including electricity production efficiency and related emissions, regional representation of electricity markets, and the market shares of electricity producers. We used the SSP2 (RCP6) and SSP2-450 (RCP2.6) scenarios. The superstructure approach (Steubing & Koning, 2021) was used to practically calculate LCA results for the range of scenario LCI databases resulting from the work of Mendoza et al. (2018). Since the scenario databases based on Mendoza et al. were calculated in ten-year time steps and the resolution in our model was five-year time steps, we linearly interpolated LCI data from Mendoza et al. to obtain a five-year time step resolution. The output data from these scenarios are based on ten-year time steps, which we linearly interpolated to five-year time steps.

2.6 | Combining variables and technical implementation

Nine different combinations of the variables described earlier are considered for both scenarios and we analyze different kinds of interactions and effects:

1. Ore grade: Variable 1 only
2. Primary market shares: Variable 2 only
3. Market shares of primary and secondary production: Variables 2 and 3
4. All but the energy transition: Variables 1–3
5. The energy transition: Variable 4 only
6. Ore grade + energy: Variable 1 and 4
7. Primary market shares + energy: Variable 2 and 4
8. Market shares of primary and secondary production + energy: Variables 2, 3 and 4
9. All Variables (1–4)

We modeled each variable in both scenarios using python. For the implementation of the unit processes and subsequent LCA, we used the Brightway 2 (Mutel, 2017a) and wurst (Mutel, 2017b) software packages. The changes from each scenario were made through the super-structure approach (Steubing & Koning, 2021). All further analysis of the results was done in python. Each ecoinvent process used was altered following the scenario-variable-combination, starting in 2010. The full technical implementation is explained in SI-1.

2.7 | Sensitivity analysis

We performed a sensitivity analysis in which three modeling assumptions were altered individually. Additionally, we applied a mass-based allocation approach. All sensitivity approaches are described in more detail in SI-1.

First, we swapped our static energy requirement assumption for processing in variable 1 to one modeled with regression based on data from Sverdrup et al. (2017). Secondly, we used a different set of assumptions for cobalt-containing product categories, lifetimes, and recycling rates to achieve a different set of market shares for primary and secondary production as a change for variables 2 and 3, based on data from Harper et al. (2012). Finally, we consider impacts from recycling processes differently. Instead of the 0% allocation to waste treatment coproducts in the ecoinvent cutoff model (Wernet et al., 2016), we assumed a "worst-case" 100% allocation. We made this assumption because of the high recycling rates of cobalt and to gain a better insight into the worst-case scenario of recycling impacts. For our sensitivity analysis on allocation, we applied mass-based allocation based on the same ten-year production average described for the revenue-based allocation.

2.8 | Impact assessment

We used six impact assessment methods: (1) climate change (CC), (2) fossil cumulative energy demand (CED), (3) particulate matter formation (PMF), (4) metal depletion (MDP), (5) human toxicity (HTP), and 6) photochemical oxidant formation (POFP). For CC, the IPCC 2013 (100a) method was used (IPCC, 2014), and as with Mendoza Beltran et al. (2018), we considered biogenic carbon through altering the CC characterization factors. For the other methods, the ReCiPe 2016 midpoint level methods were chosen (Huijbregts, 2016).

2.9 | Total cobalt impacts

As a final step, we assessed the total impact of cobalt production. For this, we used the impact of cobalt from the "market for cobalt" process per kg and multiplied it by the demand in each scenario in each year. We use this as an indication of the total environmental impact that cobalt production could have up to 2050.

3 | RESULTS

3.1 | Variable models

Increases in demand for both copper and nickel lead to a decline in variable 1 (ore grade). More detailed results of the variable changes are presented in SI-1. The change in ore grade is shown in Figure 3a,b. This decline is larger in "sustainable development" scenario, caused by the higher demand for copper and nickel to enable the energy transition. For copper, the modeled ore grade declines from 0.55% to 0.35% and 0.33% in 2050 in the "business as usual" scenario and "sustainable development" scenario, respectively. For nickel, the modeled ore grade declines from 0.8% to 0.49% and 0.45% in 2050 in the "business as usual" scenario and "sustainable development" scenario, respectively.

