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The impact of climate policy implementation on lithium, cobalt and nickel demand: The case of the Dutch automotive sector up to 2040

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The Dutch national climate agreement ('Klimaatakkoord'), stipulates a 49% decrease in greenhouse gas (GHG) emissions by 2030, relative to the 1990 level. To accommodate this target, the passenger vehicles sector must reduce its GHG emissions by 30% in 2030, which likely will come about by replacing internal combustion engine vehicles with electric vehicles. In this study, a dynamic material flow model combined was applied to investigate the future demand for (and metabolism of) lithium, cobalt, and nickel within various scenarios of Dutch electric vehicle markets stemming from climate policy implementation. Our results show that by 2040 the demand for electric vehicles rapidly grows by an order of magnitude, which expands by two orders of magnitude the annual accumulation of these metals in the Netherlands when compared to the 2019 levels. Lithium and nickel demand will keep increasing through 2040, while the demand trend of cobalt will start to drop after 2030, due to changes in battery technology. Increasing the EV driving range and replacing EV batteries during an EV lifetime will increase the demand for these metals by 10%–19%. Conversely, extending the average battery lifetime to meet the vehicle lifetime could reduce the demand of these metals by 30%. Due to the low open-loop recycling of these metals, policies must seek to minimize their presence in the electric mobility sector, while also stimulating better recycling practices and infrastructure.

1. Introduction

One of the largest carbon-emitting sectors in the Netherlands is transport, which represented 12% of total greenhouse gas (GHG) emissions, amounting to 26 billion kg CO_2-eq in 2018 (Jos. G. J. Olivier, 2019). To address this growing problem, the Dutch government has set a target of 30% GHG emissions reduction from the passenger transport sector by 2030, compared to 1990 levels (Dutch Ministry of Economic Affairs and Climate, 2019). In order to achieve this reduction, the Netherlands is proposing to cease the sale of new internal combustion energy passenger vehicles by 2030, with electric vehicles (EVs) likely to become the main form of replacement. This decarbonization policy is likely to drive the boom of EVs in the Dutch mobility sector in the coming decades, supported by decreasing EV prices and subsidies that stimulate the sale of new and second-hand small size EVs (Dutch Ministry of Economic Affairs and Climate, 2019).

EVs have become the main alternative to internal combustion vehicles in recent years in great part due to the rapid development of EV batteries. In previous decades, nickel-metal hybrid (NiMH) batteries were the primary choice for hybrid electric vehicles (HEVs). In recent years, lithium-ion batteries (LIBs) with higher specific energy and a longer lifespan have become increasingly commonplace in HEVs, plug-in hybrid vehicles (PHEVs) and pure electric vehicles (BEVs) (Cano et al., 2018; Schmuch et al., 2018). The performance of LIBs is mostly determined by the cathode chemistry, with lithium (Li), cobalt (Co) and nickel (Ni) as the key components due to their high electrochemical activity. While $LiMn_2O_4$ (LMO) and $LiCo_2O_4$ (LCO) batteries were commonly used on the first EV models, newly-launched EV models are gradually switching to $LiNiCoAlO_2$ (NCA) and $LiNi_xCo_yMn_{(1-x-y)}O_2$ (NMC) batteries, due to the higher energy content (Cano et al., 2018; Olivetti et al., 2017; Schmuch et al., 2018). In the NMC class, NMC-111 and NMC-622 batteries (where the numbers represent the ratio of Ni, Co, and Mn on a mole fraction basis) are commercially available, but NMC-811 batteries are considered to be the most promising NMC technology in the coming years (Cano et al., 2018; Hund et al., 2020; Kwade et al., 2018).

Policies to decarbonize the Dutch mobility sector will thus bring a large amount of Li, Co and Ni into the Dutch economy. Studies thus need to quantify both the variations in future material demand with different technological improvements in EV batteries, and also the timelines for

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when EV batteries reach their end-of-life. EV batteries may be recovered for reuse (e.g. grid-connected storage, backup supplies) or may be directly recycled for its materials, provided effective recycling techniques and a suitable waste management system are enacted (Harper et al., 2019; Schneider et al., 2009). Thus, assessments of future material demand and supply in the Dutch mobility sector can be used by policymakers to evaluate future potential circular strategies for secondary material use.