The decline in modeled ore grade drives energy requirement up between 40% and 66% toward 2050, depending on the scenario, co-mined metal and mining method. Energy requirements are shown in Figure 3c,d. One exception to this is the diesel requirement for nickel sulfide, which is only modeled to increase between 19% and 23%. This is likely due to less diesel being used in underground mine transport.

The market shares for variables 2 and 3 (primary and secondary market shares) fluctuate over time, and the total magnitude of demand increases substantially in both scenarios. The market shares are shown in Figure 3e–h. In both scenarios, around 2012–2015, there is a substantial increase in demand for electric vehicles (Deetman et al., 2018), which translates to an increase in demand for cobalt from copper. By 2020–2025, cobalt from recycled electric vehicle batteries becomes available for recycling, causing an increased share of secondary cobalt.

3.2 | Life cycle impact assessment

The effects of each impact category and scenario–variable combination in 2050 relative to 2010 are shown in Figure 4. More details of the LCA results are presented in SI-1. Each variable modeled influences the long-term environmental impacts of cobalt production in different ways:

- Variable 1 (ore grade) increases the environmental impacts in 2050 for each production route and impact category. This illustrates the extent to which an increase in environmental impacts from just ore grade decline could be expected.
- Variable 2 (primary market shares) shows a minor decrease in PMF while having increases in the other five impact categories in 2050 in both scenarios.
- Variables 2 and 3 (primary and secondary market shares) show a slightly larger decrease in particulate matter for the "business as usual" scenario and lower increases in the other five impact categories in 2050 compared to when only the primary market share is modeled. For the "sustainable development" scenario, impacts in all six categories increase.
- Variables 1, 2, and 3 together show the strongest increases in impacts in the "business as usual" scenario in 2050 for all but PMF, which is moderated slightly by the effects of the primary and secondary markets. In the "sustainable development" scenario, each impact category is substantially increased.
- Variable 4 (energy transition) leads to strong impact reductions for five impact categories, only MDP remains unchanged, as it is not affected by changing energy supply. The effects in the "sustainable development" scenario are notably more positive for CC and fossil CED.

Variable 4, when paired with the other variable combinations, becomes a balancing force in reducing the increasing impact effects of the other three variables. This balancing results in decreasing impact results in the "business as usual" scenario for all but fossil CED. For the "sustainable development" scenario, CC, fossil CED, and PMF decrease, while the other impact categories increase slightly.