The aim of this study is to assess the dynamics of Li, Co, and Ni in the Dutch EV sector that accommodates the Dutch national climate agreement. A dynamic material flow analysis (Fishman et al., 2018; Hund et al., 2020; Sato and Nakata, 2020; Song et al., 2019; Sun et al., 2019; Xu et al., 2020) was applied to estimate the Li, Co, and Ni demand in passenger-based EVs until 2040. This analysis further assesses the impact of changing battery lifespans, battery cathode chemistries, and battery capacity on the material flows for these elements under a future mobility sector that abides by the Dutch climate agreement.

2. Methods

2.1. Dynamic MFA model

To quantitatively study the EV demands and their potential end-of-life in the Netherlands through to 2040, we applied a dynamic MFA model (Deetman et al., 2018; Dong et al., 2019; Müller et al., 2014). As shown in equations (1)-(3), the annual new EVs sales (“$Inflow_{(t)}$”) were estimated as the sum of EVs expansion or reduction expected in a specific year ($\Delta Stock_{(t)} = Stock_{(t)} - Stock_{(t-1)}$) and the number of end-of-life EVs (“$Outflow_{(t)}$”) in that year. The number of end-of-life EVs was estimated on the basis of the stock in combination with a vehicle lifespan distribution (using vehicle lifetime distributions $f_{(T)}$, described in 2.2.1). The historical stock of EV data until the year 2019 (e.g. the base year) were collected from the Netherlands Vehicle Authority (RDW) (“RDW Open Data Source,” n.d.). RDW offers open-access datasets of Dutch vehicles, such as models, segments, and date of registration. The prospective stock of EVs from year 2020–2040 (e.g. the scenario years) was estimated on the basis of Dutch government goals for the future share of EVs in the total passenger cars. The future total passenger cars was estimated based on historical data collected from the Dutch Central Bureau of Statistics (CBS) (“CBS Open Data Source,” n.d.) by assuming a vehicle-to-population ratio and future population growth from the Shared Socio-economic Pathway, SSP2 (Riahi et al., 2017) (details in the Supporting Information (SI)).

$$Sale_{(t)} = Inflow_{(t)} = \Delta Stock_{(t)} + Outflow_{(t)} \tag{1}$$

$$Stock_{(t)} = \sum_{\tau=t_0}^{t} \left(Inflow_{(\tau)} \times f_{(t)} \right) \tag{2}$$

$$Outflow_{(t)} = Inflow_{(t)} \times (1 - f_{(t)}) \tag{3}$$

2.2. EV battery lifetime and composition

2.2.1. Lifetime distribution scenarios

To calculate the lifetime of the vehicles, we applied the Weibull cumulative distribution function $f\ (t-\tau,\ k,\ \lambda)$:

$$f(T, \tau,\ k, \lambda) = 1 - e^{-\left(\frac{T-\tau}{\lambda}\right)^{k}} \tag{4}$$

in which, k is a shape parameter and λ is a scale parameter. The parameters were taken from a previous study (Fishman et al., 2018).

In theory, an EV battery depleted to 80% of its original capacity is considered to reach its end-of-life. The average lifespan of EV battery is about 8 years as suggested by many EV automakers (Harper et al., 2019). However, the average service time of common passenger cars varies across studies in the range of 10–16 years (Huang et al., 2011; Richa et al., 2014). Considering the mismatch of lifespans between the vehicle itself and the EV battery, three scenarios were evaluated:

1. A **short lifespan scenario** assuming an average 8-year life span for both vehicle and EV battery, as suggested by previous studies (Deetman et al., 2018).
2. A **long lifespan scenario** assuming a 13-year average lifespan, equal to the lifespan of passenger cars in the Netherlands, based on the average vehicle outage data published by the Dutch Central Bureau of Statistics (CBS) (“CBS Open Data Source,” n.d.). This scenario presents a very optimistic outlook of battery lifespan.
3. An **extended EV use scenario**, which considers that the vehicle and the EV battery have different lifetimes. Here, we assumed a lifetime distribution of 13 years for the vehicles, and fixed-8 years for the EV battery, implying that the first EV battery has to be replaced after 8 years and the replaced EV battery has a lifetime of 5 years.

Note that all the parameters for different scenarios were shown in Table 1, and details for Weibull cumulative distribution are shown in Fig. S4 in SI.

2.2.2. Battery technology and capacity

The battery material demand was calculated by converting the EV units to battery material mass. This is influenced by many factors, such as manufacturing, vehicle battery type, and production year. Among these, the choice for EV types, amount of the energy content stored in the EV battery (battery capacity), battery technology and metal intensity of EV battery play essential roles in determining the quantity of required battery materials (Schmuch et al., 2018; Speirs and Contestabile, 2014).

The battery material in EVs depends on the type of vehicle powertrain. Normally, fully battery-powered BEVs are applied in larger-sized EV battery storage, as they require more energy content than the ones in HEVs and PHEVs. The sales of different types of EVs were estimated by multiplying total EV sales to a market share of different EV types. The historical market share of different EV types was calculated based on the annual numbers of registered EVs for recent years (2010–2019)

Table 1
Assumptions on factors for different scenarios.

	Lifespan parameters	Battery Capacity		Battery cathode chemistry	
		HEV and PHEV	BEV	HEV and PHEV	BEV
Short Lifespan Scenario	k = 1.89 λ = 10.3	HEV: 5 kWh PHEV: 10 kWh	Low: up to 68.6 kWh Medium: up to 84.4 kWh High: up to 96.7 kWh	NMC-111	dynamic (shown in Fig. 2)
Long Lifespan Scenario	k = 4.03 λ = 13.43	HEV: 5 kWh PHEV: 10 kWh	Low: up to 68.6 kWh Medium: up to 84.4 kWh High: up to 96.7 kWh	NMC-111	dynamic (shown in Fig. 2)
Extended EV use Scenario	EV: k = 4.03, λ = 13.43 EV battery: 8 years	HEV: 5 kWh PHEV: 10 kWh	Low: up to 68.6 kWh Medium: up to 84.4 kWh High: up to 96.7 kWh	NMC-111	dynamic (shown in Fig. 2)

collected from the RDW. The prospective market share of different EV types was fitted based on the future policies of the Climate Agreement with the Dutch government (Dutch Ministry of Economic Affairs and Climate, 2019) (shown in Fig. S1 in SI).

In this study, the battery capacity of HEVs and PHEVs were assumed with a constant average value of 5 kWh and 10 kWh for each scenario, respectively. For BEVs, the battery capacity was assumed to be dynamic as more effort is spent on developing better BEVs (Küfeoğlu and Khah Kok Hong, 2020). We assumed that driving range was the main technical factor affecting battery capacity (Delogu et al., 2017), also to reflect the efforts that BEV automakers are putting into achieving longer driving ranges (Cano et al., 2018; Li et al., 2020). The average battery capacity and average driving range of BEVs from 2010 to 2019 were calculated based on the manufacture reports of the most popular sold BEV models in the Netherlands (Table S2 in the SI). The future driving range was assumed to reach 350 km, 450 km, 550 km (Low/Medium/High) in different scenarios. The prospective battery capacity for BEVs was calculated based on an average of 0.18 kWh capacity per additional kilometer, as demonstrated by a previous study (Notter et al., 2010) (Fig. S5 in SI).

Five types of LIB cathode chemistry were chosen in our study: LMO, NCA, NMC-111, NMC-622, NMC-811. We assumed NMC-111 as the only cathode chemistry for HEVs and PHEVs, while for BEVs, we assumed a dynamic market share for the five types mentioned above. The past and current market share of LMO, NCA, NMC-111, NMC-622 on BEVs was estimated on the basis of their historical data (Table S2 in SI). Future aggregated market trends were predicted by the latest report from the World Bank (Hund et al., 2020), excluding lithium iron phosphate (LFP) batteries. These were excluded based on the consideration that no application of LFP battery on passenger-based BEV models was shown from the RDW data and more advanced cathode technology is likely to commercialize in the coming years (Hund et al., 2020). Furthermore, although NMC-811 has not been commercialized yet, it has been considered as the most promising substitution to high Co-content batteries (Cano et al., 2018; Hund et al., 2020; Kwade et al., 2018). Thus, we made an assumption of its future market share emerging by the late 2020s (Cano et al., 2018; Hund et al., 2020; Kwade et al., 2018), with a similar growth speed to that of the NMC-622 battery.

The market share of battery cathode chemistry used on BEVs was fitted by a logistic growth function (equation (5)), which described the slow introduction stage, rapid growth phase and final ubiquity of technology substitution with its S-shape as previously suggested (e.g. ((Fishman et al., 2018) and Kucharavy et al. (Kucharavy and De Guio, 2011)).

$$y_{(t,\ i)} = \frac{A(i)}{\left(1 + e^{-B(i)(t-M(i))}\right)} \tag{5}$$

where, $y_{(t,i)}$ is the market share of battery cathode chemistry i in year t; $A(i)$ is the top asymptote set to the maximum market share of battery cathode chemistry i; $M(i)$ is the point in time with the highest growth of battery i; $B(i)$ is the slope of growth.