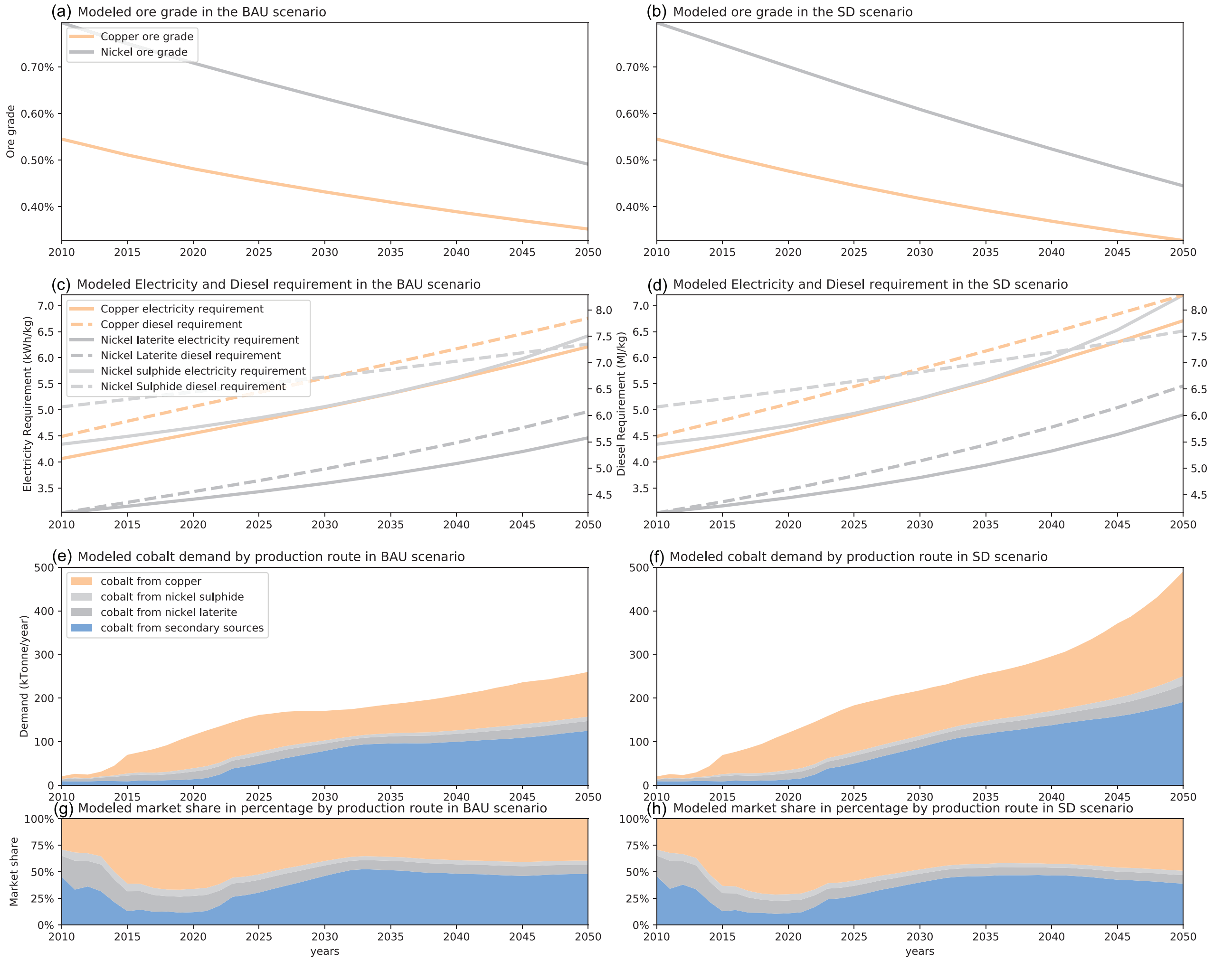

FIGURE 3 (a,b) V1 ore grade in the "business as usual" (BAU) scenario (a) and "sustainable development" (SD) scenario (b). (c,d) Electricity and diesel requirement for each source of metal for the BAU (c) and SD (d) scenarios. (e–h) Market shares of primary and secondary sources of cobalt for the BAU (e and g) and SD (f and h) scenarios. Note that the *y*-axis in (a–d) does not start at 0. The data for this figure is available in a repository (van der Meide et al., 2021)

3.3 | Contribution analysis

In all scenario–variable combinations, electricity is the main driver for CC impacts. This remains the case, even in the best-case scenario, "sustainable development" with only variable 4. This is shown in Figure 5. Fossil CED is caused for 35–40% by natural gas. In all scenario–variable combinations for PMF, cobalt and blasting (a mining activity) account for over 60% of impacts together. MDP impacts are split between concentrates and cobalt, accounting for >98% together in all cases. For HTP, tailings are responsible for >90% of impacts in all cases. Finally, POFP by blasting is responsible for >50% of impacts.

3.4 | Cobalt production impacts over time

When considering the impacts from 2010 to 2050, other effects become visible. This is shown in Figure 6 for the "business as usual" scenario. The impact-reducing effect of the secondary market share is most visible between 2010 and 2030; all impacts rapidly increase and decrease again, caused by the lack of secondary cobalt, as was also shown in Figure 3e–h. For variable 1, all impacts steadily increase over time.

For total impacts of cobalt production, we found that for CC and CED, the impacts depend heavily on the inclusion of variable 4. As displayed in Figure 7, the substantial difference in cobalt demand between the two scenarios is not reflected in the environmental impact when considering the energy transition as growth in environmental impacts is decoupled from growth in demand. This decoupling would however come with a trade-off with the other impact categories studied, as also displayed in the figure. These other impact categories (PMF, MDP, HTP, and POFP) have