The metal composition and intensities of different Li-ion battery types were derived from various studies (Cano et al., 2018; Fishman et al., 2018; Sun et al., 2019) and were listed in supporting information Table S3. A sensitivity analysis with regard to metal composition and intensity was also performed (Section 3.3 and Figs. S6 and SI).

Using the aforementioned information and assumptions, the demand of three metals (Li, Co and Ni) in EV batteries was calculated by using the equation below:

$$MD_{(y,\ t)} = \sum_i \sum_j \left(Sale_{(t)} \times PE_{(i,\ t)} \times PC_{(c,\ i,\ t)} \times D_{(i,\ j,\ t)} \times m_{(j,\ y)}\right) \tag{6}$$

in which, $Sale_{(t)}$ is annual sale calculated as before in year t; $PE_{(i,\ t)}$ is EV type i in year t (i = PHEV, HEV, BEV); $PC_{(c,\ i,\ t)}$ is battery capacity c of EV type i in year t; $D_{(i,\ j,\ t)}$ is battery cathode chemistry type j (j = LMO, NCA, NMC-111, NMC-622, NMC-811) of EV type i in year t and $m_{(y,\ j)}$ is the metal intensity of a given material y in a lithium-ion battery j.

3. Results

3.1. EV demand and battery technology innovation

3.1.1. Dutch EV growth in recent years

According to EV sale statistics (Fig. S1), HEVs accounted for over 60% of the EV market before 2014, with its market share continuously decreasing with the emergence of PHEVs and BEVs. The sales of PHEVs and BEVs have kept growing, reaching 62% of the EV market in 2019. More than sixteen thousand PHEVs and BEVs have been sold for passenger use by 2019. PHEVs occupied more of the market than BEVs before 2018 with total sales of about 98,000 units and BEVs have gained market share since 2018 with a total sales of about 66,000 units by 2019 (Fig. 1).

Based on the collected information of the most-sold BEV models (Table S2 in SI), the BEV models launched to market now are almost exclusively powered by LIBs, and the mainstream battery cathodes on BEV models before 2016 in the Netherlands were LMO and NMC-111. The NCA battery, mostly used in the Tesla models (Park et al., 2016), has been rapidly growing in the Netherlands, accounting for about 32% of the BEVs market in 2018. Another emerging battery technology is the NMC-622 battery, which has been widely used on models launched or upgraded for the quest for a longer driving range (Table S2 in SI). The market share of NMC-622 battery in the Netherlands has also continuously increased since 2016, accounting for over 40% by 2019.

3.1.2. Future EV demand and battery technology in BEV models

Following the Dutch Climate Agreement goals, BEVs will cover over half of the EV market by the year 2021 and keep increasing until reaching 100% by 2030. For the short lifespan scenario shown in Fig. 1, the estimated annual demand for BEV will be 0.06 million units in 2020 and over 0.95 million units per year after the year 2031, a circa 15-fold increase. The estimated BEV demand for the long lifespan scenario and the extended EV use scenario are both 22% less than the short lifespan scenario with about 0.8 million units per year after 2030.

The BEV cathode chemistry applied will undergo substantial changes in the coming 20 years. LMO and NMC-111 batteries will likely phase out in the next few years. Major BEV markets in the coming decades will be dominated by NCA and NMC batteries, although undergoing different trends. The market share of NCA battery will decline, and NMC-622