Route	Scenario	ariable	Climate change	Fossil cumulative energy demand	Particulate matter formation	Metal depletion	Human toxicity	Photochemical oxidant formation
Market for cobalt	BAU	V1	16%	14%	19%	7%	30%	32%
		V2	2%	2%	-4%	11%	32%	18%
		V2+3	1%	1%	-6%	10%	29%	16%
		V1+2+3	20%	18%	18%	19%	70%	58%
		V4	-10%	-17%	-3%	0%	1%	-4%
		V1+4	5%	-4%	16%	7%	31%	28%
		V2+4	-8%	-16%	-7%	11%	33%	13%
		V2+3+4	-9%	-17%	-8%	10%	30%	11%
		V1+2+3+4	9%	-1%	15%	19%	71%	54%
	SD	V1	19%	17%	23%	8%	35%	40%
		V2	2%	2%	-5%	13%	37%	20%
		V2+3	12%	10%	7%	21%	56%	36%
		V1+2+3	40%	36%	43%	34%	114%	101%
		V4	-53%	-50%	-15%	0%	-1%	-8%
		V1+4	-40%	-38%	7%	8%	33%	31%
		V2+4	-52%	-49%	-20%	13%	35%	12%
		V2+3+4	-47%	-44%	-8%	21%	55%	28%
		V1+2+3+4	-28%	-27%	24%	34%	112%	91%

Route	Scenario	ariable	Climate change	Fossil cumulative energy demand	Particulate matter formation	Metal depletion	Human toxicity	Photochemical oxidant formation
Cobalt from copper	BAU	V1	40%	39%	48%	21%	36%	51%
		V4	-8%	-13%	-4%	0%	0%	-2%
		V1+4	30%	21%	43%	21%	36%	49%
	SD	V1	50%	48%	59%	25%	41%	63%
		V4	-46%	-42%	-14%	0%	-1%	-3%
		V1+4	-13%	-10%	40%	25%	40%	58%
Cobalt from nickel sulphide	BAU	V1	6%	7%	6%	5%	26%	9%
		V4	-5%	-10%	0%	0%	1%	-1%
		V1+4	1%	-4%	6%	5%	27%	8%
	SD	V1	8%	9%	8%	7%	30%	12%
		V4	-26%	-32%	-1%	0%	-6%	-2%
		V1+4	-20%	-26%	6%	7%	23%	10%
Cobalt from nickel laterite	BAU	V1	15%	13%	17%	28%	19%	17%
		V4	-8%	-11%	-11%	1%	5%	-15%
		V1+4	8%	1%	5%	29%	25%	1%
	SD	V1	20%	17%	22%	36%	25%	21%
		V4	-46%	-37%	-42%	1%	-28%	-27%
		V1+4	-29%	-22%	-23%	37%	-4%	-7%

V1: Ore grade, V2: Primary market shares

V3: Secondary market shares, V4: Electricity supply

BAU: Business as Usual, SD: Sustainable Development

FIGURE 4 Overview of relative impact changes of relevant variables in 2050 compared to 2010 in the "business as usual" and "sustainable development" scenarios for each production route and the market for cobalt for the production of 1 kg of cobalt. The data for this figure is available in a repository (van der Meide et al., 2021)

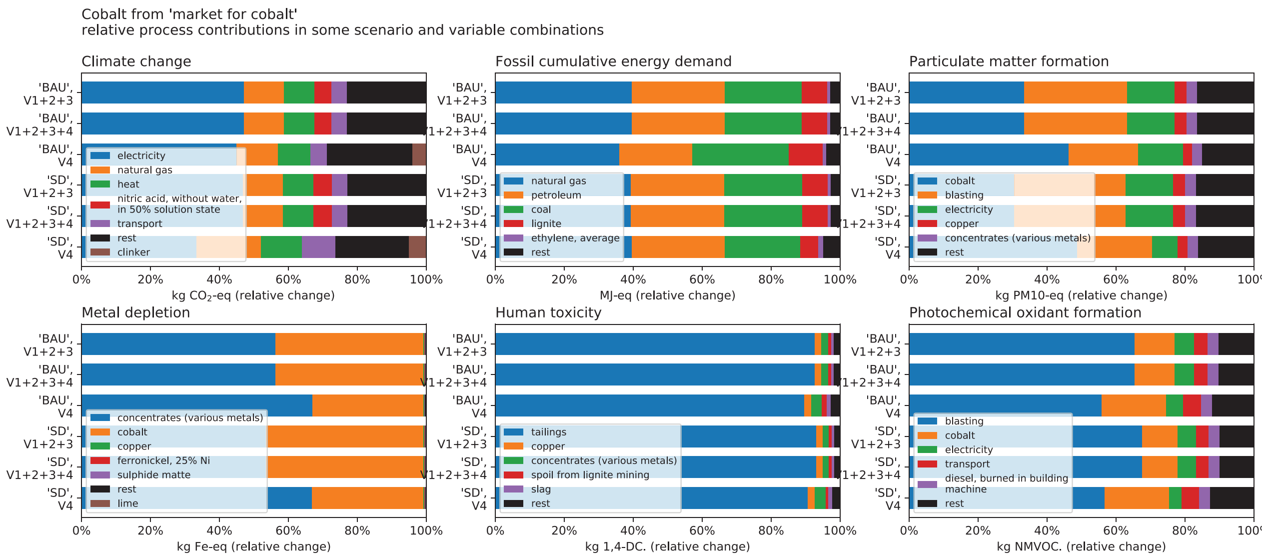

FIGURE 5 Relative process contributions for the production of 1 kg of cobalt for the business as usual (BAU) and sustainable development (SD) scenarios with variable combinations V1+2+3, V1+2+3+4, and V4. The data for this figure is available in a repository (van der Meide et al., 2021)

substantially higher impacts in the "sustainable development" scenario. This could in large part be explained by the higher demand. It is also visible that the effects of the energy transition are substantially less pronounced in these impact categories.

3.5 | Sensitivity analysis

The adjustment of static processing of energy requirements for variable 1 to dynamic processing yields only very minor differences in total results. More detailed results of the sensitivity analyses are presented in SI-1. These results are also presented in SI-1. The change in market shares in variables 2 and 3 yields decreased impacts in all six categories. This is primarily due to the estimation of a lower rate of cobalt recycling by

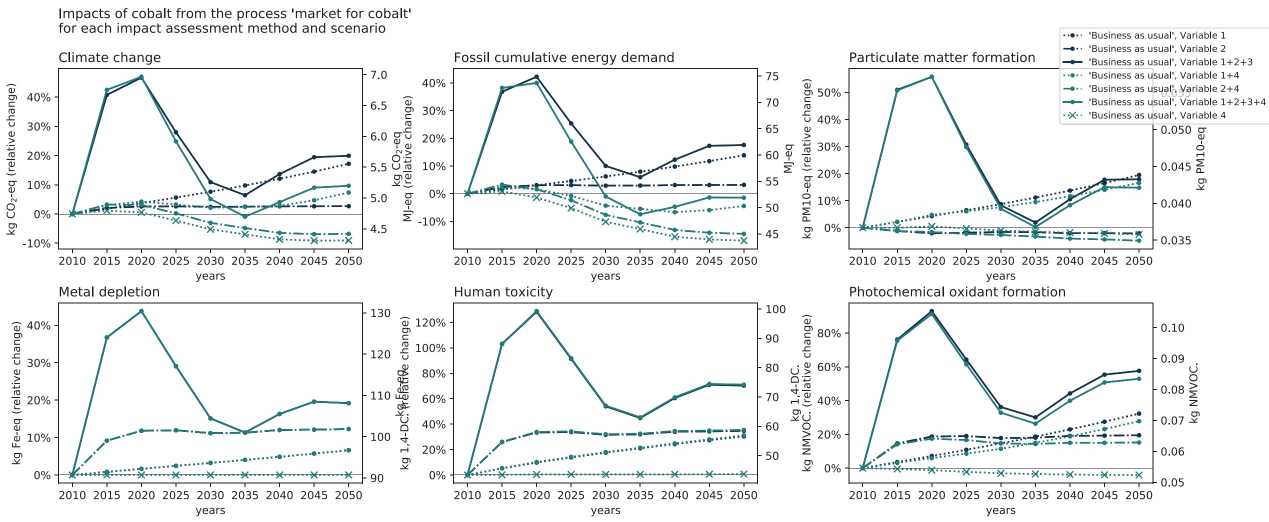

FIGURE 6 Relative (left axis) and absolute (right axis) change in impacts for the production of 1 kg of cobalt in the "business as usual" scenario for V1 ore grade, V2 primary market, V1+2+3 all variables, V1+4, V2+4, V1+2+3+4, and V4 energy transition for the market for cobalt. The turquoise lines are variable 1/2/3 combined with variable 4, energy transition, blue without. The data for this figure is available in a repository (van der Meide et al., 2021)