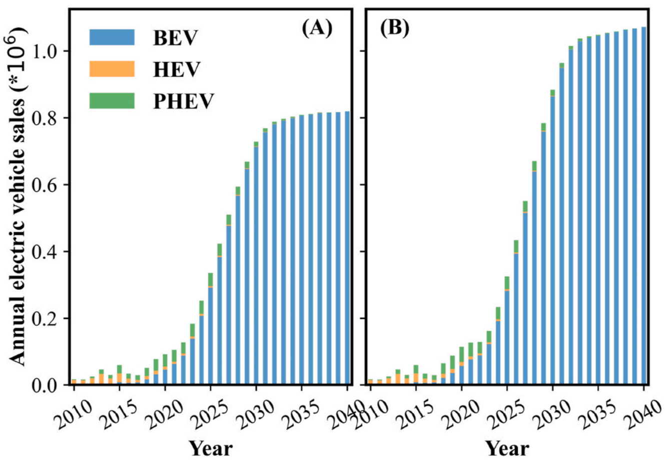

Fig. 1. Estimated annual demand for HEVs, PHEVs and BEVs in the Netherlands through 2040 for (A) the long lifespan scenario and the extended EV use scenario, and (B) the short lifespan scenario. Stacked bars before 2020 represent historical sales of HEVs, PHEVs and BEVs in the Netherlands, and stacked bars from 2020 to 2040 represent scenario years.

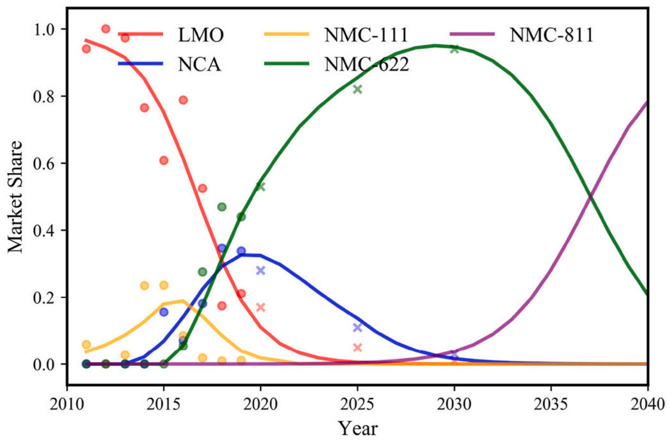

Fig. 2. Market share for different types of battery cathode technology applied on BEVs through 2040. The scatters before 2020 represent historical data in the Netherlands. Scatters between 2020 and 2030 represent the aggregated projections largely based on the report from the World Bank Group (Hund et al., 2020).

battery will continue to grow until 2030. By then, NMC-811 batteries, which currently represent one of the most promising battery technologies, will become a strong substitution of NMC-622 battery since the late 2020s.

3.2. *Metabolism of lithium, cobalt and nickel from the future EV sector*

In 2019, the total Dutch passenger mobility fleet required EV batteries that contained roughly 0.3 kilotons (kt) of Li, Co and Ni in metal content (Fig. 3). Our scenarios project that the annual demand in this sector for Li will increase until the year 2032 and subsequently drop by 2040 to an annual demand of about 11.2 kt/year for the short lifespan scenario, or 8.6 kt/year for the long lifespan scenario. Li demand for the extended EV use scenario will keep increasing until 2040 and reach around 16.6 kt/year following the increased replacement of EV battery. The annual Ni demand follows a similar trend to Li, projected to reach 65.6 kt/year for the short lifespan scenario, 50.2 kt/year for the long lifespan scenario, and 98.1 kt/year for the extended EV use scenario by 2040. The demand trends of Co differ starkly from those of Li and Ni. For the scenarios in which one EV battery is used per EV, Co demand will increase until 2032 to the highest annual need of 16.3 kt/year for the short lifespan scenario and 12.7 kt/year for the long lifespan scenario and then start to fall off. For the extended EV use scenario, the highest