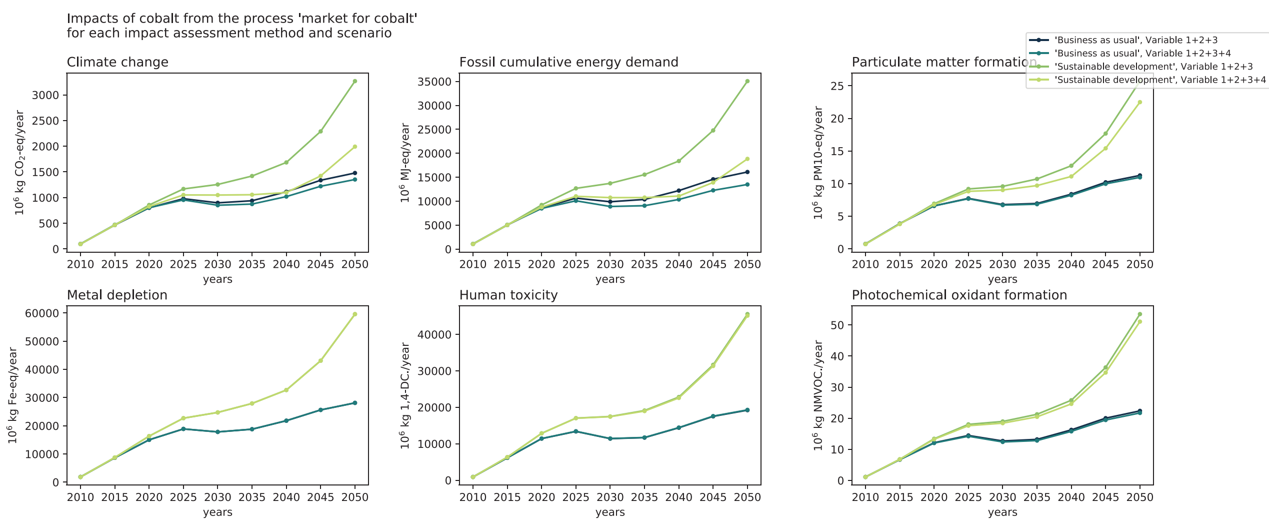

FIGURE 7 Development of total impacts in the "business as usual" (blue lines) and "sustainable development" (green lines) scenarios for variable 1+2+3 (all variables without energy transition) and variable 1+2+3+4 (all variables). The data for this figure is available in a repository (van der Meide et al., 2021)

Harper et al. (2012). When considering the 100% allocation to cobalt scenario for impacts of recycling on cobalt production, all impacts increase in the market for cobalt, with between 6.8% and 12.6% for CC, depending on the year. When combining the changed market shares and recycling impacts, final results are decreased in all six categories compared to the baseline results, with between 2.7% and 29.8% for CC, depending on the year.

4 | DISCUSSION

The aim of this study was to determine how the environmental impacts of cobalt production could change up to 2050 and to provide a method for integrating the results into other prospective LCA studies. To achieve this goal, we modeled the impact of four factors that affect the supply of cobalt from different production routes in two scenarios between 2010 and 2050. The scenario results of this study could be used as background data in further studies that consider the future environmental impacts of cobalt-containing products by following the superstructure approach (Steubing & Koning, 2021). We enable the use of the superstructure approach by providing the data files in a repository (van der Meide et al., 2021).

4.1 | Ore grade and market shares

Our model for ore grade and energy requirement allowed us to estimate future impacts of cobalt supply for two scenarios, "business as usual" (BAU) and "sustainable development" (SD), using metal demand as a driver. We found that the higher demand for metals in the SD scenario could cause a faster ore grade decline and a higher increase in energy requirements for the production of cobalt compared to BAU.