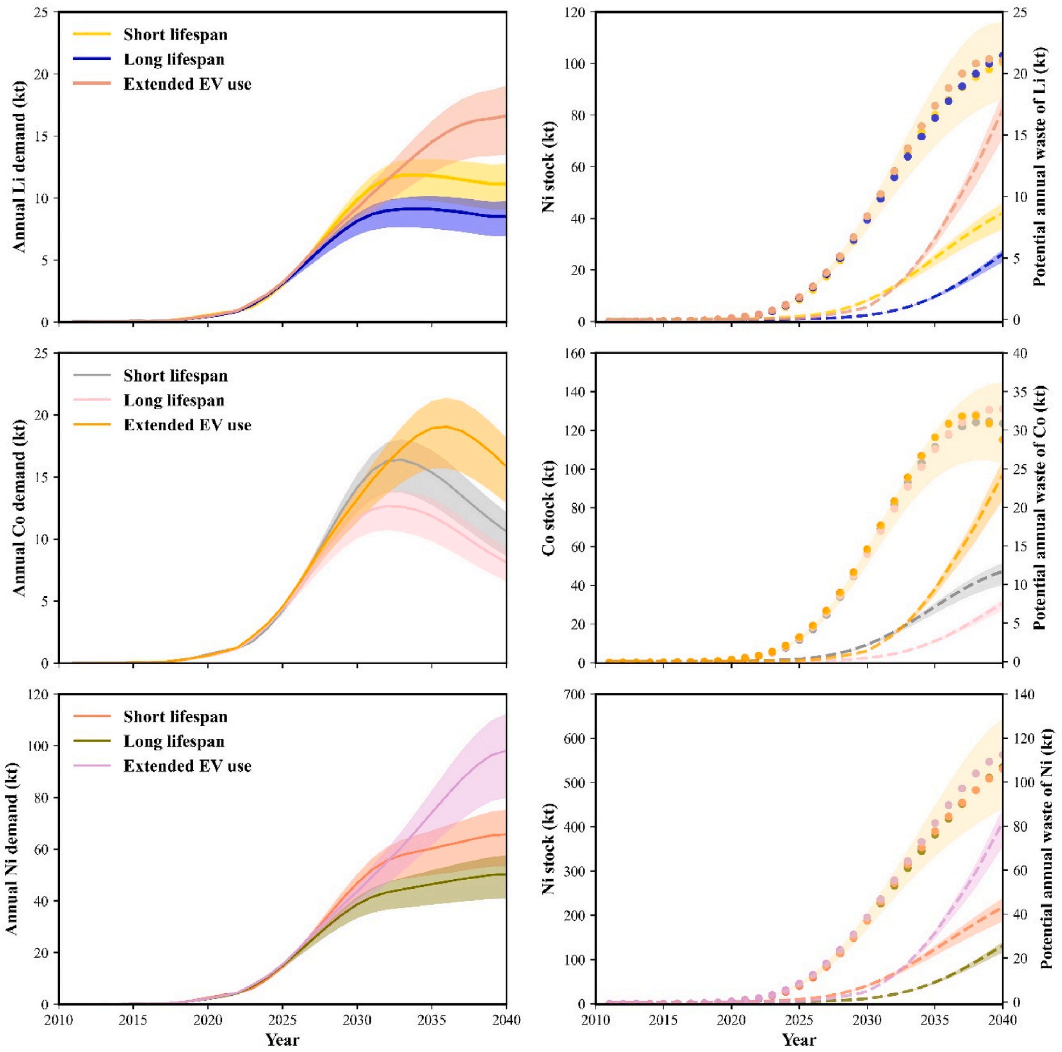

Fig. 3. Estimated annual demand (solid lines), stock (scatters) and potential annual waste (dashed lines) for Li, Co and Ni in EV batteries in the Netherlands through 2040 for different lifespan scenarios. The solid lines, scatters and dashed lines represent the results under the assumption of battery capacity for the medium driving range. The result bands represent the range of the results under different assumptions on battery capacity.

annual demand of Co will be 19.1 kt/year in 2036. Depending on the scenario, there will also be major changes in per capita (cap) metal demands by 2040. Li demand will increase from 0.03 kg/cap/year to a range of 0.5–0.9 kg/cap/year. Ni demand after 2032 significantly increases to 2.7–5.3 kg/cap/year. Co demand will reach the range of 0.7–1.1 kg/cap/year in 2023 at the highest point.

The stocks of Li, Co and Ni by 2040 will reach 103 kilotons, 130 kilotons and 530 kilotons, respectively. This entails an increase of about 147 times, 163 times and 214 times compared to their 2019 stocks. Furthermore, as EV batteries reach their end-of-life, the potential annual Li, Co, and Ni waste will drastically grow. The shorter lifetime of the EV battery, the larger amount the potential waste of these metals. The potential waste of Li, Co and Ni generated in the extended EV scenario leads to about 3 times more than their potential waste in the long lifespan scenario (Fig. 3).

3.3. *Sensitivity analysis*

The power capacity of EV batteries and changes in battery technologies also affect the metal requirement for future Dutch EV batteries. As shown in Fig. 3, the metal demands vary substantially if a low or high battery capacity is assumed, especially under the extended EV scenario where the range can reach ±17.6% for Li, ± 13.2% for Co, and ±17.6% for Ni, respectively. In relation, the variation range of metal stocks will reach ±16.5% for Li and Ni, and ±10.2% for Co. Potential Li, Co and Ni waste generated in 2040 will vary at the range of 9%–15% under different assumptions on the battery capacity. Performance improvements in current mainstream batteries, for example by optimizing the cathode structure and anode material (Cano et al., 2018; Peters et al., 2017), could lead to an 8% variation range of the demand for each metal (Fig. S6 in the SI).

4. Discussion

A key component of the climate agreement to decarbonize the Dutch mobility sector is that vehicles sold in the Netherlands from 2030 onwards will be carbon neutral, implying that EVs will drastically increase their market share in the coming 10 years (Dutch Ministry of Economic Affairs and Climate, 2019). Our results showcase that Dutch EV demand in 2030 will be at least 10 times larger than its sales in 2019, and will likely drive the formation of large Li, Ni and Co stocks within the Dutch economy. The supply will heavily depend on market adoption of novel battery technologies, battery capacity, and lifespan. Our analysis shows that Li demand will keep increasing until 2028, when it will more or less plateau at a level of more than 8-fold higher compared to the current market. Co demand shows a growing trend until the early-2030s, when the annual demand will be at least 11 times more than that of 2019, but in subsequent years it will fall off. Ni demand will keep continuously increasing until 2040, reaching at least 50-fold values as compared to its demand in 2019. These distinctive demand trends of Li, Co and Ni are mostly a consequence of the future shift toward low-Co batteries (Song et al., 2019). Higher capacity batteries for a longer driving range (an additional 100 km per charge) would imply that Li, Co and Ni demand will increase by a further 10%–19% by 2040. Metal cathode demand will likely double if two EV batteries are used per EV lifetime.

Previous assessments from the ProSUM project (Huisman et al., 2017) found that the annual amount of Li, Co, and Ni required in all batteries in the Netherlands remains relatively constant up to 2020, reaching values of 420 tons/year, 560 tons/year, and 780 tons/year, respectively. These lower outcomes resulted from a base scenario wherein no policy-incentivized growth of the EV market was foreseen, with a prediction of BEV reaching 0.05 million units by 2020. A previous study (Hache et al., 2019) found that the average Li demand in the transport sector for EU countries varied from 0.22 to 0.26 kg per capita, whereas literature focused on specific areas, like Japan (Sato and Nakata, 2020) and the U.S. (Fishman et al., 2018) found 0.058 kg–0.14 kg per capita lithium demand by 2040. All these results are much lower than 0.7 kg per capita envisioned in the Netherlands following our short lifespan scenario. Moreover, the Co demand per capita would reach 0.9 kg by 2030 from our model, which is also much larger than the findings of 0.073 kg per capita within the EU countries (Bobba et al., 2019) and 0.11 kg per capita in the U.S. (Fishman et al., 2018). This marked difference can be fully attributed to the ambitious Dutch policy target that by 2030 all passenger cars sold in the Netherlands should be carbon neutral and that this target will be met mainly by BEV's. Understanding the material economy of EVs is important for Dutch policy makers in order to assess market growth and enable appropriate end-of-life measures for EV batteries.

The promotion of EVs application in the Dutch transport sector indicates rapid accumulation of Li, Co and Ni in the coming decades. Although the results of the three scenarios show varied annual metal demands, the difference of their in-use stock is not significant, which will expand at least 140 times in 2040 compared to the stock in 2019. Our results also reveal that if only one EV battery is used during the EV lifetime, the extension of 62% average lifetime of the EV battery would reduce annual metal demand by 30%. The higher turnover of EV batteries, the lower annual primary material needs. Hence, the extension of battery service time in the Netherlands is an essential way to improve the intensity of metal use and mitigate their increasing demand for primary metal resources (Pauliuk and Müller, 2014; Tisserant and Pauliuk, 2016). Policy makers need to stimulate the prolongation of EV battery service in order to alleviate the heavy reliance on raw materials. The development of new technologies that reduce the metal intensity of EV batteries (especially of Co extracted from the conflict regions (Olivetti et al., 2017; Sovacool et al., 2020; van den Brink et al., 2020) is also crucial to ensure that reducing GHG emissions from the mobility sector in the Netherlands does not come with additional trade-offs in terms of material extraction.