Despite the usefulness of the models we developed, one major limitation should be considered with these results: Ore quality is a complex issue that is not well modeled for most metals, including copper, nickel, and cobalt. The true quality of a cobalt resource extends far beyond simple measurements such as ore grade, and should also consider the specific mineralogy, morphology, and accessibility of these deposits. These factors are all highly variable between individual cobalt-bearing mineral deposits and this translates into significant variability in the potential recovery, economics, and environmental impacts of cobalt extraction (Dehaine et al., 2021; Mudd et al., 2013). Importantly, any evaluation of the quality of a mineral resource is dependent upon the (implicitly or explicitly) assumed economic context, and so our perception of the availability and quality of cobalt resources may change drastically if future economic conditions change. A complicating factor is the various definitions of ore grades, which are sometimes confused or aggregated with each other in LCA studies (Northey et al., 2018). There is also considerable complexity and limited data available to understand how mined grades of byproducts, such as cobalt, may evolve into the future. Long-term declines in the average grade of remaining copper and nickel resources could reasonably be expected, if market conditions and technology assumptions used to define mineral resources are static and when assuming preferential extraction of high-grade mineralization and progression along the cumulative grade-tonnage relationships for copper and nickel resources. As cobalt is a coproduct of copper and nickel production, we assumed that declining ore grades of copper and nickel could be used as a proxy for changes in cobalt ore grades. Considering the inherent complexity and uncertainties underlying this assumption, the ore grades we modeled in this study should not be considered predictions, but rather loose proxies for the potential for change in resource quality.

To model the market shares for the cobalt supply, we developed a stock model and found that there could occur a period in which secondary cobalt supply is heavily outpaced by high demand for cobalt in a "circularity gap." Despite that cobalt has traditionally been a metal with good recycling efficiencies (Nansai et al., 2014), even with high recycling rates, sudden increases in demand will result in primary demand as secondary supplies will lag behind the demand. We also observed this result in our sensitivity analysis when using market shares and recycling estimates from Harper et al. (2012).

A limitation of our stock model is that it considers only the global supply of cobalt, which reduces applicability and ignores changes in transport requirements for cobalt from different sources. Additionally, the stock model does not assume changes in cobalt content in a product or changes in their recycling rates.

4.2 | LCIA results in context of other cobalt-production studies

Our results show that the environmental impacts of cobalt production could increase and that the magnitude of this increase is strongly influenced by the electricity supply. It should also be noted that even though impacts per unit of cobalt could be much lower in the SD scenario, the total demand would be nearly twice as high as in the BAU scenario, resulting in a total emissions growth.

Two notable previous LCA studies on the supply of cobalt have been conducted: The Cobalt Institute (2016) and Farjana et al. (2019), shown in Table 1. The Cobalt Institute states in their study that variability of results might be higher than with other LCA studies on metals due to the coproduction nature of cobalt and the wide range of production processes and sources. As a comparison, the reported CC and CED results per mass of production for cobalt production have often exceeded the results for bulk and base metal reported by others, such as Norgate et al. (2007) and van der Voet et al. (2018).

To validate the results of our study, we compared the impacts of copper production from our process "cobalt from copper production" with impacts of copper production of other studies. This additional comparison is discussed in the SI-2. These comparisons suggest that the outcomes of this study are in line with those of other LCA studies, such as Li et al. (2017), Memary et al. (2012), Norgate and Rankin (2000), and Yang et al. (2014).

One factor that affected our results is the use of the ecoinvent cut-off model (Wernet et al., 2016). Our stock model suggests that substantial amounts of cobalt are recycled, while the ecoinvent cut-off model allocates 0% of impacts to recycled materials. To counteract this optimistic assumption, we performed a sensitivity analysis that assumes a 100% allocation of the recycling impacts to cobalt production. This resulted in a minor increase of impacts of 12.6% in 2010 for CC. Another factor that could explain the lower impacts in our results could be that our models use the updated electricity generation data from Mendoza Beltran et al. (2018).

TABLE 1 Comparison of results with previous LCA studies on the environmental impacts of cobalt production

Study		Database	CC ($kgCO_2eq$/kg cobalt)	CED (MJ/kg cobalt)
Our study, BAU, market for cobalt, all variables	2010	Superstructure based on Ecoinvent 3.6 cut-off	4.3	53
	2025		5.3	63
	2050		4.7	52
Cobalt Institute (2016)		Gabi	38	653
Farjana et al. (2019)		Ecoinvent	12	141
Ecoinvent 3.6 cut-off (Wernet et al. 2016)		Ecoinvent 3.6 cut-off	9.5	127

Note: CC = Climate Change; CED = cumulative energy demand.