When EV batteries reach their end of life, a large amount of secondary Li, Co, and Ni could be obtained via efficient recycling processes. The ultimate recycling for end-of-life batteries would rely on a comprehensive recycling system at the national scale, together with abundant treatment capacities and mature recycling technologies. However, these are all still at a very early stage for Li-ion batteries, both in the Netherlands and globally (Danino-Perraud, 2020; Harper et al., 2019; Leon, 2020). To date, although the open-loop recycling rate of Li is still less than 1%, and over 45% for Co and Ni, enhancements are foreseen in the coming future (Godoy León et al., 2020; Graedel et al., 2011; Harper et al., 2019; Hund et al., 2020; Song et al., 2019). Under the assumption for increasing recycling rates, the expected amount of the secondary Li and Co in 2040 would be more than 2 kilotons/year, and at least 19 kilotons/year for Ni. These amount would exceed the imported record of primary Li, Co and Ni in 2019 in the Netherlands (see details in Table S4 and Fig. S7 in the SI). As no domestic production of these raw materials exists in the Netherlands, the secondary Li, Co and Ni recycled from discarded EV batteries could have the potential to meet demands for the Dutch industry. Nevertheless, this necessitates that the open-loop recycling rates are greatly improved in the coming years. Moreover, a high collection rate of the discarded EV batteries is paramount to ensure minor leakages from the recycling process. Therefore, policies should strive towards establishing a comprehensive system for tracking and collecting the end-of-life EV batteries to guarantee the control of these wastes, as they represent a strategic stock for potential secondary mining. At the same time, an efficient end-of-life battery management system and recycling infrastructure also need to be well established to ensure that the discarded EV batteries are appropriately processed and that their secondary materials can be reused for sustainable industrial production in the future.

In our study, we have only estimated metal demands for passenger-based vehicles in the transport sector as they constitute the largest portion of the mobility sector (European Commission, 2019). Vehicles for commercial use and public transport were not included, and, consequently, some battery technologies were not taken into consideration, such as the LFP, which is widely used in electric mobility in China (Olivetti et al., 2017; Song et al., 2019; Sun et al., 2019). Future studies could expand the scope to include all vehicles types, leading to a more complete understanding of the changes and challenges toward rapid decarbonization of the mobility sector in the Netherlands.

5. Conclusions

In this study, we explored the implications of the Dutch Climate Agreement on future demand of the valuable metals Li, Co, and Ni in the mobility sector following a dynamic MFA model combined with scenario analysis. Current Dutch policies require a carbon-neutral transport sector by 2030, causing EV demand to grow by an order of magnitude by 2030, and, consequently, the demand expansion of Li, Co, and Ni.

We specifically modeled the impact on metal demands from the innovation in cathode chemistry, battery capacity, and EV battery lifespans. Our results show that by 2040 the demands for Li, Co and Ni will expand at least 7 times and the stock will expand more than 140 times, compared to the 2019 levels. The dynamic change of battery cathode chemistries over time results in different demand trends for Li, Co and Ni. The quest for an additional 100 km driving range grows annual metal demand by 10%–19%. The extension of 62% average lifetime of the EV battery would reduce 30% of annual metal demand. The lack of domestic supply of raw material and heavy dependence on EV batteries imports in the Netherlands suggest that future mobility sector strategies should follow a comprehensive assessment and close monitoring on metal demand trends as the basis for policy making. Meanwhile, policies must steer technological development toward solutions that alleviate the demands on (critical) raw materials. Furthermore, they must incentivize the production of batteries with a longer lifespan and promote a lower demand of long-range driving. These strategies would lower both the demand for Li, Co and Ni, and the amount of batteries reaching end-of-life. Hence, we specifically suggest that extending the battery service time in all possible applications is key to reduce the growing demand for primary metal resources. More incentives should also be offered to promote the production and sales of vehicles in small to medium sizes.

Significant secondary metal resources will become available from EV batteries at their end of life in the coming decade. With the proper treatments of discarded Li-ion batteries, the expected end-of-life of EV stocks will present an opportunity for a non-car manufacturing country such as the Netherlands to strategically assess how to best valorize end-of-use batteries within a circular economy context. Therefore, enacting a well-organized waste management system and the improvement of recycling technology as early as possible is necessary to improve the feasibility of extracting secondary resources for creating a sustainable, resilient, and high-speed transition toward a green mobility sector.

CRediT author contribution statement

Chen Tang: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation. Writing - review & editing.

Benjamin Sprecher: Methodology, Supervision, Writing - review & editing.

Arnold Tukker: Supervision, Writing - review & editing.

José M. Mogollón: Conceptualization, Methodology, Software, Supervision, Writing - review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.resourpol.2021.102351.

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