4.3 | Limitations

Two factors that were considered static are a limitation in our study. First, estimates for cobalt recovery rate were used from Crundwell et al. (2011), which is the ratio between total cobalt content of the ore versus the extracted amount of cobalt metal. These estimates could be outdated. Besides, Tisserant and Pauliuk (2016) stated that through economic mechanisms, the recovery rate of cobalt could change over time. This would depend on the supply–demand ratio, as a higher demand for cobalt would likely increase the recovery rate of cobalt and changes to process optimization could additionally decrease the recovery rates of the host metal. Such changes could alter the environmental impacts of both cobalt and the host metal production, as the process outputs could change with only minor changes to the process inputs, causing a shift in impact per unit of cobalt produced.

The second factor is that our allocation factors were derived in a simplified way. We used the global ten-year average price and production values of copper, nickel, and cobalt. For both copper and nickel production, only a minority of mines produce cobalt (Tisserant & Pauliuk, 2016), so we only considered production volumes of countries producing cobalt where also copper or nickel is produced. The Cobalt Institute (2016) realized a more complex allocation procedure based on physical processes, intermediate product pricing (for example for cobalt hydroxide), or cobalt and other metal pricing, which was not applied in this study due to the lack of data. However, we did apply mass-based allocation as sensitivity analysis and found that this reduces impacts substantially due to the higher weightings of copper-and nickel-production routes.

4.4 | Further research

Managing the environmental impacts of the energy transition will require an improved understanding of material supply chains and the relationships between material and energy supply. By identifying important variables and modeling those in line with policy scenarios from IAMs, other materials could also be studied to expand the availability of prospective LCA background data for other studies. Studying materials that could have significantly changing impacts, materials that are of great importance to society or are used as commodities for many applications might prove most effective to expand the reach of this type of study. Ensuring a high degree of compatibility with background databases like ecoinvent and other future background studies like ours would also likely improve the reach and adoption of this type of study.

For our study, we identify three points. (1) Regionalizing production: We used global datasets, and using regionalized data could make results more specific. This could be especially useful in combination with the electricity dataset from Mendoza Beltran et al. (2018). (2) Modeling recovery rates: For a material that is coproduced such as cobalt, the demand for it and the main metal could have major effects on the recovery rate of the coproduced material (Tisserant & Pauliuk, 2016). Modeling recovery rates of each coproduct could alter both impacts and partitioning with allocation, both can have major effects on sustainability impacts. (3) Establishing models for the evolution of cobalt (and other byproducts) ore grades: There are conceptual and data difficulties in translating host metal grade scenarios (which are already highly uncertain) into grade scenarios for companion/byproduct grades, particularly for some deposit types or mineralogies where host and byproduct grades may not be strongly correlated. Methods for inferring companion metal grades developed by Werner et al. (2017) could potentially be adapted to support this form of modeling.

4.5 | Conclusion

This study demonstrates that multiple competing pressures may alter the environmental impacts of cobalt production over time. As part of this, we identified potential synergies between increased secondary production of cobalt, adoption of renewable energy in the electricity sector, and the consequent reductions in the long-term environmental impacts of the mineral and metal production. Importantly, the study demonstrates that it may be possible to decouple growth in annual cobalt production and the associated depletion of high-quality mineral resources from rises in the total annual CC impacts of cobalt production. Despite this, under both the sustainable development and business-as-usual scenarios, the total demand growth results in an increase of impacts of cobalt production across all impact categories. This study demonstrates the benefits of taking a system and life cycle approach to model and better understand interrelationships between different sectors so that the factors influencing long-term changes in environmental impacts and greenhouse gas emissions can be more clearly articulated and addressed. This should also be extended to consider the use of cobalt as a contributor to reductions in greenhouse gas emissions in other sectors of the economy, especially the energy and transport sectors through its use in battery technologies. Finally, the developed database from our study could be used as a background database in other LCA studies where the use of cobalt in the future would be relevant for the studied functional unit.

Our results indicate two major opportunities to reduce the environmental impacts of cobalt production: Firstly, improving recycling rates and efficiency could help reduce the impacts of cobalt production. As a secondary effect from this, reduced primary supply could reduce rates of decline in the availability of high-grade ores and subsequently reduce potential increases in the impacts of extraction. As a second opportunity, the energy transition could help reduce the impacts of cobalt production, despite higher cobalt demand. A range of policy and technical solutions should be developed to drive improvements over time, such as increasing recycling rates of cobalt-containing products, improving recovery of cobalt in primary production processes, and rapidly adopting renewable energy use in cobalt and electricity production more broadly.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/record/6396610, reference number 10.5281/zenodo.6396610.

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